1-1-2005

Hydrostratigraphy and allostratigraphy of the Cenozoic alluvium in the northwestern part of Las Vegas Valley, Clark County, Nevada

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HYDROSTRATIGRAPHY AND ALLOSTRATIGRAPHY OF THE CENOZOIC ALLUVIUM IN THE NORTHWESTERN PART OF LAS VEGAS VALLEY, CLARK COUNTY, NEVADA

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science

in

Geology

Department of Geoscience
University of Nevada, Las Vegas
August, 1996

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August, 1996

ABSTRACT

This investigation was conducted to determine the location, nature, and boundaries of the most permeable unit within the alluvial aquifer material in Las Vegas Valley. It was prompted by declines in specific capacity of about 90% at the Las Vegas Valley Water District's West Central Well Field. It was hypothesized that the decline in specific capacity resulted from dewatering of the most permeable interval of the alluvium. Lithologic descriptions from wells and aquifer test information were analyzed for geologic and hydrogeologic variability. New information, in the form of detailed unpublished lithologic and hydrologic information, was available from twenty water wells drilled between 1989 and 1994.

The geology was defined using allostratigraphic units. Allostratigraphic units were selected because the alluvium exhibits more lithologic variation within each stratigraphic unit than between units. The detailed new information was combined with, and compared to, drillers' logs of older wells. Four (4) allostratigraphic units are introduced in this investigation; they have a combined thickness of about 300 meters and cover an area of about 225 km^2. The allostratigraphic units were useful in describing the general shape of depositional stratigraphic units within the alluvium.

Aquifer test and lithologic information was used to define the boundaries of units of differing permeability within the subsurface. These units of differing permeability are the six (6) hydrostratigraphic units introduced in this investigation. The most permeable hydrostratigraphic unit is a distinct 20 to 90 m thick horizon, lying generally above 230 m below land surface. When the production wells were first installed at the West Central Well Field in the 1960's, most of the permeable unit was saturated. In 1993 the potentiometric surface was at or below the bottom of this hydrostratigraphic unit.

The results of this investigation are designed to be incorporated into a hydrogeologic model of Las Vegas Valley. The model is being developed to predict changes in water levels associated with different pumping strategies and thus more accurately predict yields of new wells proposed in the area of investigation. This is the first use of either allostratigraphic or hydrostratigraphic units in Las Vegas Valley and may be the first investigation to map both kinds of units at the same time.

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ACKNOWLEDGMENTS

This thesis has been a struggle to complete, and was accomplished through the help of many people. Briefly mentioning their names here does not touch upon my indebtedness to them. I would like to thank my committee members, Dr. Paul Seaber, Dr. Fred Bachhuber, Dr. Steve Rowland, Dr. Don Schmiedel, and Dr. David Weide who served on the committee during the sabbatical of Dr. Bachhuber, for their patience, advice, and effort reviewing and guiding this thesis.

A special thanks to current and former members of the Southern Nevada Water Authority, Resources Department (formerly known as the Las Vegas Valley Water District, Research Department) Jeff Johnson, Erin Cole, Alan Bernholtz, and Kim Zikmund. Everyone was a tremendous help, especially in keeping me somewhat sane. A very special thanks to Terry Katzer, Kay Brothers, and Mike Johnson for their advice, support, and review. Without their support this thesis would have been much more difficult, if not impossible, to complete while working full time at the Southern Nevada Water Authority. It has been a pleasure to know and work with people of such high caliber, and I am deeply indebted to them.

I would also like to thank Craig and Charity Shirley, as well as Eric Caldwell, for their support and review and the faculty of the Geoscience department. Last but by no means least, thanks to my parents Judy O'Neill and Terry Donovan for instilling in me the importance of education, and for their moral and financial support over the years.

Charity Shirley suggested the name Las Vegas Wash Aquitard and Mike Johnson suggested the name La Madre Mountain aquifer.

This research was funded by the Las Vegas Valley Water District.

CHAPTER 1

INTRODUCTION

This investigation examines the hydrogeologic framework of the alluvium in Las Vegas Valley. The investigation is designed to complement related research on the physical, hydrogeochemical, and isotopic variation within the alluvial aquifer system and the interaction between the aquifers undertaken by the Desert Research Institute (DRI), Geoscience Department of the University of Nevada, Las Vegas (UNLV), Las Vegas Valley Water District (District), and the U.S. Geologic Survey (USGS).

Purpose

The purpose of this investigation is to identify the spatial occurrence of high and low permeability units within the alluvium of the northwest part of Las Vegas Valley (fig. 1) by detailed analysis of District and nearby wells. At least one distinct high permeability interval of approximately 60 meters thickness can be identified at these wells. The nature and boundaries of the permeability intervals (hydrostratigraphic units) in the alluvium are addressed in this investigation.

The recent municipal supply wells drilled by the District between 1989 and 1994 are completed (screened/perforated) in predominately coarse-grained alluvial fan sediments on the west side of the valley. The distribution of flow rates and reported transmissivity values from aquifer tests of some of these new District wells are not adequately explained by

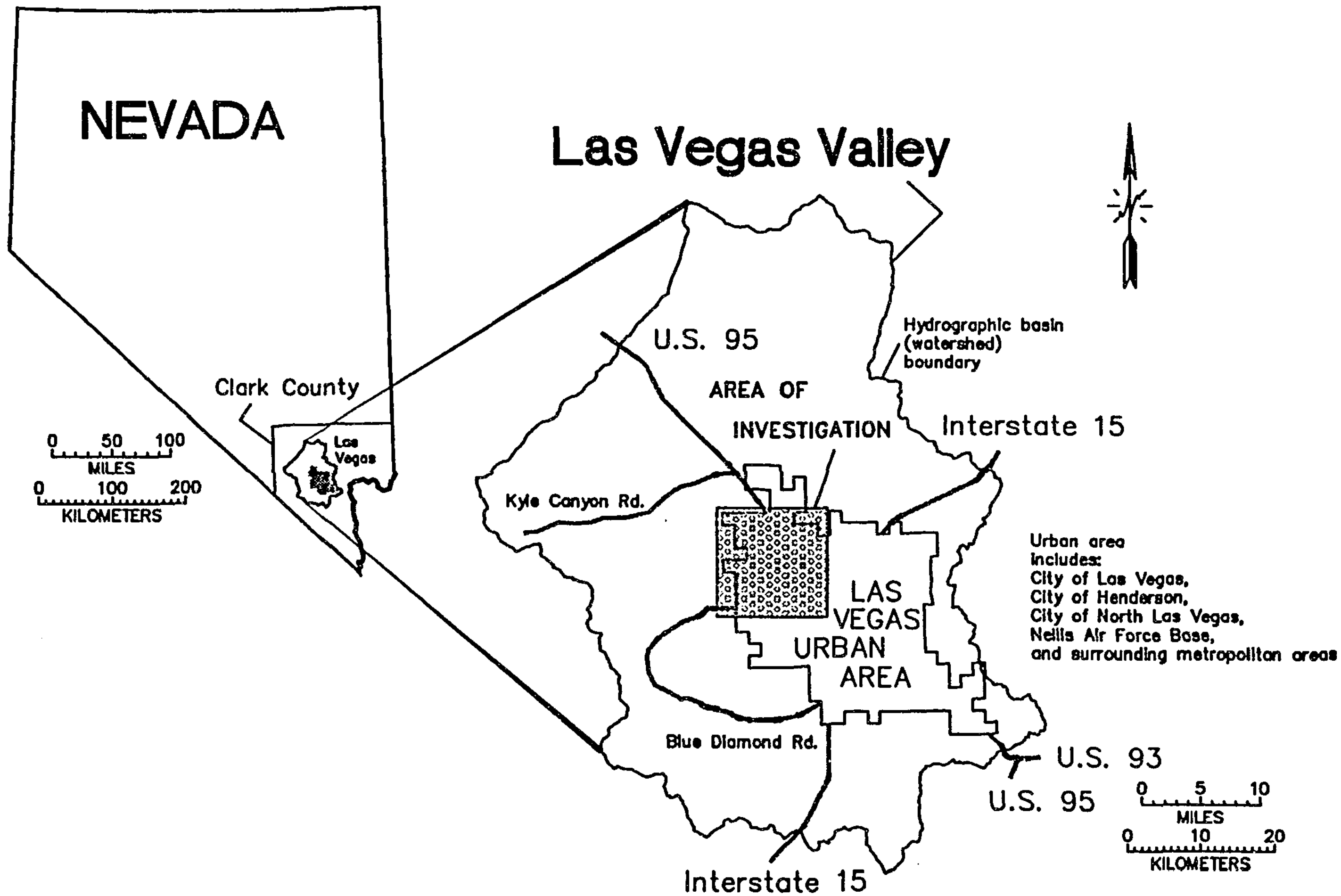


Figure 1. — Location of area of investigation within Las Vegas Valley, Clark County, Nevada.

previous descriptions of Las Vegas Valley hydrology. Earlier reports emphasized grain size as the primary criterion for dividing the geologic units and the principal feature controlling permeability. Within the alluvial fans the lithologic variation is subtle; the primary mappable feature is the degree of cementation. This investigation applies two stratigraphic methods that are independent of lithology. The hydrogeologic variation is mapped as hydrostratigraphic units and the geologic variation is mapped as allostratigraphic units.

Most of the data used in this investigation were collected between 1989 and 1993 by District personnel and include detailed lithologic, hydrologic, and geophysical data. The District plans to incorporate the results of this research into a new hydrologic model of the Las Vegas Valley. The new District model is being developed to predict changes in water levels associated with different pumping scenarios in the valley and to more accurately predict yields of new wells proposed for the area of investigation.

Objective

The objective of this investigation is to develop a hydrogeologic and geologic framework to better explain observed variations in permeability found in the northwestern part of Las Vegas Valley. To develop this new framework, the four work elements listed below were performed.

Work Elements

1. Document geologic variation within the alluvial-basin fill using allostratigraphic units.
2. Determine lateral and vertical variations in permeability by analyzing aquifer test data.

3. Document variability in the potentiometric surface that may be related to the heterogeneity of the alluvial aquifers by collecting static water-level measurements.
4. Describe and analyze the relationship between the allostratigraphic and hydrostratigraphic units.

The District is developing a numerical flow model of the Las Vegas Valley based upon MODFLOW (McDonald and Harbaugh, 1988). This investigation explains hydrogeologic variation within the area of investigation. The greatest range of permeability, the least understood controls on permeability, and the largest capacity wells in the valley are within the area of investigation. The hydrostratigraphic units described in this investigation can be converted to computer modeling units for input into a hydrologic flow model.

Approach

This investigation uses the following approach to accomplish the previously described work elements:

1. Review previous work to determine methods used to document hydrogeologic variation within Las Vegas Valley. In previous reports, drillers' logs were interpreted, transmissivity (and/or specific capacity) estimated, and static water-levels reported. These traditional hydrogeologic investigation methods are used in this investigation.

   One of the most important features of Las Vegas Valley hydrology is the significant water-level changes reported since the first well was drilled in 1906. Most of the in-depth reports on the hydrogeology of the valley quantified the water-level changes. Both water-level declines associated with pumping and water-level rises associated with injection have been reported.

2. Determine the area of investigation through the availability of detailed lithologic and hydrologic information. Most of the previous investigations describe hydrogeology for the entire Las Vegas Valley. In the eastern part of the area of investigation, these earlier reports define the hydrogeologic unit names, intervals of differing permeability, and alluvium flow characteristics. This investigation modifies previous work and refines previously defined intervals of permeability, within the alluvial fans on the west side of the valley.

3. Compile a database of static water-levels, well performance characteristics, aquifer-test information, lithologic information from drillers' logs, and detailed well logs. Most of these data are unpublished. Obtain historic water-level data from the District files, supplemented with limited provisional data of the U.S. Geological Survey (USGS). Collect static water-level measurements in October, 1993 specifically for this investigation. Obtain well performance characteristics, aquifer test information, borehole geophysics, and detailed lithologic information from the files of the District and City of North Las Vegas (NLV). Drillers' logs used in this investigation are on file at the Nevada Department of Water Resources (State Engineer).

4. Plot the data to determine the spatial variablity and evaluate the geologic and hydrogeologic variability within the alluvium. First generate maps, then create cross-sections. Calculate and plot contours for numeric data with good spatial control, such as water-levels, using the minimum curvature estimation (Briggs, 1974, p. 39)

package in the SURFER® contouring program. Static water-level measurements are important because the effects of water-level declines described in previous reports (e.g. Harrill, 1976) have continued. Manually contour quantitative data without good spatial control and all lithologic contacts.

This report includes information from previously published reports as well as data from wells drilled between 1989 and 1994. These new wells are generally deeper than the earlier wells to the east and south. The new wells are typically about 375 m deep, with the deepest well in this investigation being 495 m deep.

Evaluate both the reported data and data collected between 1989 and 1994 to determine the changes attributable to variations in permeability. Transmissivity values published in previous reports are of special interest because standard field hydrogeologic methods used to determine transmissivity depend on the saturation of the units tested. Declining water-levels may cause the variation in reported transmissivities between new wells and older wells in the same area. Permeability is a fundamental rock property, but most common aquifer tests stress only saturated units.

5. Investigate allostratigraphic and hydrostratigraphic units as a means of reconciling anomalous geologic and hydrologic data. Plotted data indicate that geologic units are better defined using allostratigraphic units. Similarly, hydrostratigraphic units can better describe the observed hydrogeologic variation.

6. Map the geologic variation using allostratigraphic units and the hydrogeologic variation using hydrostratigraphic units. Most of the sediments described in this

investigation are alluvial fan deposits. Allostratigraphic units are appropriate geologic mapping units because of two features common to most alluvial fans (fig. 2). First, within the upper (proximal) part of the alluvial fan there is minor lithologic variation. Second, within the lower (distal) part of the alluvial fan channelized deposits of coarse and fine-grained deposits are intermingled due to reworking of the alluvial fan deposits. Allostratigraphic units commonly have more lithologic variability within a unit than between units.

Use traditional methods to draw the contacts between both allostratigraphic and hydrostratigraphic units. The hydrostratigraphic units are defined using a combination of lithologic, physical, and aquifer test data, primarily from seventeen municipal wells drilled by the District between 1989 and 1994.

Lithologic and hydrologic control is provided by data from 50 other wells. These control wells are older District wells, City of North Las Vegas wells, domestic wells with water- levels measured by either the District or the USGS, and one City of Las Vegas well.

Data documenting general trends, and site-specific, detailed information are used to define the continuity, correlation, and boundaries of the units defined in this investigation. Static water-levels, geophysical and specific capacity data, and lithologic and hydrologic information from drillers' logs document general trends. Detailed lithologic logs, borehole geophysical logs, and aquifer tests are site specific types of information. The mapped units are defined by combining both general and site specific types of information.

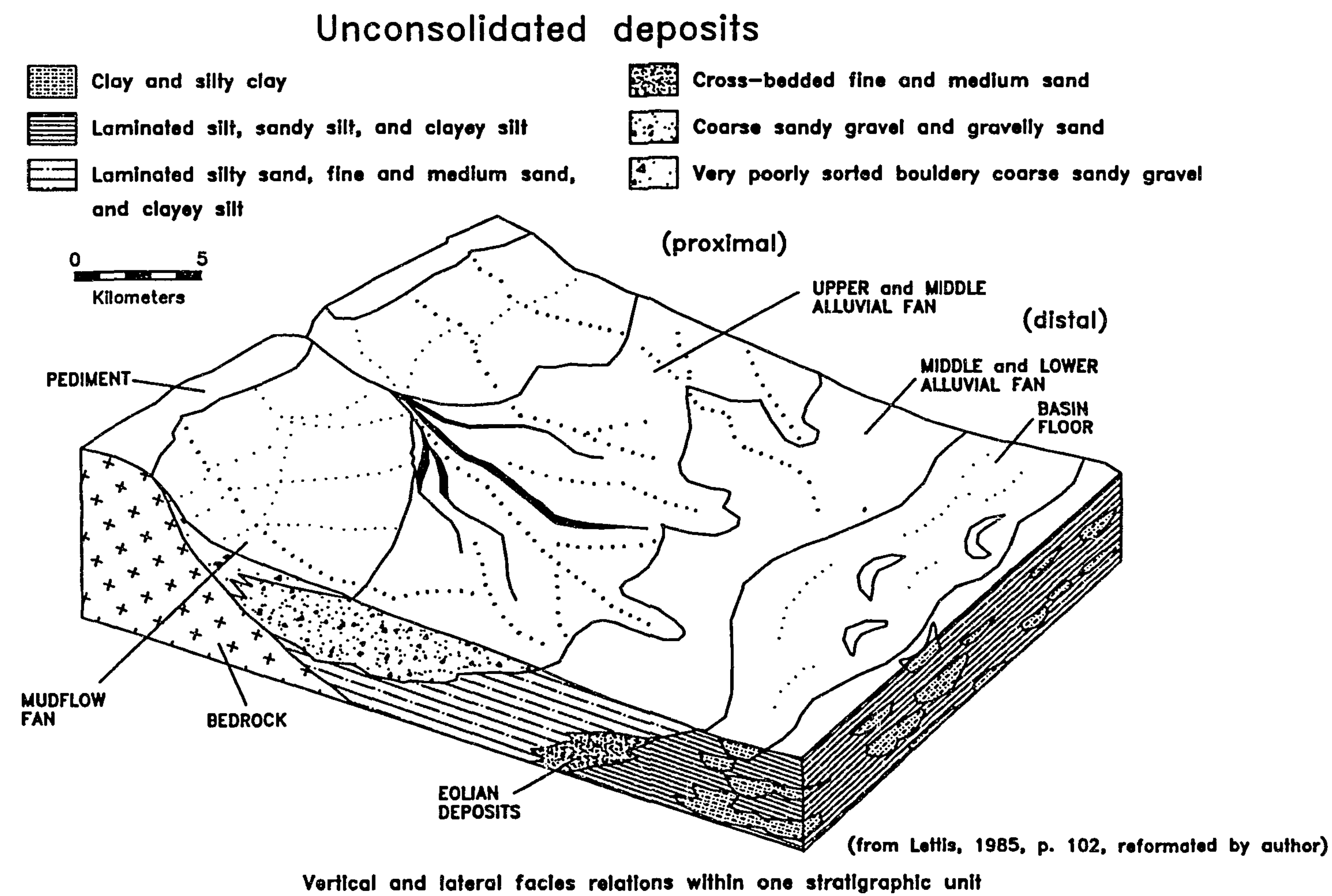


Figure 2. -- Distribution of sediments within an alluvial fan, from Lettis (1985)

7. Compare the newly mapped stratigraphic units to existing defined categories of stratigraphic units. This analysis demonstrates both the utility of the types of units selected in this investigation and their relationship to the older types of stratigraphic units.

Use of Stratigraphic Terms

This investigation uses the ideas and some terminology from several disciplines and specialties. These specialties include, but are not limited to, ground-water hydrology, surface-water hydrology, mathematical hydrologic flow modeling, geomorphology, and stratigraphy. Words commonly have multiple meanings within a specialty and different meanings in different specialties. The word "flow" is a good example of a word with multiple meanings. "Flow" may mean a body of sediment as in a "debris flow" or a volume of water such as "the flow rate of the well."

The use of stratigraphic terms are very important in this investigation. The five most important terms are lithostratigraphic units, allostratigraphic units, hydrostratigraphic units, aquifer, aquitard, and caliche. This investigation uses new stratigraphic terms to more precisely and accurately define the nature of the mapped units. Older stratigraphic, hydrologic, and geologic terms are used with specific definitions. The following section describes the usage of various terms in this investigation.

The 1983 North American Stratigraphic Code (NACSN, 1983) is the source of most of the relatively new stratigraphic terminology used in this investigation. Appendix C is the relevant section of the NACSN (1983) describing allostratigraphic units. Appendix D is a draft of Seaber's (1992) proposed addition to the 1983 NACSN.

Lithostratigraphic units and allostratigraphic units are different kinds of geologic stratigraphic units used to understand the geologic history of an area. The following nomenclature is used within this report:

Lithostratigraphic units (formations) are stratified and tabular bodies that are mapped and characterized by lithic character and stratigraphic position (NACSN, 1983, article 22).

An allostratigraphic unit (alloformation) is "... a mappable stratiform body of sedimentary rock that is defined and identified on the basis of it's bounding discontinuities." The bounding discontinuities are typically depositional hiatuses and erosional unconformities. These units are used to distinguish deposits of similar lithology and to combine within a single unit deposits characterized by lithic heterogeneity (NACSN, 1983, article, 58, in Appendix C). A basin with alluvial fans surrounding a playa is an example of an appropriate use of allostratigraphic units identified in the NACSN (1983, p. 866).

In this investigation, the geologic units mapped in both the alluvial fans and playa are stratiform bodies of sediment characterized by bounding discontinuities that are marked, in part, by caliche horizons. The term allostratigraphic units is used to indicate that the mapped stratigraphic units are stratiform but vary internally in lithologic character.

Within the investigated alluvial fans, the boundaries between the allostratigraphic units tend to divide units of similar lithology. Within the playa and at the alluvial fan/playa contact, the allostratigraphic unit boundaries tend to divide units of different lithology. The important characteristic of an allostratigraphic unit is the bounding discontinuity. Previous subsurface investigations (Maxey and Jameson, 1948; Harrill, 1976; Plume, 1989; Morgan and Dettinger, 1994) emphasized grain-size as the defining characteristic of both the geologic and hydrogeologic units. Allostratigraphic units were not formally defined until 1983 (NACSN, 1983, article 22).

Hydrostratigraphic and allostratigraphic units are equivalent in the stratigraphic hierarchy to lithostratigraphic units. The rank and continuity of the units mapped in this investigation are major concerns.

"Hydrostratigraphic unit" is a term for bodies of rock distinguished and characterized by porosity and permeability (Seaber, 1988 and 1992, article 98). Aquifer, aquitard, and aquifuge are descriptive terms for types of hydrostratigraphic units. Hydrogeologic and hydrostratigraphic terminology used in this report are from Seaber's (1992) proposed addition to the NACSN (1983). Seaber (1992, article 101(b), in Appendix D) defined an aquifer as "... a porous and permeable geologic unit that can transmit significant quantities of fluid under ordinary hydraulic gradients." This is one of several definitions of "aquifer(s)" existing in the literature and differs from most because saturation is not a defining characteristic. Laney and Davidson, (1986, p. 4-6) and Freeze and Cherry, (1979, p. 47) all discuss the various uses of the term "aquifer." Poland and others (1972, p. 2) defined an aquifer system as comprised of "... two or more permeable beds (aquifers) separated at least locally by aquitards (confining units) that impede ground-water movement but do not greatly effect the regional hydraulic conductivity of the system."

In contrast to the term aquifer, the term "aquitard" is applied to units with mappable characteristics and low permeability. Seaber (1992, article 101(b)) defined an aquitard as "... a permeable and porous geologic unit that is incapable of transmitting significant quantities of fluid under ordinary hydraulic gradients." The major difference between Seaber's (1992, article 101(b)) aquifer and aquitard definitions is the ability of the geologic unit to transmit water. This ability is related to relative differences in porosity and permeability. Both aquifer and aquitard are descriptive terms used in naming formal and informal hydrostratigraphic units.

Much of the previous work in Las Vegas Valley was conducted by the USGS. In USGS reports, the terms “confining unit”, “semi-confining unit”, and “reservoir” are used in preference to the term “aquitard.” Unlike this investigation, the USGS reports in Las Vegas Valley were concerned with water supply and therefore emphasized saturated units. When the words "aquifers" and "reservoir" are used as the descriptive part of historical terms, like "principal aquifers,” the term is bracketed by quotation marks to indicate the historic use. Unlike their usage in this report, confinement, saturation, and lithic character were all implied in the historic use of the term. Like the terms used in this report, the historical terms distinguish units differing in permeability.

The terms “aquifer” and “aquitard” are used in this report to indicate the ability of the unit to transmit fluid and as the descriptive part of hydrostratigraphic units. From large to small, the stratigraphic hierarchy of hydrostratigraphic units is: aquigroups, aquiformations, aquimembers, and aquibeds (Seaber, 1992, article 101).

Hydrostratigraphic units (aquiformations) is a term for the stratigraphic units that control flow though a geologic body and are material units defined by their physical properties related to porosity and permeability. Aquifers, aquitards, and aquifuges (Seaber, 1992, article 101) are descriptive terms used to designate specific hydrogeologic features. Saturation and confinement are not fundamental properties of the rock (Seaber, 1992, article

99(l)) and therefore are not used in Seaber's definition of aquifer , aquitard, and aquifuge.

The term "hydrostratigraphic units" should not be confused with the terms "allostratigraphic units" and "lithostratigraphic units." Allostratigraphic and lithostratigraphic units are used to interpret the geologic history of an area (NACSN, 1983, articles 22(a) and 24(a), in Appendix C). Hydrostratigraphic units are used to define the porosity and permeability (i.e., hydrologic properties) of an area.

The term caliche was coined by Blake (1902, p. 225) for deposits in southern Arizona. Caliche has a wide variety of meanings and other terms including: "calcrete," "pedogenic calcrete," "calcic soils," "pedocal," "K horizon," and "Bk horizon," have all been proposed as more suitable terms, especially when inferring genesis (Machette, 1985, p. 3). The term "caliche" is used in this investigation to indicate calcium carbonate cementation formed at or near the surface by soil processes. Due to the nature of available information, the identification of these deposits as pedogenic caliche is not as rigorous as is possible in surficial mapping.

The caliche of this investigation may have been caused by either (1) the infiltration and evaporation of calcium carbonate-rich waters on the alluvial fans, especially near washes, as described by Sowers (1985, p. 75), or (2) evapotranspiration at and near spring areas as described by Quade and others (1995, p. 218). Both of these are near-surface soil processes.

Maps and well locations use the Universal Transverse Mercator grid in Zone 11, North American Datum of 1927 (UTM) projection. This projection, developed by the

Department of the Army (Pearson, 1990, p. 207) , is used on 7.5 Quadrangle maps of the USGS. The coordinate system is used to minimize errors in geographic position.

Previous Investigations

This section describes the previous work on the hydrogeology of Las Vegas Valley, and the development history of allostratigraphic units and hydrostratigraphic units.

Las Vegas Valley Hydrogeology

Ground water in the Las Vegas Valley has been investigated since Carpenter (1915, p. 39) reported that there were 125 water wells drilled in the valley. The relationship between the hydrogeologic and geologic controls in Las Vegas Valley was first described by Maxey and Jameson (1948). The hydrogeology of the valley was subsequently investigated by: Domenico and others (1964), Malmberg (1965), Harrill (1976), Plume (1989), and Morgan and Dettinger (1994). The valley geology was described by Longwell and others (1965). Recent investigations on the hydrogeology of the valley have concentrated on geochemistry and stable isotopes of water (Katzer and Brothers, 1988; Noack, 1988; and Hines and others, 1993) and subsidence (Bell, 1981; and Bell and Price, 1991).

Allostratigraphic units

Although allostratigraphic units were codified relatively recently (NACSN, 1983, article 58, in Appendix C), the developmental history of the these units is long (ISSN, 1987). The concepts embodied in these units can be traced through sequence stratigraphy (Sloss, 1963), seismic stratigraphy (Vail and Mitchem, 1977), and geomorphic surface mapping (Morrison, 1985).

Allostratigraphic units are mapped on the basis of bounding discontinuities, typically unconformities. Allostratigraphic units are used as mapping units where sediments of different age have similar lithology and where sediments of similar age have different lithologies. Sequence stratigraphy has been used where similar lithologic assemblages tend to repeat (form sequences) over geologic time scales. Both allostratigraphic units and sequences are unconformity bound stratigraphic units.

Sequence stratigraphy has been used in marine and terrestrial sediments. Marine sequences occur because of changes in sea level. Terrestrial sequences repeat because a basin responds to tectonism (Hanneman and Wideman, 1991, p. 1335) or climatic changes (Oviatt and others, 1994, p. 133) causing changes in the size of the playa area and alluvial fans. Oviatt and others (1994) documented the use of sequence stratigraphy with allostratigraphic units in Quaternary sediments in Utah. The primary difference between allostratigraphic units and sequences are that sequences are genetic interpretations closely tied to age interpretation whereas allostratigraphic units are field mappable units based upon bounding discontinuities.

Hanneman and Wideman (1991, p. 1338) used "calcic paleosols" as a bounding discontinuity, similar to the use of "caliche" in this investigation. Erosion-resistant caliche horizons are good reflectors for seismic stratigraphy which can document continuity. Confidence that the caliche represents an unconformity is increased if other pedogenic features are present such as other soil horizons or fossils.

Hydrostratigraphic units

Seaber (1988) proposed hydrostratigraphic units as stratigraphic material units defined by the physical properties controlling porosity and permeability, such as the size, shape, and orientation of the pores, and the nature of the interstitial material. Several issues common to hydrologic investigations were addressed by Seaber's (1992) proposed definition. Three of the most significant issues are: (1) the use of the terms aquifer and aquitard (confining unit/semi-confining unit) in a geologic/hydrogeologic context; (2) the relationship between the saturated and unsaturated parts of the same hydrogeologic unit; and (3) the separation of intrinsic properties of the geologic medium from site specific economic considerations.

Seaber's (1988) article on hydrostratigraphic units stressed the need for a stratigraphic solution to the issues described above by reviewing the development of the stratigraphic codes and the history of hydrogeologic mapping. Maxey (1964), who proposed the term hydrostratigraphic units, included both the flow system and the saturation of the geologic medium in the definition. Both are transient properties, and are therefore not included in Seaber's (1992) proposed addition to the 1983 stratigraphic code (NACSN, 1983).

Aquifers have been named using a variety of criteria (Laney and Davidson, 1986, p. 17; and Jorgensen and Rosenshein, 1987, p. 210). Some of the criteria include: (1) redefining conventional lithostratigraphic units as aquifers and aquitards, (2) naming aquifers by geographic area, (3) defining aquifers by purely hydrologic criteria without reference to the geologic variations, and (4) defining aquifers by depths below land surface. These criteria reflect the focus of the research and background of the researcher, not the variation of the geologic medium. Because of this, areas that have been the focus of a wide variety of hydrologic investigations have conflicting sets of aquifer names.

For example, in Las Vegas Valley there are at least two sets of aquifer names in use. Reports focusing on potential aquifer contamination related to urbanization (Van Denburgh and others, 1982; Hines and others, 1993) use aquifer names developed by Kaufmann (1978, p. 1). Kaufmann's (1978) names are dependent on depth and independent of geologic medium. By contrast, this investigation focuses on the geologic medium and therefore uses the aquifer names developed by Maxey and Jameson (1948) and later modified (Malmberg, 1965; Harrill, 1976; Dettinger, 1987; and Morgan and Dettinger, 1994).

Some problems inherent in the various methods used to define aquifers, were described by Jorgensen and Rosenshein (1987) with reference to the "Dakota Aquifer,." Many of these problems are related to both Meinzer's (1923) definition of the term aquifer and the geologic background of the hydrogeologists naming the aquifers. "Aquifer" is a general term that is dependent on the scale of the investigation.

Although Meinzer mentions formations in the definition, aquifers are not necessarily a lithostratigraphic body and may cross formation boundaries. Meinzer (1923, p. 52) defined an aquifer as "A rock formation or stratum that will yield water in sufficient quantity to be of consequence as a source of water supply is called an 'aquifer'..." The geologic background of many hydrogeologists has led to naming aquifers after the lithostratigraphic units containing the aquifers. Inherent in this method is the assumption that the aquifers are coextensive with the lithostratigraphic units. This method is flawed for at least two reasons. The first is that hydrogeologists are concerned primarily with the openings in the geologic medium. These opening are commonly related to alteration and faulting. Conversely, lithostratigraphic units are mapped on the basis of lithic character (NACSN, 1983, article, 22). Aquifers may be composed of several lithostratigraphic units, and the boundaries between units may not occur at the lithostratigraphic boundaries. The second reason is that aquifers named for the geologic age of the sediments is an incorrect use of stratigraphic terminology and may lead to incorrect assumptions about the age of the water in the hydrologic unit(s) of interest (Jorgensen and Rosenshein, 1987, p. 210).

Although stratigraphic terms are significant to most geologic and hydrogeologic investigations, Owen (1987) described a common confusion of time and place stratigraphic terms in geologic investigations. Examples of this confusion are using Early and Late to designate sediments and stratigraphic (formation) names to indicate age.

Seaber's (1992, article 101) proposed definition of hydrostratigraphic units recognizes aquifers and aquitards as unique stratigraphic bodies mapped and characterized by the openings in the rock bodies. The saturation of the rock bodies should not be a criterion in the definition of the hydrogeologic framework because: (1) saturation is a transient condition of the geologic medium and, (2) hydrologic flow and contaminant modeling efforts are commonly concerned with flow in unsaturated parts of an "aquifer." Seaber's (1992) proposal is designed to provide new criteria for naming aquifers in both the hydrogeologic and geologic communities. One of the reasons for naming aquifers is to provide a consistent framework for hydrogeologic and geologic investigations. When aquifers are named, especially if defined as formal stratigraphic units, the differences and relationships between the aquifers and other kinds of stratigraphic units such as lithostratigraphic and allostratigraphic units must be defined.

Physiographic Setting

The Las Vegas Hydrographic Basin (fig. 3) of southern Nevada is bounded by the Spring Mountains on the west, the Sheep Range to the north, Frenchman Mountain to the east and the River Mountains and McCullough Range to the south. The northern part of the hydrographic basin is mountainous. The central and southern parts of the hydrographic basin are dominated by a broad alluvial valley surrounded by mountain ranges. The mountain ranges in the northern part of the hydrographic basin are generally higher than in the southern part. The cities of Las Vegas, Henderson, and North Las Vegas and Nellis Air Force Base are located in the alluvial valley in the central and southern parts of the basin. The eastern edge is about 7 km from Lake Mead and encompasses 4,050 km^2 in Clark County (Harrill, 1976, p. 2).

Las Vegas Valley is drained by Las Vegas Wash which is tributary to the Colorado River. The valley is arid and most of the flow in Las Vegas Wash is the result of urbanization (Plume, 1989, p. A2). The central part of the valley normally receives 10.5 cm per year of precipitation (NOAA, 1994, p. 5, Las Vegas WSO Airport site). The higher parts of the Spring Mountains normally receive greater than 50 cm per year (Emett and others, 1994, p. 589, Kyle Canyon site).

Las Vegas Hydrographic Basin

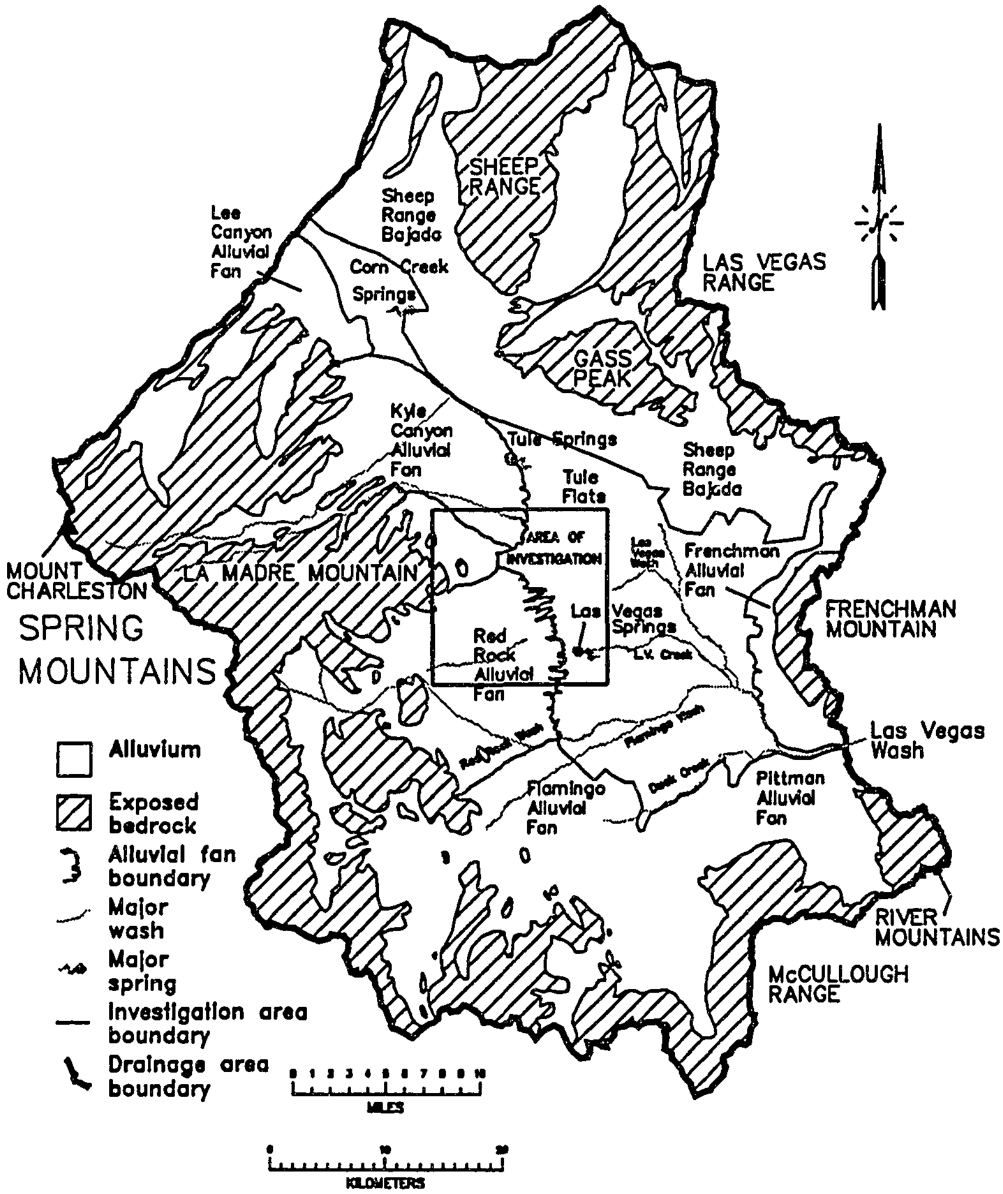


Figure 3. –– Physiographic features of Las Vegas Hydrographic Basin.

Ground-water use

Since the founding of the City of Las Vegas in 1905, the number and areal distribution of wells has increased; prior to 1942, ground water was the only water supply source in the valley (Maxey and Jameson, 1948, p. 9). The importance of ground water to the water supply of Las Vegas Valley has decreased since 1971 because of increased importation of Colorado River water and the revocation of ground-water permits by the Nevada Division of Water Resources (State Engineer). The largest yearly withdrawal of ground water occurred in 1968 (fig. 4).

In 1993, approximately 8.27×10^7 m^3 of water were extracted from the alluvial aquifers, about 15 percent of total water used in the valley (Coache, 1995, p. 19). The remaining 85 percent of the water supply was imported from the Colorado River at Lake Mead. The valley water purveyors, most notably the District, use ground water to meet peak water demand in the period from May to October. The production wells, along with dedicated recharge wells, are also used to artificially recharge the alluvial-aquifer system with Colorado River water from October to May. Between 1988 and May 1994, about 9.90×10^7 m^3 were recharged (E. Cole personal communication, 1994).

The District's and City of North Las Vegas' high capacity wells (100 to 250 ℓ/s) are located in the northwestern part of the valley. This area not only has good flow to wells, but also the best water quality (Hines and others, 1993) in Las Vegas Valley.

Ground–water pumpage in Las Vegas Valley 1905–1994

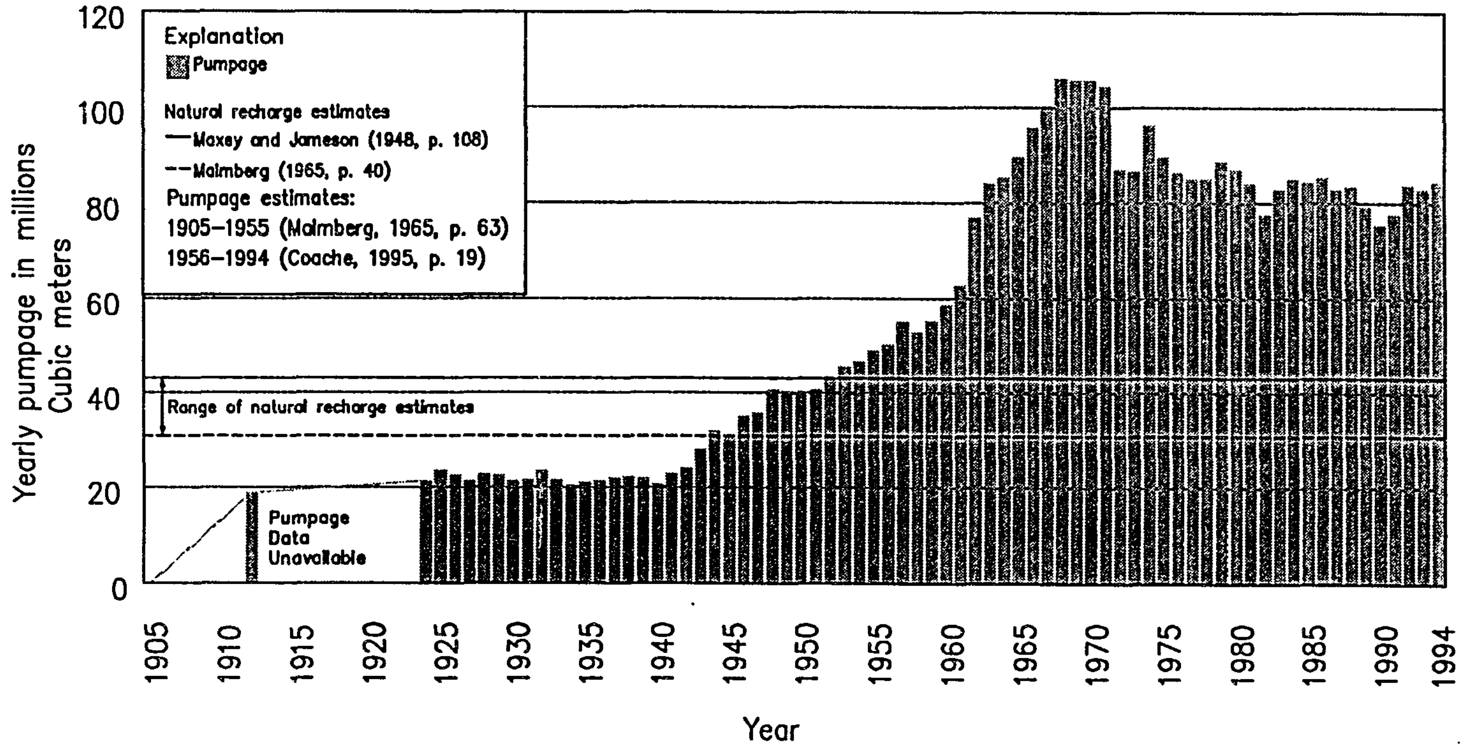


Figure 4. –– Ground–water pumpage in Las Vegas Valley with natural recharge estimates.

Area of Investigation

The area of investigation is located on the piedmont of the Spring Mountains on the west side of Las Vegas Valley (fig. 3). The largest surface feature is the Red Rock Alluvial Fan. Parts of the Kyle Canyon Alluvial Fan, the zone of coalescence between the two fans, and the central playa are also within the area of investigation. The municipal water wells with the greatest flow rates in the valley are located within the area of investigation.

Five subareas that differ in both geologic and hydrogeologic characteristics are defined within the area of investigation (fig. 5). These subareas are:

Subarea 1 -- The southernmost lobe of the Kyle Canyon Alluvial Fan and the zone of coalescence between the Kyle Canyon and Red Rock Alluvial Fans

Subarea 2 -- The northern lobe of the upper Red Rock Alluvial Fan

Subarea 3 -- The central lobe of the upper Red Rock Alluvial Fan

Subarea 4 -- Lower Red Rock Alluvial fan

Subarea 5 -- The central playa, including Tule Flats and the playa beneath the City of North Las Vegas and downtown Las Vegas (The main part of the central playa is east and southeast of the area of investigation.)

Figure 6 is a map of the public land survey in the area of investigation. This map is at the same scale as most of the of the maps of the area of investigation and is provided as a separate illustration to simplify the various maps made in this investigation.

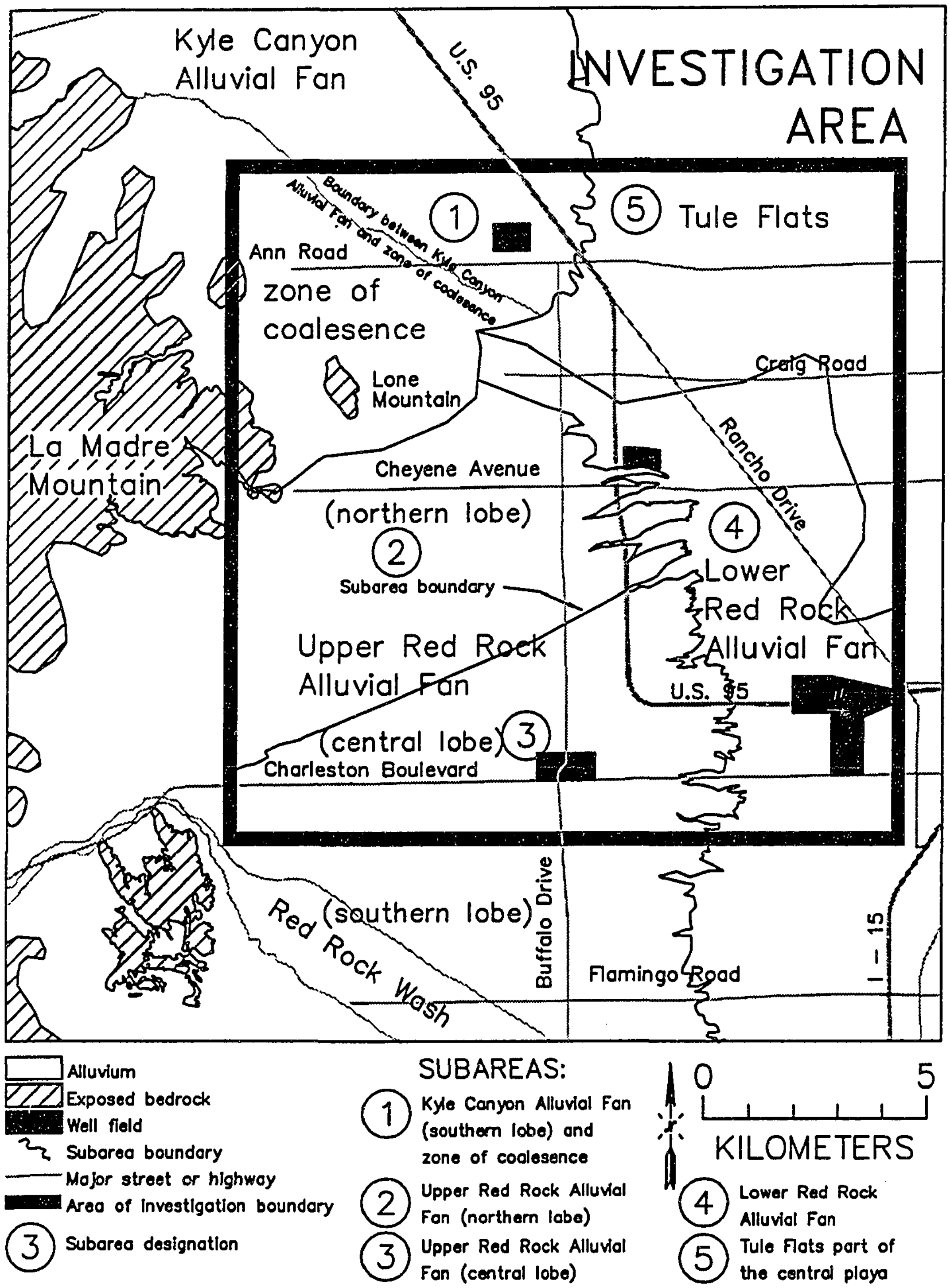


Figure 5. –– Map of the subareas within the area of investigation.

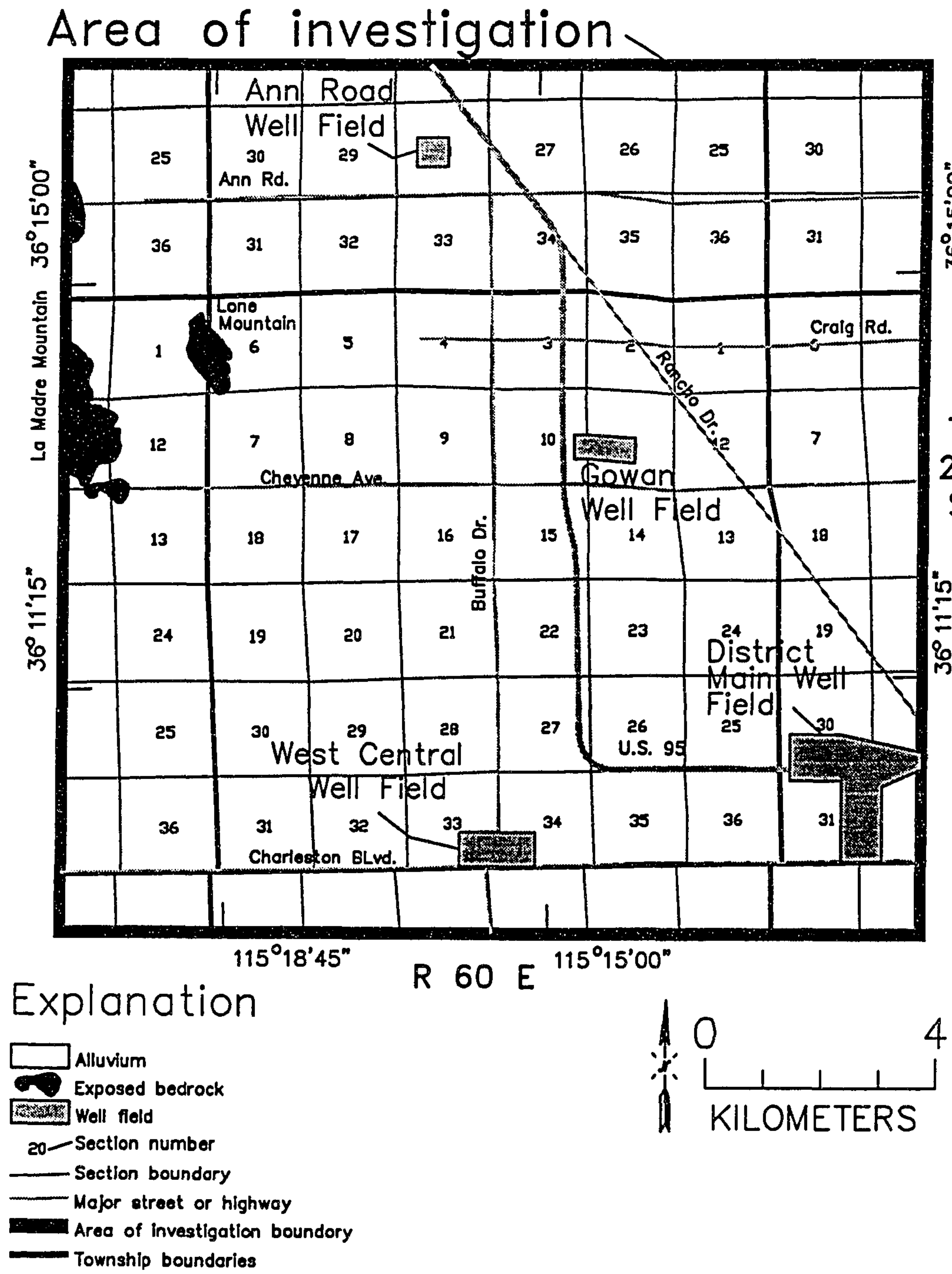


Figure 6. -- Public land survey in the area of investigation.

CHAPTER 2

GEOLOGY

General Geology of Northwest Las Vegas Valley

The most prominent features in northwestern Las Vegas Valley are the Spring Mountains, Sheep and Las Vegas Ranges, and the alluvial fans and bajadas at the bases of these ranges. Figure 7 is a generalized bedrock map modified from Plume (1989, pl. 1).

Plume (1989, A4) divided the bedrock into four categories:

1. "Precambrian metamorphic rocks" that include "Gneiss at the base of Frenchman Mountain" (Plume 1989, pl. 1). The exposure is small and is excluded from figure 7.
2. "Precambrian and Paleozoic carbonate rocks" include: Wood Canyon Formation, Tapeates Sandstone, Pioche Shale, Lyndon Limestone, Chisholm Shale, Goodsprings Dolomite, Pogonip Group, Eureka Quartzite, Ely Springs Dolomite, Lone Mountain Dolomite, Sultan Limestone, Monte Cristo Limestone, Rodgers Springs Limestone, Bird Spring Formation, and Callville Limestone. The "Precambrian and Paleozoic carbonate rocks" is a partial misnomer because it includes non-carbonate formations.
3. "Permian, Triassic, and Jurassic clastic rocks" include: Coconino Sandstone, Toroweap Formation, Kaibab Limestone, Moenkopi Formation, Chinle Formation, and Aztec Sandstone.

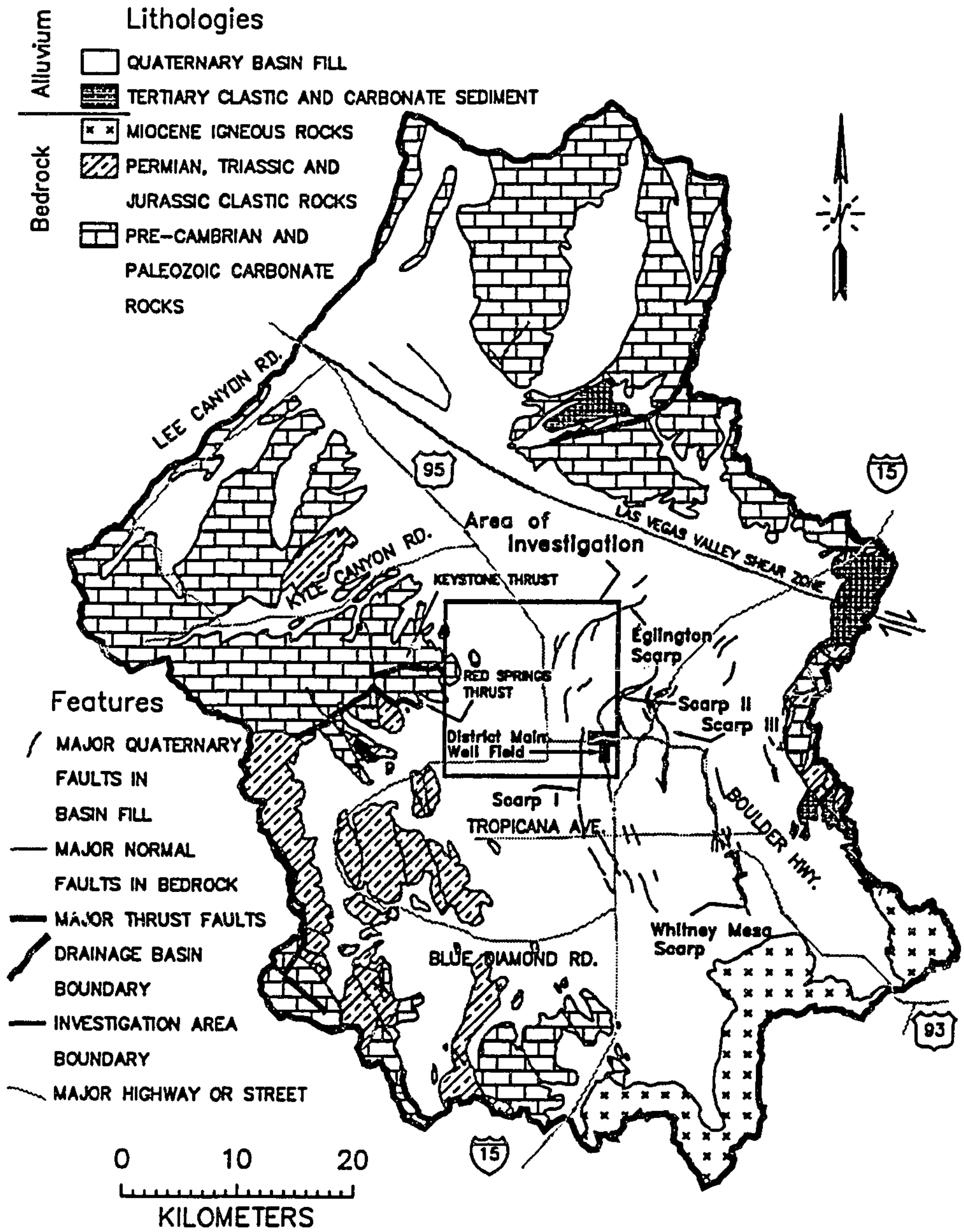


Figure 7. –– Generalized map of lithology and structures in Las Vegas Valley featuring the bedrock lithology catagories and structures of Plume (1989, pl. 1. and pg. A4).

4. "Miocene igneous rocks" include: volcanic flows, flow breccias, and shallow intrusive rocks of dacite, andesite, and basalt in the River Mountains and McCullough Range and also includes quartz monzonite in the McCullough Range. Plume (1989, pl. 1) subdivided the Miocene and Pliocene (Tertiary) sediments into two categories, "Miocene clastic deposits" and the Miocene(?) Muddy Creek Formation. The "Miocene clastic deposits" include the Horse Spring Formation as well as a variety of sediments inferred to be older than the Muddy Creek Formation. On figure 7, the "Miocene clastic deposits" and Muddy Creek Formation are combined into one unit.

The bedrock of the northern Spring Mountains is composed predominantly of Paleozoic carbonate rocks. Bedrock lithologic units in the Sheep and Las Vegas Ranges, located on the eastern side of the valley, are similar to the northern Spring Mountains and Paleozoic carbonate rocks units are assumed to underlie most of the alluvium in the northern part of Las Vegas Valley (Plume, 1989, p. A4).

The southern Spring Mountains are composed primarily of late Paleozoic carbonate and siliciclastic rocks and Mesozoic siliciclastic rocks. The northern and southern parts of the range are divided by La Madre Mountain. Bedrock adjacent to and, presumably, underlying the area of investigation south of La Madre Mountain is Mesozoic siliciclastic rocks. At least four water wells, 2 to 3 km east of the bedrock-alluvium contact, penetrate Jurassic age Aztec Sandstone southwest of La Madre Mountain.

Alluvium

The alluvium in Las Vegas Valley ranges in age from Miocene to Quaternary (Plume, 1989, A4). The central part of Las Vegas Valley (playa) is dominated by fine-grained sediment (silts and fine sands) and the basin margins are dominated by coarse-grained alluvial fan sediments (gravel and sands). Most of the available lithologic data are from the upper 305 m of alluvium. Table 1 is part of Harrill's (1976, p. 6) description of the sediments of this interval.

Most of the exposed alluvium in the area of investigation is mapped as Quaternary in age. Some of the sediments, high on the alluvial fans west and north of the area of investigation and within the central playa may be Pliocene or older (Sowers, 1985; Matti and others, 1987; McDonnell-Canan, 1989).

Coarse-grained alluvial fan and fine-grained spring (paludal) and playa deposits are the most common Quaternary sediments in the valley. The alluvial fan deposits are not part of a formal unit, although the spring and wet playa deposits are either the Quaternary Las Vegas Formation of Longwell and others (1965, p. 50) or possibly Tertiary Muddy Creek Formation. Throughout much of the valley, the total alluvium thickness is over 1,225 m and is at least 1,525 m thick in the central part of the valley (Plume, 1989, p. A1).

Previous investigations of the geology and hydrogeology in Las Vegas Valley have used lithostratigraphic units to describe the alluvium. The lithostratigraphic units most commonly used are the Miocene Horse Spring Formation, Miocene(?) Muddy Creek Formation, and the Late Quaternary Las Vegas Formation.

Table 1. -- Alluvial lithologic units described by Harrill (1976, p. 6, part of table 1)

Age	Lithologic unit	Thick-ness [meters]	Lithology	Occurrence
Quaternary (Pleistocene and Holocene)	Surficial Deposits	15±	Unconsolidated gravel, sand, silt, and clay	Occurs throughout area of valley fill. Exposures not continuous but are limited to areas of Holocene and Late Pleistocene deposition. On alluvial fans unit consists of stream-channel and slope wash deposits. In lower parts of the valley, unit occurs as fairly extensive deposits of sand, silt and gravel
Quaternary (Pleisto-cene)	Lake and playa deposits (includes Las Vegas Formation)	90±	Predominately clay, silt, and fine sand. Contains some regular, thin bedded layers of sand and gravel.	Exposed at base of alluvial fans along the west side of valley; as prominent lake-bed deposits at northwest end of study area; and as irregularly exposed deposits in central part of valley. Well logs indicate upper valley-fill deposits in central part of the valley commonly consist of a sequence of silt, clay and caliche.
Quaternary (Pliesto-cene)	Fanglomerate and valley floor deposits	305±	On alluvial fan, predominately gravel and sand with some silt and clay. Deposits may be well cemented with caliche. On valley floor, generally silt and clay with interbedded sand and gravel. Lithology similar to overlying lake-bed and playa deposits. Upper contact arbitrarily placed at top of first significant water producing sand or gravel.	Occurs throughout are of valley fill. Exposed as alluvial fans but generally concealed by surficial deposits or lake and playa deposits on valley floor.
Tertiary	Muddy Creek Formation	1220±	Silt, and clay with sandstone with some lenses of pebble conglomerate. Locally contains salt and gypsum beds. Interstratified basalt flows in some areas.	Forms prominent bluffs in southeast part of the valley. Also exposed north of and south of Frenchman Mtn. Probably underlies Quaternary valley-fill deposits throughout much of valley.

The type sections of the Tertiary units are located near Lake Mead east of Las Vegas Valley. In both the Lake Mead area, where there is good exposure, and in Las Vegas Valley, where the Tertiary units are buried, the boundary between these lithostratigraphic units is difficult to identify. The different criteria used to distinguish these units in the Lake Mead area can be found in Bohannon (1984) and Duebendorfer and Wallin (1991), and in Las Vegas Valley in Bell (1981) and Plume (1989).

The type section of Las Vegas Formation of Longwell and others, (1965, p. 52) is located north of the area of investigation in fine-grained sediments near Tule Springs. This name is restricted to the fine grained-deposits near Tule and Corn Creek Springs, and other parts of Las Vegas and adjacent valleys. The surficial deposits were mapped in detail by Haynes (1967). Prior to the 1970's, the fine-grained deposits near Tule Springs were thought to be result of a lacustrine depositional environment (Carpenter, 1915, p. 16; Maxey and Jameson, 1948, p. 66; Longwell and others, 1965, p. 51; Haynes, 1967, p. 21). Mifflin and Wheat (1979, p. 27) rejected the hypothesized Pleistocene Lake Las Vegas by documenting that the fossil and stratigraphic evidence for this lake could have originated in a paludal depositional environment.

Subsequent research, primarily by Quade (1986; Quade and others, 1995), at Corn Creek Springs and other spring areas in southern Nevada support a paludal environment of deposition for the fine-grained deposits. The contemporaneous alluvial fan sediments are not included in the Las Vegas Formation because it is a lithostratigraphic unit.

The area of this investigation is within the pediment of the Spring Mountains. Most sediment is alluvial fan deposits composed of at least 60 percent gravel-sized clasts derived from Paleozoic carbonate rocks in the Spring Mountains at least 470 m deep. The alluvial fan sediments are not part of any formal stratigraphic unit. The surficial sediments were mapped by Longwell and others (1965) on the Clark County geologic map simply as Quaternary alluvium. Harrill (1976, p. 6) informally assigned the upper 305 m of subsurface alluvial fan deposits to a Pleistocene "Fanglomerate and valley-floor deposits" lithologic unit. Harrill (1976, p. 6) also assigned the sediments below this to the Tertiary "Muddy Creek Formation" which was described as a fine-grained unit.

Coarse-grained alluvial fan deposits as deep as 470 m below land surface (bls) are described in this present investigation. This implies that either the bottom of the "Fanglomerate and valley-floor deposits" is deeper than previously described, or that the "Muddy Creek Formation" is coarse-grained in at least some parts of the area of investigation.

The sediment described in this present investigation are assumed to be both Tertiary and Quaternary in age, and only the uppermost unit outcrops in the area of investigation. The maximum thickness of units similar in lithology to the surficial deposits where fossils and/or isotopic ages were obtained is less than 100 meters. Sowers (1985, p. 20) collected isotopic age samples from the surface of the Kyle Canyon Alluvial Fan. All of the valid samples were less than 120,000 years ± 25,000 years before present (bp). Carbon 14 ages collected by Spaulding (personal communication, 1992), near Tule Springs were less than 30,000 years bp.

Applicability of Allostratigraphic Analysis

Many of the features used to identify surficial units, such as angular unconformities, could not be identified with the presently available subsurface information. The unit bottoms cannot be observed in surficial expression and the thickness and areal extent of the units are impossible to determine. In the subsurface, all of the units in the central part of the valley tend to be dominated by fine-grained sediments. Coarse-grain sediments dominate the alluvial fans at the base of the ranges surrounding the valley. Figure 8 is a detail of Plume's (1989, pl. 1) map of the surficial expression of fine- and coarse-grained alluvial sediments.

Allostratigraphic units rather than lithostratigraphic units are used for the alluvium in the area of investigation due to the previously described difficulties in working with named lithostratigraphic units. These units require more evidence for formal designation than is given here; however, as informal units they are useful in this investigation.

Allostratigraphic units are recognized in the Code of Stratigraphic Nomenclature (1983, article 58, in Appendix C) as appropriate for basin-fill deposits. These units are defined by bounding discontinuities which are commonly unconformities. The lithologic character of each unit is commonly diverse and boundaries between units may divide sediments of similar lithology (fig.2, p. 10). The bounding discontinuities used in this investigation are buried caliche horizons in the alluvial fan and playa sediments.

Although this investigation is designed to improve the hydrogeologic understanding of the alluvial aquifers, the approach is influenced by stratigraphic principles. The nature, boundaries, continuity, and stratigraphic rank of each unit are important in this investigation. For these reasons, several stratigraphic units are informally named.

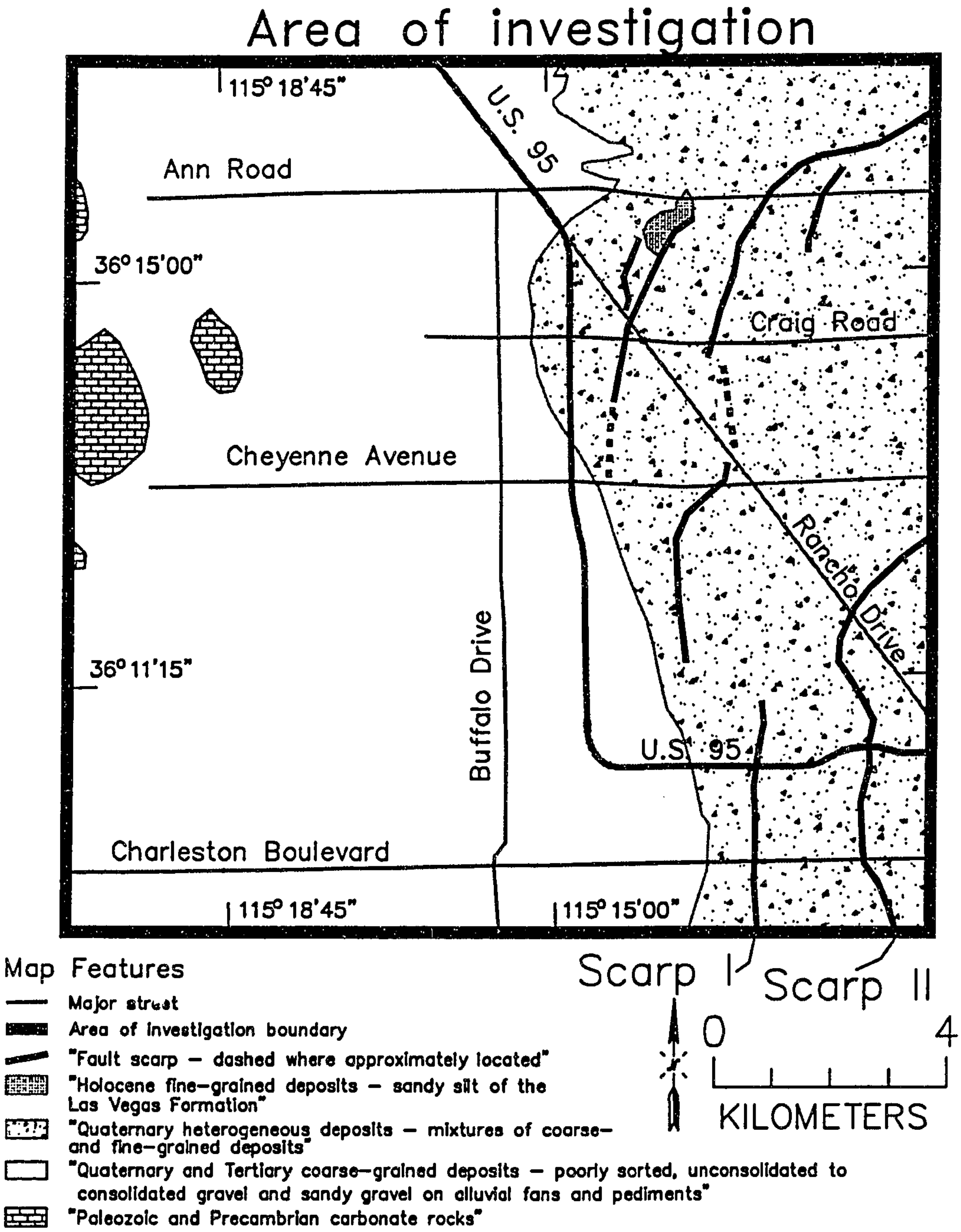


Figure 8. –– Detail of Plume's (1989, pl. 1) generalized geologic map of Las Vegas Valley, in the area of investigation. (reformated by author)

The sediments most closely researched in this investigation are within the upper 250 m of alluvium, informally named the Lone Mountain Allogroup. This unit is an allostratigraphic unit because it is defined by its bounding discontinuities. It is an allogroup because it is composed of two to three units of alloformation rank. The upper 30 to 75 m of the Lone Mountain Allogroup constitutes a distinct alloformation, informally named in this investigation the Tule Springs Alloformation.

Structure

Major structures in the northern Las Vegas Valley shown on figure 7 are the Mesozoic thrusts, folds, and normal faults in the Spring Mountains; the Miocene Las Vegas Valley Shear Zone; and Quaternary fault scarps in the central part of the valley.

Mesozoic thrusting and normal faulting were the first major structural disturbances within Las Vegas Valley (Plume, 1989, p. A7). This tectonism produced a complex series of thrust blocks exposed in the Spring Mountains. The oldest and best exposed of these thrusts is the Sevier age or older Red Springs-Contact-Wilson Cliffs Thrusts which Burchfiel and Davis (1988, p. 91) describe as a single thrust.

Cambrian Bonanza King Formation structurally overlies Jurassic Aztec Sandstone in typical exposures of this thrust. The easternmost surficial expression of this thrust is about 3.5 km east of the area of investigation, at the intersection of Sections 15, 16, 21 and 22 of T20S, R59E, Mount Diablo Baseline and Meridian (MDBM) (Axen, 1985, fig. 2).

Evidence from water wells penetrating bedrock in the western part of the area of investigation suggests that this thrust is buried beneath the alluvial sediment of Section 12, T20S, R59E, MDBM. The exposed bedrock in this area at the eastern end of La Madre

Mountain (Sections 2, 11 and 12 T20S, R59E, MDBM) and Lone Mountain (Section 6, T20S, R60E, MDBM) are Paleozoic carbonate rocks comprising the upper plate of this thrust. A water well in Section 12 and three water wells in the adjacent sections (Sections 5, 7, and 8, T20S, R60E, MDBM) penetrate Aztec Sandstone, the lower plate of this thrust. The thrust must therefore be located west of these four water wells and east of the exposed bedrock.

Burchfiel and Davis (1988, p. 91) report that the thrust exposed higher on La Madre Mountain is the younger Keystone Thrust. The thrusts exposed on La Madre Mountain separate lower plate, upper Paleozoic carbonate rocks and Mesozoic siliciclastic rocks in the southern Spring Mountains from the upper plate, lower Paleozoic carbonate rocks in the northern Spring Mountains.

Emplacement of the right-lateral Miocene Las Vegas Valley Shear Zone with approximately 65 km of strike-slip displacement (Plume, 1989, p. A7) was the next major structural disturbance in Las Vegas Valley. The shear zone cuts across the northern part of the valley with a west-northwestern orientation (Plume, 1989, p. A7). The "bending" of topographic features in the northern part of the valley was noted by Longwell and others (1965, p. 62) in their report on Clark County. Recent work by, Bohannon (1984), Wernicke and others (1984), Guth and others (1988), and Duebendorfer and Wallin (1991) both east and west of Las Vegas Valley have placed limits on the age of deformation as Miocene and placed the shear zone in a larger structural context.

Normal faults cut the alluvial sediments in the central, eastern, and southern parts of Las Vegas Valley (figs. 7 and 8). The time of initiation and origin (tectonic or compaction) of most of these structures has not been determined. Haynes (1967, p. 55) documented a tectonic origin for the Eglington Scarp. These structures cut Quaternary sediments and therefore are assumed to be Quaternary in age. The importance of the structures on the hydrogeology of the valley has not been quantified, although the structures may be conduits for ground-water movement between aquifers.

Geologic Features of Area of Investigation

The deposits in the area of investigation were mainly derived from two watersheds in the central Spring Mountains (fig. 3). The larger and southernmost alluvial fan is the Red Rock Alluvial Fan investigated by McDonnell-Canan (1989). North of the Red Rock Alluvial Fan is the Kyle Canyon Alluvial Fan investigated by Sowers (1985), and a zone of coalescence between the two alluvial fans (fig. 5). The alluvial fans are separated by La Madre Mountain with the zone of coalescence located east and north of Lone Mountain. No perennial streams flow from these watersheds and parts of the associated alluvial fans are derived from intermittent flows. The northeastern part of the area of investigation is located in the Tule Flats part of the central playa and the sediments are composed of fine-grained deposits derived from the Kyle Canyon Alluvial Fan and the Sheep Range Bajada. The Sheep Range is lithologically similar to the northern Spring Mountains and the sediment derived from both ranges is lithologically similar.

General Geology of Subareas

Five subareas (fig. 5) with differing geologic and hydrogeologic character are defined in this investigation (p. 23). Each subarea is dominated by different aspects of the alluvial fan depositional system. Some areas are dominated by proximal coarse-grain alluvial fan sediments while other areas are dominated by fine-grained distal alluvial fan, spring, and playa deposits.

The subareas are roughly triangular or arcuate shaped because the areas are segments of alluvial fans or are bound on the edges by alluvial fans. The boundaries of areas designated as lobes are determined by changes in slope transverse to the topographic contour lines.

The alluvial fans are elongated along the central axis of the fans. The elongation of the fan at the axis is not unique to the Kyle Canyon and Red Rock Alluvial Fans. Bull (1964, p. 114) reported a similar elongation in 75 alluvial fans in California. French (1992, p. 1006) evaluated an additional 19 alluvial fans in California and Nevada and documented that this elongation trend has statistical significance and may be normal for most alluvial fans.

The surficial sediments in the central lobes of the Kyle Canyon and Red Rock Alluvial Fans are strongly cemented by calcium carbonate. The areas designated as the northern and southern lobes are distinctly part of the alluvial fans but are generally not as strongly cemented as the central lobes.

Subarea 1 (Kyle Canyon Alluvial Fan, southern lobe)

The southern lobe of the Kyle Canyon Alluvial Fan, as described by Sowers (1985), is covered by sand- and gravel-sized sediment derived mostly from Lower Paleozoic carbonate rocks in the northern Spring Mountains. The coarse-grained alluvial fan sediments partially cover the fine-grained sediments of the Las Vegas Formation of Longwell and others (1965, p. 50) where these units are in contact at Tule Springs (Haynes, 1967, p. 27; Sowers, 1985, p. 22).

Caliche is abundant in this area, as it is on all of the alluvial fans on the west side of Las Vegas Valley (Sowers, 1985; McDonnell-Canan, 1989). The amount of caliche varies (Stage III to VI+ using the criteria of Bachman and Machette, 1977, p. 40) across the fan surfaces and is best developed in the central lobe of individual alluvial fans. The caliche on the southern lobe of the Kyle Canyon Alluvial Fan (Sowers, 1985, fig. 4) is not as abundant as on the central part of the alluvial fan.

Based on drillers' logs, Plume (1989, pl. 2) described the subsurface deposits as heterogeneous mixtures of coarse-grained sediments with silt. Most of the drillers' logs from this area describe the dominant lithology as gravel with silt. By contrast, gravel with sand is the most common lithology in the other parts of the alluvial fans on the west side of the valley. The relative abundance of silt has a distinct effect on the hydrogeologic properties of this area, especially when combined with the caliche and/or calcite cementation.

The southern lobe of the Kyle Canyon Alluvial Fan has no mapped faults, similar to most of the areas dominated by coarse-grained sedimentation. The Quaternary faults mapped by Bell and Price (1991, pl. 2) are located to the east, in the Tule Flats area.

The southern lobe of the Kyle Canyon Alluvial Fan and the zone of coalescence between the Kyle Canyon and Red Rock Alluvial Fans are characterized by (1) coarse-grained deposits dominated by gravel-sized clasts of carbonate rocks, (2) abundant caliche or calcite cementation, (3) a relatively high percentage of silt compared to similar areas in the Red Rock Alluvial Fan and other parts of the Kyle Canyon Alluvial Fan, and (4) a lack of fault scarps.

Subarea 2 (upper Red Rock Alluvial Fan, northern lobe)

The second subarea is the northern lobe of the upper (proximal) Red Rock Alluvial Fan. Similar to the Kyle Canyon Alluvial Fan, the boundary between the lobes is placed at a break in slope perpendicular to the topographic contour lines. Also similar to the Kyle Canyon Alluvial Fan, the surficial sediments of the central lobe are more strongly cemented than the northern lobe (McDonnell-Canan, 1989, pl. 1). Most of the channels are rills. This subarea is characterized by (1) sand- and gravel-sized clasts of carbonate detritus, (2) moderate calcite cementation, (3) the rarity of distinct washes, and (4) the absence of Quaternary faults scarps.

Subarea 3 (upper Red rock Alluvial Fan, central lobe)

The third subarea is the central lobe of the upper (proximal) Red Rock Alluvial Fan. Subarea 3 is lithologically similar to Subarea 2 (Plume, 1989, pl. 2) and contains no mapped faults. Subarea 3 is distinguished from Subarea 2 primarily because of the observed variation in the hydrologic characteristics, but geologic differences were observed as well. It was observed in this investigation that the subsurface deposits were more strongly cemented in the central lobe of the Red Rock Alluvial Fan and the boundaries of the mapped stratigraphic units are shallower within the alluvium when compared to the northern lobe. The surficial expression of Subarea 3 also differs from Subarea 2. The central lobe of the Red Rock Alluvial Fan (McDonnell-Canan, 1989, pl. 1), the surficial expression of Subarea 3, shows strong cementation and large distinct washes incised into the caliche surface. Subarea 3 is characterized by (1) sand- and gravel-sized clasts of carbonate detritus, (2) strong calcite cementation, (3) abundant large distinct washes, and (4) absence of Quaternary fault scarps.

Subarea 4 (lower Red Rock Alluvial Fan)

The fourth subarea of this investigation is the lower part of the Red Rock Alluvial Fan. The surficial deposits are predominately sand- and silt-sized fine-grained material (Matti and others, 1987) with minor amounts of clay and gravel sized clasts. This subarea is topographically part of the Red Rock Alluvial Fan, although the fan shape is more subdued and has been modified by Quaternary faults. The geomorphic and lithologic characteristics of this subarea is quite similar to a "phreatophyte flat" as described by Quade and others (1995, p. 218) at Tule Flats, Corn Creek Springs and other spring areas in southern Nevada. The water table is close to the surface (5 to 7 m bls) in a “phreatophyte flat,” encouraging an increase in plant growth. The plants act as filters, trapping fine-grained sediments.

This subarea is located between Quaternary fault Scarp I and Scarp II (Bell and Price, 1991, C-3). The fault scarps are conduits for ground-water flow to the surface, and most of the springs and phreatophyte areas existed near the fault scarps prior to the development of the valley. Las Vegas Springs, which dried up in the 1960's because of ground-water development, were located on Scarp II in what is now the Las Vegas Valley Water District Main Field.

Subsurface units in this subarea have not been subdivided into formal stratigraphic units although the lithologic variation has been evaluated by many hydrologic investigations (Maxey and Jameson, 1948; Domenico and others, 1964; Malmberg, 1965; Harrill, 1976; and Plume, 1989, Morgan and Dettinger, 1994) in Las Vegas Valley. The sediments are interfingering, fine- and coarse-grained deposits, of which the fine-grained deposits are aquitards and the coarse-grained deposits are aquifers.

Subarea 4 is the only location where the boundaries between the lithologic units described by previous workers coincide with the boundaries of the allostratigraphic units of this investigation. The coincidence occurs because Subarea 4 is the transition area between the fine- and coarse-grained sediments. The fine-grained sediments thicken to the east. By contrast, the coarse-grained sediments thin to the east and thicken to the west. The observed sedimentological variation in this subarea can either be described as interfingering fine-coarse grained sediments (lithologic units) or, alternatively, as overlapping parts of allostratigraphic units of contrasting texture.

Subarea 4 is the transitional area between the fine- and coarse-grained sediments. It therefore is very important in understanding the distribution of sediment within both the area of investigation and the entire valley. Previous subsurface investigations based their informal sediment subdivisions on information from wells in Subarea 4 and areas further east. Subarea 4 is characterized by (1) fine-grained material at the surface, (2) interbedded fine- and coarse-grained material, and (3) Quaternary fault scarps.

Figure 9 is an east to west cross-section of the subsurface distribution of the alluvial fine- and coarse-grained deposits modified from Maxey and Jameson (1948, pl. 6b). Maxey and Jameson's original (1948, pl. 6b) cross-section is generally accurate; subsequent researchers have not significantly changed this interpretation. Similar cross-sections appear in Bell (1981, p. 18) and Morgan and Dettinger (1994, p. 25).

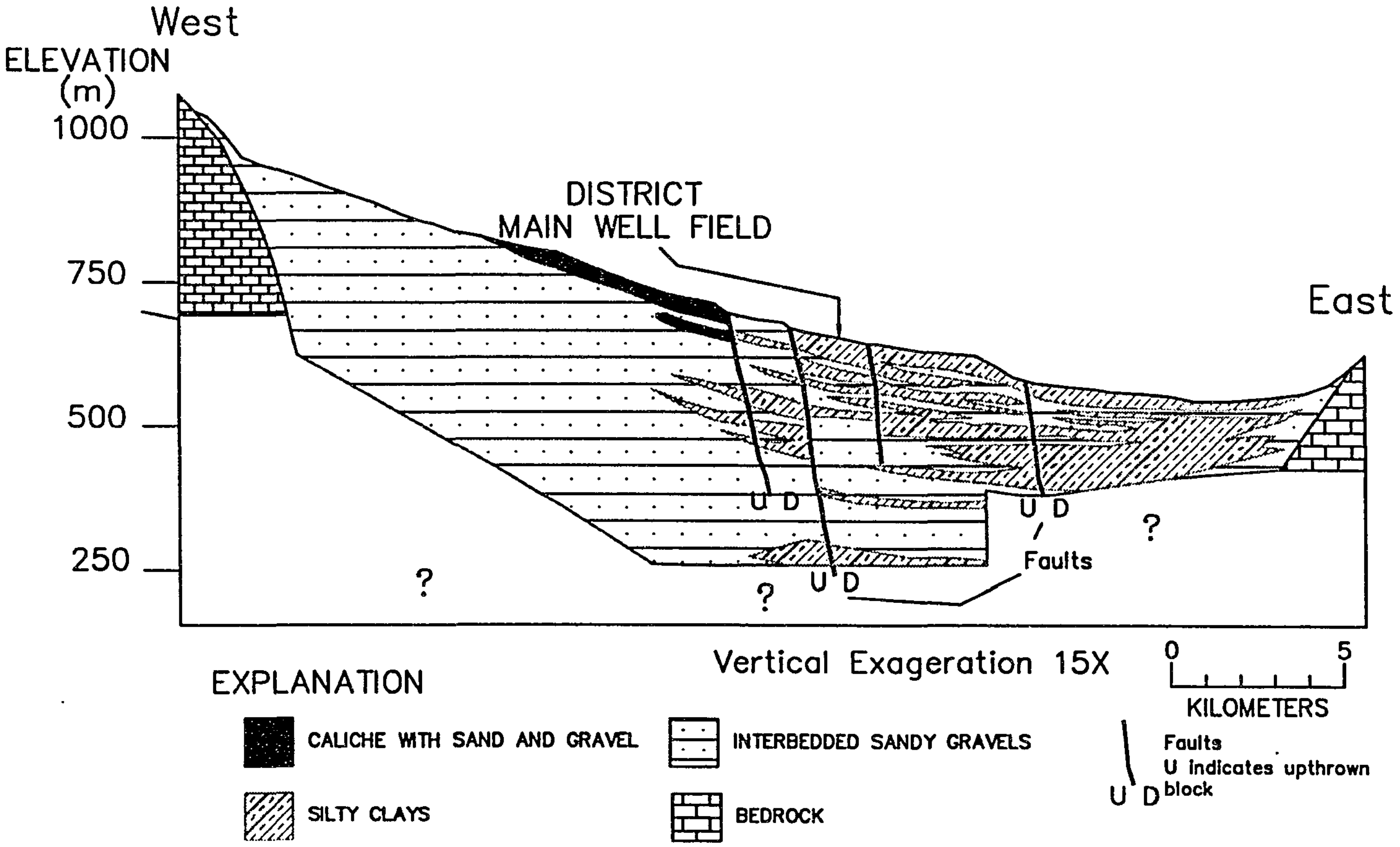


Figure 9. -- Generalized west to east geologic cross-section of Las Vegas Valley.
Modifed from Maxey and Jameson (1948, pl. 6b).
Similar cross-sections appear in Bell (1981, fig. 6) and Morgan and Dettinger (1994, fig. 2.2-1).

The top 250 meters, approximately, of basin-fill alluvium is composed of nearly equivalent amounts of fine- and coarse-grained sediment. This 250 meter section has been described in most of the hydrologic reports and there is general agreement about the distribution of the sediments.

Maxey and Jameson (1948, p. 82) were the first to describe the subsurface deposits within Las Vegas Valley, and reported the occurrence of "... several sand and gravel lenses which occur at approximate depths of 250, 300, 350 to 400, and 450 feet [75, 90, 105 to 120 and 135 m]." A lower interval was described (Maxey and Jameson, 1948, p. 68) as:

> "Several relatively thick sand and gravel lenses are present beneath the blue clay in the vicinity of Las Vegas. They occur at depths ranging from 450 to 700 feet [135 to 215 m] and west of the city are as much as 100 feet [30 m] thick."

The "blue clay" mentioned above was a 6 m thick stratigraphic marker described by Maxey and Jameson (1948, p. 68) in the central part of the valley. This marker is observed only on the eastern margin of the area of this present investigation.

Subarea 5 (Tule Flats)

The fifth subarea in this investigation is the Tule Flats part of the central playa in Las Vegas Valley (fig. 3). Tule Flats is roughly diamond shaped. It is bound on the west by the Kyle Canyon Alluvial Fan, on the east by the Sheep Range Bajada and Las Vegas Wash, and on the south by the ENE-WSW part of Quaternary fault Scarp II (figs. 7 and 8) as designated by Bell and Price (1991 pg. C-3) and the northeastern margin of the Red Rock Alluvial Fan. The fine-grained material of the surficial deposits extends to at least 300 m below surface (Plume, 1989, pl. 2). This area is similar to Subarea 4 in that the Quaternary faults and springs play an important role in controlling the grain size of the deposits. It differs from

Subarea 4 in that the subsurface deposits are almost exclusively fine-grained instead of interbedded fine- and coarse-grained.

Quaternary fault scarps were mapped primarily by Bell (Haynes, 1967; Harrill, 1976; Bell, 1981; Matti and others, 1987; and Bell and Price, 1991) near the western edge of the Tule Flats area (fig. 7 and 8) and within two bands oriented about N. 70° E. The faults located near the western edge of the playa are near the boundaries of the fine-grained sediments and coarse-grained alluvial fan sediments. The northern band of scarps is the Eglington Scarp named by Haynes (1967, p. 51). The southern band of fault scarps is an ENE extension of Scarp II (Bell and Price, 1991, C-3), which trends generally north to south. The Tule Flats area is characterized by (1) fine-grained sediment, (2) generally weak cementation, and (3) Quaternary fault scarps.

CHAPTER 3

HYDROGEOLOGY

Precipitation on the surrounding mountain ranges, primarily the Spring Mountains and, to a lesser extent, the Sheep Range recharges the alluvial-aquifer system. The alluvial aquifers are recharged by ground water moving through the carbonate bedrock into the alluvium. Natural discharge is through a series of springs in the central axis of the valley, including Corn Creek Springs, Tule Springs, and Las Vegas Springs (Malmberg, 1965, p. 59). The springs are located along Quaternary fault scarps which, near the area of investigation, are located in the lower part of the Red Rock Alluvial Fan.

General Hydrogeology of Las Vegas Valley

The alluvial aquifer system of the Las Vegas Valley is composed of all the alluvial sediment in the valley. It is 1525 meters thick (Plume, 1989, p. A1) or thicker (G. Dixon, 1993, USGS, pers. comm.) in the central part of the valley. The names and numbers of hydrogeologic units vary in the literature but there is general agreement about the hydrogeologic properties of the units.

Three major intervals and the overlying discontinuous Holocene surficial deposits are mapped in most of the hydrogeological investigations of Las Vegas Valley. The following two tables display the lithologic and hydrogeologic properties of the major intervals.

Table 2 is from Harrill's (1976) investigation of Las Vegas Valley. Tables 1 and 2 are parts of a table from Harrill's (1976, table 1) report. Table 3 compares Harrill's units with hydrogeologic units defined by other investigators in Las Vegas Valley. All of the units on table 3 are derived from Maxey and Jameson's (1948, p. 82) original hydrogeological units. Figure 10 displays the location and names of Maxey and Jameson's (1948, pl. 6b) original hydrogeologic units.

The deepest interval is a low permeability aquifer named by Maxey and Jameson (1948, p. 82) as the "Deep Zone of aquifers" and Morgan and Dettinger (1994, p. 8) as the "deep-zone aquifers." The two reports differ in placement of the boundary between this and the overlying more permeable aquifers. Maxey and Jameson (1948, p. 82) placed the boundary at about 215 m below land surface whereas Morgan and Dettinger (1994, p. 26) put the boundary at 305 m below land surface.

The location of this boundary is very important in the western part of the valley. If the boundary is located at 215 meters below land surface or higher, the high permeability interval in several municipal wells may become or have become unsaturated, reducing the flow rates of these wells. This observation led to the hypothosis mentioned in the Abstract that the reduction of specific capacity (flow rate divided by drawdown) at the District's West Central Well Field was related to the dewatering that has occurred in the last thirty years.

Table 2. -- Alluvial hydrogeological units defined by Harrill (1976, p. 6, part of Table 1).

Age	Lithologic unit	Thick-ness [meters]	General Hydrologic Properties	Hydrogeologic unit
Quaternary (Pleistocene and Holocene)	Surficial Deposits	15±	Generally above the zone of saturation on alluvial fan. In the southwest part of the valley, saturated deposits may form a thin water table aquifer. Westphal and Nork (1972, p. 1) estimated the average horizontal conductivity of these deposits in the Henderson-East Las Vegas area to be about 400 gpd/ft^2 [5 m^2/d].	near-surface reservoir[1]
Quaternary (Pleistocene)	Lake and playa deposits (includes Las Vegas Formation)	91±	When saturated, fine-grained deposits may store appreciable quantities of water but have low permeability and transmit water poorly. Unit acts as a confining layer. When water is removed from storage, compaction and land subsidence will result. Unit yields some water to domestic wells.	near-surface reservoir[2]
Quaternary (Pleistocene)	Fanglomerate and valley floor deposits	305±	Gravel deposits along lower parts of fans transmit water readily and from most productive aquifers in valley. Finer gravel deposits in central part of valley produce water less readily but provide adequate supplies for domestic and moderate-capacity industrial and public supply wells. Heavy pumping in area of fine grained deposits may result in land subsidence.	principal aquifers[3]
Tertiary	Muddy Creek Formation	1220±	Low permeability deposits which do not readily yield water to wells. Gypsum and sulfate content may effect ground-water quality.	principal aquifers[4]

Footnotes:

[1] Commonly referred to as the "shallow aquifer(s)" since 1978 (after Kaufmann, 1978, p. 1) each report defines this unit differently, but the defining characteristic is the source of the water (turf irrigation) and is therefore not an aquifer as used in this report.

[2] Defined only where saturated and a relatively fine-grained unit.

[3] Defined only where saturated and a relatively coarse-grained unit.

[4] Defined by Dettinger as "the untapped deep zone of basin-fill sediments" (Dettinger, 1987, p. 8) and the "deep-zone aquifers" (Morgan and Dettinger, 1994 p. 26) with a boundary at 305 m below land surface and credited Harrill (1976 p. 9-11), however, Harrill (1976, p. 11) only reported that "The lower boundary (of the principal aquifers) is poorly defined; however most large-capacity wells are less than 1,100 feet deep."

Table 3. -- Hydrogeologic units used in previous reports, and proposed aquiformations.

Interval	Maxey and Jameson (1948)	Thickness (meters)	Harrill (1976)	Thickness (meters)	Morgan and Dettinger (1994)	Thickness (meters)	Proposed Aquiformations (This report)	Hydrogeologic type
upper 60-135 m of alluvium	near-surface water	90±	near-surface reservoir	90±	near-surface aquifer	75±	Las Vegas Wash Aquitard	aquitard
60-135 m bls[1]	Shallow Zone of aquifers	305±	principal aquifers[2]	305±	developed-zone aquifers[2]	30±	Las Vegas Springs Aquifer[6]	aquifer
5-15 m thick	"blue clay"					60±		aquitard
150-215 m bls[1]	Middle Zone of aquifers					60±		aquifer
all aquifers below 215 m bls	Deep Zone of aquifers					> 60+[5]	Duck Creek Aquifer	low-permeability aquifer[5]
		1220±	undefined[3]	undefined[4]	deep-zone aquifers[4]			low-permeability aquifer

Footnotes:
[1] Gravel lenses in these intervals.
[2] Harrill (1976) defined only saturated units, and the upper 135 m of coarse-grained unsaturated sediments in the alluvial fans were not defined as a hydrogeological unit. Harrill (1976, p. 9) specifically included Maxey and Jameson's (1948) Deep Zone of aquifers but excludes all sediments below 305 m bls.
[3] All sediment below 305 m bls were described as low permeability. Harrill (1976) referred to the 1220 m interval as the Muddy Creek Formation.
[4] Includes all sediment and bedrock below 305 m bls. Morgan and Dettinger (1994) named this unit but did not specify a thickness.
[5] Prior to 1987, wells in Las Vegas Valley were generally not drilled deeper than 305 meters. A 60 meter+ interval of coarse-grained sediment below 215 m bls is interpreted in this report as the uppermost part of an underlying lower permeability aquifer.
[6] The aquiformation rank, Las Vegas Springs Aquifer is composed of three aquimembers. The lower aquifer, La Madre Mountain aquifer, is the most permeable unit in the Las Vegas Springs Aquifer. The upper aquifer, Las Vegas Creek aquifer, is locally important. The Twin Lakes aquitard separates the two aquifers.

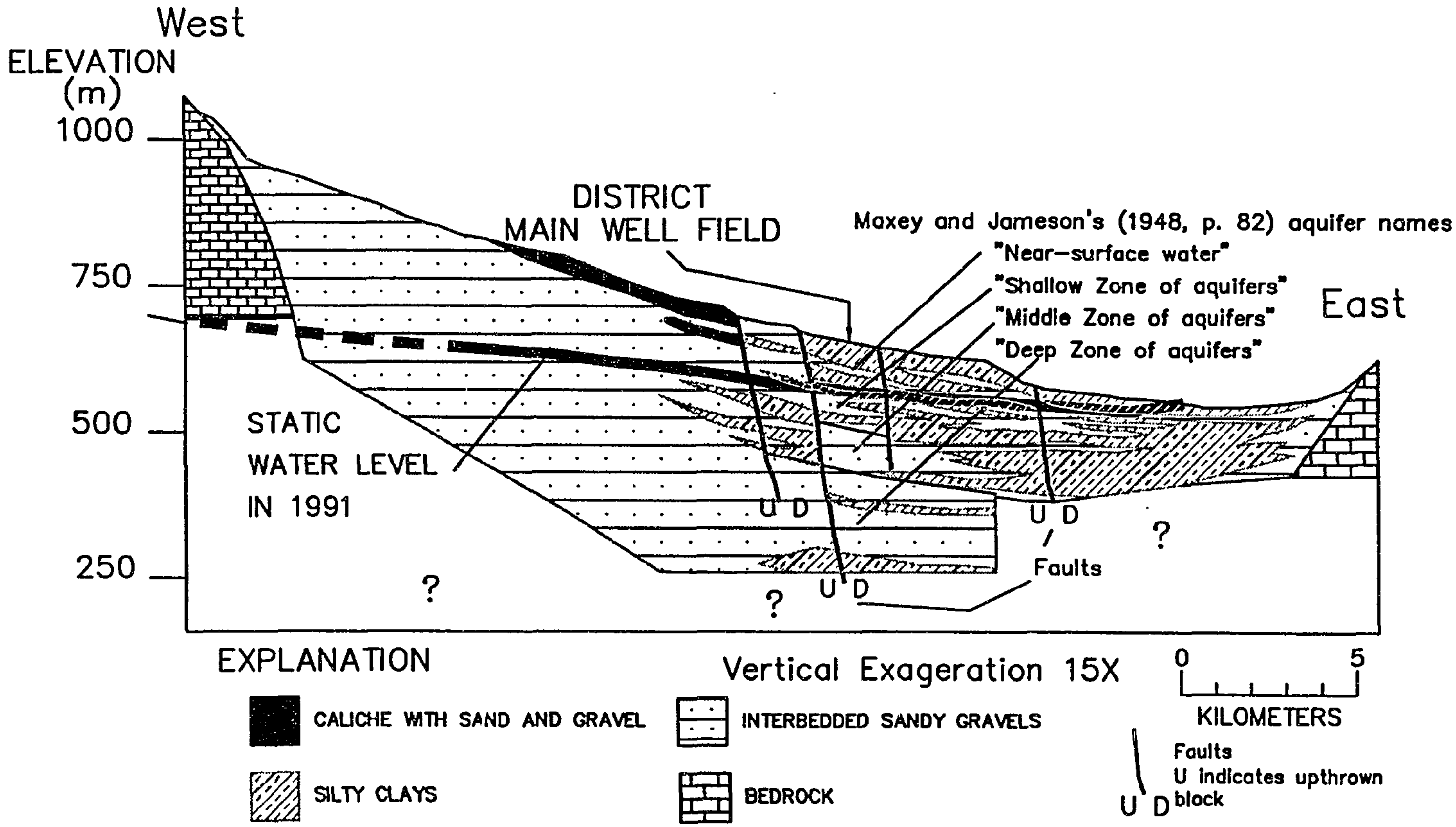


Figure 10. –– Generalized west to east hydrogeologic cross-section of Las Vegas Valley. Modifed from Maxey and Jameson (1948, pl. 6b). Similar cross-sections appear in Bell (1981, fig. 6) and Morgan and Dettinger (1994, figs. 2.2-1 and 3.1.1-1).

The boundary between the deepest aquifer and the overlying aquifers can be best delineated by examining well performance in wells screened or perforated in both intervals. Two methods of comparison can be used. First, the performance of two wells that are adjacent but have different screened or perforated intervals can be compared. Second, past and present flow rates and specific capacity in the same or adjacent wells can be compared in areas where the overlying aquifers are dewatered.

Overlying this deep interval are Maxey and Jameson's (1948, p. 82) "Middle" and "Shallow Zone(s) of aquifers" , Morgan and Dettinger's (1994, p. 26) "developed-zone aquifer," and the most permeable part of Harrill's (1976, p. 9) "principal aquifers." The "principal aquifers" combine Maxey and Jameson's (1948, p. 81) "Shallow, Middle and Deep Zones of aquifers" into a single hydrogeological unit and are similar to Malmberg's (1965, p. 23) "artesian aquifers." The descriptions of the Las Vegas Valley as an artesian basin are related to the high permeability of these "middle" sediments and the lower permeability of both the lower and overlying sediments discussed later. The wells with the highest flow rates are completed in the "principal aquifers" located approximately 70 m to 200 m below land surface. The boundary between this and the overlying hydrogeological unit is the

"... top of the first significant water-producing sand or gravel." (Harrill, 1976, p. 6),

or

"... the first indication of water-bearing material (Harrill, 1976, p. 9)."

Overlying the "principal aquifers" of Harrill (1976, p. 9) is the "near-surface reservoir" of Malmberg (1965, p. 24), called by Maxey and Jameson (1948, p. 81) "near-surface water" and by Morgan and Dettinger (1994, p. 8) the "near-surface aquifers." This unit generally has much lower permeability than the underlying aquifers and acts as an aquitard. Bernholtz (1994, p. 50) reported transmissivity values at least one order of magnitude lower in this unit than in the underlying aquifers. In the central part of the valley, this unit is usually fine-grained.

In the urbanized part of the valley, the water in the upper 15 meters of alluvium is usually more saline than the underlying ground water. The source of much of this water is excessive irrigation of turf grass with water imported into the valley from the Colorado River (Brothers and Katzer, 1988, p. 10). Colorado River water is more saline than the native ground water in the northwest part of the valley. The water generally does not infiltrate deeply into the alluvium because of the low permeability of the "near-surface reservoir" and artesian nature of the underlying aquifers. Evapotranspiration concentrates the salts, thus increasing the salinity. This 15 meter interval of the "near-surface reservoir" is referred to as the "shallow aquifer(s)" (Kaufmann, 1978, p. 1). This "shallow aquifer" is defined by source and geochemistry. It is not an aquifer as used in this investigation and is part of the "near-surface reservoir." The "near-surface reservoir" as a whole is an aquitard.

General Hydrogeology of Area of Investigation

The area of investigation has long been recognized as an area that yields large quantities of water (Carpenter, 1915; Maxey and Jameson, 1948). Maxey and Jameson (1948, p. 82) identified the southeastern corner of the area of investigation, near the District's Main Well Field, as the area with the highest specific capacity in the valley. Artesian flow rates of 125 to 315 ℓ/s (2000 to 5000 gpm) are reported from wells drilled in the late 1940's near the District's Main Well Field (Maxey and Jameson, 1948; State Engineer's drill log records, District records). Water levels did not decline below land surface until about 1960 (District records). During the early 1960's, the lower part of the Red Rock Alluvial Fan (Subarea 4) was recognized as a productive area for wells (Domenico and others, 1964, p. 18; Malmberg, 1965, p. 24). About twenty District and City of North Las Vegas wells were drilled in Subarea 4 in the early 1960's. The wells in the District's West Central and Gowan Well Fields were established, along with both District and North Las Vegas wells near Rancho Drive. During the 1970's and early 1980's the District expanded the distribution of their wells to include the eastern margin of the upper Red Rock Alluvial Fan (Subareas 2 and 3) at Buffalo Road.

Harrill's (1976, fig. 6) map of the distribution of transmissivity (fig. 11) was based upon the specific capacities calculated by Harrill (1976) and transmissivity values calculated by Malmberg (1965) from aquifer test data at wells drilled in the 1950's and early 1960's. The variance between Harrill's (1976, p. 16) predicted transmissivity and the transmissivity values calculated from aquifer tests at wells drilled in the late 1980's and early 1990's is one of the primary problems analyzed in this present investigation.

The alluvial aquifers are recharged from the deeper bedrock aquifers. Although the conduits for recharge are unknown, the most likely pathways are thrusts or normal faults. There are three reasons for this assumption. First, both the lower section of alluvium and the underlying bedrock below the alluvial aquifers have low permeability. Second, wells drilled near Quaternary fault scarps tend to have higher specific capacity and transmissivity values than wells farther from the scarps. The higher specific capacities may be caused by increased permeability near the scarps. Third stable isotope and geochemical investigations by Noack

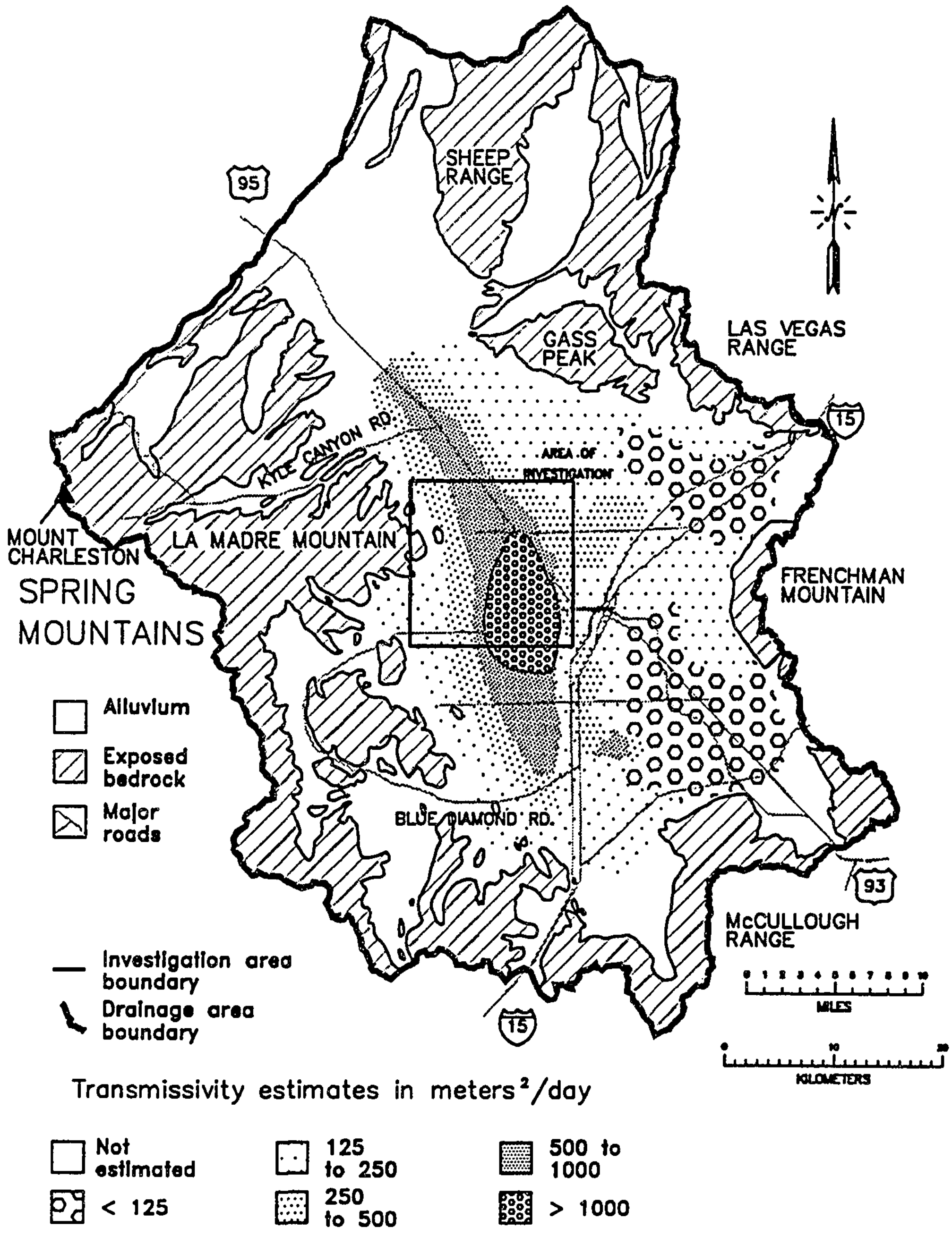


Figure 11. — Distribution of transmissvity in the "principal aquifers." Modified after Harrill, (1976, fig. 6).

(1988, p. 99) on the sources of ground-water recharge document "regional" water upwelling from depth near the Quaternary fault scarps.

General Hydrogeology of Subareas

As discussed previously, the area of investigation was divided into five subareas that vary in their geologic and hydrogeologic properties.

Subarea 1 (Kyle Canyon Alluvial Fan, southern lobe)

This subarea includes the southern lobe of the Kyle Canyon Alluvial Fan and the zone of coalescence between the Kyle Canyon and Red Rock Alluvial Fans. Most of the water wells in this area are domestic wells. Aquifer test data was not available in this area until the late 1980's. Previous hydrogeologic investigations (Maxey and Jameson, 1948; Domenico and others, 1965; Malmberg, 1965; Harrill, 1976; Plume, 1989; and Morgan and Dettinger, 1994) assumed this area was relatively permeable because of the coarse-grained nature of the sediments. Plume (1989, pl. 2) mapped "heterogeneous deposits" in this area but characterized the water bearing properties as:

> "May have water-bearing properties of either coarse- or fine-grained deposits, depending on location. Horizontal permeability may be greater than vertical permeability in places."

Subarea 2 (upper Red Rock Alluvial Fan, northern lobe)

As discussed in the Geology section, coarse-grained sediments are the most common lithology in this subarea. The factors controlling permeability and flow to wells are poorly defined in previous hydrogeologic reports. Deep wells were not drilled in most of this subarea until the late 1980's and 1990's. Harrill (1976, p. 16, see also figure 11 of this investigation) predicted moderate to low transmissivity for this subarea which is generally west of the data available to previous reports.

Transmissivity values calculated from aquifer tests of municipal water wells drilled in the late 1980's and early 1990's in Subarea 2 are higher than predicted by previous hydrologic reports (Maxey and Jameson, 1948; Malmberg, 1965; Harrill, 1976; and Morgan and Dettinger, 1994) of Las Vegas Valley.

Subarea 3 (upper Red Rock Alluvial Fan)

This subarea contains the District's West Central Well Field (WCWF). This subarea, like Subarea 2, is dominated by coarse-grained sediments. When investigated by Malmberg (1965) and Harrill (1976) in the 1960's and early 1970's, the WCWF contained wells with high reported transmissivity values. The three wells investigated by Harrill (1976) have an average reported transmissivity of about 1100 meters^2/day. Therefore, the WCWF was included within Harrill's (1976, p. 16) zone of highest transmissivity in Las Vegas Valley. Harrill (1976, p.16) predicted high to moderate transmissivity in this subarea.

Harrill (1976, p. 16) estimated the reported transmissivity values from specific capacity. An examination of the District specific capacity values for the three wells investigated by Harrill (1976) and new wells drilled within the same well field show a reduction of 80 to 90 percent in specific capacity. This information led to an initial hypothesis of this investigation that the decline in specific capacity was due to dewatering of the most permeable unit within the alluvium. The location of the most permeable unit and the factors controlling permeability in this subarea and Subarea 2 were therefore analyzed in this investigation.

Subarea 4 (lower Red Rock Alluvial Fan)

This subarea has been a known area of high transmissivity since Maxey and Jameson's (1948) report on the hydrogeology of Las Vegas Valley. The "Shallow, Middle, and Deep zones of aquifers" of Maxey and Jameson (1948, p. 82) were defined in this subarea. The aquifers defined by Maxey and Jameson (1948) are the coarse-grained facies of the alluvial fans and the aquitards are the fine grained playa deposits.

Subarea 5 (Tule Flats)

Maxey and Jameson (1948) also defined the hydrogeology of this subarea. Transmissivity values of wells in this subarea are low unless located near the Quaternary fault scarps. The low transmissivity values are caused by the abundance of fine-grained sediments.

CHAPTER 4

ANALYSIS OF DATA

Topographic Data

The area of investigation is located in parts of the Las Vegas NW, Blue Diamond NE, Tule Springs Park, and Gass Peak SW 7.5 minute quadrangles (fig. 12). The low point of the valley is about 10 km east of the area of investigation. Surface-water flow is generally west to east, however, there is a significant northwest to southeast slope in some parts of the area of investigation (fig. 13). This area is one of the steeper of the alluvial parts of the valley. USGS digital elevation models (DEMs) are available for each of the four quadrangles. The DEMs were combined together to generate a topographic basemap of the area of investigation. Figure 3 displays the physiographic features of the area of investigation in the context of the whole valley.

Geologic Data

The following sections describe the available surficial and subsurficial geologic information. Most of the surficial geologic mapping in Las Vegas Valley was conducted independently of hydrogeologic investigations. By contrast, most of the subsurficial geologic mapping in the valley was conducted for and concurrently with hydrogeologic investigations.

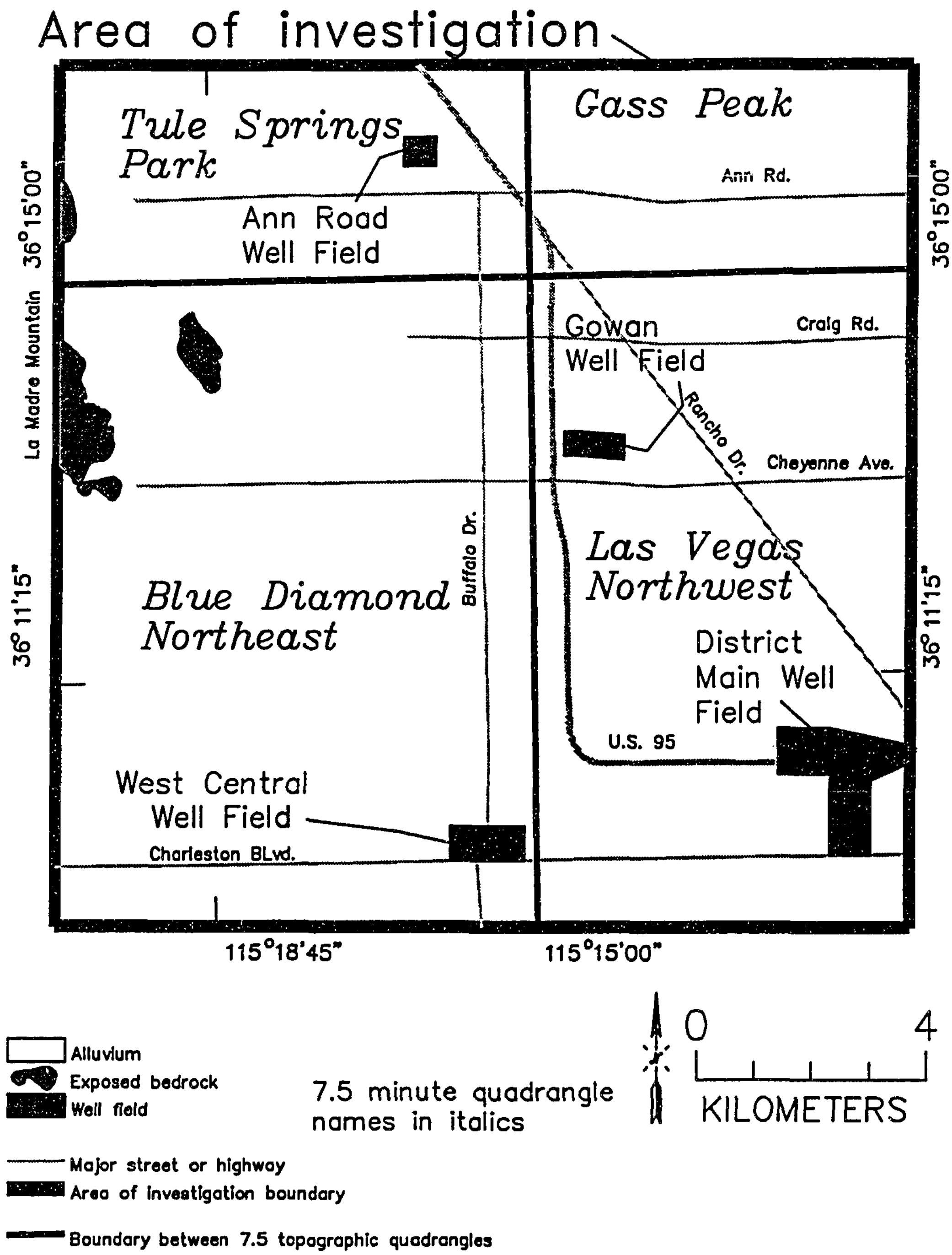


Figure 12. -- 7.5 minute USGS topographic/geologic coverage of area of investigation.

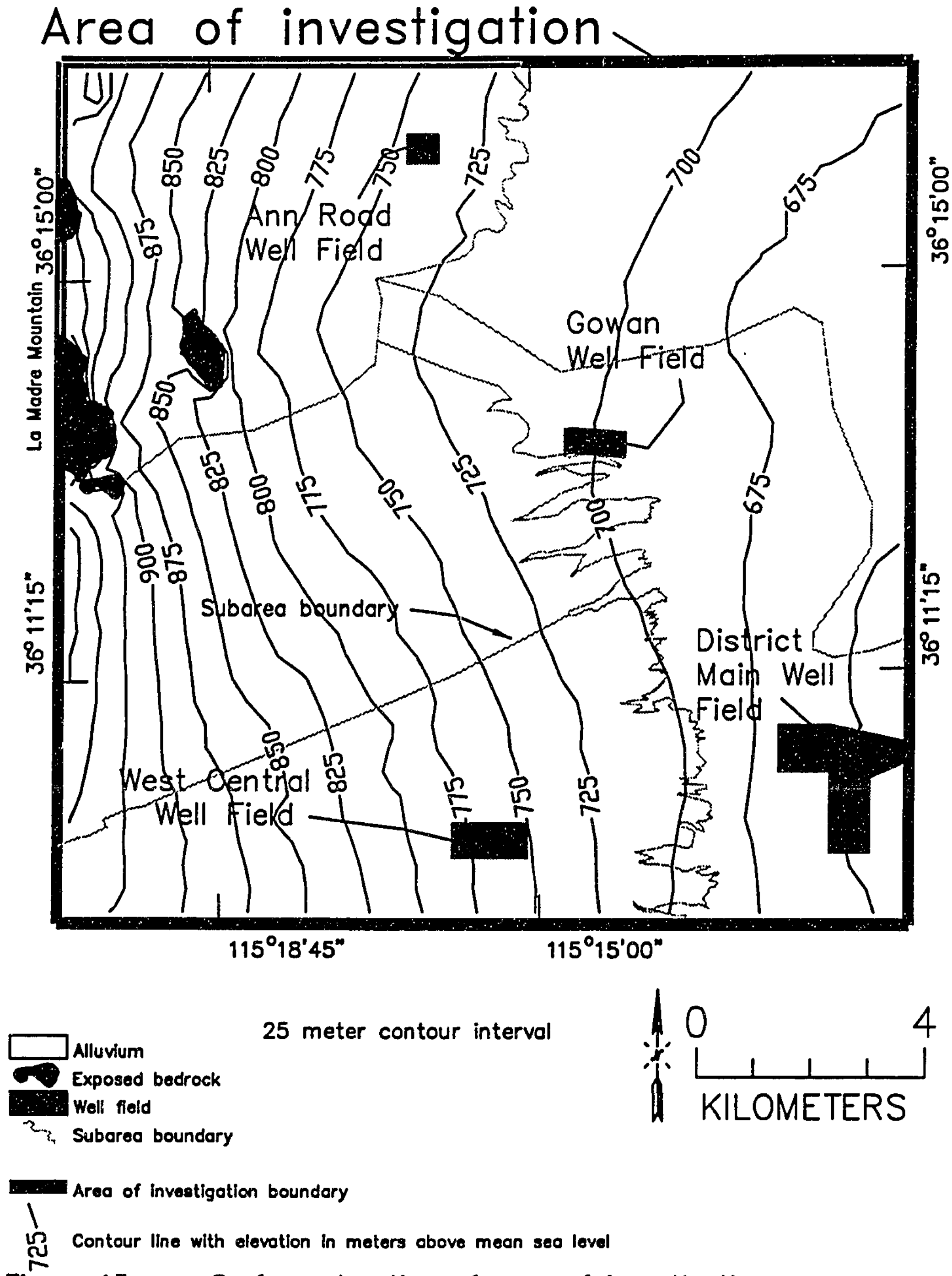


Figure 13. -- Surface elevation of area of investigation.

Surficial Geologic Data

The Las Vegas NW (Matti and others, 1987) 7.5 minute geologic map was mapped in support of the State of Nevada's geologic hazards assessment in the Las Vegas Valley. Quaternary geomorphic units on the Blue Diamond NE 7.5 minute quadrangle map were mapped by McDonnell-Canan (1989). Geomorphic units on the Tule Springs Park 7.5 minute quadrangle map were mapped by Sowers (1985). Haynes (1967) mapped part of the Gass Peak SW 7.5 minute quadrangle near Tule Springs. Bell and others (Bell, 1981; Matti and others, 1987; Bell and Price, 1991) mapped Quaternary fault scarps on all four Las Vegas 7.5 minute quadrangles in support of the geologic hazards assessment.

The primary source of regional geologic information was Plume's (1989) map of Las Vegas Valley derived from Longwell and others' (1965) geologic map of Clark County. Most of the published geologic mapping is a combination of field mapping and photo reconnaissance. The boundaries between the alluvial fan sediments and the adjacent playa deposits can be observed on LANDSAT images and aerial photos. The physiographic features shown on figure 2 and the Subarea boundaries on figure 5 were partially defined by the available surface mapping and partially by LANDSAT image analysis. The surficial mapping provided an analog to understand the distribution of the subsurface alluvial fan deposits.

Subsurface Geologic Data

Detailed lithologic logs that include information about grain-size percentages, roundness, and degree of cementation exist for seventeen wells drilled by the District between 1989 and 1994. In addition, two wells drilled by the City of North Las Vegas in and one well drilled near the area of investigation have information about grain-size percentages and degree of cementation. Drill logs from about fifty other water wells were used for control between the wells with detailed information and areas without detailed information. The additional wells are municipal supply wells owned by the District, City of North Las Vegas, City of Las Vegas, and domestic wells currently or historically monitored by the USGS or the District for water level information. The well logs in Appendix B were selected for their areal distribution.

Domenico and others (1964, p. 23), Harrill (1976, p. 14), and Plume (1989, pl. 3) all contoured the fine- and coarse-grained sediment at land surface, 0 to 61, and 61 to 213 meters below land surface from well logs. The western and southern parts of the area of investigation are west of the 60 percent coarse-grain contour. The northeastern part of the area of investigation is east of the 30 percent coarse-grain contour.

Geophysical Data

Data are available from both surficial geophysical investigations and geophysical logging of water wells within the area of investigation.

Surficial Geophysical Data

Plume (1989, pl. 5) estimated the depth to bedrock in Las Vegas Valley using gravity. This technique may have under-estimated the depth, because one well (W72) drilled in 1988 to 485 meters bls, did not encounter bedrock. Plume's (1989, pl. 5) estimate of depth to bedrock in this area was less than 300 meters bls. Zohdy and others (1992) measured the electrical resistivity from surface down to about 700 meters bls on the western part of the area of investigation.

Subsurface Geophysical Data

The resistivity of the sediments was measured in the seventeen wells drilled by the District and three wells drilled by NLV between 1989 and 1994. The absolute value of the resistivity is not indicative of either rock type or porosity because the logs are uncalibrated. The resistivity logs show similar variations (highs and lows) which appear to correspond to unconformities, lithology changes, and changes in degree of cementation. In two of the wells (W78 and W87) acoustic geophysical logs have been used to estimate porosity. These techniques have yielded inconclusive results. The one well (W78) where the data have been the most carefully evaluated actually has an inverse relationship between porosity and permeability. The porosity of the gravel with sand in this well ranged between 25 and 15 percent, which is typical for this type of alluvial deposit (Heath 1983, p. 26).

Hydrologic Data

Static water-levels, aquifer tests, and geophysics were analyzed to locate permeability intervals and are described in the following sections.

Static-Water Levels

In October, 1993, water levels were measured in sixty one (61) wells completed in the "principal aquifers" in the area of investigation. These wells were active District municipal wells, inactive municipal wells owned by the District, NLV or CLV, and domestic wells used by the District for water-level monitoring. This data set provided good areal coverage but was supplemented with four domestic wells measured by the USGS in 1990 and 1991 in the northern part of the area of investigation. A potentiometric map of the area of investigation was generated using the technique of minimum curvature (Briggs, 1974) in SURFER®.

The difference in water levels in the area of investigation is about 150 m from south to north and about 25 m from west to east. The shape of a potentiometric surface and observed changes with time can be used to identify the different areas of hydraulic conductivity in an aquifer (Domenico and Schwartz, 1990). The potentiometric map is only indicative of trends in permeability, because the water in the aquifer(s) is not in equilibrium. The water-level data are more areally extensive than more direct measures of permeability such as specific capacity or transmissivity.

Water-Level Changes

Water-levels and water-level declines were used for three purposes in this investigation. The first use of the water-levels is to determine saturation. The second use is to evaluate previously reported hydrologic measurements, such as hydraulic conductivity, that are affected by saturation. The third use of water-levels is to infer aquifer characteristics from the shape and change in shape through time of the potentiometric surface. Water-levels were therefore both a methodology as well as a result.

Four different years (1912, 1947, 1965, and 1993) were compared to determine the magnitude, location, and shape of water-level declines. The fact of water-level declines is well established by most of the reports written about the hydrogeology of Las Vegas Valley. The magnitude, location, and shape of these water-level declines are not as well defined.

The first available water-level information from Las Vegas Valley is Carpenter's 1912 data (Carpenter, 1915, pl 1). These data were collected six years after the first well was drilled and is as close to pre-development conditions as is possible. Only five (5) measurements were collected in the area of investigation. These are located near the Las Vegas Springs in the southeast corner of the area of investigation, which are today surrounded by District's Main Well Field (MWF). Figure 14 displays the potentiometric surface, contoured from the 1912 data. Figure 15 shows the declines calculated between the 1912 and 1947 data.

Beginning in the middle to late 1940's, the USGS started systematic collection of water-levels. Most of the long term records are from wells drilled in this period. This activity was conducted in conjunction with the State Engineer and included not only water-level measurements but also the drilling of new wells and systematic evaluation of the hydrology in Las Vegas Valley, described in Maxey and Jameson's 1948 report. The 1947 data set includes the wells drilled at that time and is much more extensive than previously collected data. This time period is also significant because this is when the basin began to be overdrafted. Maxey and Jameson (1948 p. xii) reported that "The total annual discharge from the ground-water reservoirs in Las Vegas Valley probably never exceeded 35,000 acre-feet until 1946." Maxey and Jameson (1948 p.xii) estimated 35,000 acre-feet (43 million cubic meters per year) was the natural recharge for the valley.

Most of the water levels in the 1947 data set are generally located east of or along the eastern edge of the area of investigation. Figure 16 displays the potentiometric surface contoured from the 1947 data. Figure 17 is the declines calculated between the 1947 and 1965 data.

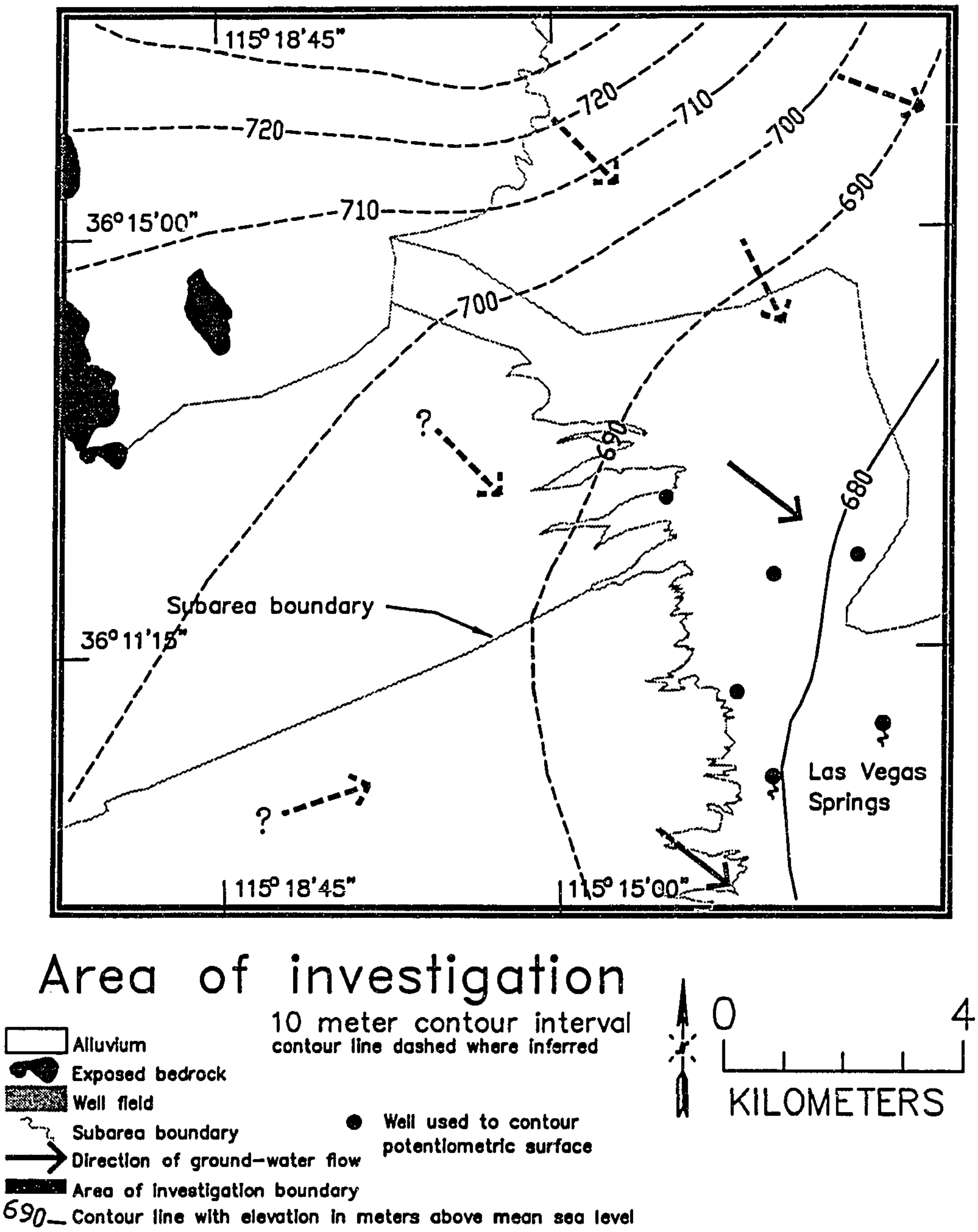
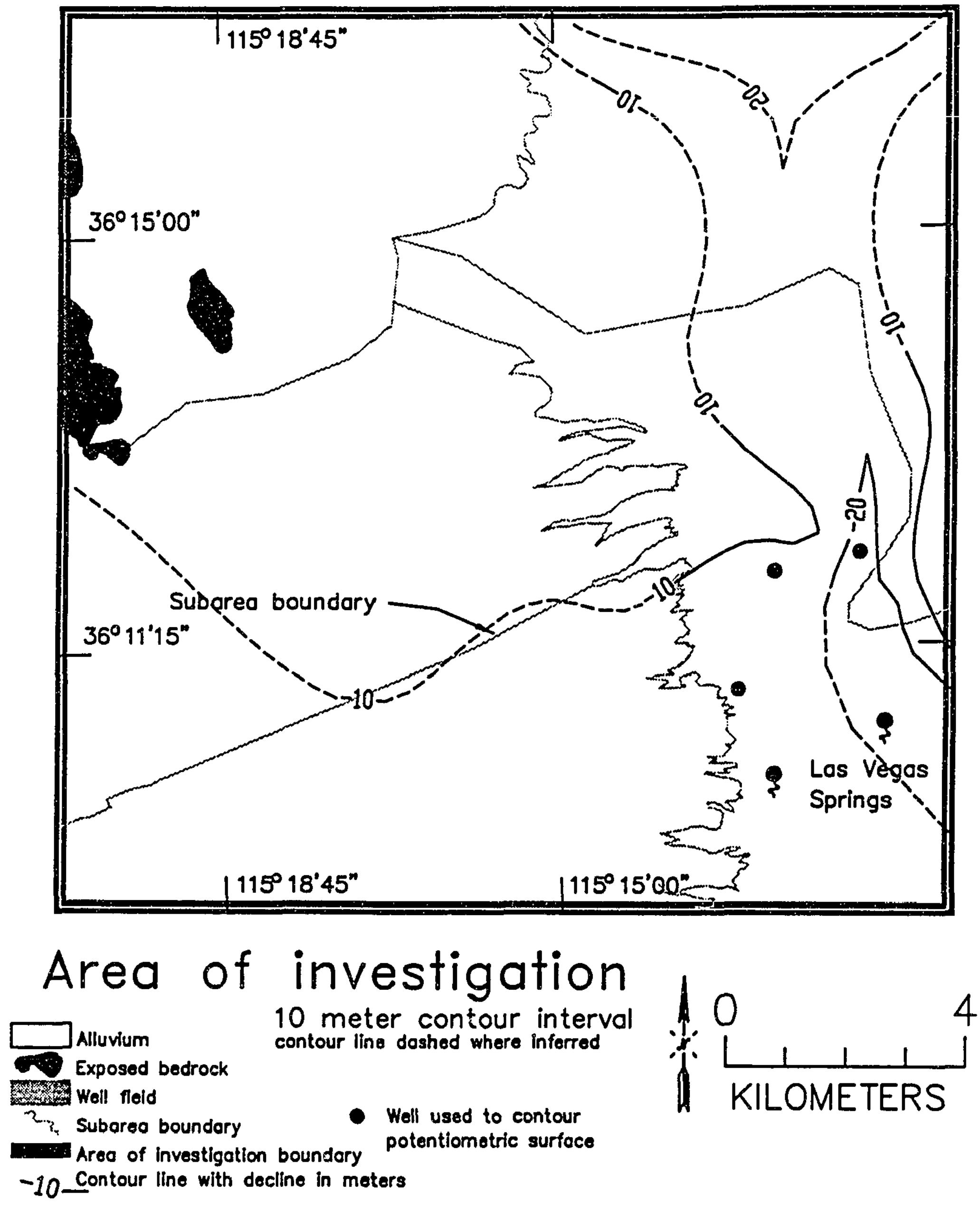


Figure 14. – Potentiometric surface 1912, in area of investigation.



Data source: Carpenter (1915, pl. 1)

Figure 15. — Water level declines 1912 to 1947, in area of investigation.

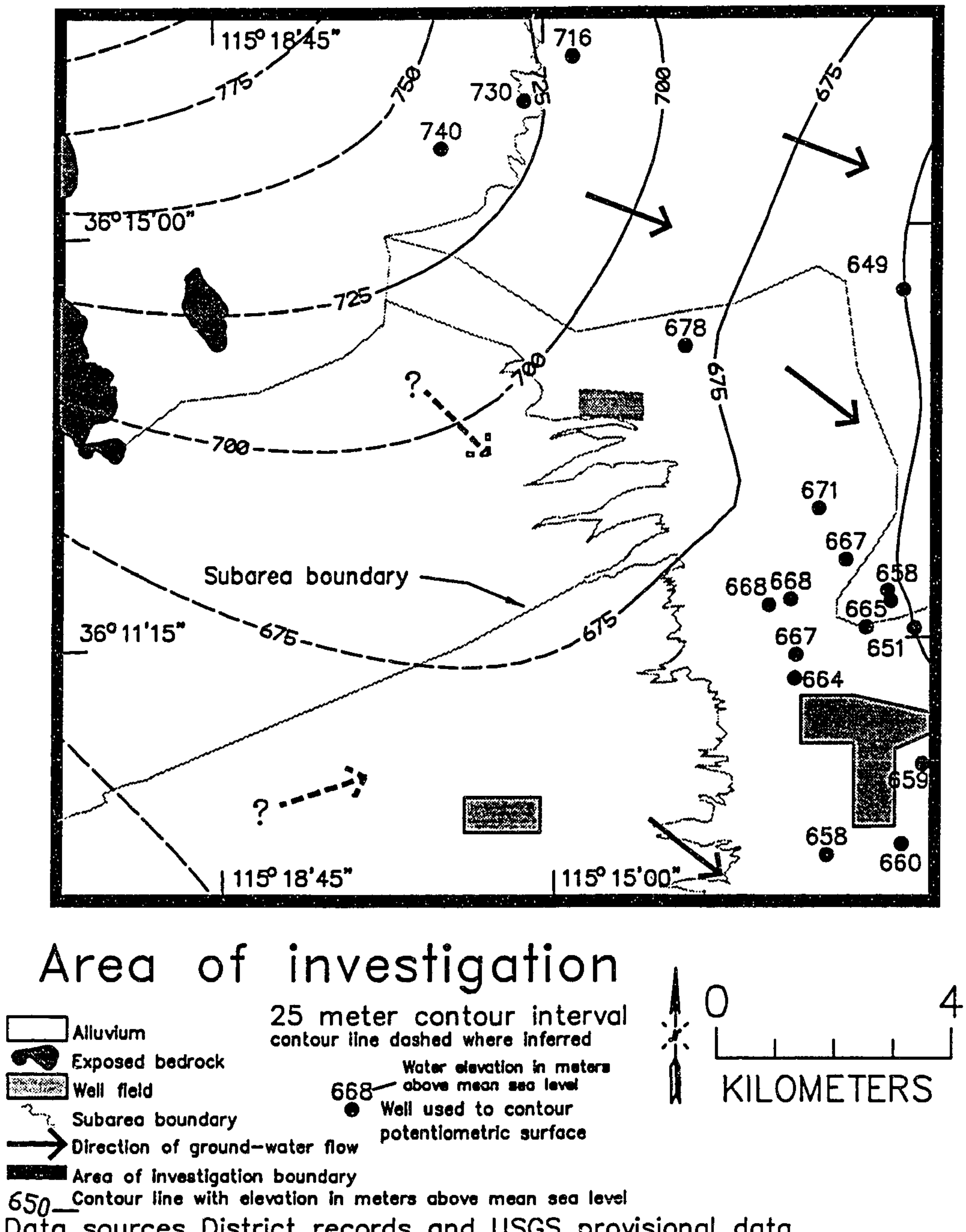
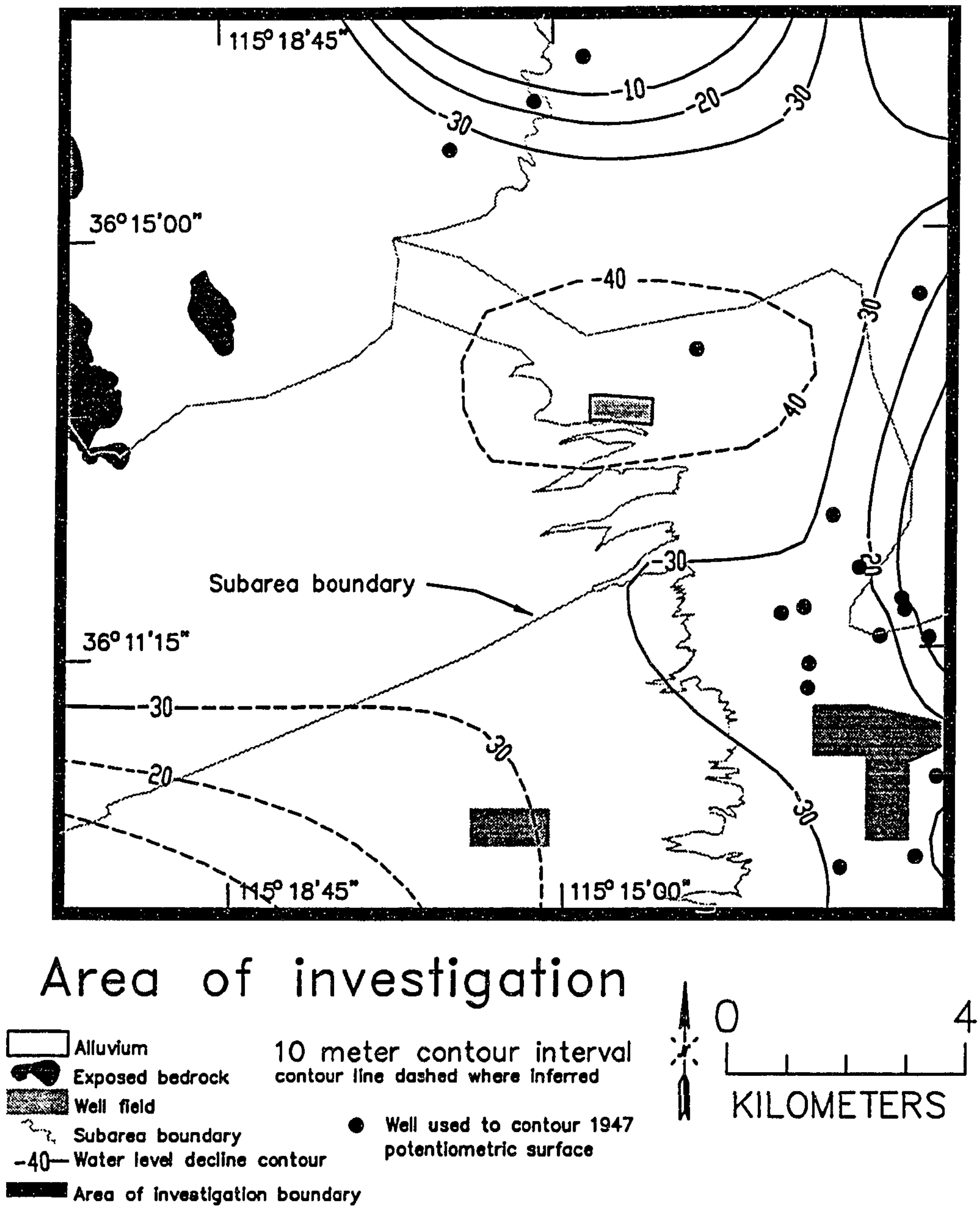


Figure 16. — Potentiometric surface, 1947, in area of investigation.



Data sources District records and USGS provisional data

Figure 17. —— Water level declines, 1947 to 1965, in area of investigation.

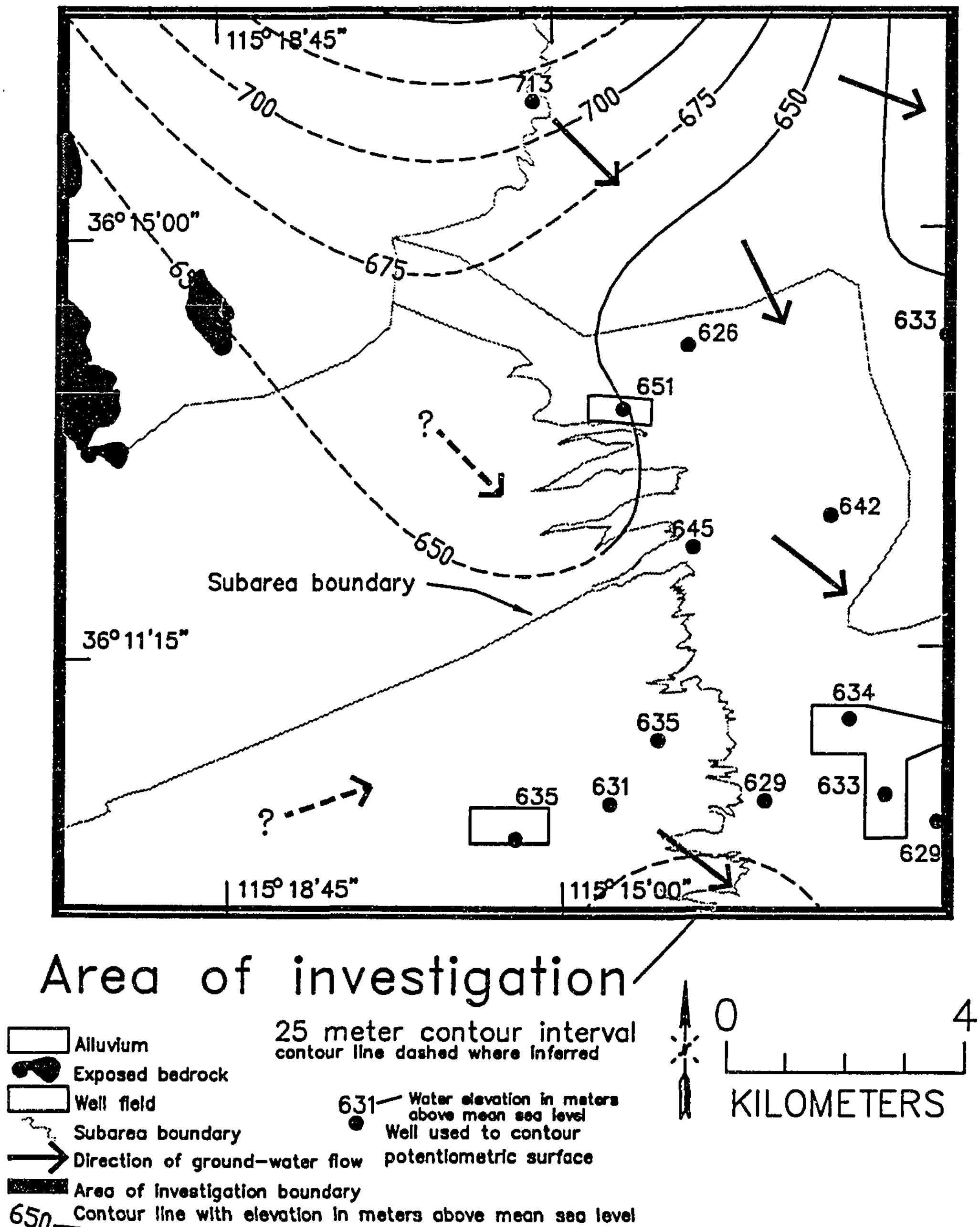
Many of the District and NLV wells were drilled in the early 1960's. Prior to 1962, over half of the ground water extracted through wells in the valley was from an area of about 1600 m^2 within the District's current Main Well Field (Domenico and others, 1964, p. 26). The data sets from 1965 and 1947 were selected as a compromise between areal coverage and a minimum of pumping effects.

Figures 18 displays the potentiometric surface contoured from the 1965 data. Figure 19 shows the water-level declines calculated between the 1965 and 1993 data. Figures 20 displays the potentiometric surface contoured from the 1993 data. Figure 21 shows the declines calculated between the 1912 and 1993 data. All of the water level data were contoured using the method of minimum curvature estimation (Briggs, 1974, p. 39) in SURFER®.

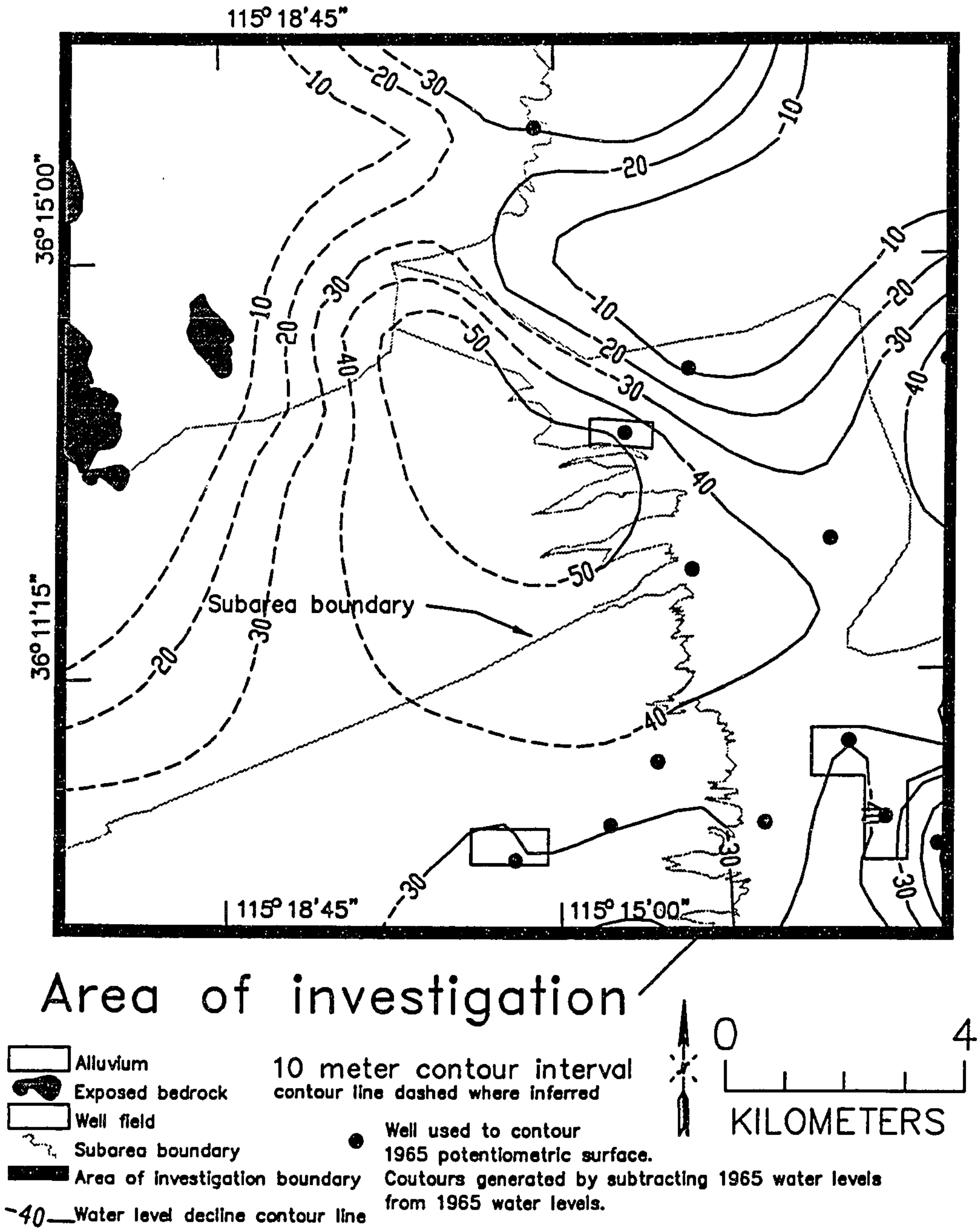
Figure 22 is a hydrograph of two wells drilled in the middle 1940's showing water level changes in the period 1945 to 1995. The well designated as W8 is located in the District's MWF. The well designated U1110 is about 3.5 km north of the area of investigation.

Aquifer Tests

Estimates of transmissivity were calculated from three sources: specific capacity measurements, single well step-drawdown tests, and single well 24-hour constant rate tests. Single well step-drawdown aquifer tests were conducted for seventeen District wells drilled between 1989 and 1994. The majority of these wells also have 24-hour constant flow rate



Data sources District records and USGS provisional data
Figure 18. -- Potentiometric surface, 1965, in area of investigation.



Data sources District records and USGS provisional data

Figure 19. – Water level declines, 1965 to 1993, in area of investigation.

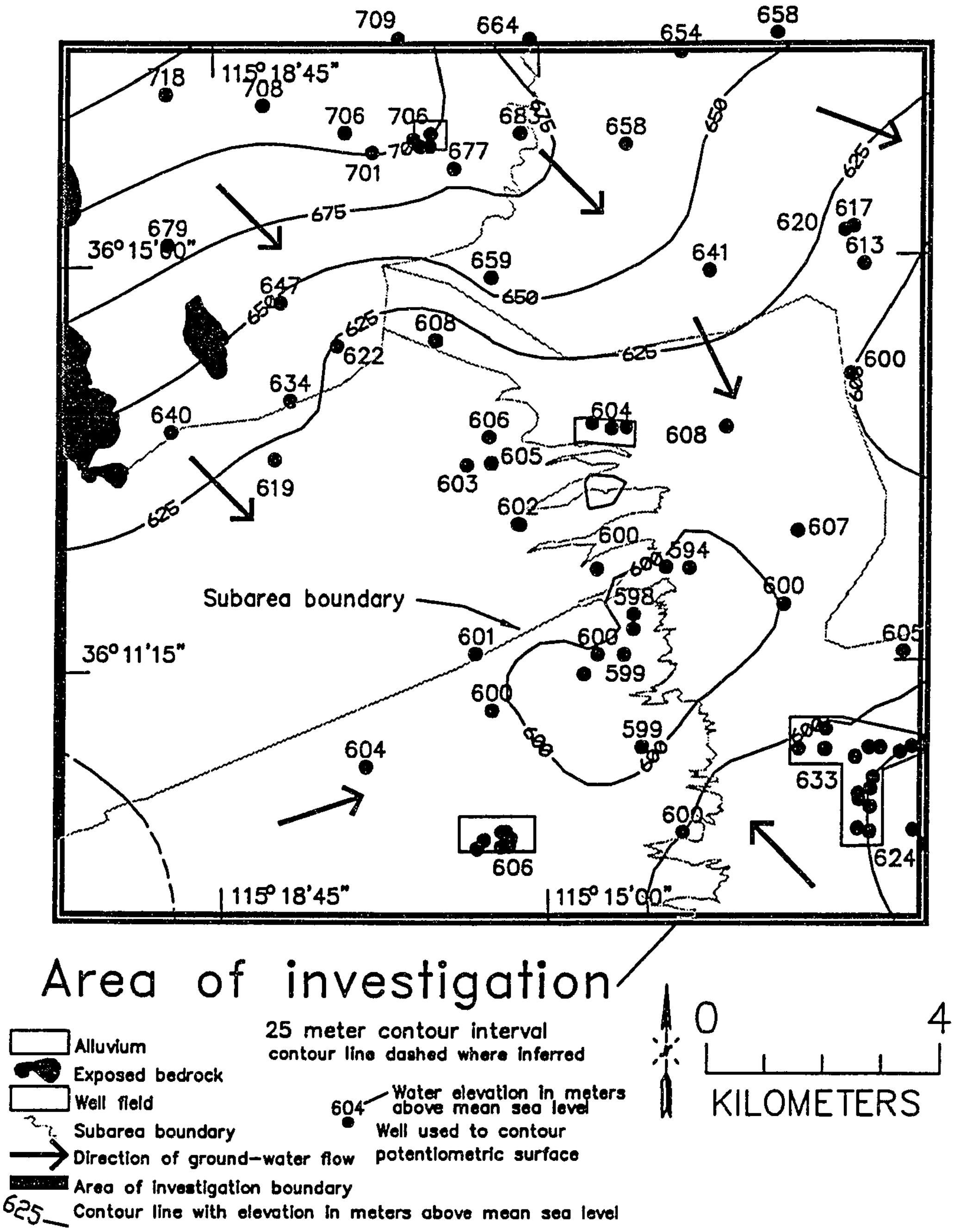
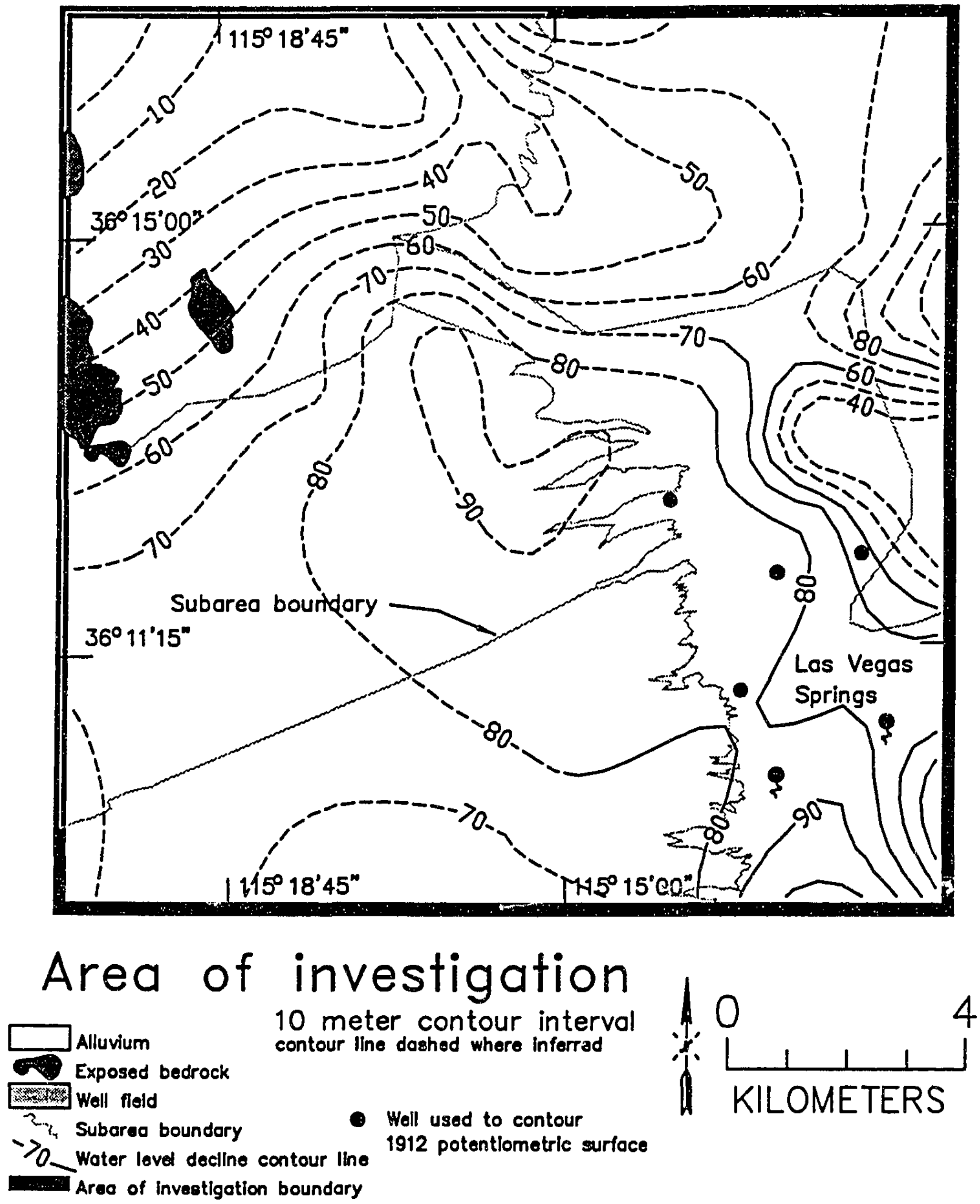


Figure 20. – Potentiometric surface, October 1993, in area of investigation.



Data source: Carpenter (1915, pl. 1)

Figure 21. —— Water level declines 1912 to 1993, in area of investigation.

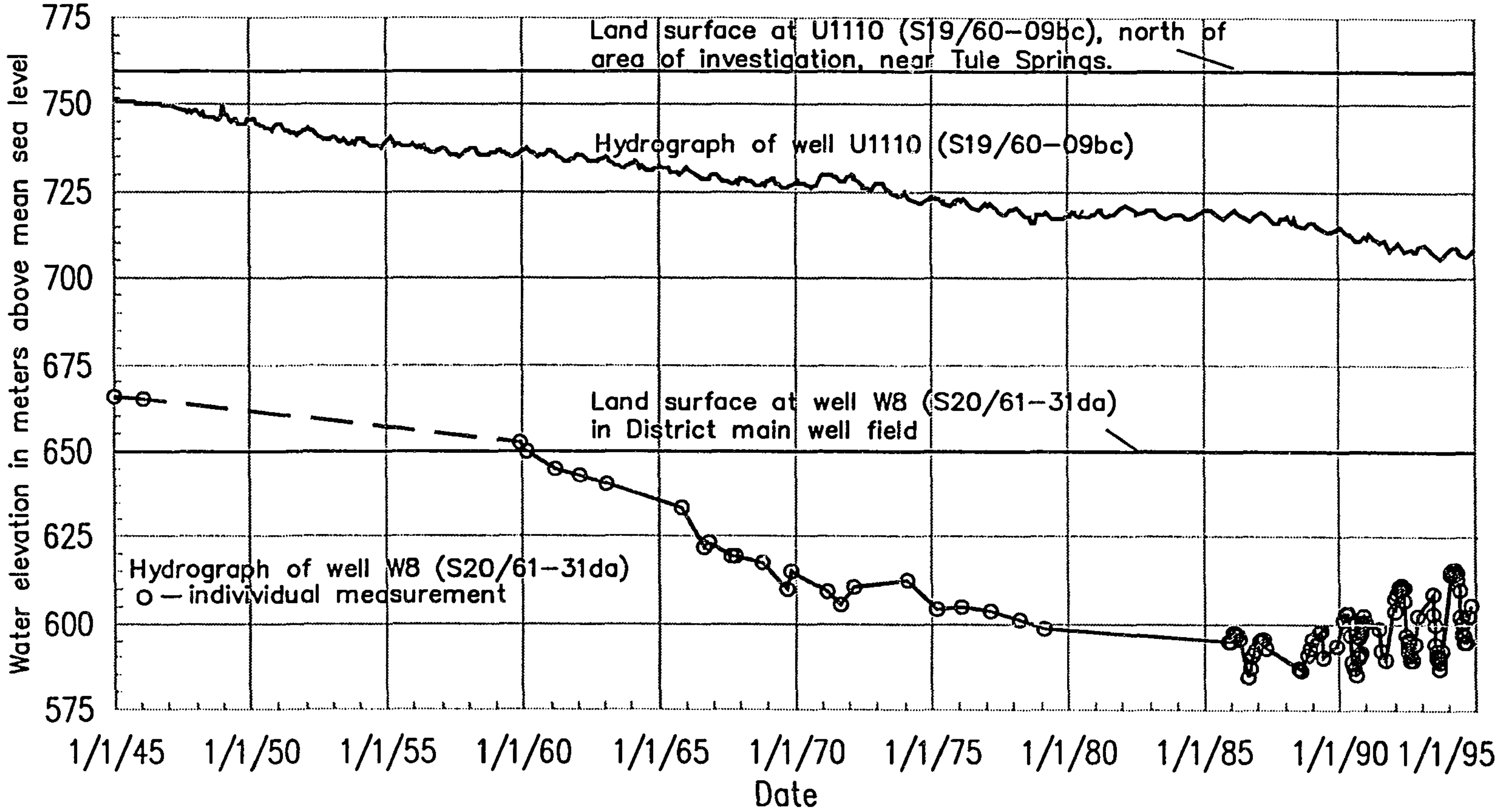


Figure 22. — Hydrograph of wells W8 (S20/61–31da) and U1110 (S19/60–09bc) from 1945 to 1995.

aquifer tests. In addition, three NLV wells were drilled and 24-hour constant flow rate tests conducted between 1991 and 1993. Figure 23 displays distribution of transmissivity. See Appendix A for data.

The tests were generally conducted in mid summer and may be suspect in areas of existing well fields. Despite this problem, these wells represent the best measure of transmissivity of the various aquifers at individual wells. A goal of this investigation was the delineation of the areal distribution of permeability in discrete hydrostratigraphic units. The municipal wells are perforated in multiple aquifers, therefore assumptions must be made about the relative contribution of each aquifer.

To be valid, significant differences in permeability must be observed between aquifers and aquitards and between aquifers. In the Las Vegas Valley where adjacent wells tap different moderate to high permeability hydrostratigraphic units (aquifers), hydraulic conductivity varies by at least an order of magnitude. The difference in permeability between aquifers and aquitards is several orders of magnitude. For all of the above reasons, the use of even crude techniques such as the estimation of transmissivities from specific capacities by the technique of Driscoll (1986, p. 1021) will give meaningful results.

Development of Stratigraphic Units in Cross-section

Four cross-sections were developed to display the vertical spatial variations of the allostratigraphic and hydrostratigraphic units (fig. 24). Four figures displaying the location of the wells, lithologic variation, boundaries of the allostratigraphic units, and the location of the hydrostratigraphic units were created for each cross-section making a total of sixteen figures. The mapped units of this investigation are displayed and described in the Results

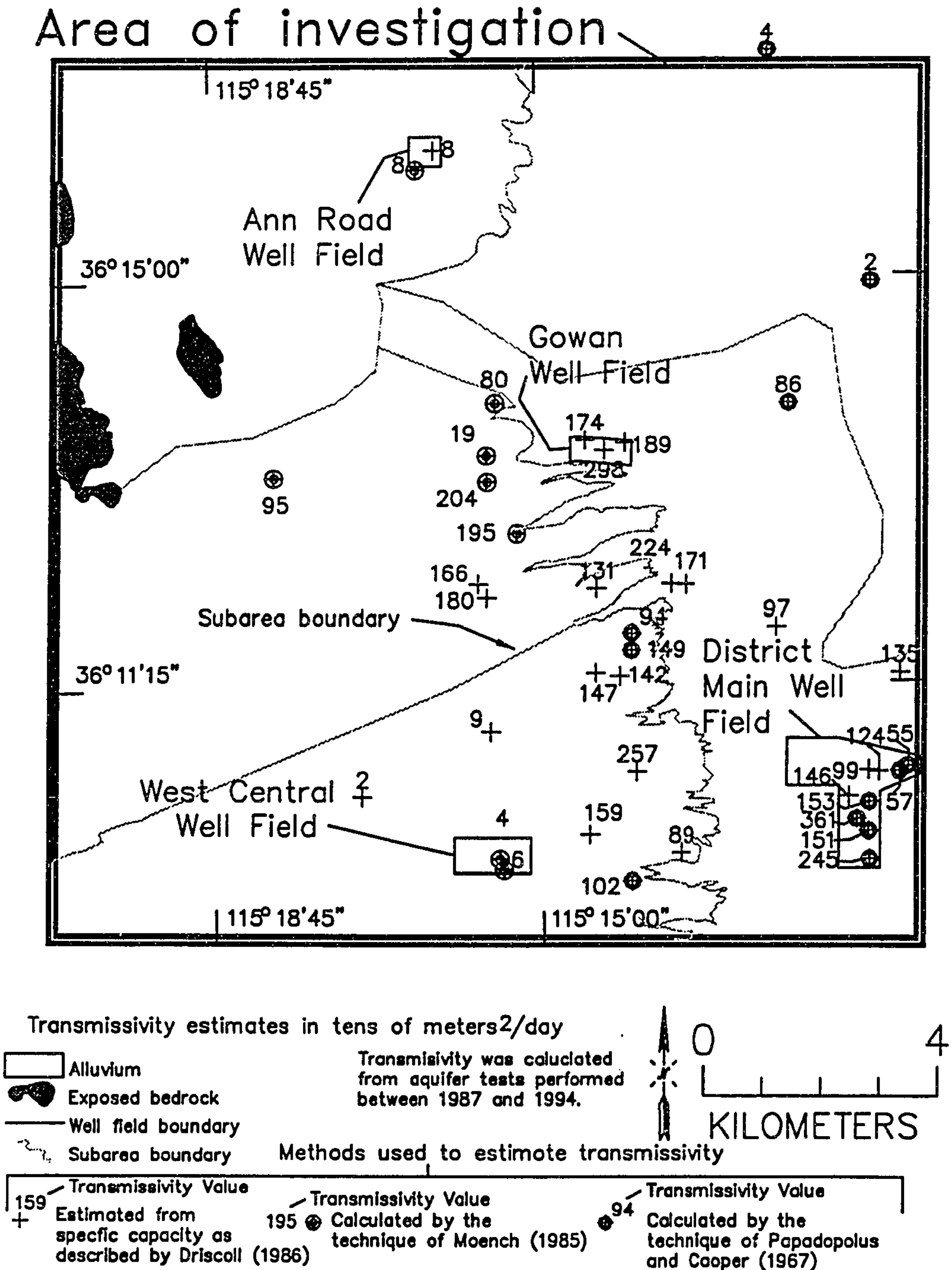


Figure 23. -- Transmissivity estimates for municipal supply wells on the west side of Las Vegas Valley.

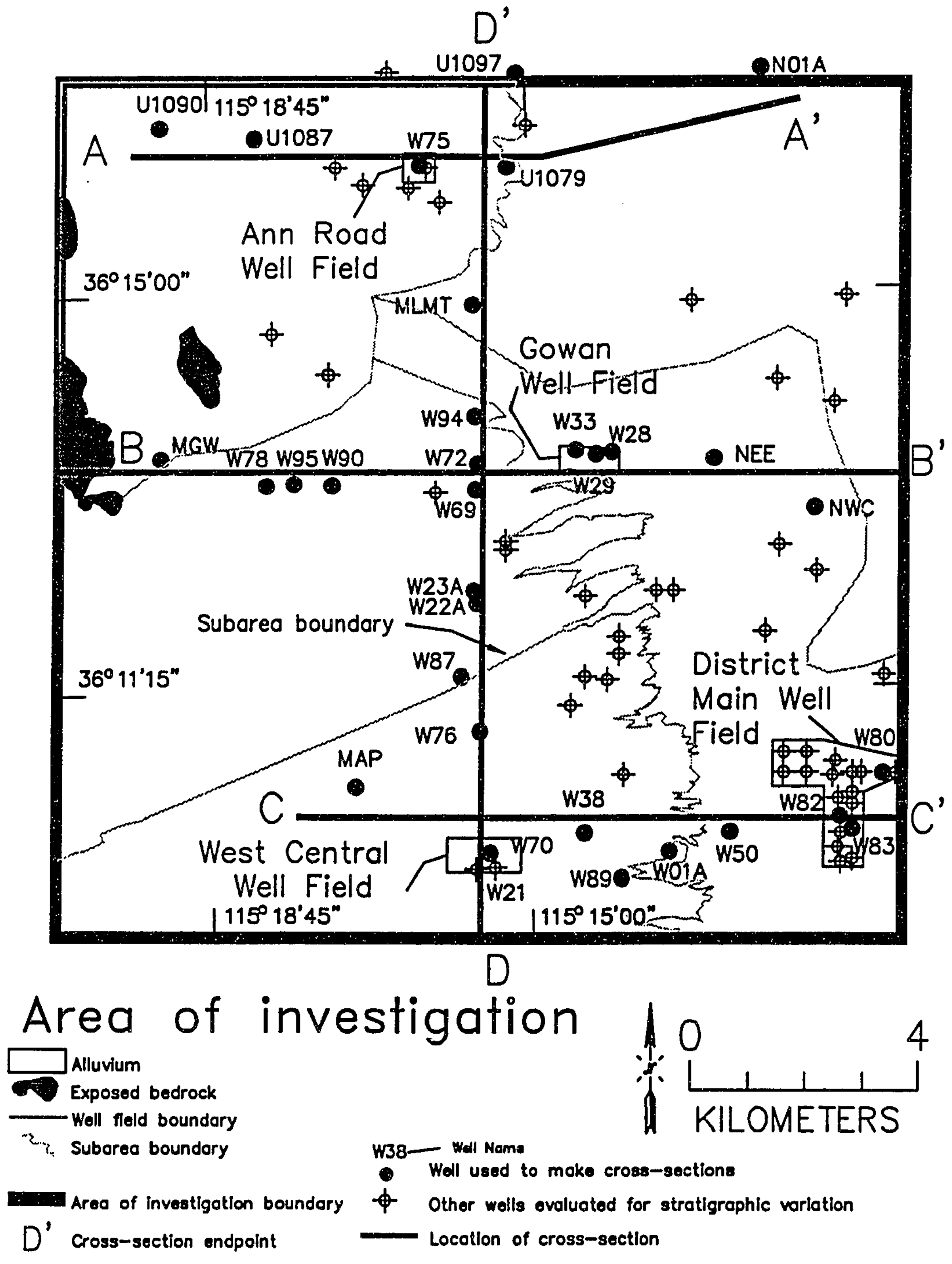


Figure 24. -- Location of cross-sections in area of investigation.

section of this investigation. The locations of the cross-sections were determined by the availability of data and the dispersal pattern of the sediments. Figures 25, 26, 27, and 28 display the location of wells, land surface, and potentiometric surface on each cross-section.

Three of these cross-sections are oriented from west to east and one cross-section is oriented from south to north. The axis of the Red Rock Alluvial Fan is nearly west-east and the southernmost (C to C') cross-section is sub-parallel with this axis. Because the cross-sections are orientated from west to east and south to north, the cross-sections are roughly parallel with major streets in the Las Vegas Road network. The northernmost west to east cross-section (A to A'), is roughly parallel with Tropical Parkway. The central (B to B') is roughly parallel with Gowan Road and the southernmost (C to C') parallels Alta Boulevard. The south to north cross-section is roughly parallel with Buffalo Drive. Each of the west to east cross-sections are about 5 km apart and the south to north cross-section is near the center of the area of investigation. Each cross-section is between 10 and 15 km long.

The western margin of the A to A' and B to B' cross-sections are within the upper (proximal) part of the Red Rock Alluvial Fan. The eastern margin is within the central playa. The C to C' cross-section crosses the southern lobe of the Kyle Canyon Alluvial Fan. The eastern edge of this cross-section is within the Tule Flats part of the central playa. The southern part of the D to D' cross-section is within the medial part of the Red Rock Alluvial Fan and the northern part is within the Tule Flats part of the central playa. The B to B' and D to D' cross-sections have the best geologic and hydrogeologic control. Together they comprise the fence diagram which will be displayed and discussed in the Results section of this investigation.

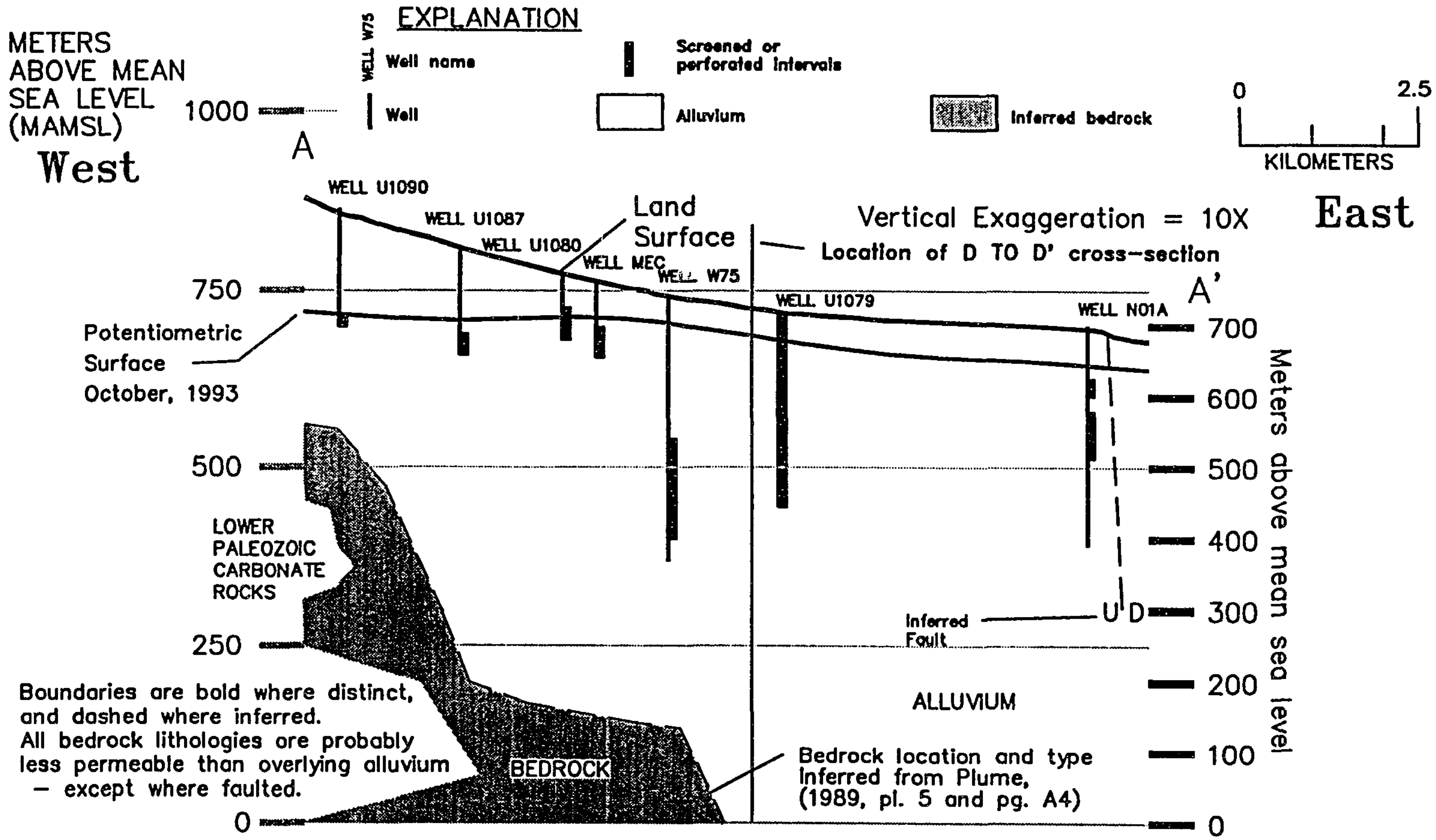


Figure 25. –– Locations of wells, land surface and potentiometric surface on A to A' cross-section.

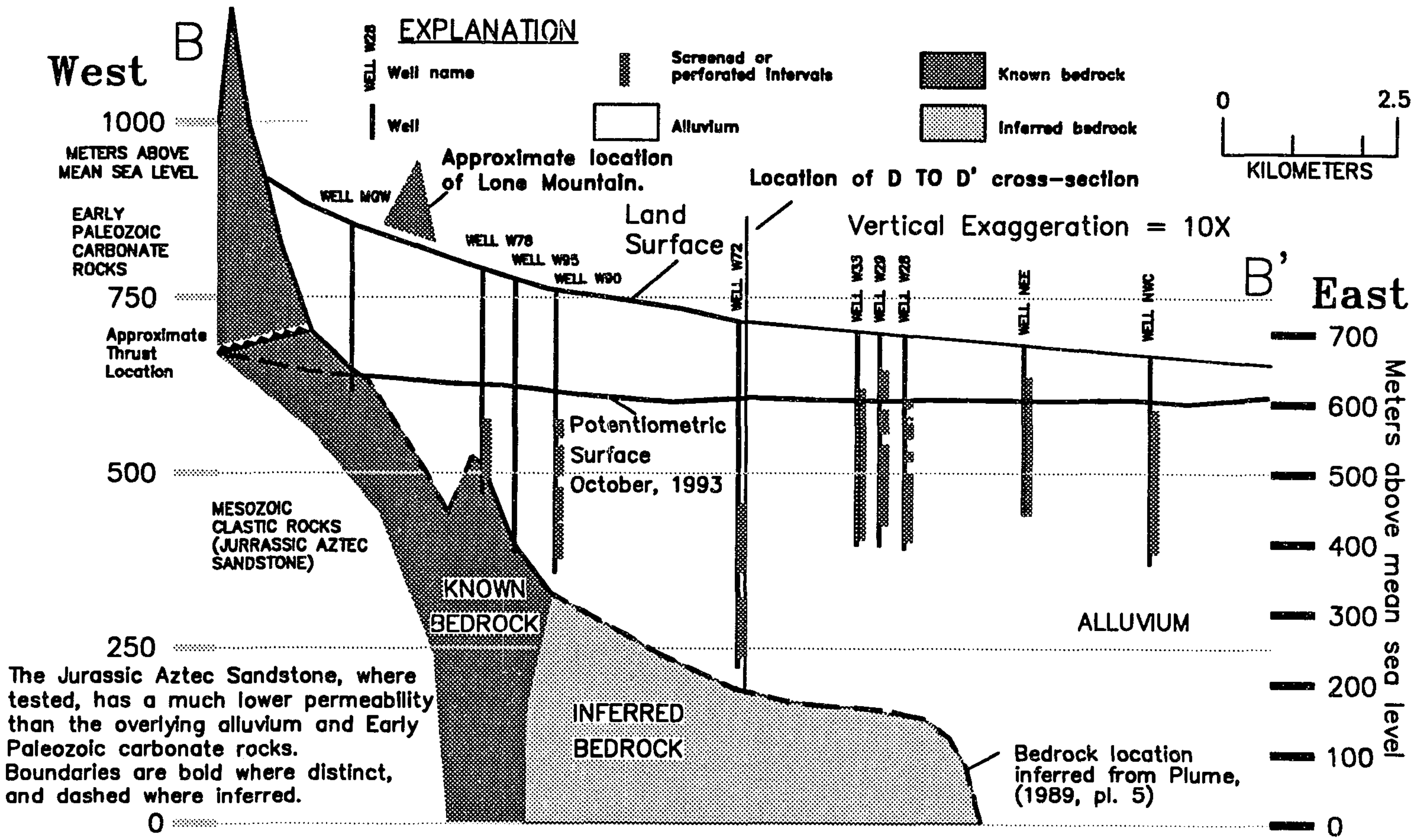


Figure 26. –– Locations of wells, land surface and potentiometric surface on B to B' cross-section.

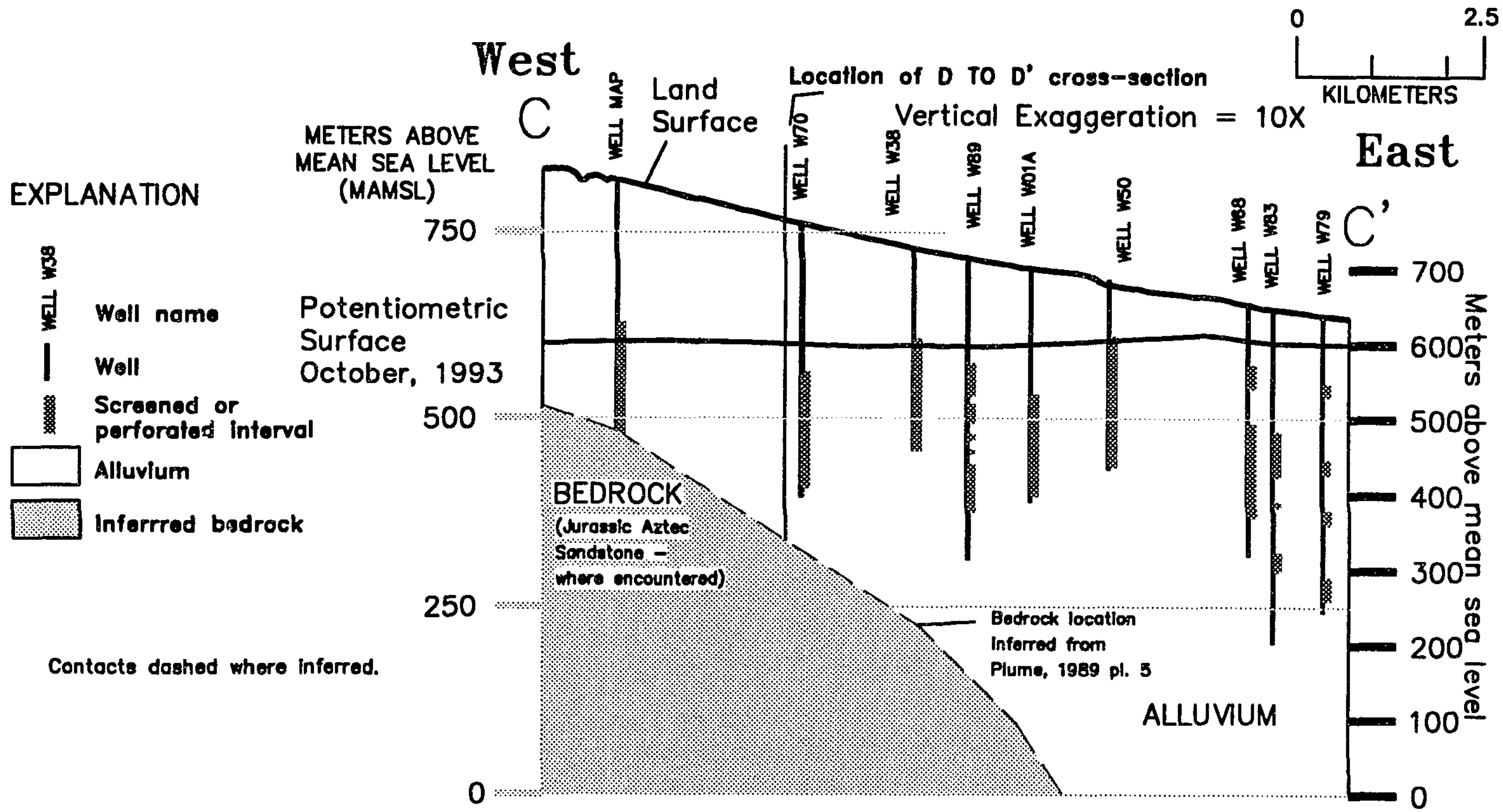


Figure 27. –– Locations of wells, land surface and potentiometic surface on C to C' cross–section.

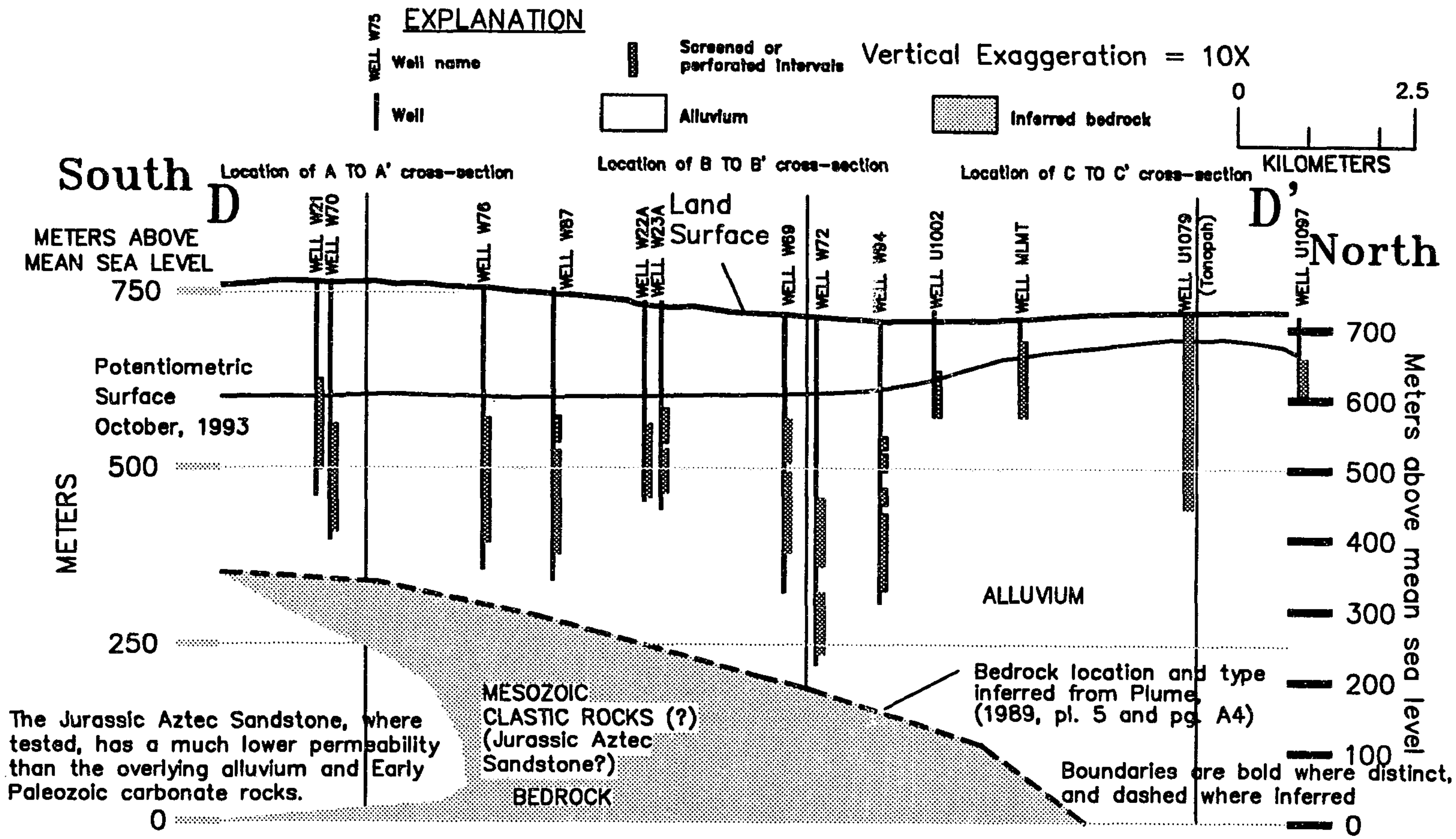


Figure 28. –– Locations of wells, land surface and potentiometric surface on D to D' cross–section.

The wells were plotted onto the cross-sections as strip-logs. Each strip-log contains information about lithology, degree of cementation, and perforated or screened intervals. Most of the detailed logs report the percentages of gravel, fine fraction (sand, silt and clay combined), and the roundness of the grains.

Descriptions of the sediments from the detailed lithologic and drillers' logs were classified into sixteen textural categories (Appendix B). The textural categories were developed using the grain size of the major and minor components of the sediment and allowed the sediment types to be classified systematically. Systematic classification was important because the seventy wells used in this investigation were drilled over a fifty year time period and the lithologic descriptions varied widely in style and completeness.

For the purposes of plotting graphical representations of the variation in the wells (strip-logs), the textural categories were abbreviated using the Unified Soil Classification System (USCS) (Pipkin, 1982, Sheet 26.1) with the addition of eight abbreviations for sediment that contains a significant amount of calcium carbonate cementation. The original detailed lithologic and drillers' logs described these intervals as "caliche" or "gravel and caliche."

The six textural classes portrayed on the eight "geologic cross-sections" are simplified categories similar to those used by Plume (1989, pl. 2). The cross-section figures are about 1:100,000 scale representations of the correlations developed at the 1:24,000 scale and were therefore simplified to document general trends.

A typical well 300 m in depth contains about 25 different lithologic units between 1 and 60 m thick. The twenty logs with detailed geologic information contain units as small as 0.15 m, with several hundred lithologic changes in a single well. In these wells, the original summary made by the person who logged the borehole was the basis for the strip-log. These summaries typically contain about 25 units. Some summaries were modified to better reflect the detailed logs, generally with the addition of one or two units.

Cementation and roundness were assigned values ranging from one to five. A one in cementation indicates no cementation and a five indicates very strong cementation. This is similar to, but a modification of, Hodgens (1974) technique to estimate rock hardness in field mapping. The numeric designation was used only to give a visual representation of the original descriptions of "well cemented", "poorly cemented", etc. Numerical values of roundness were assigned by the method of Powers (1982, sheet 18.1). A roundness number of 0.5 indicates very angular sediments and 5.5 indicates well rounded sediments. Intervals without significant sand or gravel were assigned a 0 value. When plotted, the cementation and roundness values were multiplied by twenty so that these values would have a scale similar to the gravel, fine fraction, and silt percentages.

The strip-logs were plotted onto cross-sections at 1:24,000 with a vertical exaggeration of ten. This scale facilitated the use of 7.5 minute geologic and topographic maps. The area described in this investigation covers an area about 1.5 times as large as a 7.5 minute map.

Once the strip-logs were plotted onto the cross-sections, large and small scale variations in the gravel, fine-fraction, and silt percentages, cementation, roundness, and borehole resistivity were correlated between individual wells.

The large and small scale variations, along with the borehole resistivity logs and the areal resistivity measurements made by Zohdy and others (1992, figs. 3-7), suggest that sediments within the alluvial fans are stratiform. These stratiform bodies are not mappable as distinct lithostratigraphic units because the boundaries of the stratifrom bodies do not correspond to major and distinct changes in lithic character.

Development of Allostratigraphic Units

Four allostratigraphic units of formation rank were identified in the area of investigation. The primary criterion of the allostratigraphic units is the boundary, not internal character. The features that represent an unconformity were used to identify the boundary of an allostratigraphic units. These features are intervals interpreted as caliche.

Allostratigraphic units were preferred over lithostratigraphic units because the observed grain-size changes are primarily the result of distance from the source area. Predominately coarse-grained sediments are located near the valley margin and fine-grained sediments in the central part of the valley. The lithologic descriptions of the deeper wells, (W72, W74 and W83) document coarse-grained sediments (sands and gravel) as deep as 500 m below surface and gravel-dominated coarse-grained units 40 m thick as deep as 450 m below surface. Wells W72 and W74 are in the medial parts of the Red Rock and Kyle Canyon Alluvial Fans respectively. Well W83 is located in the District's Main Well Field, which is east of the surface expression of the Red Rock Alluvial Fan. The lithologic descriptions of wells drilled in the playa (N01A, U1079) document 300 m of silt-dominated fine-grained sediments.

Stratigraphic units should be correlatable regionally (or at least basin-wide), therefore, allostratigraphic units were used in this investigation to classify the geologic units. The lithologic and calcium carbonate cementation variations described in this investigation are localized and discontinuous. The correlatable feature observed in both the fine- and coarse-grained units is caliche horizons. These caliche horizons are the bounding discontinuities which are the basis of the allostratigraphic units. Hanneman and Wideman (1991, p. 1338) used a similar approach in identifying unconformities between sequences of subsurface units in southwestern Montana.

The top surface of a soil represents an unconformity because it requires a stable environment and time to develop. In this investigation, the units identified as caliche are discrete intervals of calcium carbonate cementation overlain by a clay horizon. If the units are soils, the clay horizon is a pedogenic accumulation formed as part of the caliche forming process. Both of these features should be present because neither feature in isolation indicate a soil and each can be formed by depositional or post burial processes.

Hanneman and Wideman (1991, p. 1338) also reported pedogenic accumulations of clay (B horizon) above the caliche (K horizon) horizons. This B horizon above the caliche horizon was also reported by Sowers (1985, p. 31) and McDonnell-Canan (1989, pl. 1) in the surface mapping of the Kyle Canyon and Red Rock Alluvial Fans. The presence of this soil horizon gives support to the interpretation that the caliche is pedogenic.

In this investigation, distinct deposits of clay up to 5 m thick were observed above the caliche horizons in most of the wells with detailed logs. These deposits may be B soil horizons. The varying reported deposit thickness may be related to thinning by erosion or thickening by the deposition of sediments previously located higher on the alluvial fans.

Within the alluvial fans, the caliche horizons overlie an interval about 15 to 25 m thick of moderate to strong cementation. The caliche surface itself, however, is generally less than 5 m. The 15 to 25 m thick interval aided the identification of the caliche horizon within the alluvial fans. The caliche horizon itself was identifiable in both the fine- and coarse-grained sediments.

Development of Hydrostratigraphic Units

Six hydrostratigraphic mapping units composed of one high permeability, two moderate, and three low permeability units were identified in this investigation. Table 4 displays allostratigraphic and hydrostratigraphic units mapped in this investigation. The differences in permeability produced noticeable differences in the hydraulic behavior at the individual wells. Three phenomena related to fluid behavior can be seen at the individual wells. These phenomena were used as methods to determine the location and magnitude of differences in permeability between wells and vertically within the well. Different information is available at individual wells, therefore the method used at an individual well was determined by the available data.

The first method is to compare the differences in transmissivity from adjacent wells with different screened or perforated intervals. This method gives both the location and magnitude of the differences in permeability (see fig. 24). The second method used the intervals of water loss or gain, or changes in water-level (head) that occurred during drilling,

Table 4. - Allostratigraphic and hydrostratigraphic units used in this investigation.

Age	Thick-ness (meters)	Allostrati-graphic units	Characteristics	map-ping unit	Hydrostratigraphic units	
					Aqui-formations	Aqui-members
Quaternary	usually > 15 locally up to 40	Tule Springs Alloformation	Locally derived, generally lightly cemented, typically coarse grained, surfical deposits. Usually thin and sand dominated on Red Rock Alluvial Fan, thick and gravel dominated on Kyle Canyon Alluvial Fan and adjacent playa areas.	1	Las Vegas Wash Aquitard	Undivided
Tertiary (Pleistocene)	usually ~ 75 locally 40 to 100		This unit combines the all of the exposed Pleistocene sediments into one unit. The Las Vegas Formation is the fine-grained facies, and the contemperaneous alluvial fan sediment is the coarse-grained facies. A mixed facies occurs, locally, at the contact between fine-and coarse facies, and on the east side of the area of investigation.			
Tertiary (Pleistocene?)	~ 35	Middle part of - Lone Mountain Allogroup	On the east side of area of investigation, contact is the top of first significant gravel unit. On west side upper contact is a strongly cemented interval.	2	Las Vegas Springs Aquifer	Las Vegas Creek aquifer
Tertiary (Pliocene?)	~ 45		Contact between this and overlying unit is transitional. On east side usually composed of fine-grained sediment. On west side usually composed of cemented coarse-grained sediment.	3		Twin Lakes aquitard
Tertiary (Pliocene?)	~ 70	Lower part of - Lone Mountain Allogroup	Composed of weakly cemented coarse-grained sediment that tends to maintain consistant thickness. Near the bedrock contact, bottom of aquifer is deeper than bottom of allostratigraphic unit.	4		La Madre Mountain aquifer
Tertiary (Pliocene?)	~ 15	Paradise Valley Alloformation	Stratigraphic marker unit composed of a 15 to 25 meter thick zone of strong cementation within the alluvial fans.	5	Duck Creek Aquifer	Undivided
Tertiary (Pliocene? or Miocene?)	> 60		Includes all of the sediment below the marker. Upper 60 meters, over most of area of investigation is coarse-grained unit.	6		

and were identified by the driller. The third method used temperature changes observed on water temperature logs. The second and third methods only identify the location of intervals of high to moderate permeability. The three methods directly measure flow away from or to the well. The best method is the differences in transmissivity because this is a nearly direct measure of the permeability. The intervals identified by these methods correlate with intervals defined using other indirect measures of flow or permeability such as change in grain size, degree of cementation, and electrical resistivity.

The differences in transmissivity between adjacent wells with different screened or perforated interval can best be observed in two wells near the intersection of Cheyenne Avenue and Buffalo Drive (W69 and W72) and in several wells (W21, W70, W71) located in the Districts's West Central Well Field (WCWF) at the intersection of Charleston Boulevard and Buffalo Drive (see fig. 13). The differences in transmissivity in these wells can be attributed to the difference in permeability between a high and a moderate permeability interval with similar lithologic character.

Two other areas, the District's Gowan Well Field (GWF) and Main Well Field (MWF), were evaluated for permeability differences attributable to different completion intervals. Differences related to completion interval can be observed in these areas, however, the differences are difficult to quantify due to specific problems with the data collection or local geologic variation observed between wells.

High to moderate permeability units were found at similar depth intervals in the subsurface, as reported by Maxey and Jameson (1948, p. 82). Grain size does not directly correlate with the permeability and finer-grained material is more permeable than coarser-grained material in specific areas. The more permeable intervals are composed of sand-size or coarser material.

Spatial Correlation of Hydrostratigraphic Units

A series of maps was created describing the thickness of the informal hydrostratigraphic mapping units from the cross-sections described earlier. The hydrostratigraphic mapping units are based upon the lithic variation combined with observed differences in fluid behavior measures of permeability as described earlier in the Hydrology section. Isopach and depth-to-top maps of the hydrostratigraphic mapping units and named hydrostratigraphic units were created. The surficial geologic map of Plume (1989) and the thickness and depth to top maps all show a strong relationship with the fan morphology similar to the potentiometric contour maps. The isopach maps combined with measures of transmissivity were used to estimate hydraulic conductivity in the Las Vegas Springs Aquifer.

The Red Rock Alluvial Fan has three distinct lobes, each varying in degree of cementation, slope of the potentiometric surface, and the thickness of individual units within the subsurface. Facies changes tend to occur at the subarea boundaries and variations in permeability appear to be controlled by the sedimentation pattern.

Two of the cross-sections (B to B' and D to D') described earlier were combined to form the fence diagram in the Results section. The fence diagram provides a three dimensional view of the hydrostratigraphic mapping units. The primary tool used to map and characterize the geology and hydrogeology of the area of investigation are the cross-sections described earlier.

Hydrologic Analysis

Static wate-levels, aquifer tests, and permeability were analyzed and are described in the following sections.

Static Water-Levels

In late September and early October, 1993, water levels were measured in 38 active District production wells, recharge wells, monitor wells, and three NLV wells. The timing of the measurements was critical because many of the municipal water wells are both pumped (April-October) and injected (October-April) and the seasonal variation is quite large within the wellbores (> 50 m). Static water-level measurements are only valid in April and October when there is a minimum of pressure response caused by pumping and injection. Water levels were remeasured if a well within 1.5 km was pumping on October 5, 1993, the day nearly all the water levels were measured. Seasonal variation of water levels in wells on the far west side of the area of investigation is < 3 m and the year to year variation is < 1 m. Therefore, water levels from four wells collected by the USGS in September 1990 and 1991 on the far western side of the area of investigation were used to augment the water-level data set.

The potentiometric maps generated from the data set described earlier were compared to potentiometric maps generated from water-level information collected in 1912, 1947, and 1965 by the USGS. The 1947 data represent water levels in the period of early development of the ground-water resource. The 1947 data set has limited utility within the area of investigation because of the scarcity of control points. Domenico and others (1964, p. 26) estimated that as late as 1962 over half the ground water extracted from the alluvial aquifers was from wells in a 1600 m^2 area at what is now the Las Vegas Valley Water District's Main Well Field.

The 1965 data set includes water-level information from the wells drilled in the early 1960's. This data set has better control in the area of investigation, so the amount and location of water-level decline was estimated from this data set.

Potentiometric maps generated from the 1947, 1965 and 1993 data sets display the same general trends. The change in slope is greater north to south than west to east. The area of greatest water-level decline is offset from the area of heaviest pumpage, therefore the declines may be an indication of the anisotropy of the aquifer as well as an indication of stress caused by pumpage.

Aquifer tests

Seventeen wells were drilled by the District and three wells were drilled by NLV between 1989 and 1994. The estimated transmissivities calculated from aquifer tests of these wells are composite values because multiple intervals were screened. In only two cases were adjacent wells with significantly different screened interval tested (W74 and W75, and W69 and W72) (see fig. 23 and Appendix A).

Transmissivity values are: (1) affected by multiple screened/perforated intervals; (2) influenced by regional pressure effects from other wells; (3) valid only where the aquifers are saturated; (4) point values, with the areal boundaries of the transmissivity zones determined by geostatistics, quantitative, or semi-qualiative techniques; (5) spatially restricted and do not cover the area of investigation as fully as do specific capacity, lithologic information, or water-level measurements; (6) only representative of the screened intervals; (7) influenced by mechanical problems such as casing storage and variable flow rates caused by the pump; and (8) affected by loss of enough confinement on the west side of the area of investigation to invalidate the use of the Theis (1935) equation.

Despite the factors influencing the transmissivity values, these data are the best available quantitative measure of permeability. Specific capacity values exist and are recalculated semi-annually for 38 District wells. The three NLV wells drilled in 1991 have both specific capacity and transmissivity values. The specific capacity for two other NLV wells were recalculated in 1990. A specific capacity of < 0.2 ℓ/s/m was measured in one CLV well (MAP) in 1981. The specific capacity at this well has likely decreased due to declining water-levels and was included only because no other well exists within 2 km.

The specific capacity measurements are affected by the: (1) method of well construction, (2) condition of the well, (3) flow rate, (4) size of the well, and (5) position of the pump within the well. For these reasons, specific capacity is used in this investigation only as a semi-quantitative value with an error probably as large as the reported values. Specific capacities were used in this investigation because some of the older wells have only specific capacity values. The aquifer test data from some of these wells is as much as fifty years old. Additionally, no other technique is available to estimate permeability in unsaturated aquifers. Some of the older wells are perforated or screened in intervals different from the wells drilled between 1989 and 1994.

Permeability from aquifer tests

The permeability of the aquifers was calculated from the transmissivity using two equations:

$T/b = K$ and $\kappa = K\mu/\rho g$

where T = transmissivity,

K = hydraulic conductivity,

b = aquifer thickness,

μ = dynamic viscosity of the fluid (water),

ρ = density of the fluid,

g = acceleration due to gravity, and

κ = permeability of the medium in L^2.

The thickness of the aquifers were estimated from the cross-sections.

Permeability from geophysics and grain-size

In two of the wells (W78 and W87) drilled by the District between 1989 and 1994, acoustic geophysical logging was performed. These acoustic logs can be used to estimate porosity and do not directly measure permeability. Techniques to estimate permeability directly from porosity have existed since Hazen's formula of 1892 (cf. Vukovic and Soro, 1992). They have generally been unsuccessful primarily because the angularity of the pores, and relatively small changes in the interstices, such as cementation and small changes in the grain size sorting, have a large impact upon permeability. In many of the techniques described by Vukovic and Soro (1992), the effective grain diameter is in the 10 to 20th percentile. This means that a gravel with 25 percent silt will have a calculated permeability similar to a pure silt and gravel with 25 percent sand will have a calculated permeability similar to pure sand.

The alluvial sediments in Las Vegas Valley are usually variable mixtures of clay, silt, sand, and gravel. Changes in the sand and silt percentages are difficult to document. Neither the small grain-size changes described earlier nor slight changes in cementation would change the lithologic descriptions which are usually based upon the dominant grain size.

Estimates of permeability of a hydrogeological unit calculated from aquifer tests reflect the surrounding area because a pumping well draws water from a large to very large area around the well. Porosity and permeability calculated directly from grain size is suspect because it is a point value and may reflect only local variations at the well bore. Aquifer tests therefore, reflect the permeability of an area surrounding the well. Local variations in porosity or permeability may have little or no impact on the flow paths and the overall permeability of the hydrogeological units.

CHAPTER 5

RESULTS AND DISCUSSION

Origin of Geologic Units

Most, if not all, of the basin-fill in the area of investigation is derived from erosion of the Spring Mountains. The Spring Mountains are a complex structural block of Paleozoic carbonate and siliciclastic rocks and Mesozoic siliciclastic rocks. The area of investigation is located within the piedmont of the Spring Mountains (figs. 2 and 5). The primary features of the area of investigation are the Red Rock and Kyle Canyon Alluvial Fans and La Madre Mountain. La Madre Mountain is transverse to the axis of the Spring Mountains and separates the watersheds of the two alluvial fans.

Both of the fans are of similar size but have a different depositional history related to the rock type of the source area, the location of the depositional area, and the complexity of the depositional environment. The southern alluvial fan, the Red Rock Alluvial Fan, is described in detail below. The northern alluvial fan, the Kyle Canyon Alluvial Fan is a single alluvial fan whose source area is almost entirely Paleozoic carbonate rocks.

Deposition

Where the Red Rock Wash emerges from the mountain block ½ kilometer west of the area of investigation, it is confined by the unnamed alluvial fan in Section 21 of T20S, R59E, MDBM and the unnamed bedrock hill centered at Section 10, T21S, R59E, MDBM.

Below this hill the wash bends to the southeast. Within ½ kilometer of this point are two other apexes for the two other lobes of the Red Rock Alluvial Fan. The surface of the unnamed fan in Section 21, T21S, R59E, MDBM is older than 730,000 years (McDonnell-Canan, 1989, p. 85). The modern wash has flowed in its present course for the last 10,000 years because older alluvial fan deposits, 120,000 to 10,000 year old, (McDonnell-Canan, 1989, p. 90) cover the northern and central lobes of the Red Rock Alluvial Fan. The Red Rock Wash is actively headcutting these older deposits, as are washes within the central and northern lobes of the Red Rock Fan. The head cutting of the other lobes may be primarily driven by on-fan precipitation and a minimal sediment supply.

Three distinct lobes can be seen on the Red Rock Alluvial Fan. Each of these lobes exhibit different depositional features. The modern wash is contained within the southern lobe.

Geomorphic Controls on Red Rock Alluvial Fan Sediment Sources

The source and depositional areas of the alluvial fans studied in this report vary by type and location. Within the Red Rock Alluvial Fan watershed, the primary source rocks are the late Permian Kaibab and Toroweap Formations. These predominantly limestone units contain abundant chert, gypsum, and anhydride. As a consequence, both of these formations are more susceptible to erosion than older carbonate rocks thrusted above these formations, in this area, but less susceptible than the underlying Mesozoic siliciclastic rocks in normal stratigraphic position. The resulting topography in this area is a series of low hills, usually composed of Kaibab or Toroweap Formations, generally steeply dipping to the east and shallow dipping to the west. These hills control the location of the Red Rock

Wash until it exits the mountain block north of an unnamed hill centered in Section 10 T21S, R59E, MDBM.

The western edge of the Red Rock watershed is the axis of the Spring Mountains and the northern edge of the watershed is the axis of La Madre Mountain. The exposed lithology of both these areas are Paleozoic carbonate rocks thrust over Mesozoic siliciclastic rocks.

The thrust surface(s) may be the preferential zones of erosion where the overlying carbonate rocks are undercut and transported downfan forming a pediment on the underlying siliciclastic rocks near the thrust contact. This style of erosion would result in deposition of sediment dominated by carbonate basin-fill detritus overlying the siliciclastic rocks.

The southern slope of La Madre Mountain contains two small alluvial fans. The western fan is located in Red Rock Canyon proper and the eastern fan is an unnamed fan centered in Section 21, T20S, R59E, MDBM (Section 21 fan). The fans are separated by Turtlehead Mountain. These two alluvial fans have different effects on the overall Red Rock Alluvial Fan. The western fan is a significant source of water and sediment for the Red Rock Alluvial Fan whereas the eastern fan has low stream power and controls the locus of deposition of the fan.

Geologic description of the cross-sections

The geology of the cross-sections are described in the following sections.

Cross-section A to A'

This cross-section is oriented west to east and has the least amount of detailed information. The most prominent feature is a gravel channel sub-parallel with the cross-section along the edge of the Kyle Canyon Alluvial Fan. North of this cross-section both the subsurface (geophysics and drill logs) and surficial geologic data indicate the abundance of fine-grained sediments. East of Rancho Drive, silt with only minor gravel intervals is the most common sediment type.

Table 4 correlates the allostratigraphic and hydrostratigraphic units mapped in this investigation. Figure 29 displays the distribution of sediment as interpreted from well logs on the A to A' cross-section. Figure 30 displays the distribution of sediment and the allostratigraphic units mapped in this investigation on the A to A' cross-section.

Cross-section B to B'

This cross-section is oriented from west to east and is parallel with Gowan Road. This is the primary west to east cross-section and documents many of the features within the subsurface. The most distinctive features of this cross-section are: (1) a fine-grained cap approximately 100 m thick with an intercalated gravel lens 10 to 30 m thick, (2) a predominance of gravel below the fine-grained interval, and (3) bifurcation of the lower gravel interval into an upper and lower unit separated by a finer-grained interval east of Buffalo Drive (between W72 and W33). Although this cross-section crosses the zone of the Quaternary fault scarps, no mapped fault scarps cross the line of section. At depth, however, the offset of beds between W33 and W29 and the increase in cementation in W29 are indicative of faulting. A line of vegetation can be seen on 1950 aerial

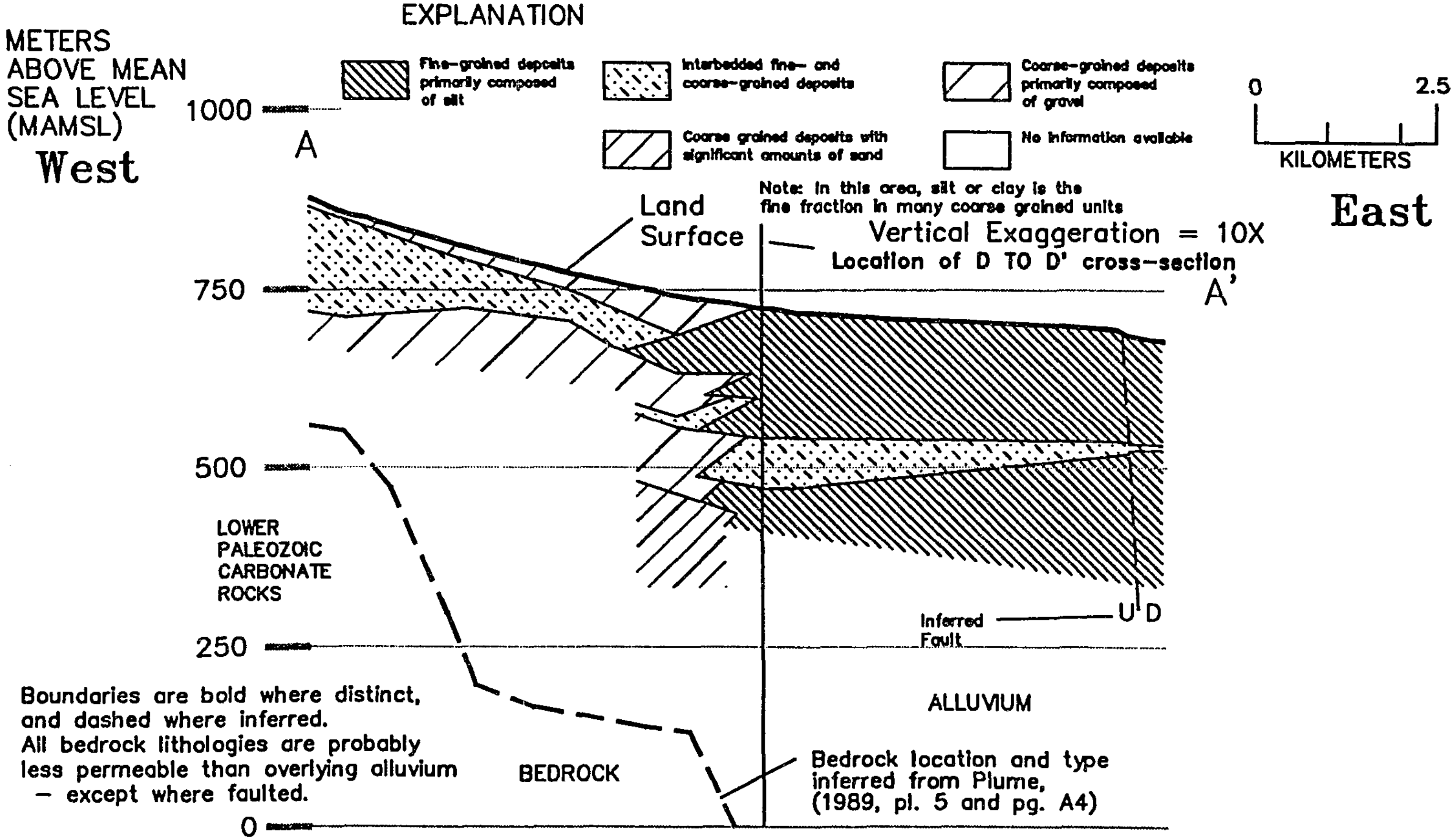


Figure 29. –– Distribution of major textural classes on the A to A' cross-section.

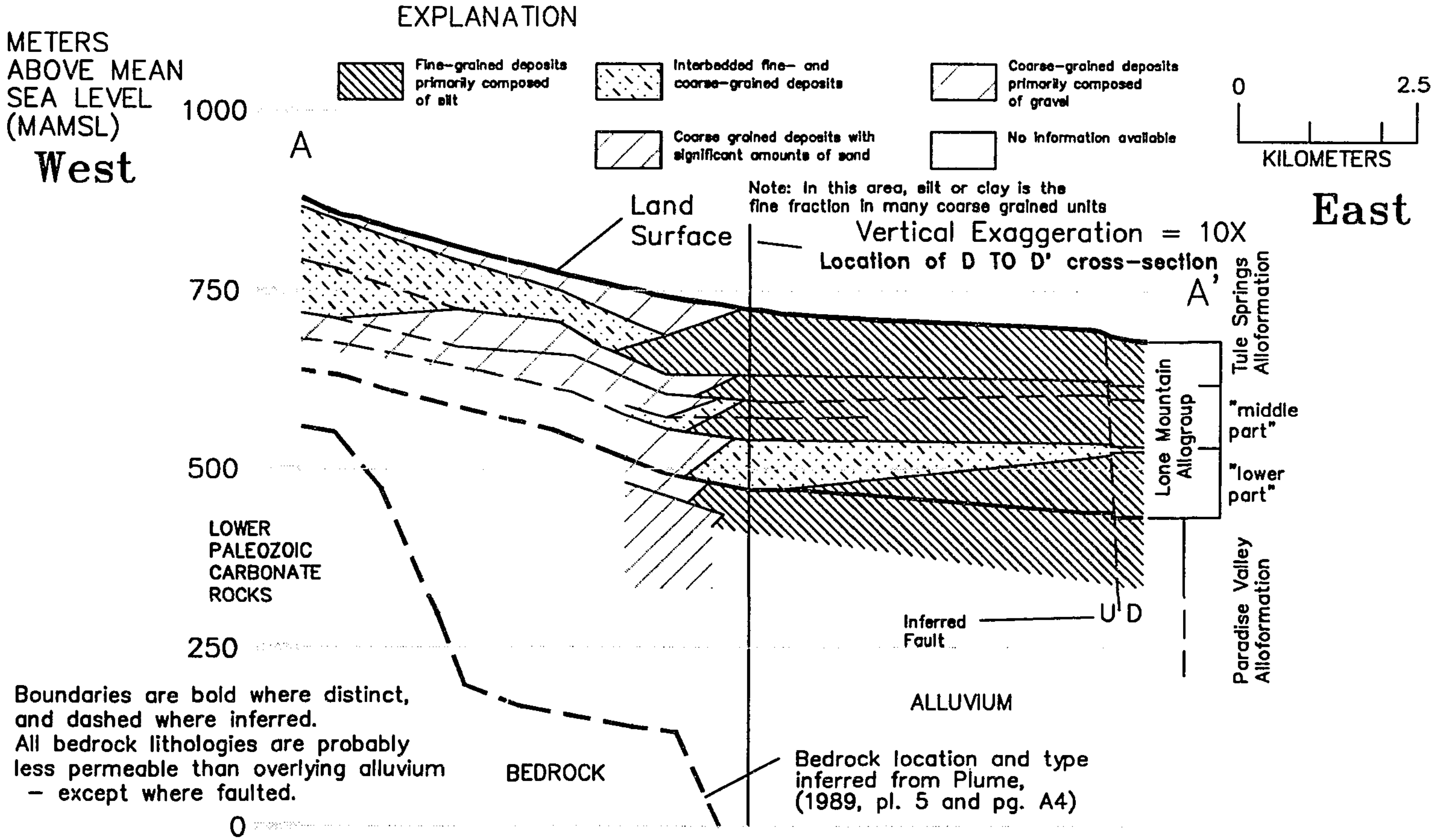


Figure 30. –– Distribution of major textural classes, bounding discontinuites, and allostratigraphic units on A to A' cross-section.

photographs of this area where the proposed fault would be exposed at the surface. Figure 31 displays the distribution of sediment as interpreted from well logs on the B to B' cross-section. Figure 32 displays the distribution of sediment and the allostratigraphic units mapped in this investigation on the B to B' cross-section.

Cross-section C to C'

This cross-section is oriented west to east roughly parallel with Charleston Boulevard and subparallel with the Red Rock Alluvial Fan axis. The dominant lithology is gravel and sand with a relatively rapid decrease in grain size near the District MWF on the eastern side of the section. The correlations are strongly influenced by downhole resistivity measurements which are primarily the result of variations in cementation and minor lithologic variation.

This western side of this cross-section is similar to the western side of the cross-section B to B' where the deposits are gravel and sand primarily distinguished by variations in cementation. The various deposits are usually bounded by horizons of strong cementation. The boundaries are assumed to be pedogenic caliche (calcrete) partially because they appear to be continuous with the lithostratigraphic units defined from variations in grain size.

The geologic variation is not as well defined in this cross-section as it is in cross-section B to B'. Figure 33 displays the distribution of sediment as interpreted from well logs on the C to C' cross-section. Figure 34 displays the distribution of sediment and the allostratigraphic units mapped in this investigation on the C to C' cross-section.

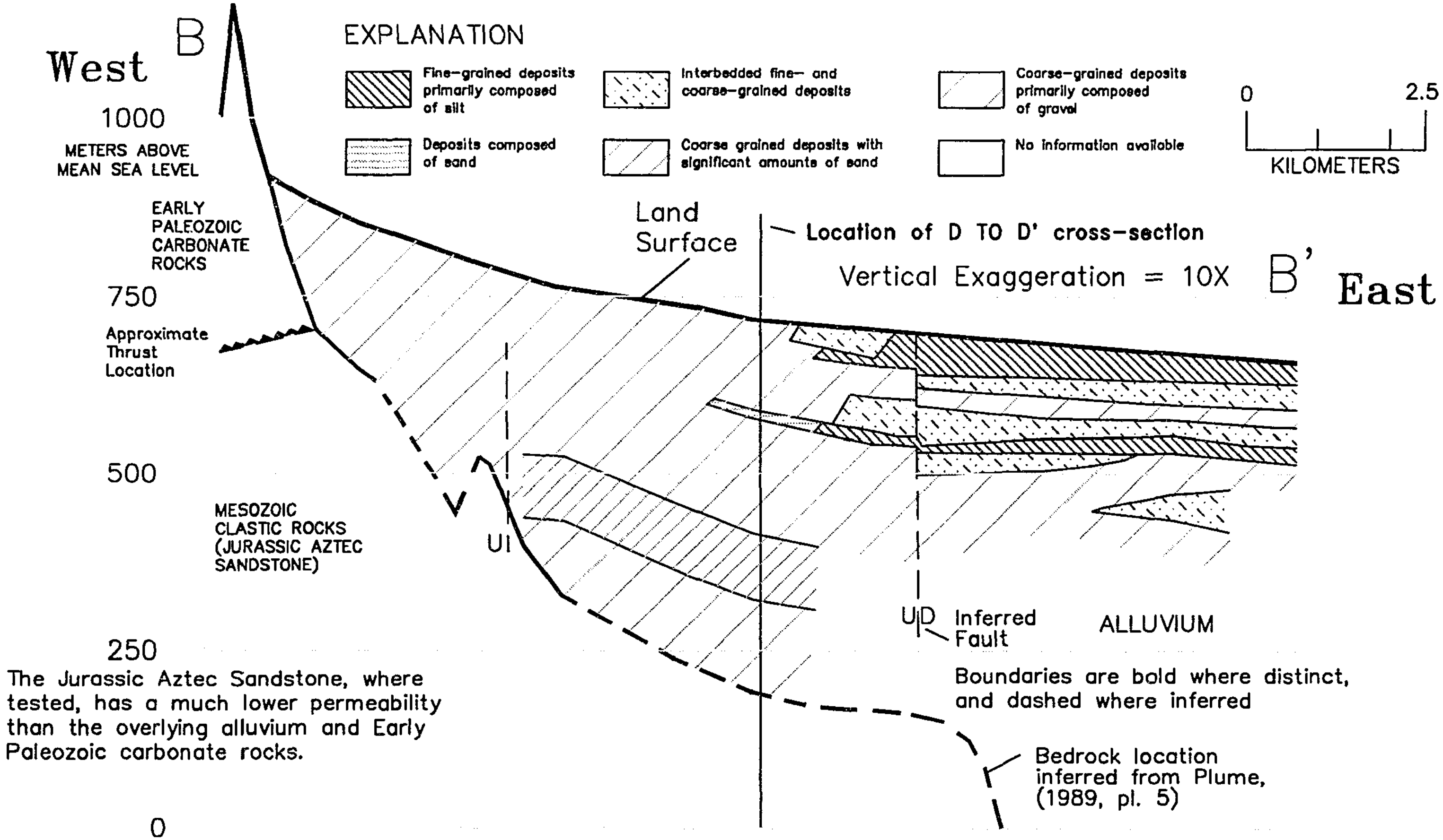


Figure 31. –– Distribution of major textural classes on B to B' cross-section.

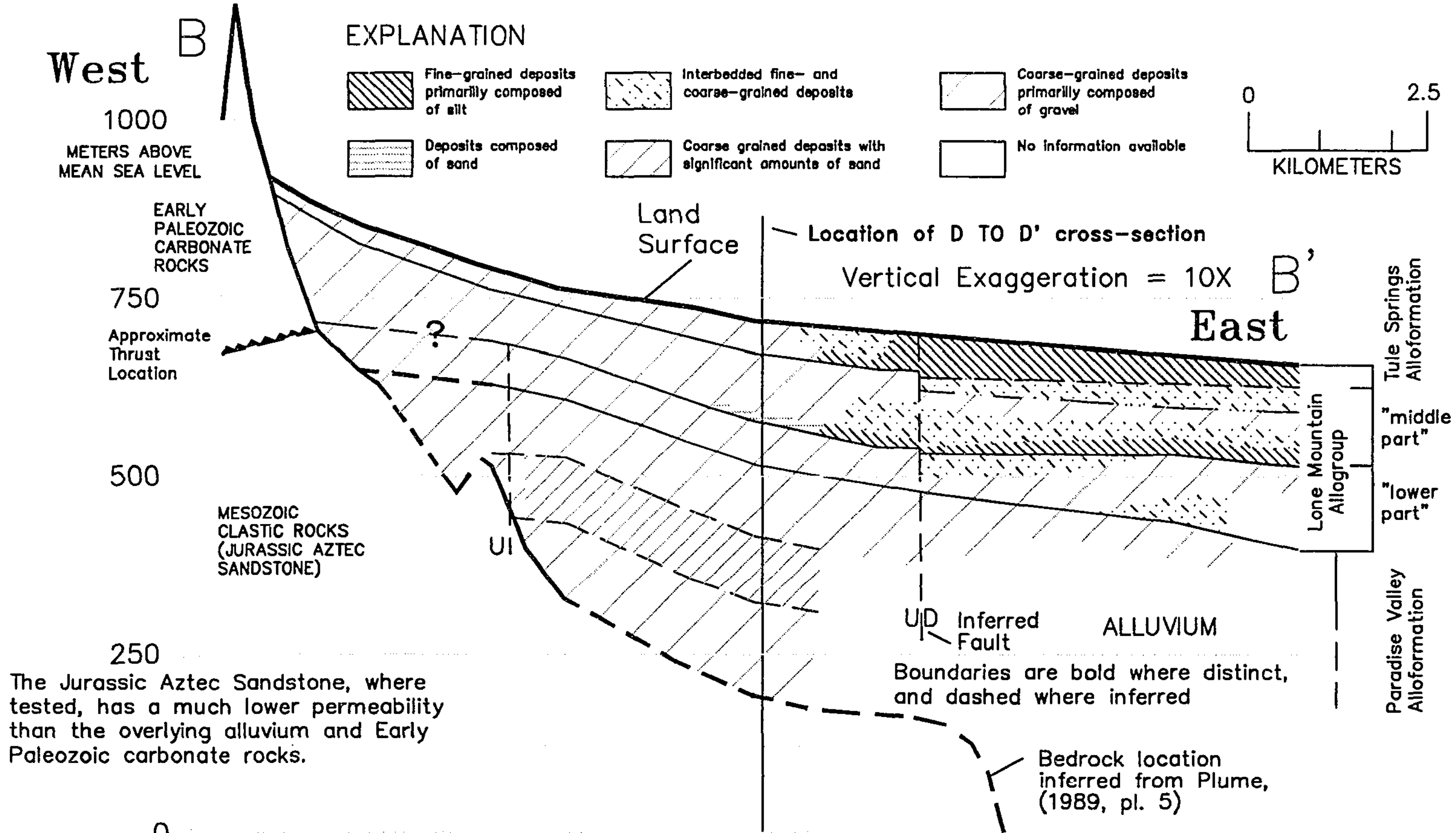


Figure 32. -- Distribution of major textural classes, bounding discontinuites, and and allostratigraphic units on B to B' cross-section.

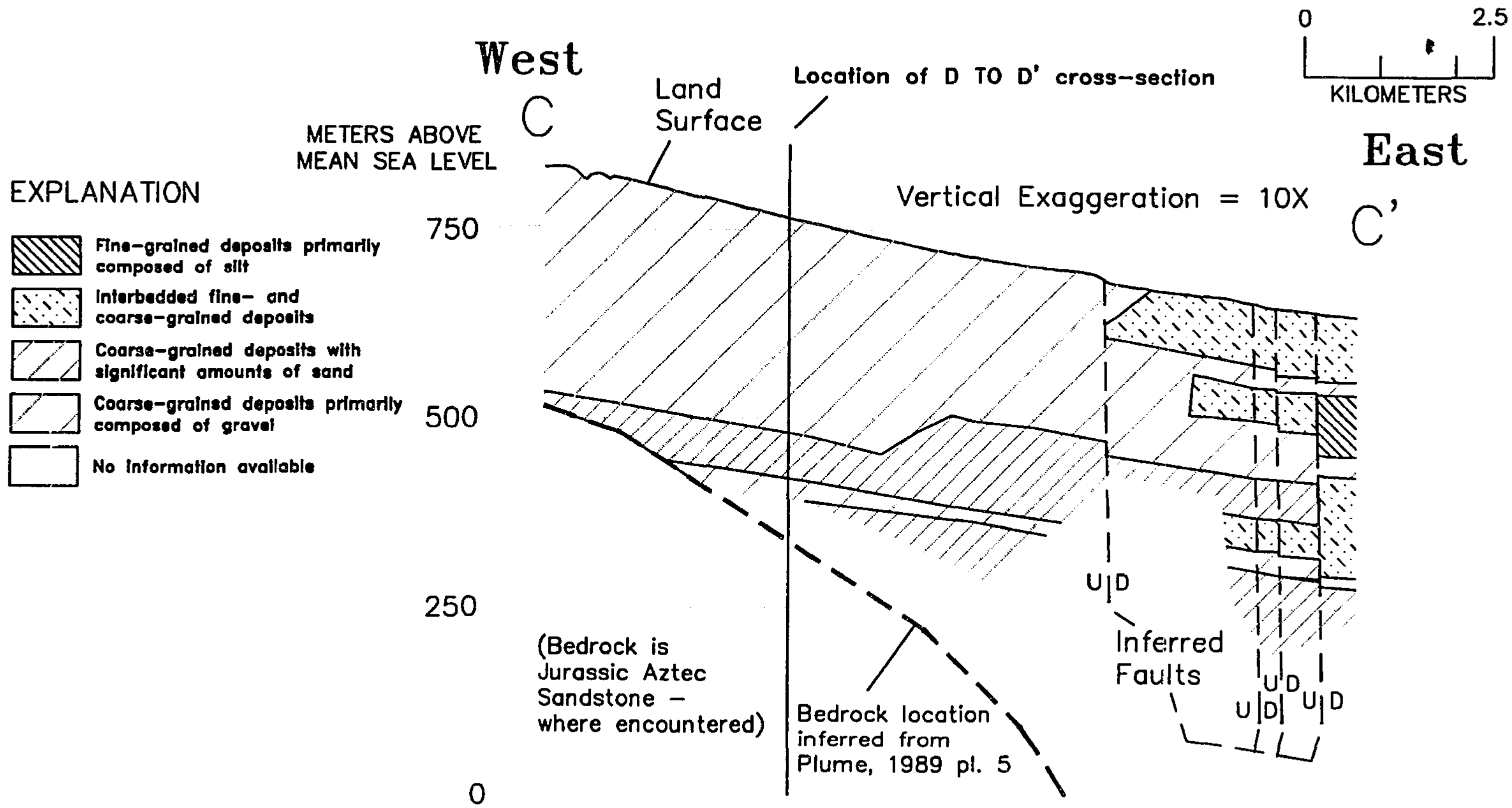


Figure 33. -- Distribution of major textural classes on the C to C' cross-section.

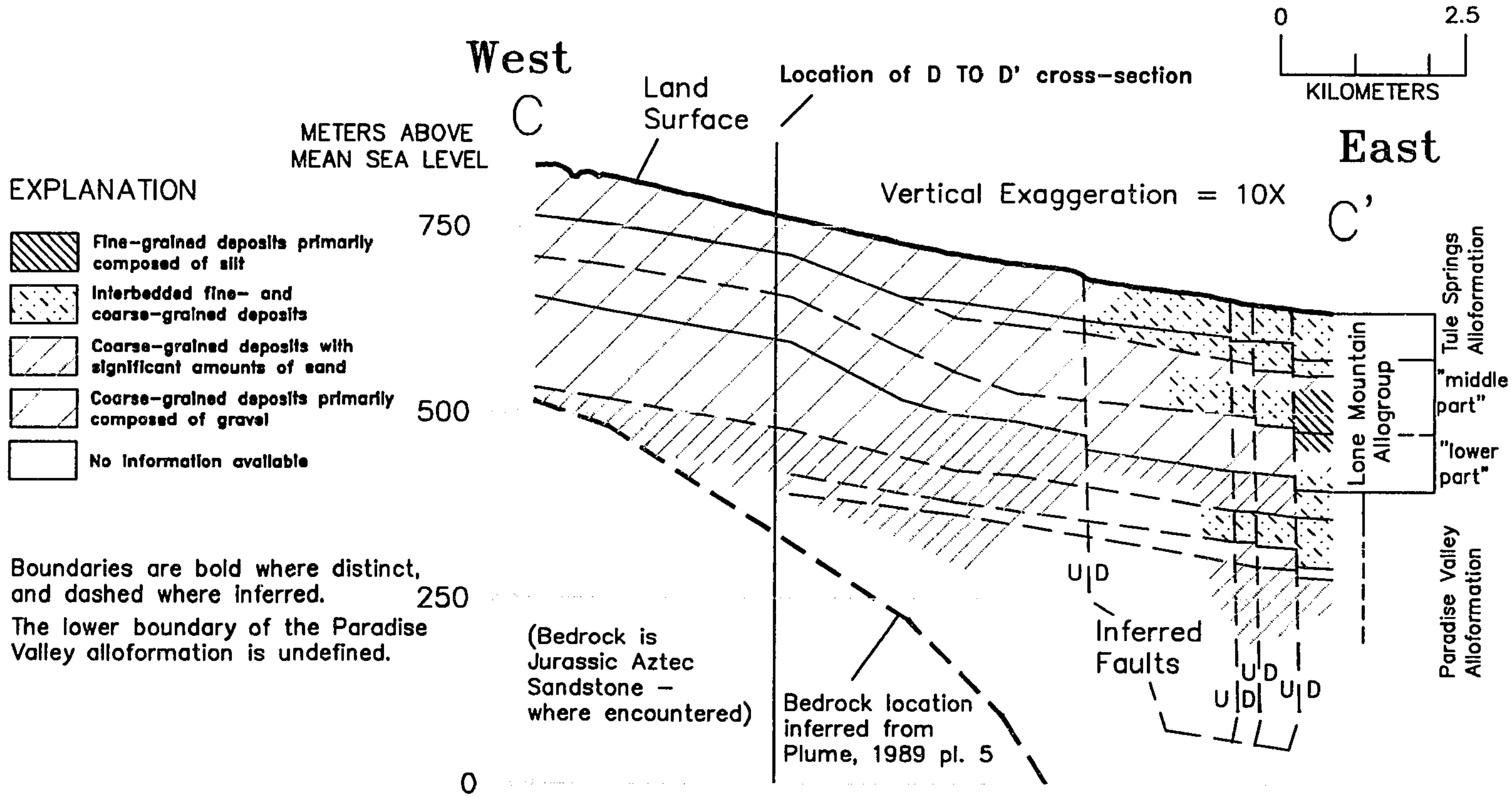


Figure 34. -- Location of textural classes, bounding discontinuites, and allostratigraphic units on C to C' cross-section.

Cross-section D to D'

This cross-section is oriented south to north along Buffalo Drive and transverse to the axis of the Red Rock Alluvial Fan. The purpose of this cross-section is to document the continuity of units between lobes of the Red Rock Alluvial Fan. The cross section is at the boundary between major grain-size changes (west to east).

In addition, detailed information from wells drilled by the District between 1989 and 1994 is available along this cross-section. In most of the alluvial fan literature (Bull, 1964; Denny 1967; French, 1992) the emphasis is placed on the continuity of the individual lobes. In an arid alluvial fan such as the Red Rock and Kyle Canyon Alluvial Fans, continuity is most likely only within lobes. This continuity arises from similar depositional conditions such as: (1) size and lithology of the source area, (2) intensity of storms, (3) position of the apex and intersection point, and (4) amount of vegetative cover. Lobe to lobe correlation is likely to occur only if the lithostratigraphic or allostratigraphic units are thick, if similar depositional conditions persist over a significant percentage of the total age of the fan, or if the depositional conditions are cyclic.

The allostratigraphic units persist across the northern part of the cross-section within the northern lobe of the Red Rock Alluvial Fan; however, these units are thin or are eroded across the axis of the fan in the southern part of the cross section. Figure 35 displays the distribution of sediment as interpreted from well logs on the D to D' cross-section. Figure 36 displays the distribution of sediment and the allostratigraphic units mapped in this investigation on the D to D' cross-section.

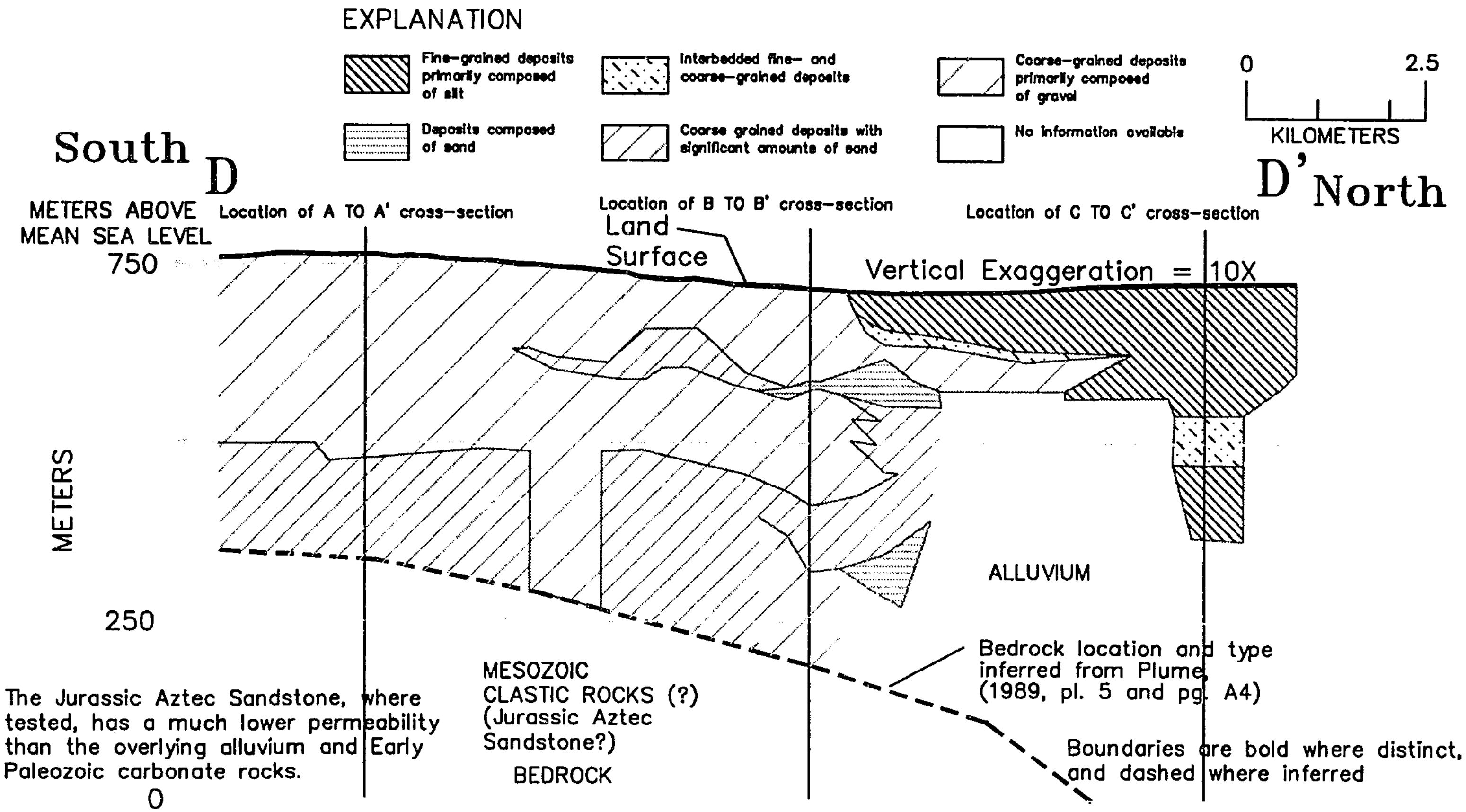


Figure 35. -- Distribution of major textural classes on D to D' cross-section.

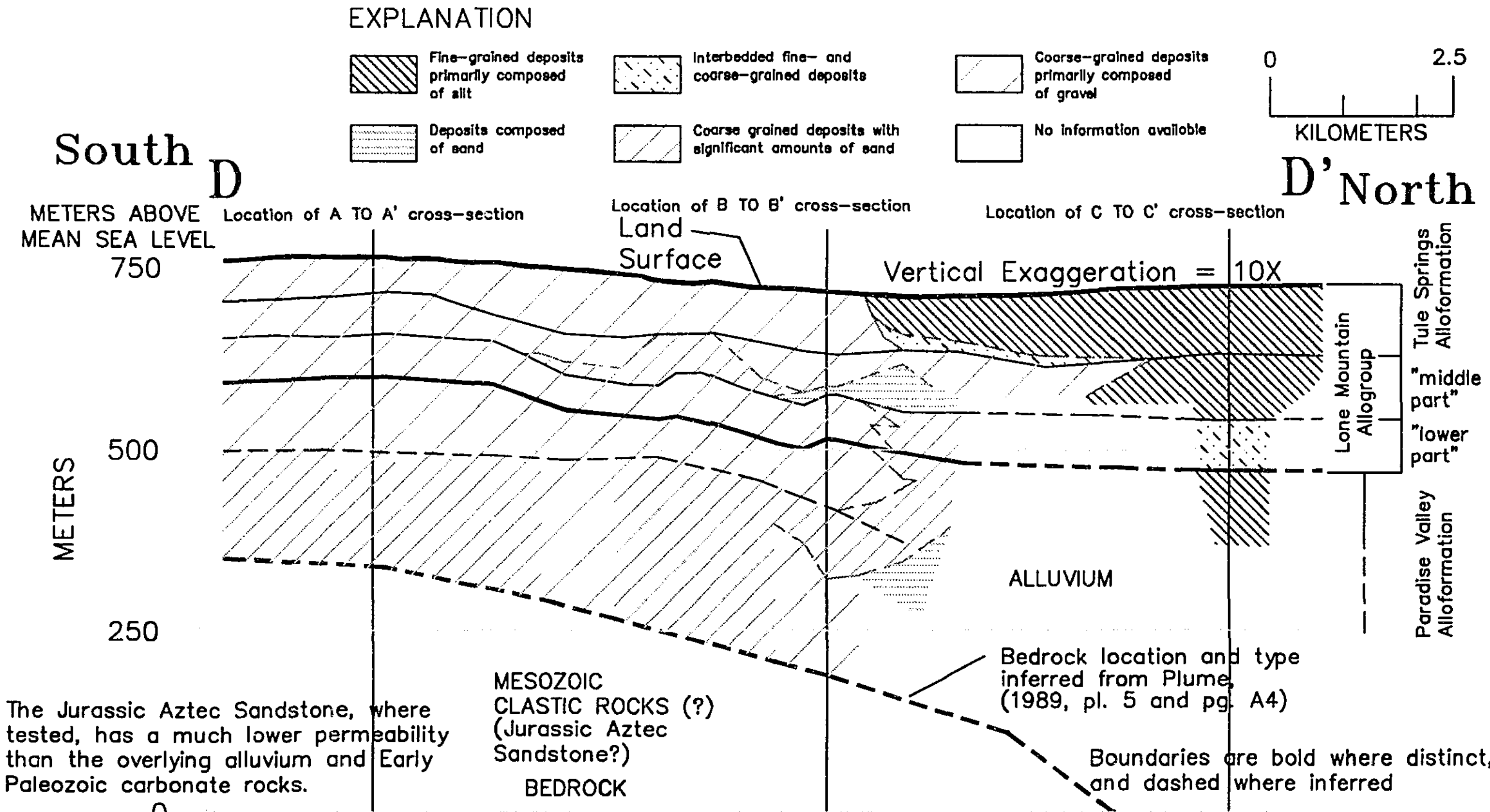


Figure 36. —— Distribution of major textural classes, bounding discontinuites, and allostratigraphic units on D to D' cross-section.

Hydrostratigraphic Units

This investigation identified and described six units within the basin-fill of the Las Vegas Valley. The hydrostratigraphic units are mapped and characterized by porosity and permeability but traditional geologic methods are used to map the units in cross-section.

Lithologic Controls on Permeability

Throughout the area of investigation the facies transitions in the subsurface are consistent with the alluvial fan depositional environment. In the western part of the area of investigation, in the proximal portions of the Kyle Canyon and Red Rock Alluvial Fans near the Spring Mountains and La Madre Mountain, gravel with sand is the dominant type of lithology. This transitions into a zone (medial and distal part of the fans) where the gravel lenses interfinger with finer-grained sediment (minor clay, silt, fine sands and spring-deposited caliche).

The coarse-grained deposits in the proximal part of the alluvial fans are several hundred meters thick. The interbedded coarse- and fine-grained deposits are also several hundred meters thick in the medial and distal parts of the alluvial fans. Although the units interfinger, the changes in grain size down slope appear to be abrupt. East of Rancho Drive in the Tule Flats and central playa of Las Vegas Valley, fine-grained sediments are the dominant lithology. Figures 37, 38, 39 and 40 display the hydrostratigraphic units mapped in this investigation.

The fine-grained sediment are usually less permeable than the coarse-grained units, however, the permeability of the coarse-grain units is variable. The permeability of the coarse-grained units appear to be strongly controlled by degree of cementation and continuity

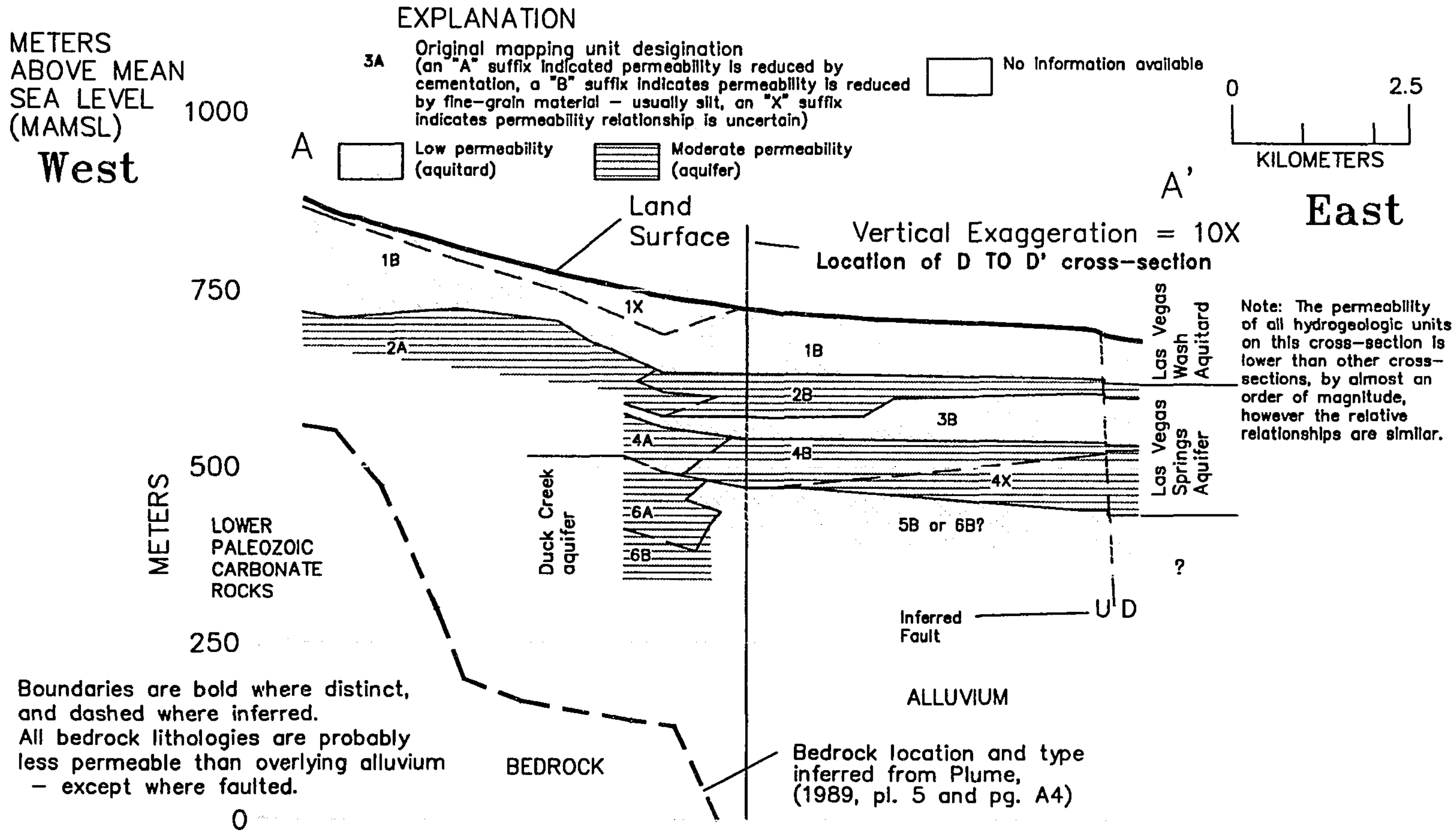


Figure 37. -- Location of hydrostratigraphic units on A to A' cross-section.

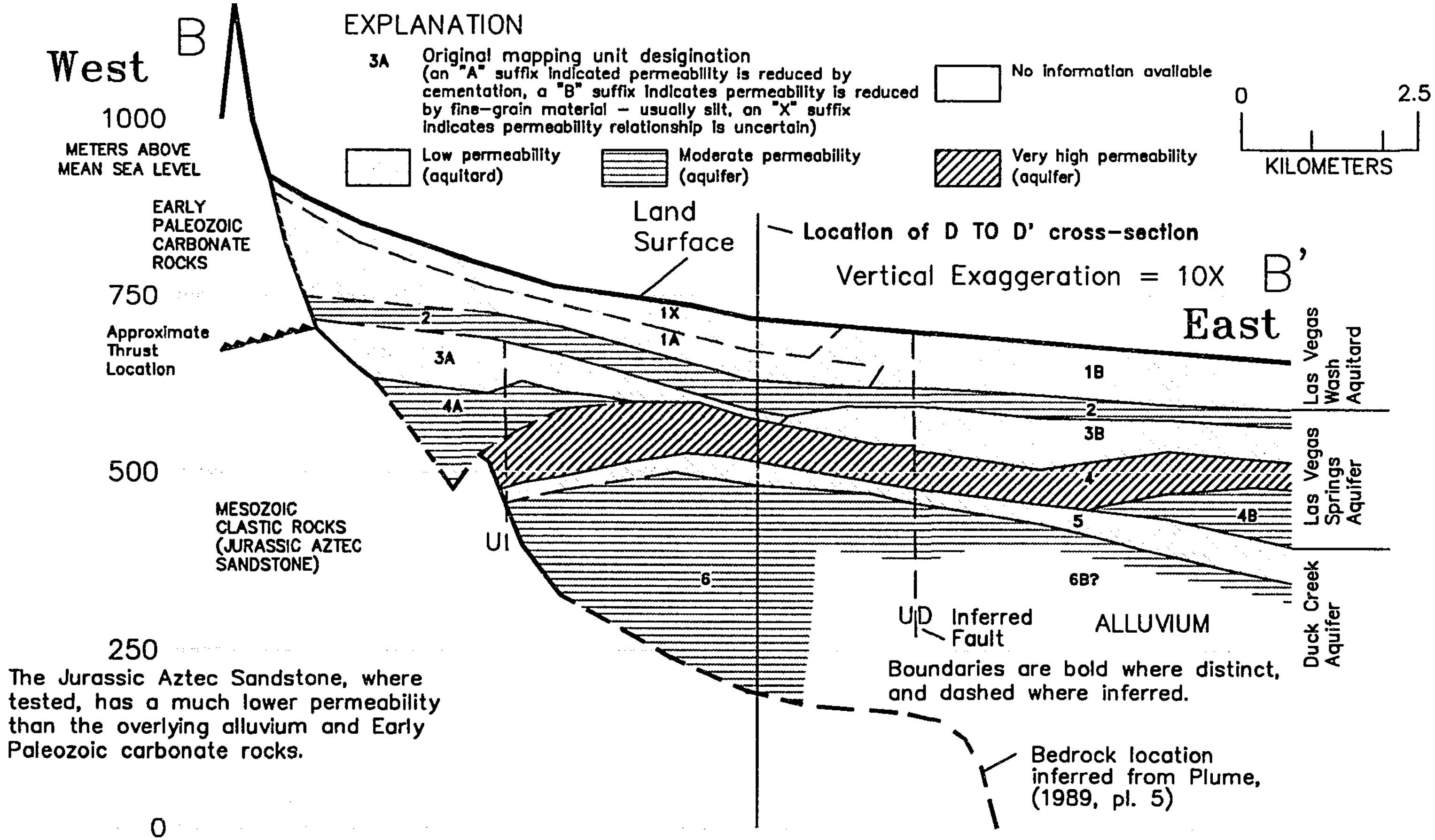


Figure 38. -- Location of hydrostratigraphic units on B to B' cross-section.

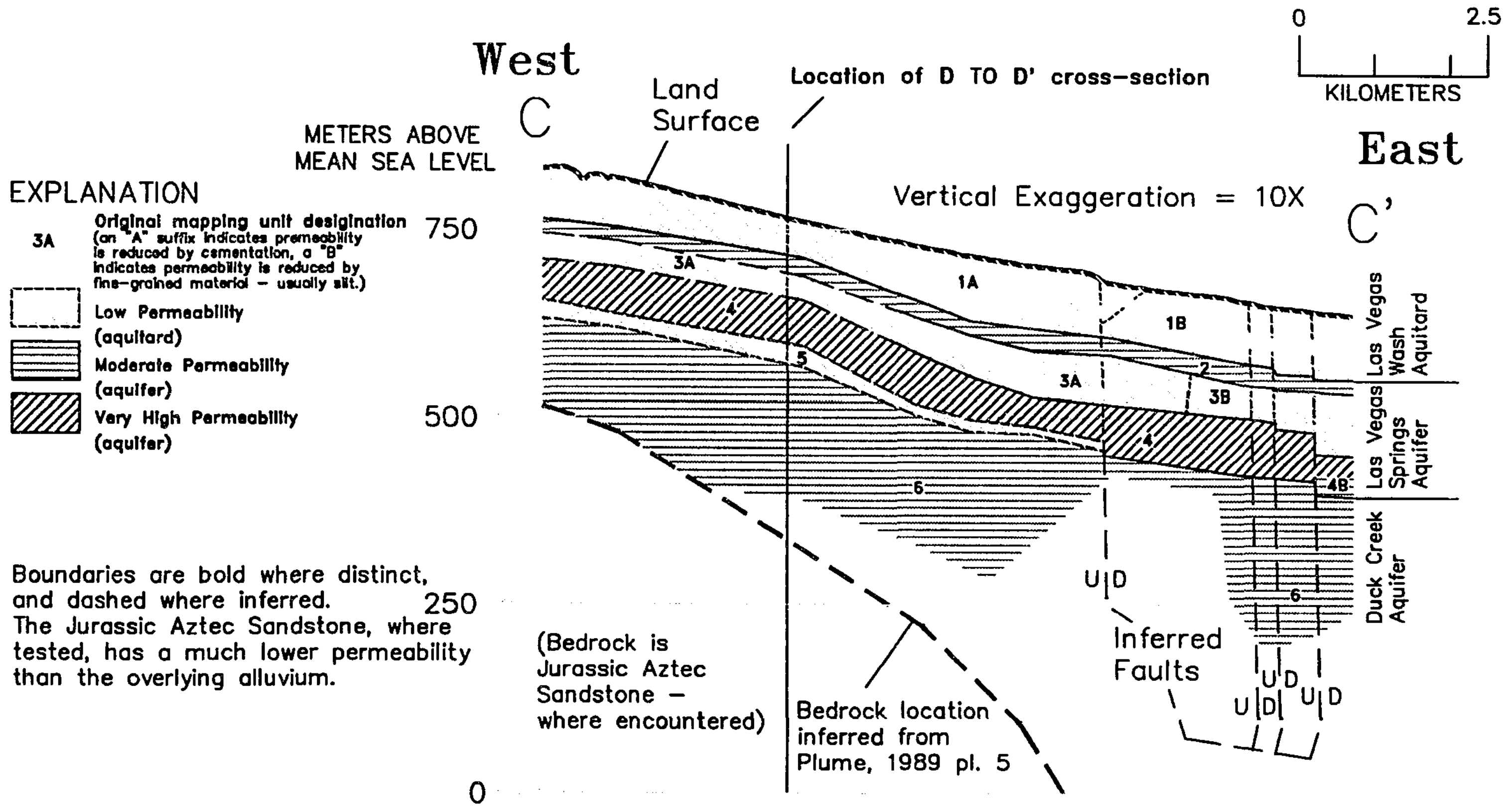


Figure 39. –– Location of hydrostratigraphic units on C to C' cross-section.

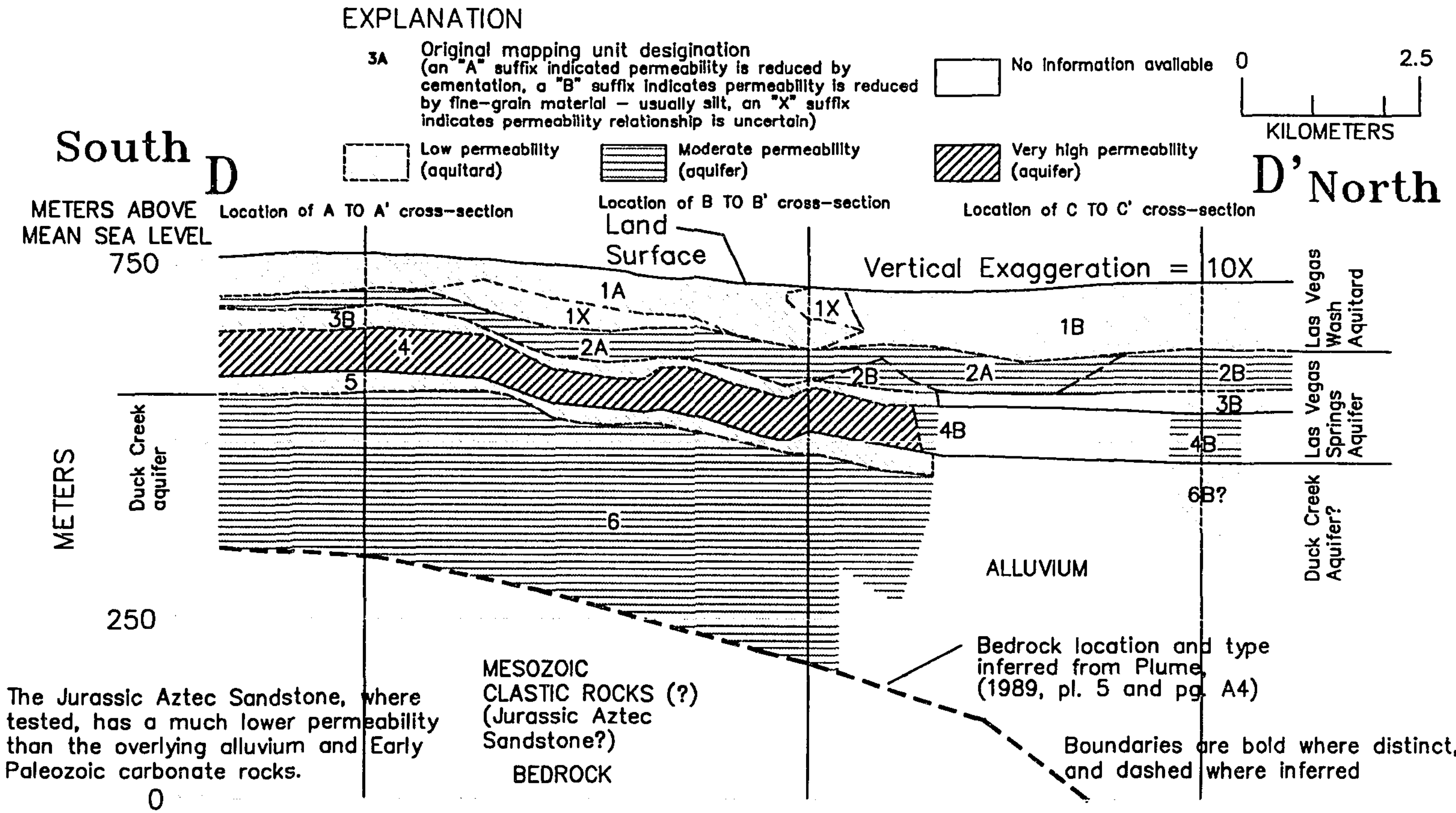


Figure 40. –– Location of hydrostratigraphic units on D to D' cross–section.

between sediment lenses. These are sediment dispersal pattern features and are controlled by fan morphology. This may be the reason for the spatial correlation between the hydrologic properties and the geometry of the fans.

Mapping criteria for Hydrostratigraphic units

Grain size and cementation are the primary mappable characteristics within the subsurface and were used as the basis for the physical description of the hydrostratigraphic units. Other stratigraphic characteristics that aid in the description of hydrostratigraphic units are: (1) the relative percentages of gravel, sand, silt and clay in each interval, (2) degree of sorting, (3) roundness of the grains, and (4) apparent thickness of beds. These types of data are available only for the seventeen wells drilled between 1989 and 1994 and there is variation in the quality of the data. Not only are the data of variable quality but the detailed stratigraphy may also represent individual depositional flows.

Exact correlation between individual depositional flows is neither possible nor desired in this investigation. The minimum thickness of a mappable unit is 10 m. This is many individual depositional flows and probably represents hundreds to thousands of years of deposition.

Lateral Variation of the Hydrostratigraphic Units

The hydrostratigraphic units exhibit both lateral and vertical variation. The lateral variation is related to the location of the lobes of the fan, specifically the areas of preferential cementation and the grain-size distributions. The two areas with the highest reported transmissivities in the area of investigation are within the District's MWF and at wells W69 and W88. (see fig. 23). These two areas are contained with a larger zone where the reported transmissivity of wells is usually greater than 1000 m^2/day and where specific capacity of wells is generally greater than 5 ℓ/s/m. This zone is about 6 km wide along Charleston Boulevard and about 7.5 km wide along Gowan Road. The zone extends from south of the area of investigation north to about Craig Road. Wells W69 and W88 are located near the center of the northern lobe of the Red Rock Alluvial Fan which is characterized by coarse-grained sediment, unchannelized depositional flows, and relatively weak cementation.

Within the southeastern part of the area of investigation (Subarea 4), the location and nature of the hydrostratigraphic units described in this investigation are similar to previously named alluvial aquifers characterized by grain-size variations. Grain-size of the sediment also appears to strongly control the permeability in Subarea 5; however, the differences in permeability between aquitards and aquifers are not as pronounced.

The simple relationship between grain size and permeability does not appear to be consistent in areas with significant amounts of coarse-grained sediment (Subareas 1, 2 and 3). The coarse-grained sediment should be viewed as potentially highly permeable, but locally have moderate to low permeability due to the presence of silt and/or cementation. The hydrostratigraphic units appear to be similar to the allostratigraphic units, indicating that cementation reduces permeability and is an aquitard within the alluvium.

The hydrostratigraphic units were refined with detailed lithologic and hydrologic data collected between 1989 and 1994 north of Craig Road and west of Rainbow Boulevard (Subareas 1, 2, 3, and 5). Municipal wells were emphasized as indicators of hydrologic characteristics because they are operated near maximum capacity and are routinely monitored. Thus they provide good data for evaluation of aquifer properties.

Within the area of investigation, three major factors control transmissivity and permeability: major grain size changes, amount of silt as the fine fraction, and degree of cementation. In all previous reports (Maxey and Jameson, 1948; Domenico and others, 1964; Malmberg, 1965; Harrill, 1976; Dettinger, 1984; Plume, 1989; Morgan and Dettinger, 1994), transmissivity and permeability north of Craig Road and west of Rainbow Boulevard (Subarea 1) were estimated using descriptions of grain size in domestic well logs because of the minimal amount of aquifer test data in this area.

This technique is suspect in Subareas 1, 2, 3, and 5. Fine-grained material and cementation in the interstices of the coarse-grained units appear to control transmissivity and permeability, rather than major grain-size variations such as that seen in Subarea 4. North of Craig Road, despite gravel percentages similar to Subareas 2 and 3, the transmissivity of any existing well, no matter how constructed, is less than 95 m^2/day (7,500 g/d/f). This is probably due to the presence of silt rather than sand as the fine fraction within the gravel deposits.

The sediments west of Rainbow Boulevard and south of Craig Road (Subareas 2 and 3) are almost exclusively gravel with sand. The variation in transmissivity and permeability is related to the degree of cementation in the interstices and possibly the size and shape of the channels containing the individual depositional units. It is very important to have measures of permeability independent of lithology because the changes in cementation and grain size can be very subtle.

Vertical Variation of the Hydrostratigraphic units

In this report, six hydrostratigraphic mapping units composed of three aquifers and three aquitards were delineated and defined. Subarea 4 is the only location where all six hydrostratigraphic mapping units can be distinguished solely by grain-size variation. The interpreted thickness of the hydrostratigraphic mapping units (HMUs) at individual wells is reported in table 5.

Figure 41 is a thickness map of the uppermost HMU one (1) designated in this investigation as the Las Vegas Wash Aquitard, an aquiformation. Figure 42 is a map of the surface between HMU one (1) and the underlying more permeable sediments designated in this reports as the Las Vegas Springs Aquifer, an aquiformation. Figure 43 displays the thickness of the "upper" aquifer with the Las Vegas Springs Aquifer, HMU two (2) or the Las Vegas Creek aquifer, an aquimember. Figure 44 displays the thickness of the "middle" aquitard within the Las Vegas Springs Aquifer, HMU three (3) or the Twin Lakes aquitard, an aquimember. Figure 45 is a map of the thickness of the "lower" aquifer within the Las Vegas Springs Aquifer, HMU four (4), the La Madre Mountain aquifer, an aquimember. Figure 46 display the total thickness of the Las Vegas Springs Aquifer (HMUs 2, 3, and 4 combined). Figure 47 displays the surface between the Las Vegas Springs Aquifer and the underlying less permeable sediments, designated in this investigation as the Duck Creek Aquifer, an aquiformation (HMUs 5 and 6 combined). The thickness maps are displayed from top to bottom because the amount of information decreases with depth.

Table 5. - Thickness of hydrostratigraphic mapping units (HMUs) in meters.

Well Name	Easting (UTM)	Northing (UTM)	Thick-ness of HMU 1	Thick-ness of HMU 2	Thick-ness of HMU 3	Thick-ness of HMU 4	Thick-ness of HMUs 5 & 6
MAP	654287.2	4004238.8	60.8	19.7	35.6	59.1	158.2
MEC	654423.7	4014619.7	89.0				
MGW	650876.1	4009958.7	112.8	33.2	59.7		
MLMT	656313.5	4012750.0	103.6	44.2			
N01A	661193.1	4016782.0	76.1	21.2	68.2	95.2	
NEE	660468.3	4010073.8	75.3	32.2	74.9	46.4	
NRO	662312.7	4008140.2	44.8	48.8	61.5	74.4	
NWC	662293.2	4009156.2	69.0	22.8	46.4	93.9	
U1002	655436.8	4011538.9	91.7	60.6			
U1079	656871.3	4015078.6	86.0	62.8	28.5	71.1	
U1080	653850.7	4015086.3	65.2	33.0			
U1087	652419.7	4015554.3	86.3	66.7			
U1090	650744.2	4015740.9	153.2	25.7			
U1097	657017.0	4016684.1	91.5				
W01A	659794.5	4003154.7	82.1	28.9	62.5	37.9	
W03A	663527.0	4006230.0	86.3	49.9	33.0	68.5	
W22A	656423.3	4007453.4	76.2	42.6	30.1	46.3	
W23A	656276.1	4007688.4	77.8	41.3	16.3	56.3	
W28	658774.0	4010119.9	77.1	26.6	65.4	52.2	
W29	658423.6	4009990.3	80.6	26.6	53.5	58.4	
W33	658096.4	4010161.7	80.1	26.5	50.3	55.9	
W38	658232.1	4003456.0	69.8	24.2	46.0	70.2	
W45	661471.0	4007037.0	68.6	39.6	61.0	54.2	
W50	660831.1	4003518.7	78.4	24.6	66.8	66.9	
W60	662675.2	4004116.4	81.8	28.9	46.9	72.4	
W69	656412.1	4009435.3	86.5	55.0	17.6	61.3	
W70	656680.4	4003032.9	52.0	24.5	30.1	59.0	278.7

Table 5. - Thickness of hydrostratigraphic mapping units (HMUs) in meters(Cont'd.)

Well Name	Easting (UTM)	Northing (UTM)	Thick-ness of HMU 1	Thick-ness of HMU 2	Thick-ness of HMU 3	Thick-ness of HMU 4	Thick-ness of HMUs 5 & 6
W72	656388.8	4009888.1	85.6	40.8	13.3	60.6	
W75	655464.1	4015069.0	104.2	61.2	17.4	62.1	
W76	656429.6	4005231.5	53.8	23.8	11.7	59.3	
W78	652747.1	4009488.7	63.6	37.0	77.7	99.8	
W79	663678.2	4004642.4	87.0	16.8	83.6	55.7	
W83	663010.7	4003529.1	89.2	20.0	49.8	68.3	
W87	656164.0	4006176.7	94.5	41.4	16.2	48.9	
W90	653939.5	4009718.4	55.9	40.7	46.5	122.8	166.8
W94	656564.6	4010787.2	72.7	62.6	21.2	57.6	
W95	653286.7	4009635.1	60.7	36.0	56.9	135.5	87.4

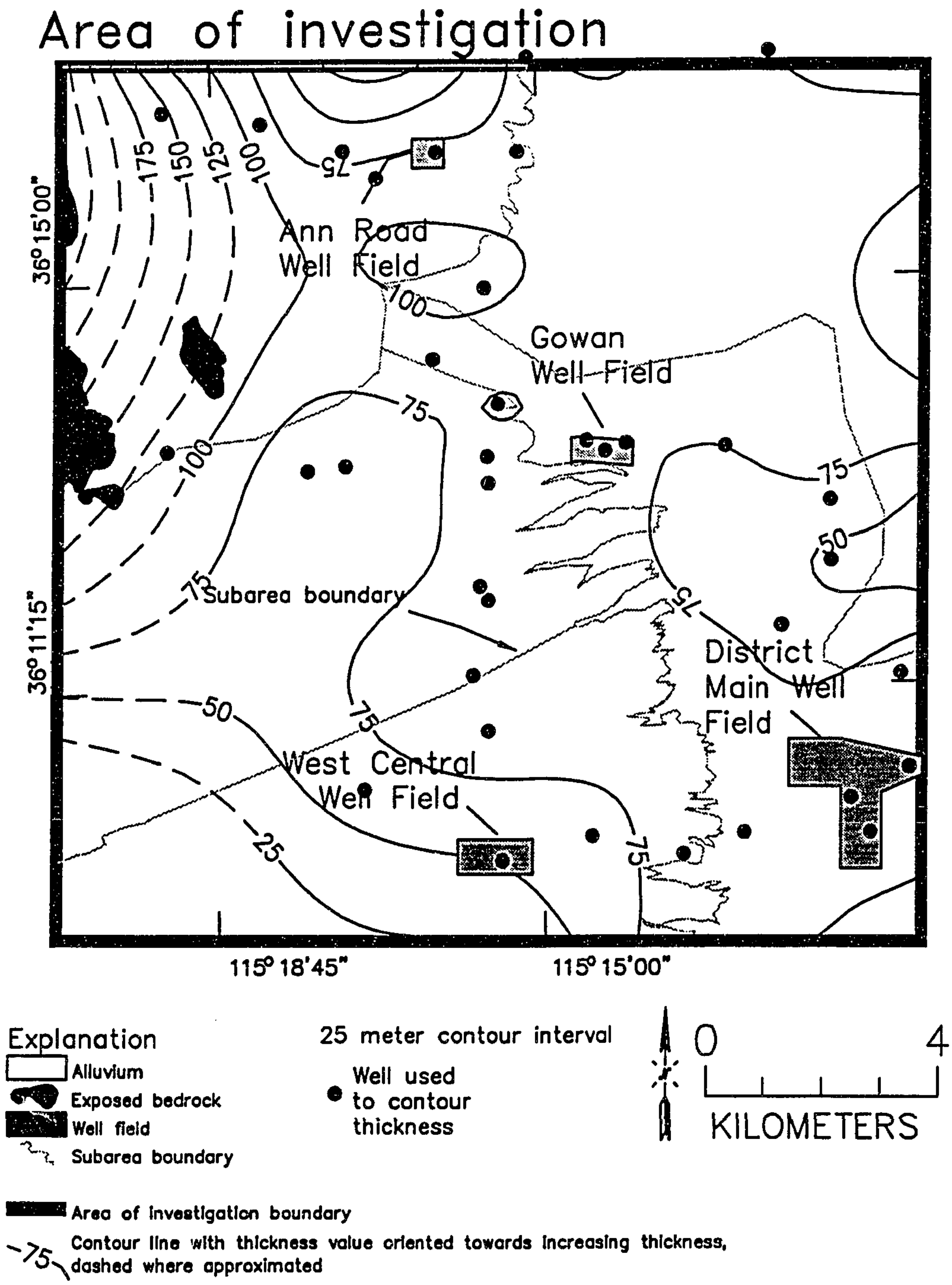


Figure 41. -- Thickness of the Las Vegas Wash aquitard.

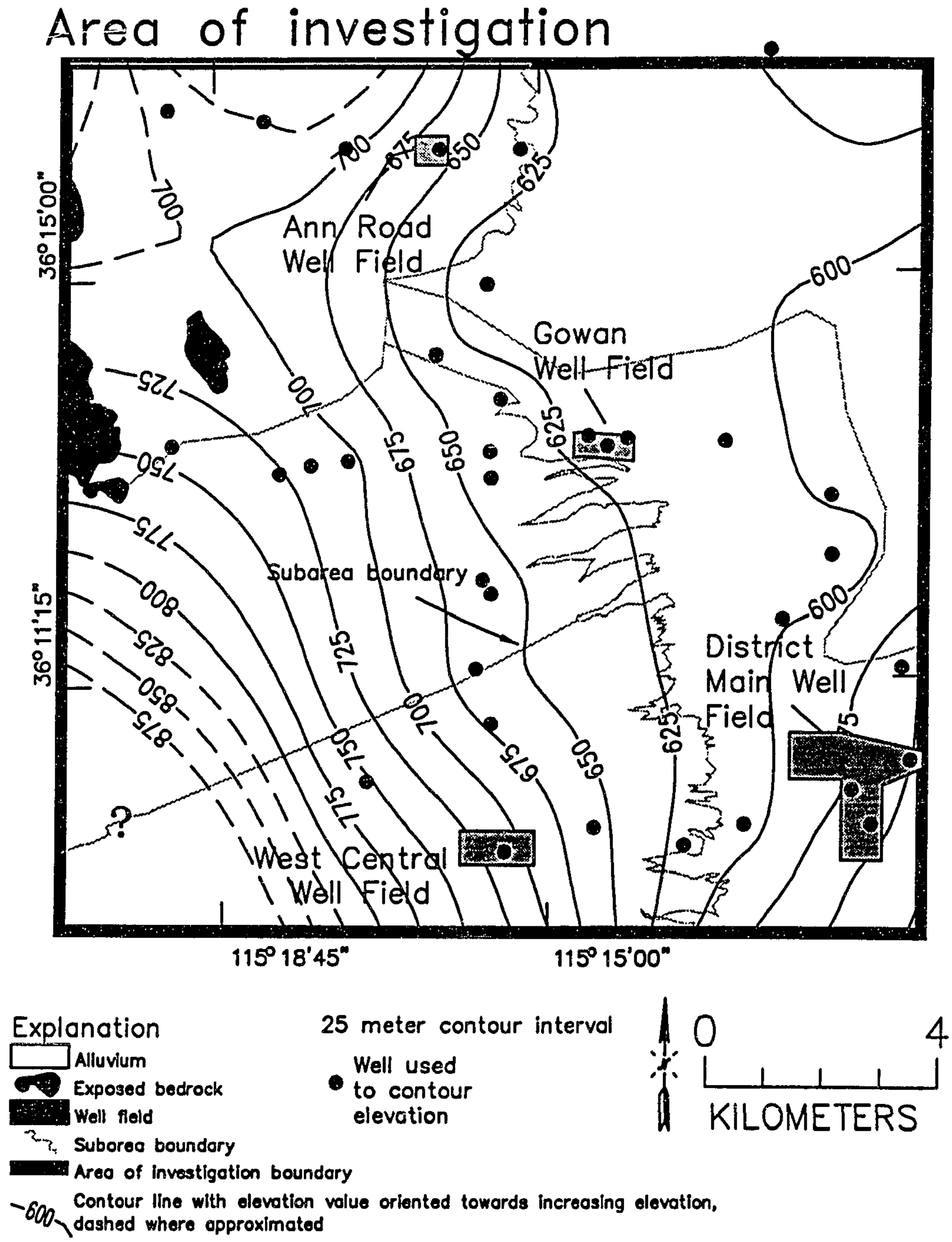


Figure 42. –– Top surface of the Las Vegas Springs aquifer.

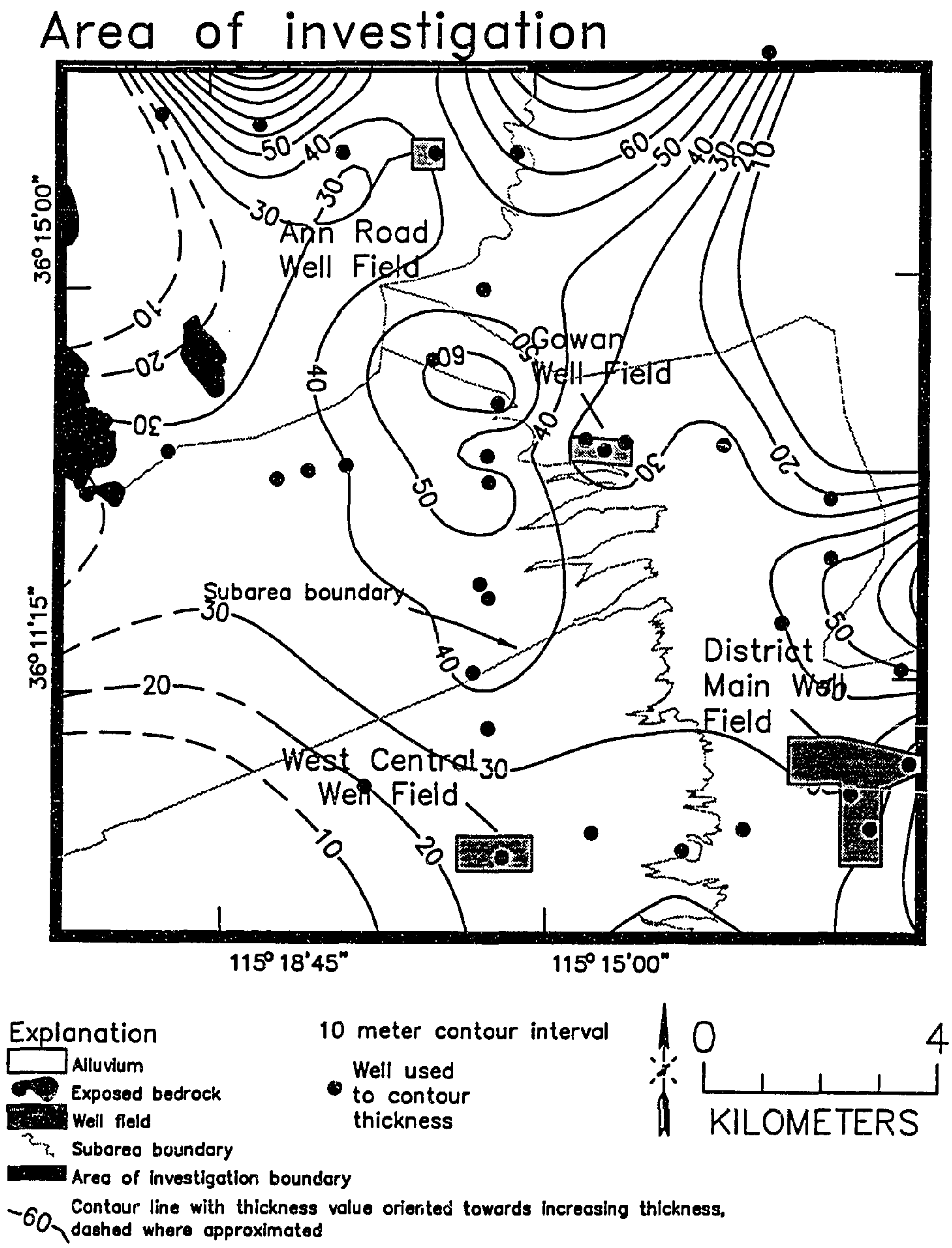


Figure 43. –– Thickness of the "upper" aquifer in the Las Vegas Springs aquifer (Hydrostratigraphic mapping unit 2).

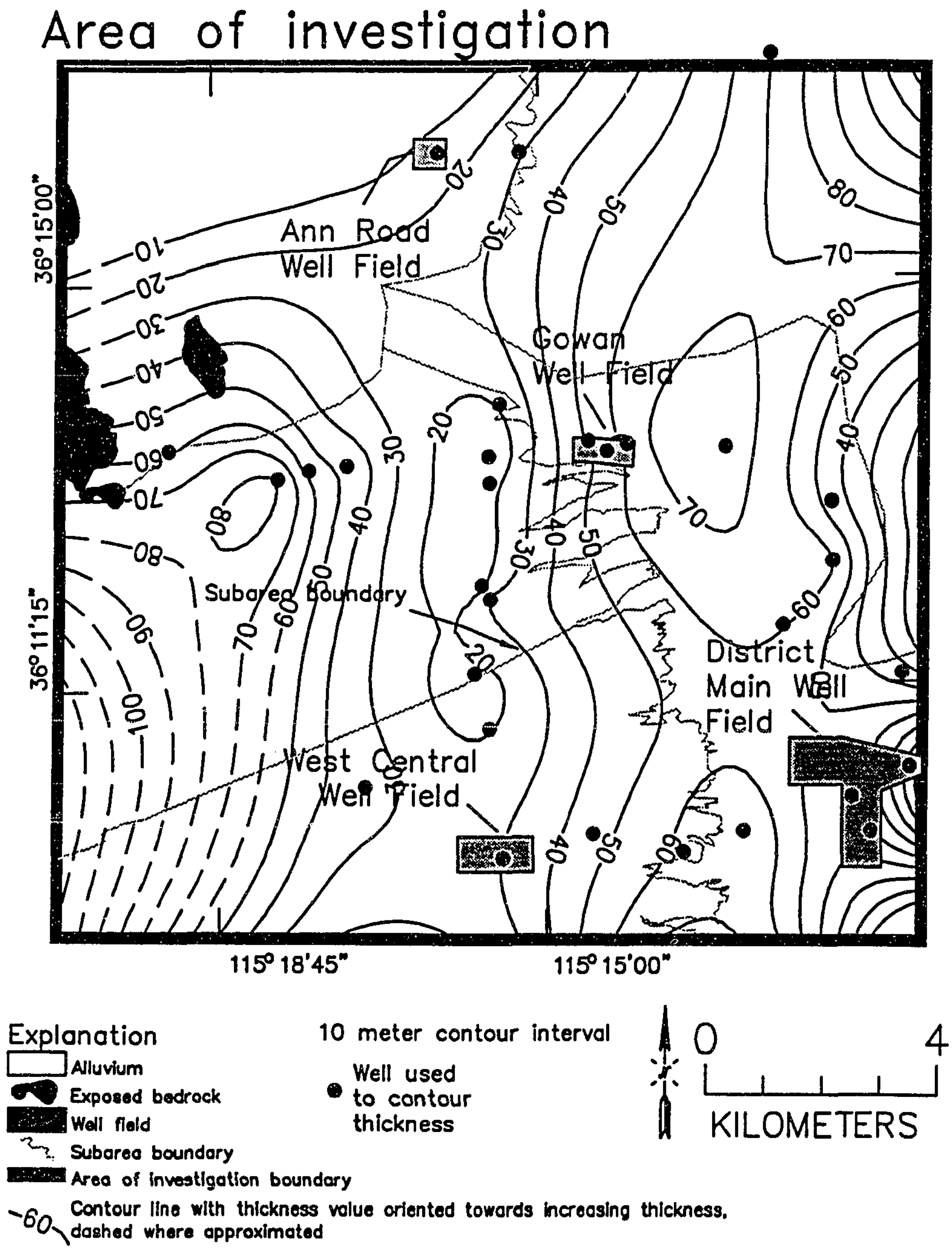


Figure 44. –– Thickness of the "middle" aquitard in the Las Vegas Springs aquifer (Hydrostratigraphic mapping unit 3).

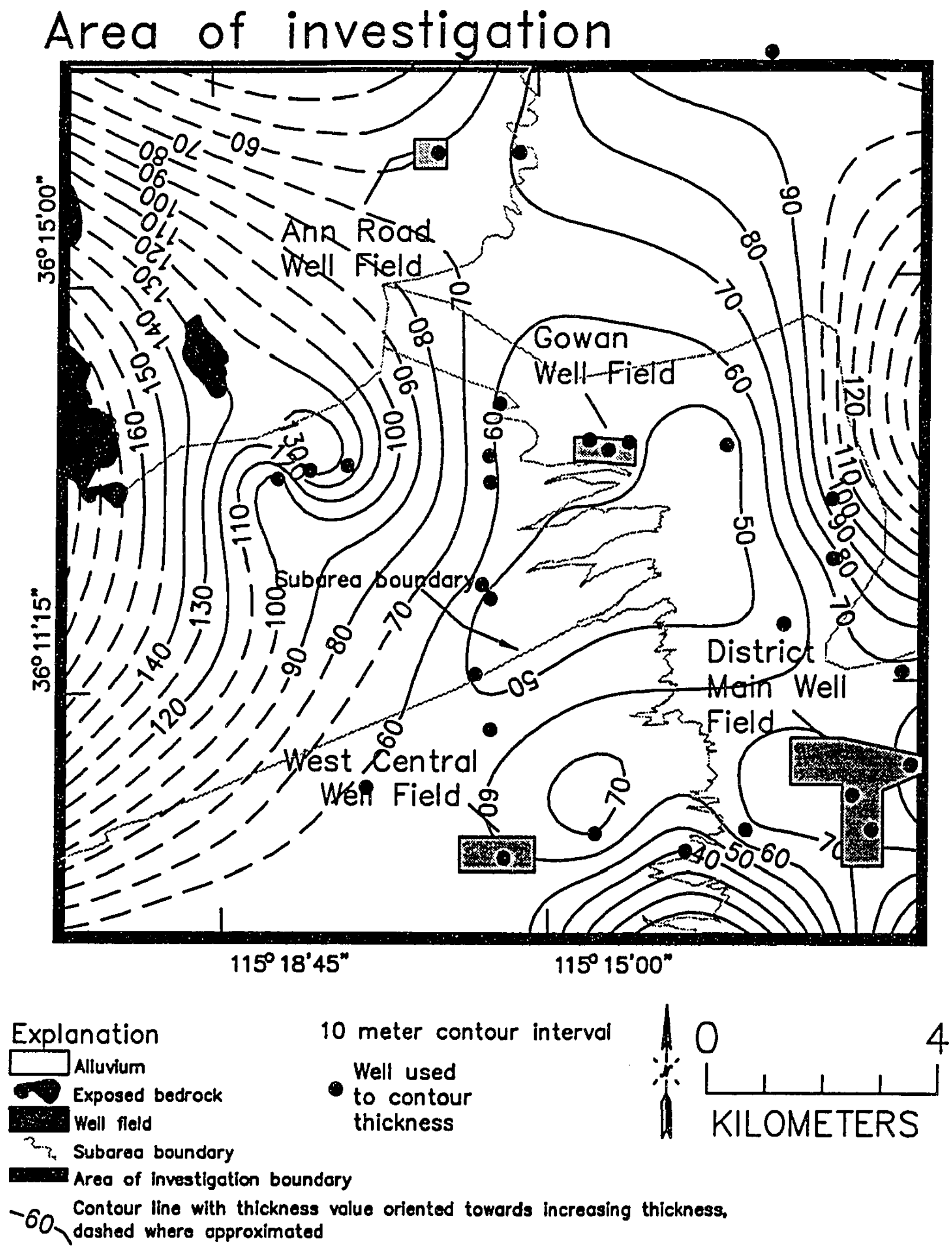


Figure 45. –– Thickness of the "lower" aquifer in the Las Vegas Springs aquifer (Hydrostratigraphic mapping unit 4).

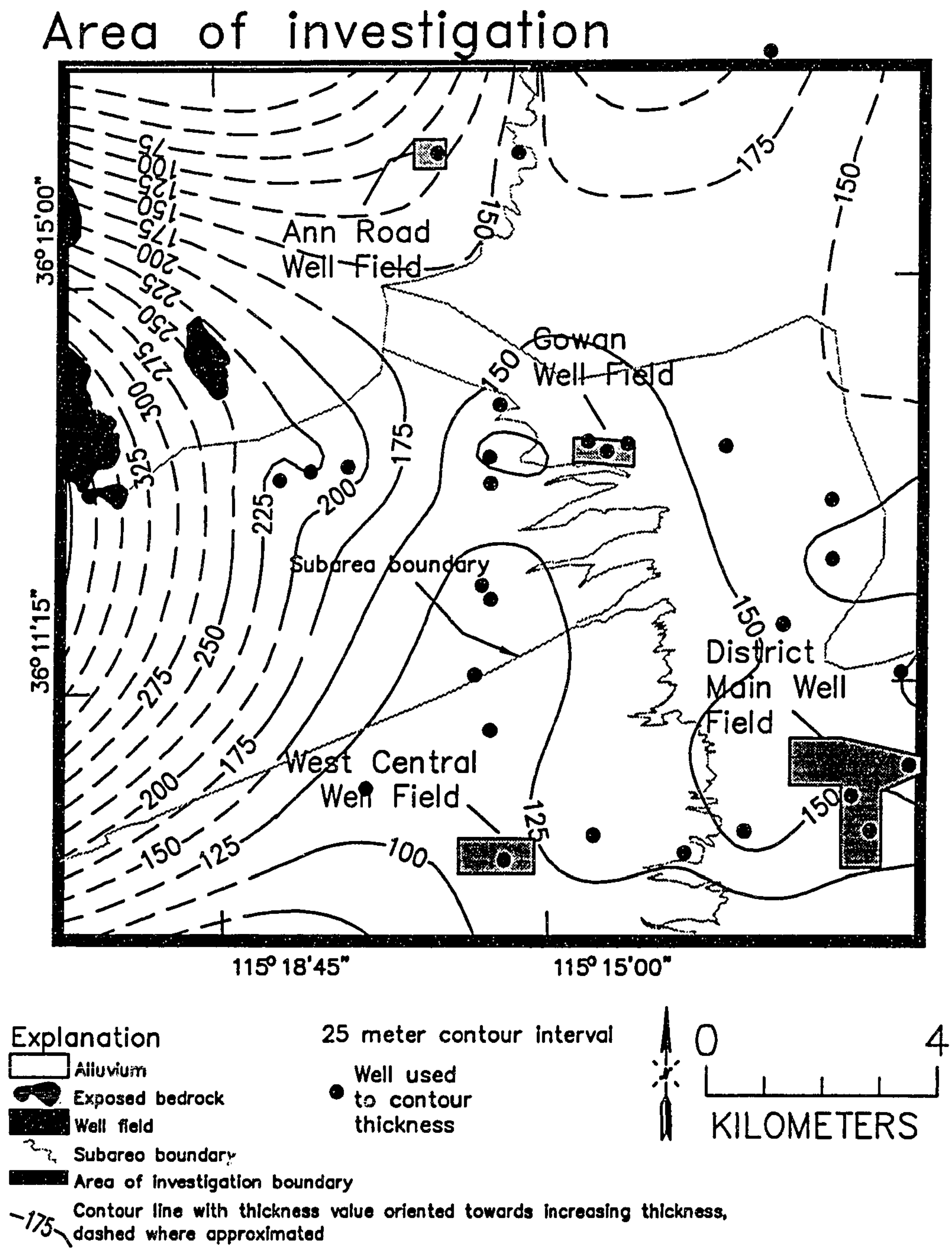


Figure 46. —— Thickness of the Las Vegas Springs aquifer (Hydrostratigraphic mapping units 2, 3 and 4 combined).

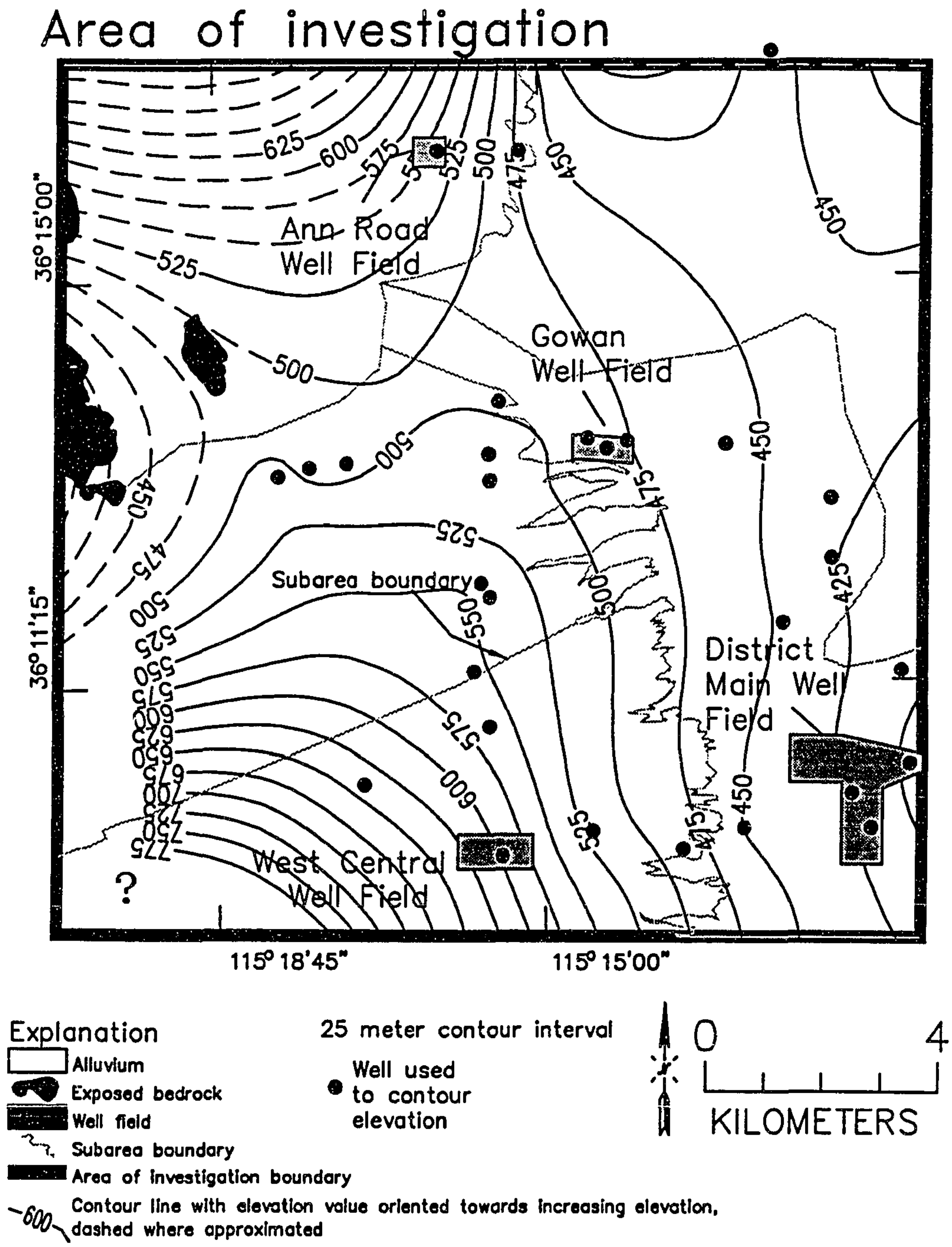


Figure 47. — Top surface of the Duck Creek aquifer.

The lowermost unit, informally called HMU six, is the gravel below about 250 m below land surface. The total thickness is unknown but exceeds 300 m in the District's Main Well and 200 m at the intersection of Cheyenne Avenue and Buffalo Drive. This unit is similar to Maxey and Jameson's (1948, p. 82) "Deep Zone of aquifers" or the lower part of Harrill's (1976, p. 9) “principal aquifers.” HMU six is lithologically similar to the overlying sediments, especially in the alluvial fans, but has a very different permeability. Significant permeability differences were observed at wells W69 and W72 and also at the District's West Central Well Field (WCWF). At both of these locations there are wells that are completed exclusively in HMU six. These wells have a much lower transmissivity than adjacent wells that are completed in both HMUs six and four.

Within the District's MWF, the boundary between HMU six and four is a fine-grained unit (silts, fine sand, and minor gravel) about 15 m thick. This fine-grained unit is located at approximately the same depth as an interval of strong cementation interpreted as pedogenic caliche, also about 10 to 25 m thick at the District's WCWF. Together, these units comprise HMU five (figs. 38, 39, and 40). The 10 to 25 m thick cementation interval may not have been deposited at the same time as the fine-grained sediments but probably represents an erosional surface. If the unit is caliche, it and the and finer-grained material would have been more difficult to erode than sand and uncemented gravel, therefore the mapped boundary may be an erosional unconformity rather than a depositional hiatus. The correlation surface mapped from well to well looks like an erosional surface cut into the underlying finer-grained sediments. The coarse-grained sediments above the contact are poorly cemented, indicating a relatively high energy depositional environment.

HMU four (figs. 37, 38, 39, and 40) is the poorly cemented gravel with sand above the caliche/fine-grained marker bed. This unit is equivalent to Maxey and Jameson's (1948, p. 82) "Middle Zone of aquifers" and is the most productive interval of the "principal aquifers" of Harrill (1976, p. 9). This interval is the source of most of the water in most of the District's and NLV's wells. The thickness of this unit ranges from 30 to 75 m with an average thickness of 63 m.

Subunits labeled 4A and 4B are moderate permeability parts of HMU four. Permeability is reduced in subunit 4A by cementation and in 4B by the presence of silt.

Above HMU four, east of Rainbow Boulevard (Subarea 4), there is an interval of fine-grained material, generally about 75 m thick, designated in this report as HMU 3B (figs. 37, 38, 39, and 40). West of Rainbow Boulevard and south of Craig Road (in Subareas 2 and 3) is an interval of sand with gravel or gravel with sand. The lithologic variation is slight and the primary mappable characteristic is cementation. This interval was mapped as HMU 3A. Although the reasons for the reduction in permeability is different in the two HMU'S, the two units appear to be continuous and form one aquitard unit designated HMU three. Additionally, this and the overlying units are not now saturated and no historic aquifer test data is available to estimate permeability in this interval. HMU'S four, three and two are sometimes difficult to map into distinct units but are locally important and were assigned member status. West of Rainbow Boulevard and south of Craig Road (Subareas 2 and 3) HMU two may sit directly above unit four.

East of Rainbow Boulevard (Subarea 4) the upper aquifer HMU (HMU two) is composed of gravel-sized sediment. The HMU is about 15 to 30 m thick in a interval of finer-grained material (figs. 38 and 39). This "gravel" interval is commonly reported in lithologic logs over most of the eastern part of the area of investigation (Subarea 4). This is the "Shallow Zone of aquifers" of Maxey and Jameson (1948, p. 81) or the uppermost interval of the "principal aquifers" of Harrill (1976, p. 9). Everywhere in the area of investigation, this unit is thinner than HMU four and has a lower transmissivity value.

At the District's MWF the permeability is similar to hydrostratigraphic unit four, with the difference in transmissivity related to thickness. At the District's Gowan Well Field (GWF), the dewatering of this interval has had minimal impact on the specific capacity of wells. This suggests that the transmissivity of this HMU is not only lower due to thickness, but also has a lower permeability. This interval remains an important aquifer for domestic wells north of Craig Road and east of Jones Boulevard. It is at least 30 m below the water table and it is the first gravel interval encountered. Above HMU two is HMU one (figs. 37, 38, 39, and 40).

HMU one is approximately 60 m thick and is similar to the "near-surface reservoir" of Malmberg (1965, p. 59) and the "shallow aquifer" of Bernholtz (1994, p. 22). East of Rainbow Boulevard this unit is composed of silt, sand and minor gravel and is commonly described as the Las Vegas Formation (Longwell and others, 1965, p. 50). West of Rainbow Boulevard this unit transitions into a caliche cap, especially south of Vegas Drive near the central axis of the Red Rock Alluvial Fan. The Las Vegas

Formation and the "near-surface reservoir" designation only applies to the fine-grained uppermost deposits, seen east of Rainbow Boulevard.

Within the area of investigation north of Craig Road the stratigraphy is similar, however, the hydrology is significantly different. The two production wells in this area have low specific capacity values compared to wells in Subareas 2, 3, and 4. The relatively low specific capacity values indicate that the permeability of the screened intervals is relatively low for an aquifer. The low permeability combined with the lithologic variability makes identification of distinct permeability intervals difficult.

With the available data, three lithologic intervals can be distinguished within the subsurface of Subareas 1 and 5. The deepest is a gravel-dominated interval, below 180 m below land surface. Above this is a silt dominated interval between 180 m and 30 m below land surface. The upper 30 m is dominated by gravel and is thickest (up to 45 m) in a channel, at least 750 m wide and at least 150 m deep, located on the edge of the Kyle Canyon Alluvial fan, south of Ann Road.

The lowest "gravel-dominated" interval was subdivided into HMUs four and six based on subtle variations in the amount of silt and on depth to relatively coarse-grained deposits farther to the east in Subarea 1 (fig. 38). The upper part of the "gravel-dominated" interval is continuous with the coarser-grained intervals in the fine-grained sediments of Subarea 1. Both the fine-grained interval between 180 and 30 m below land surface and the coarse-grained deposits were assigned to HMU one.

The coarse-grained deposits in the upper 30 m were interpreted as a relatively thick section of laterally discontinuous surficial deposits. If subsequent investigations can document continuity in these deposits it may be appropriate to designate this as an aquifer hydrostratigraphic unit above the hydrostratigraphic units identified in this investigation.

Flow Parameters

Porosity, permeability, hydraulic conductivity, and transmissivity are described in the following sections.

Porosity

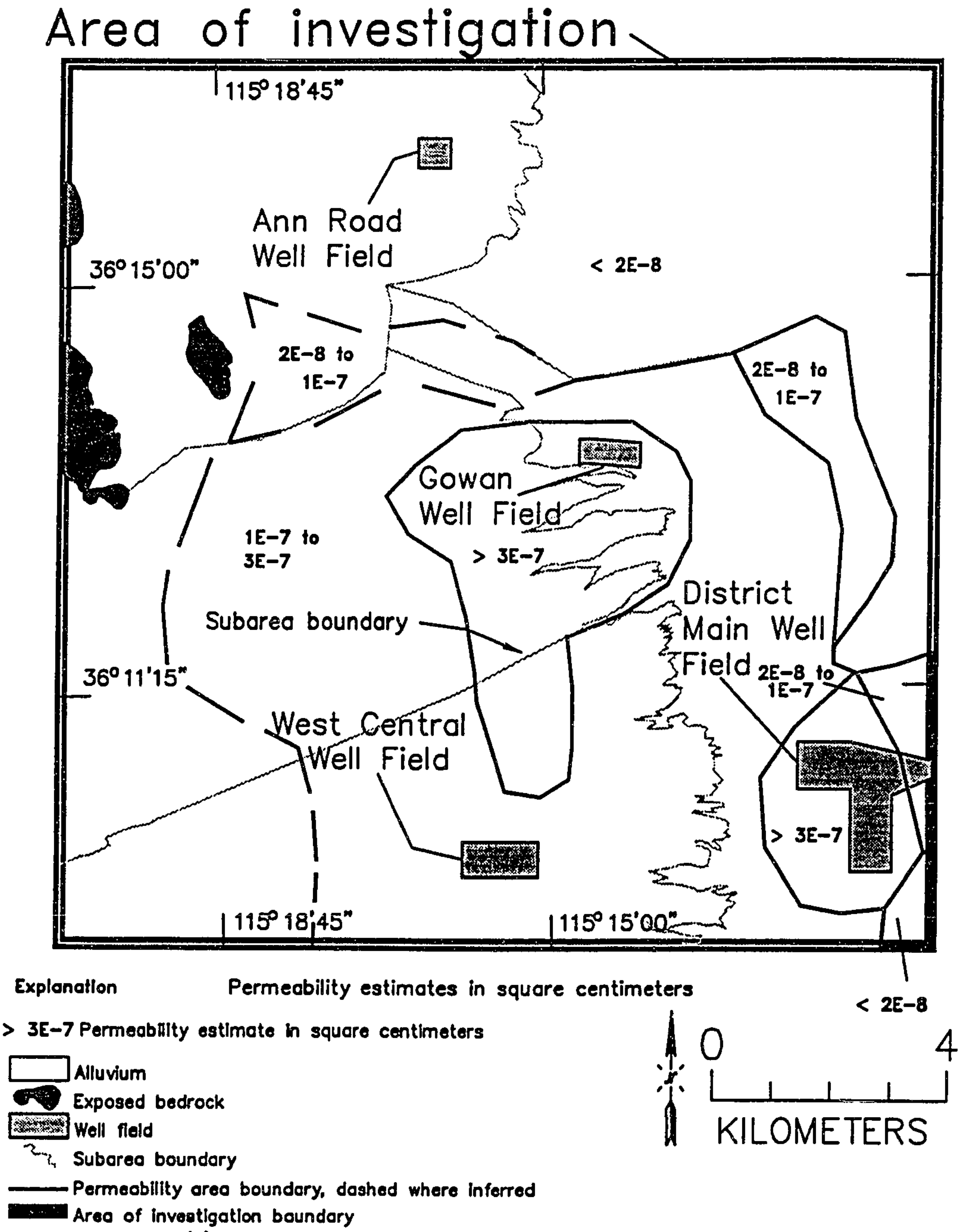
As previously discussed, porosity of the basin-fill gravel deposits has been estimated from acoustic geophysical logs. The interpretation is non-rigorous but results fall within the range of alluvial fan deposits at 15 to 25 percent porosity. The estimation is non-rigorous primarily due to mechanical problems such as loss of fluid in the borehole during logging. The porosity of the coarse-grained deposits are approximately 15 to 25 percent and the fine-grained deposits are approximately 40 percent. Both of these estimates are on the low range of the table listed in Freeze and Cherry (1979, p. 37). Although the total porosity in the coarse-grained deposits is lower than in the fine-grained deposits the effective porosity is generally higher. The storativity is in all cases at least an order of magnitude less than the porosity, and less than 0.0002 in the more confined parts of the aquifer east of Rainbow Boulevard

Permeability

The value of permeability varies from well to well but ranges from 3.2×10^{-07} cm^2 in hydrostratigraphic unit four to 2.9×10^{-09} cm^2 (Bernholtz, 1994, p. 50) in hydrostratigraphic unit one at the District's MWF. The first value falls within the range of "Clean sand" and the second fall within the range of "Silt, loess" (Freeze and Cherry, 1979, table. 2.2, p. 29). These categories are consistent with the lithic character of the sites where these measurements were collected. The sediment at the low permeable site can be characterized as a sandy silt with minor clay and gravel and the second location as sandy gravel.

HMU four or the La Madre Mountain aquifer of the Las Vegas Springs Aquifer is the best defined of all the HMU's mapped in this investigation. The lithologic character is usually well defined and the locations of the screens in the individual wells allow estimates to be made about amount of water contributed by this aquifer. Figure 48 is a map of the permeability estimated for HMU four, contoured using traditional geologic methods.

The contributions from the other HMU's are not as well defined. The permeability in HMU six is difficult to calculate because all of the District wells only partially penetrate the unit and the total thickness is unknown. The permeability of HMU six seems to be similar to or slightly higher than HMU one. The permeability of HMU five cannot be estimated. Many of the District and NLV wells fully penetrate this unit but any water contribution and therefore any effect on calculated transmissivity by this interval is much smaller than the errors in estimating transmissivity. No well is exclusively completed within HMU's five and three. These units are lithologically similar to HMU one and are likely to have a similar permeability. Hydrostratigraphic unit two appears has a similar permeability to hydrostratigraphic unit four at the District's MWF. Wells that are completed in HMU's two, four, and six have specific capacities roughly 25 percent higher than wells completed only within HMU four and six. HMU two is about one-half as thick as HMU four.



Permeabilility (k) estimated from hydraulic conductivity (K) by factoring in dynamic viscosity (u), density, (p) and acceleration due to gravity (g). k = Ku/pg.

Figure 48. — Distribution of permeability in hydrostratigrophic unit four (La Madre Mountain member of the Las Vegas Springs aquifer), in meters/day.

Hydraulic Conductivity

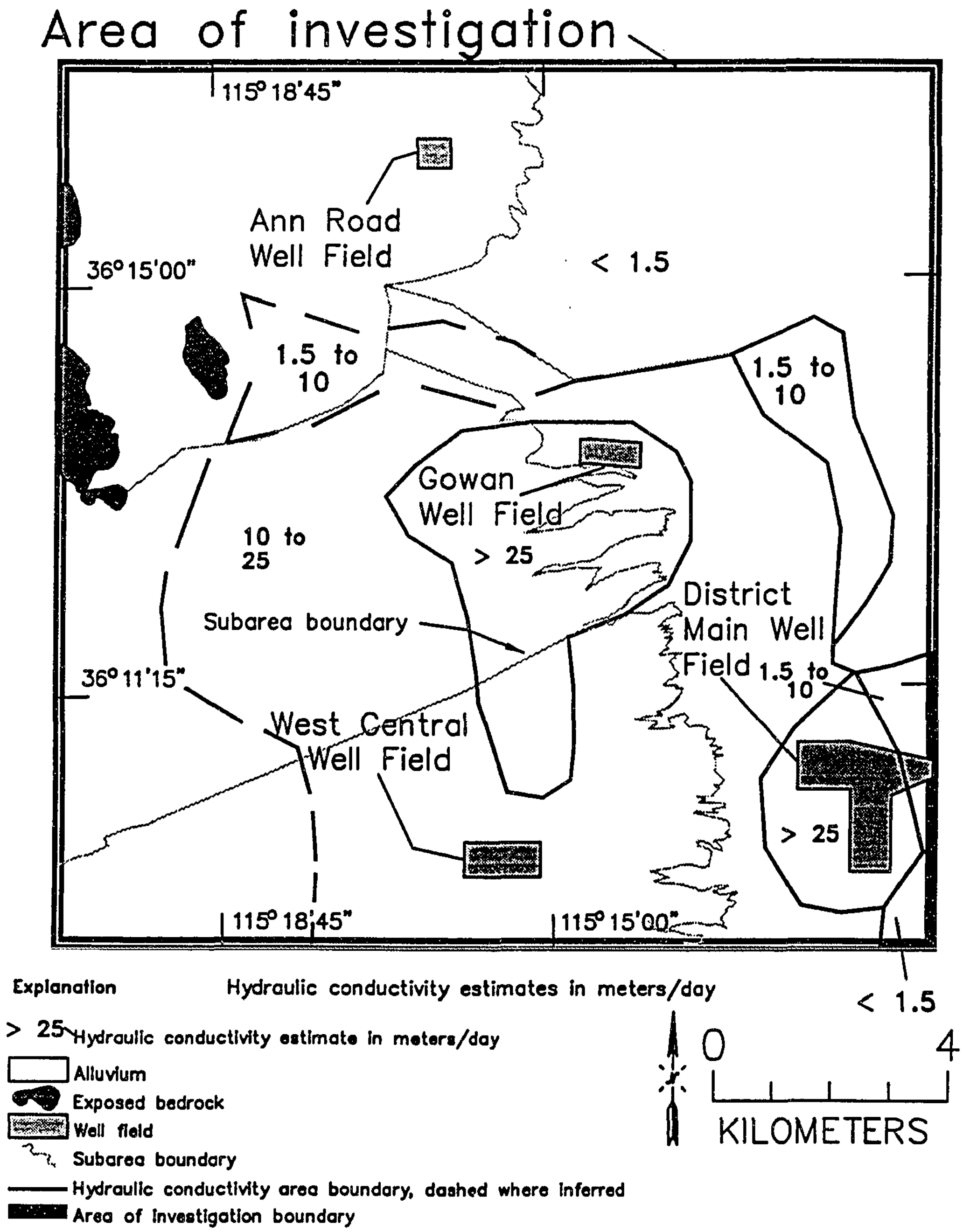
Hydraulic conductivity was estimated from transmissivity by the equation $T/b = K$. The main difficulties in estimating hydraulic conductivity are the transmissivity estimates, defining the thickness of the units, and assigning percentages of the total transmissivity to the individual horizons. Figure 49 is a map of the hydraulic conductivity in HMU four.

Transmissivity

The reported transmissivity of an aquifer test at a well is a composite of all of the hydrostratigraphic units the well fully or partially penetrates. The relative significance of each hydrostratigraphic unit within each well must be determined by either nearby wells with different perforated (screened) intervals, or comparisons of historic to modern transmissivity estimates. As with all quantitative approaches to natural phenomenon, there are always deviations from the underlying assumptions. Within the District's MWF, aquifer data best fits with Papadopulous and Cooper (1967) modification to the Theis (1935) confined aquifer solution, and Moench's (1985) modification to Hantush's 1960 solution for leaky semi-confined aquifers. Both of these modifications are designed to minimize the effects of casing storage in large diameter wells. Casing storage can be seen in every well analyzed in this investigation. The municipal wells analyzed in this investigation range from 410 to 860 centimeters in diameter.

Correlation Between Geology and Hydrogeology

The mappable characteristics in the basin-fill of the Las Vegas Valley are grain size and degree of calcium-carbonate cementation. Calcium carbonate-cementation is a post-depositional characteristic and is not usually a mappable characteristic of lithostratigraphic



Hydraulic conductivity (K) estimated by dividing transmissvity (T) assigned to hydrostratigraphic unit four by thickness (b). $K = T/b$

Figure 49. –– Distribution of hydraulic conductivity in hydrostratigraphic unit four (La Madre Mountain member of the Las Vegas Springs aquifer), in meters/day.

units. Consequently, grain size is the primary mapping characteristic of lithostratigraphic units mapped in this and previous investigations.

One of the conclusions of this investigation is that the boundaries between the allostratigraphic and hydrostratigraphic units are similar. This is a very unusual conclusion because the allostratigraphic units are defined by bounding character whereas hydrostratigraphic units are defined by the internal character of the unit. The similarity arises from small scale variations in grain size and cementation that occur between the allostratigraphic units.

Each of the allostratigraphic units have slightly different grain-size distributions and cementation. These slight variations, in turn, control the distribution of permeability. Pedogenic caliche is formed by soil forming processes and is therefore a bounding discontinuity. The allostratigraphic units mapped and informally named in this investigation are bound by horizons within the subsurface that were interpreted to be pedogenic caliche, not simple calcium carbonate cementation.

The allostratigraphic units and the hydrostratigraphic units described in this investigation tend to mimic the alluvial fan shape. By contrast the boundaries of the lithostratigraphic units appear to be primarily controlled by distance from the source areas in the Spring Mountains.

Neither formal nor informal allostratigraphic units have been previously defined in Las Vegas Valley and no formal lithostratigraphic units exist in most of the basin-fill in the area of investigation. One informal and one formal lithostratigraphic unit exist but these units are not in contact. The Miocene (?) Muddy Creek Formation has been assumed to be equivalent to the "Deep Zone of aquifers" of Maxey and Jameson (1948) by most (Maxey and Jameson, 1948; Domenico and others, 1964; Harrill, 1976; Bell, 1981; Brothers and Katzer, 1988; Plume, 1989; and Bell and Price, 1991) of the hydrologic investigations of Las Vegas Valley.

Although the Miocene (?) Muddy Creek Formation of Stock (1921) is a formal lithostratigraphic unit, its existence and location in Las Vegas Valley is unproven (Bell, 1981, p. 20). The Muddy Creek Formation is generally used to describe fine-grained pre-Pleistocene units in the valley and is only an informal designation within Las Vegas Valley. The two primary criteria used to identify this unit in Las Vegas Valley are low transmissivity and the fine-grained nature of the sediments. In most of the area of investigation, in the lower parts of the wells, the sediments are coarse grained but have a low transmissivity (< 20 percent of the transmissivity of the HMU four). Although the Muddy Creek Formation is generally assumed to be fine-grained, Longwell and others (1965, p. 50), Bohannon (1984, p. 58) and Rice (1986, p. v) document a variety of facies in this unit with coarse-grained material near the basin margin, in depositional settings similar to the area of this present investigation.

Between the Muddy Creek Formation and the other named lithostratigraphic unit the Pleistocene age Las Vegas Formation lies an informal unit named by Harrill (1976, p. 6) as “Fanglomerate and valley floor deposits.” Within the area of investigation this unit is predominately composed of gravel. Harrill’s informal unit was carefully examined because it contains the most productive aquifers in Las Vegas Valley. The gravel facies of this unit is the most aerially extensive of all the gravel units in Las Vegas Valley and appears to be deposited during a period of significant progradation of the Red Rock Alluvial and Kyle Canyon Alluvial Fans.

The Pleistocene Las Vegas Formation is a lithostratigraphic unit, therefore the proper usage of the name is restricted to Quaternary fine-grained deposits located in the central axis of the valley. Coeval gravel deposits were not included within this formation even though they are products of the same depositional process.

The descriptions below are from top to bottom because of the importance of the units to the hydrogeology and the amount of available information decreases with depth. With the exception of the uppermost unit, all of these units are not exposed at the surface in the area of investigation.

A buried caliche surface near the base of the surficial fine-grained deposits was mapped at about 75 m below land surface. The surface was also mapped into the coarse-grained sediments of the alluvial fans to the west and therefore independent of lithology. The surficial geologic mapping (Longwell and others, 1965; Haynes, 1967; Sowers, 1985; Matti and others, 1987; McDonnell-Canan, 1989; Quade and others, 1991) documents that all the alluvial fan gravel deposits and the fine-grained sediments of the Las Vegas Formation, in the area of investigation, are Quaternary in age. The deposits interfinger at the contacts and are caused by changes in the local depositional environment that are time independent. Specific mechanisms may have been more important at specific times in the past, because of climatic change, but the same mechanisms are still active in Las Vegas Valley. For the above reasons the sediments in the upper 50 to 75 m of alluvial-basin fill are included in a single unifying Quaternary (Pleistocene?) allostratigraphic unit informally named the Tule Springs Alloformation. The overlying Holocene deposits are thin and discontinuous and were not specifically mapped in the subsurface deposits. The Tule Springs Alloformation is the upper part of the Lone Mountain Allogroup of this present investigation. Figure 50 is the fence diagram developed from cross-section B to B' (fig. 38) and D to D' (fig. 40).

The following descriptions of the lithic character of the allostratigraphic units are for the purposes of illustrating the reasons for the similarity in boundaries between the allostratigraphic and hydrostratigraphic units. The boundaries between the Tule Springs Alloformation and the underlying parts of the Lone Mountain Allogroup and the boundary between the Lone Mountain Allogroup and the underlying Paradise Valley Alloformation are distinct bounding discontinuities interpreted to be a buried pedogenic caliche surfaces.

In general, the lower boundary of the Tule Springs Alloformation occurs at a similar depth as that of HMU one. HMU one was informally designated as an aquiformation rank hydrostratigraphic unit, named the Las Vegas Wash Aquitard in this present investigation. In the eastern part of the area of investigation, where the surficial sediments are fine-grained, the grain-size increases near but usually below the alloformation boundary. The District plans to use the Las Vegas Wash Aquitard as the topmost unit in their four layer hydrologic model of Las Vegas Valley. The three subunits originally mapped in the upper hydrostratigraphic unit (1A, 1B, 1X) are continuous with each other and have low permeability. Together these units form one continuous unified aquitard. 1A is characterized by coarse-grained sediment with strong cementation. 1B is characterized by fine-grained sediment and, in most places, is silt dominated. This unit is, in most places,

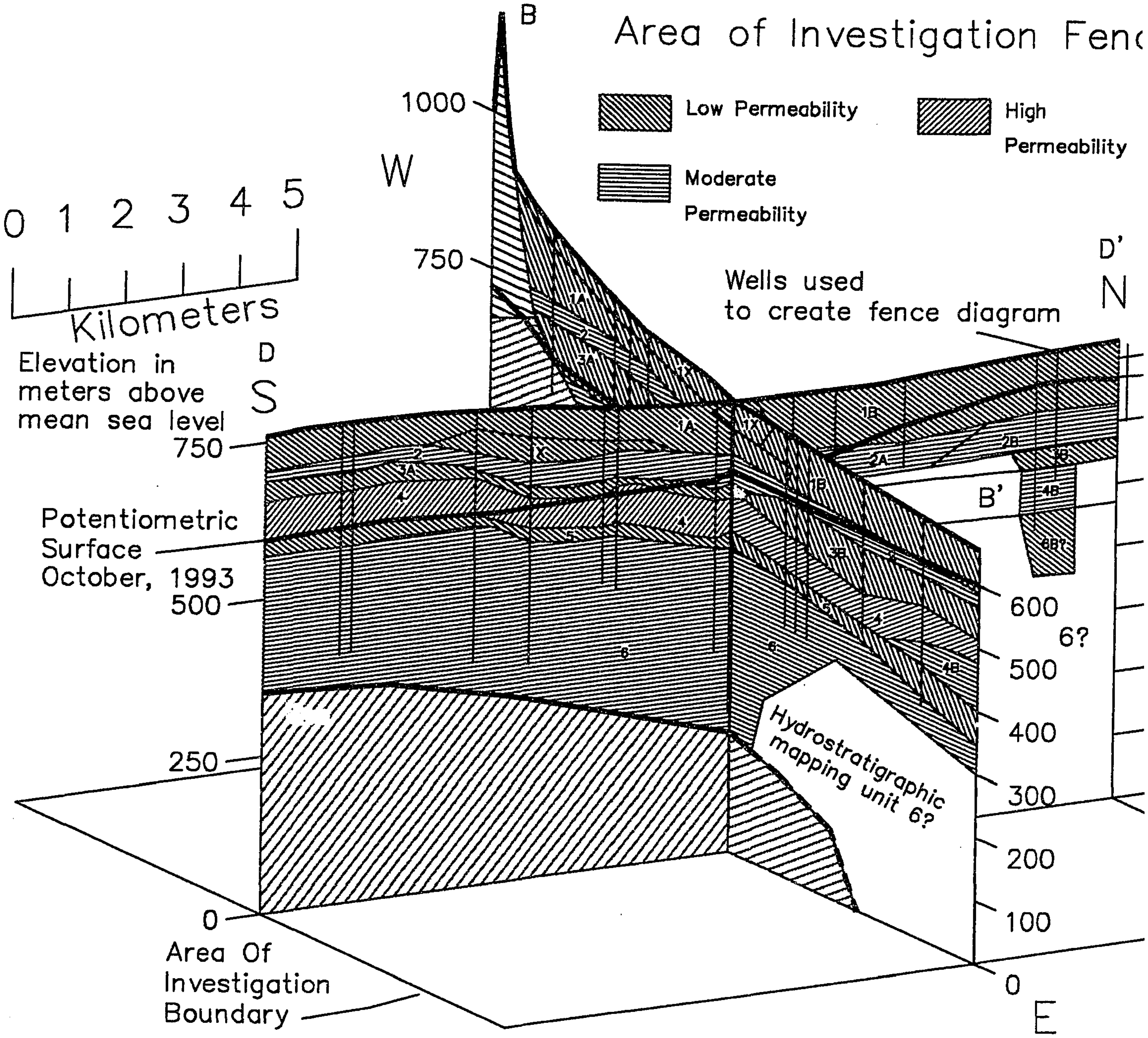
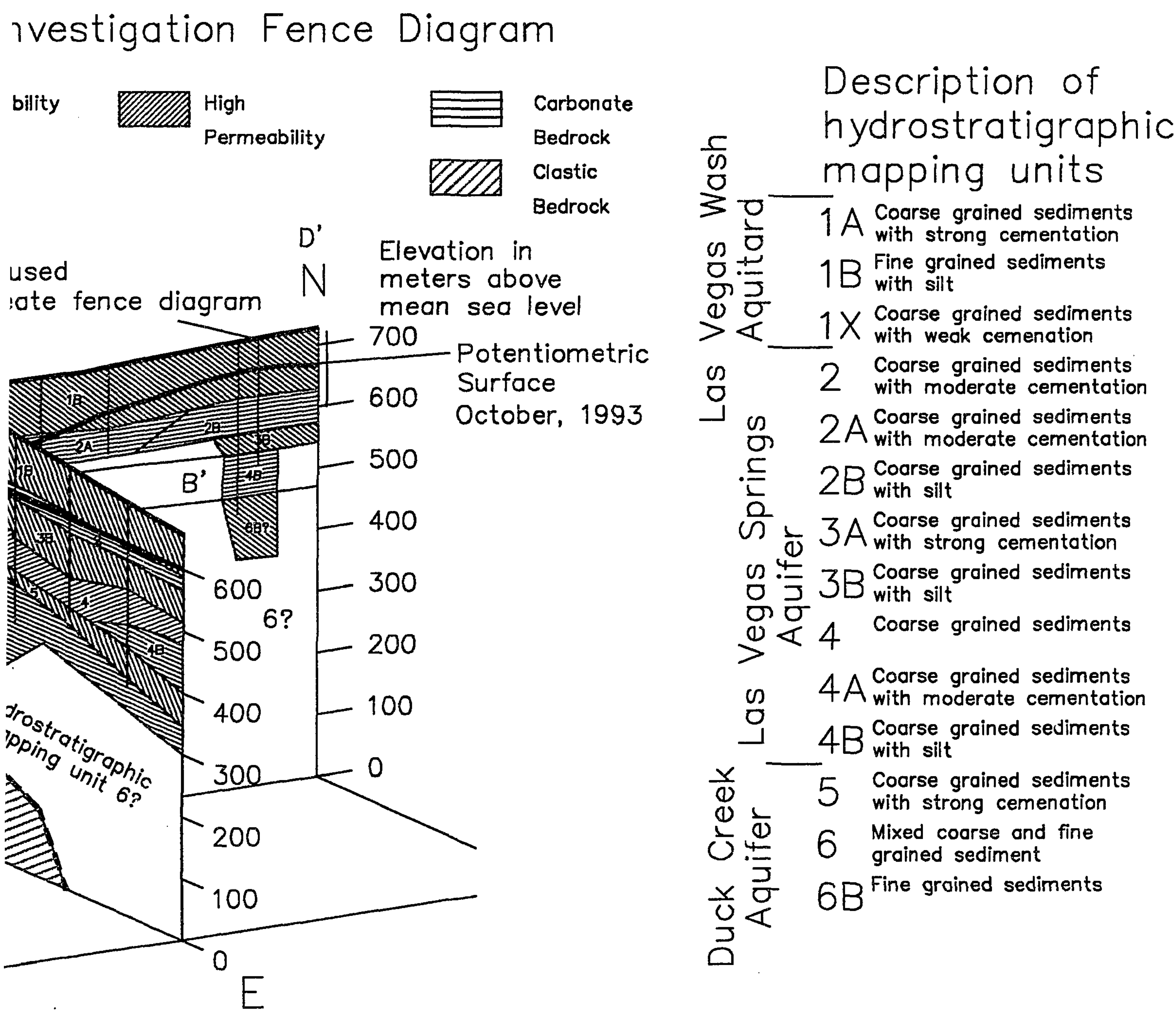


Figure 50. -- Fence diagram of hydrostratigraphic units.


ıvestigation Fence Diagram
bility
High Permeability
Carbonate Bedrock
Clastic Bedrock
D'
N
used
ıate fence diagram
Elevation in meters above mean sea level
700
600
500
400
300
200
100
0
Potentiometric Surface October, 1993
1B
2A
2B
3B
4B
6B?
B'
3B
4
5
4B
600
6?
500
400
300
200
100
0
E
drostratigraphic pping unit 6?
Description of hydrostratigraphic mapping units
Las Vegas Wash Aquitard
Las Vegas Springs Aquifer
Duck Creek Aquifer
1A Coarse grained sediments with strong cementation
1B Fine grained sediments with silt
1X Coarse grained sediments with weak cemenation
2 Coarse grained sediments with moderate cementation
2A Coarse grained sediments with moderate cementation
2B Coarse grained sediments with silt
3A Coarse grained sediments with strong cementation
3B Coarse grained sediments with silt
4 Coarse grained sediments
4A Coarse grained sediments with moderate cementation
4B Coarse grained sediments with silt
5 Coarse grained sediments with strong cemenation
6 Mixed coarse and fine grained sediment
6B Fine grained sediments

similar to the "near-surface reservoir" (Malmberg, 1965, p. 24; Harrill, 1976, p. 11). 1X is characterized by coarse-grained sediment with only moderate to weak cementation but is generally surrounded by strongly cemented sediments of subunit 1A.

The next two geologic units below the Tule Springs Alloformation are the middle and lower parts of the Lone Mountain Allogroup. The bottom of Lone Mountain Allogroup is located 150 to 260 m below land surface with boundary between the middle and lower parts at about 105 to 180 meters below land surface. The boundary is distinct in the central and eastern parts of the area of investigation but discontinuous and difficult to map in the western part. The grain-size tend to increase in diameter up section in all of the individual allostratigraphic units mapped in this investigation. The upper part of the unit informally named the "middle part of the Lone Mountain Allogroup" tends to be coarse-grained and locally, less cemented. The lower part of the informal "middle part of the Lone Mountain Allogroup" tends to be finer-grained and moderately to well cemented. The coarser-grained facies of this unit tends to be more strongly cemented than the units above and below. The allostratigraphic unit informally named the "lower part of the Lone Mountain Allogroup" is dominated by coarse grain sediments generally less cemented than units above or below.

The aquiformation rank hydrostratigraphic unit below the Las Vegas Wash Aquitard is the informally named Las Vegas Springs Aquifer composed of three aquimembers. From shallowest to deepest these aquimembers are the Las Vegas Creek aquifer, Twin Lakes aquitard, and La Madre Mountain aquifer. The Las Vegas Creek aquifer member of the Las Vegas Springs Aquifer aquiformation is contained within the upper part of the allostratigraphic unit designated the "middle part" of the Lone Mountain Allogroup. The contact between the Twin Lakes aquitard and La Madre Mountain aquimembers of the Las Vegas Springs Aquifer (aquiformation) is generally located at or below the boundary between the "middle" and "lower" parts of the Lone Mountain Allogroup.

The boundary between the Las Vegas Springs Aquifer and the Duck Creek Aquifer aquiformation is usually at the boundary between the Lone Mountain Allogroup and the underlying Paradise Valley Alloformation. West of Buffalo Drive at Cheyenne Avenue the bottom of the Las Vegas Springs Aquifer is about 100 meters deeper than the bottom of the Lone Mountain Allogroup. The boundary between the Las Vegas Springs Aquifer and Duck Creek Aquifer is an interval of strong calcite cementation about 15 to 25 m thick.

The most distinctive part of the Paradise Valley Alloformation is the upper 60 m of gravel-sized coarse-grained sediment. This unit is generally much more indurated than the units above it and contains a slightly higher percentage of silt in the fine fraction. In this investigation, this upper 60 m of coarse grained sediment is interpreted to be above the Muddy Creek Formation.

The sediments in the lower part of the Paradise Valley Alloformation tend to be sandier than the upper part. This lower part may have a similar stratigraphic position as the Muddy Creek Formation but has very difference lithologic character. The Muddy Creek Formation is usually described as a fine-grained unit with interbedded gypsum (Harrill, 1976, p. 6). The lower part of the Paradise Valley Alloformation is, most commonly, a coarse-grained unit with interbedded finer-grained intervals, and no evidence of gypsum.

Most of the aquifers contained within the Paradise Valley Alloformation are low to moderate permeability and are informally designated in this investigation the Duck Creek

Aquifer. The Duck Creek Aquifer is the lower, less permeable, parts of the "principal aquifers" (Harrill, 1976, p. 11) and Maxey and Jameson's (1948, p. 82) "Deep zone of aquifers" (see table 3).

Often, there are small and large scale reduction in grain-size or increases in the degree of calcium-carbonate cementation in the sediments near the allostratigraphic unit boundaries. It is also observed that individual allostratigraphic units tend to finer-grained and or more cemented than the allostratigraphic units above or below. It is assumed that these changes in grain size and cementation were related to changes in the depositional environment of the alluvial fans. An analysis of the cause of these changes is well beyond the scope this investigation and is not a criteria of allostratigraphic units (see NACSN, 1983, Article 58(f), in Appendix C). The differences in grain size and cementation are often subtle and, by themselves, are not appropriate criteria for any of the stratigraphic units mapped in this present investigation, however, intervals of differing permeability are often localized by these changes in grain size and cementation.

Aquifer test data at the individual wells document differences in fluid behavior. The differences in fluid behavior were attributed to differences in permeability in the alluvium. The intervals in individual wells where changes in fluid behavior were observed were located in intervals where the grain size or degree of cementation changes. Hydrostratigraphic units are defined by the observable characteristics of the rock or sediment (see Seaber, 1992 Article 98(b), in Appendix D). The changes in grain size or cementation are mappable features in the sediment and are therefore used as the basis of the hydrostratigraphic units. The observed changes in fluid behavior are independent supporting evidence and not the primary criteria of the hydrostratigraphic units (see Seaber, 1992, Article 98(l) in Appendix D).

Effect of water level changes with time

This investigation identified criteria used to map the aquifers, documented the location and spatial distribution of the aquifers within the alluvium. Where the highly permeable units are saturated, relatively high specific capacities are reported in wells (Specific capacities < 5 ℓ/s/m, 25 gpm/ft) (fig. 51). The western margin of most productive area for wells is controlled by both permeability and the saturation level. In Subarea 2 the western margin bends to the west because the bottom of HMU four is about 150 m deeper than in other areas and is saturated. By contrast, the boundary bends to the east in Subarea 3 because HMU four is closer to land surface and has been dewatered since the 1960's.

The bottom of hydrostratigraphic unit four is at or near the potentiometric surface in the District's West Central Well Field. The potentiometric surface here, between 1965 and 1989, declined about 40 meters and the specific capacity declined by about 90 percent. Harrill (1976, fig. 6) included the District's West Central Field within the most permeable part of the "principal aquifers." By contrast, the potentiometric surface at the District's Gowan Well Field declined by about 45 m between 1965 and 1993 and there has been minimal effect on specific capacities. Declines in the potentiometric surface of 40 to 20 m (fig. 19, p. 76) between 1965 and 1993 in Subareas 1, 4 and 5 appear to have minimal effects on specific capacities.

The position of the boundary in Subarea 3 is therefore dependent on the elevation of the potentiometric surface. This implies that the size of the most productive area for

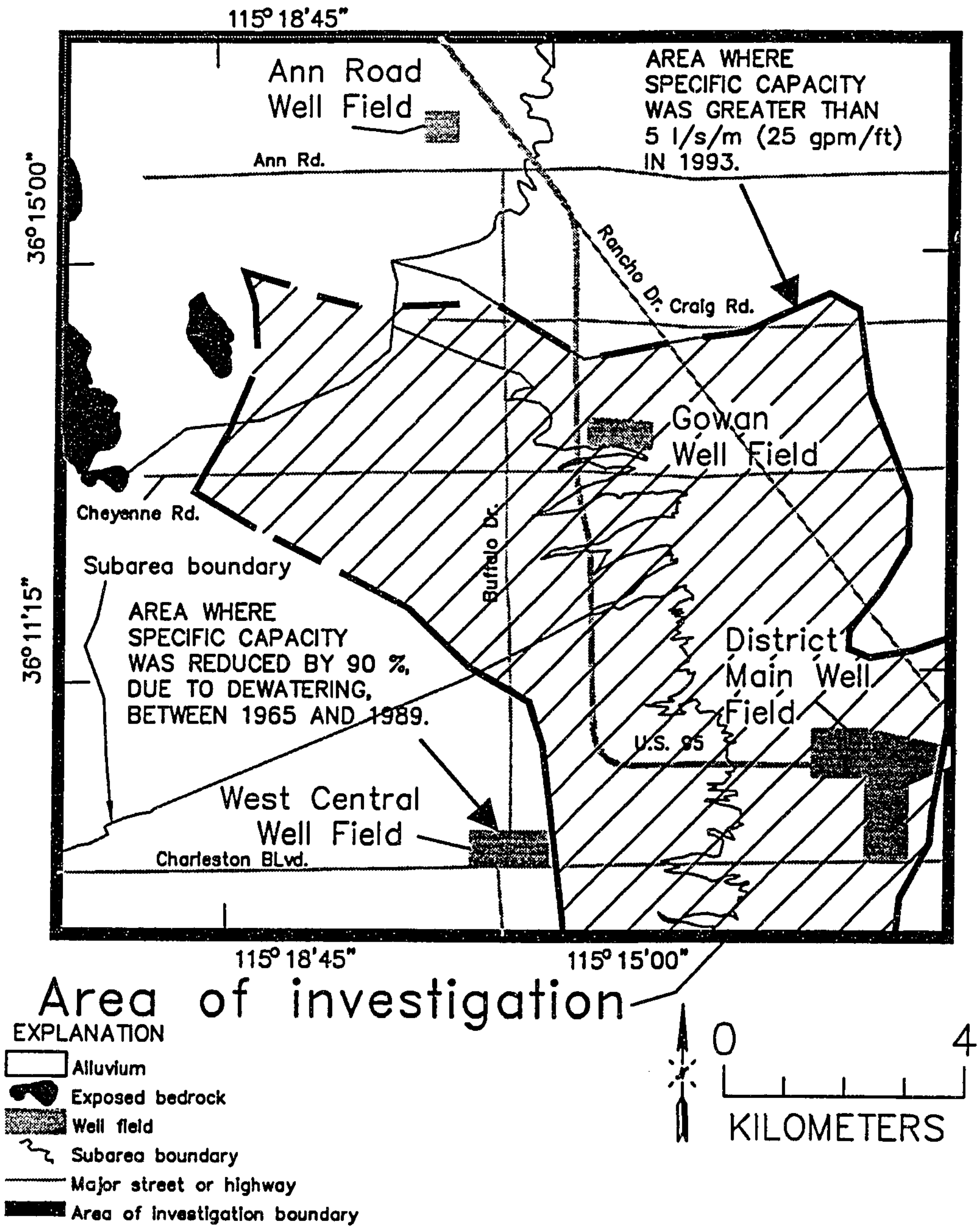


Figure 51. –– Area where specific capacity was greater than 5 l/s/m, in 1993.

pumping wells will increase or decrease in size depending on whether water levels are rising or falling.

CHAPTER 6

SUMMARY AND CONCLUSION

Stratigraphic units

Both the hydrogeologic and geologic stratigraphic units used in this investigation are relatively new kinds of units, therefore the defining criteria are described below. The available data were probably insufficient for formally designating these stratigraphic units at this time. The informal units of this investigation were mapped and named as closely as possible to formal naming criteria. Mapping and naming the units was designed to illustrate the hydrogeologic and geologic relationships of the alluvium.

The fundamental hydrostratigraphic unit is the aquiformation equivalent in stratigraphic rank to the formation in lithostratigraphic mapping, and the alloformation, in allostratigraphic mapping. Table 4 correlates the allostratigraphic and hydrostratigraphic units used in this investigation. The informal designation is designed to indicate the geographic area of the most typical section, stratigraphic rank, and nature.

Lithologic analysis was used to define the nature and boundaries of the alluvial aquifers, because of the kind and location of data available. The subsurface alluvium in Las Vegas Valley is not and cannot be divided into formal lithostratigraphic units.

Lithostratigraphy was of limited utility in this investigation because this investigation focused on the coarse-grained alluvial fan-dominated deposits. The aquifers and aquitards previously defined by lithostratigraphy were found to conform to parts of the hydrostratigraphic units mapped in this investigation.

Allostratigraphic Units

Four allostratigraphic units were mapped in this investigation (Table 3). Allostratigraphic units are unconformity bounded units that are used to map genetically similar or coeval deposits that are lithologically dissimilar. Four discontinuities were identified and these form the boundaries between the allostratigraphic units.

The upper three allostratigraphic units form the Lone Mountain Allogroup informally named in this investigation. These sediments are designated an allogroup because the topmost unit is of alloformation rank, which is informally designated the Tule Springs Alloformation. This alloformation includes all of the fine- and coarse-grained deposits exposed at the surface in the area of investigation. The fine-grained deposits mapped in previous geologic reports as Las Vegas Formation (Longwell and others, 1965, p. 50) is a fine-grained facies of the alloformation. The bottom bounding discontinuity of this unit is a buried caliche horizon at about 50 to 70 meters below land surface that is traceable in both the fine- and coarse-grained units. The bounding discontinuity between second and third mapped allostratigraphic units is not as distinct as the upper bounding discontinuity, however both of the units may be alloformations. These two units were simply designated as the "middle part of the Lone Mountain Allogroup" and the "lower part of the Lone Mountain Allogroup."

The lowermost of the four allostratigraphic units is informally named the Paradise Valley Alloformation. A major division was placed between third and fourth allostratigraphic mapping units for two reasons. First, the buried caliche horizon used as the bounding discontinuity is underlain by a 15 to 25 m interval of strong cementation in the alluvial fans and is thus relatively easy to map. Second, the lower part of the Lone Mountain Allogroup contains the thickest and most broadly distributed of the coarser-grained intervals.

The fourth allostratigraphic unit is composed of interbedded fine- and coarse-grained sediment, however, each fine grained unit is generally thinner than the one above. At least three potential allostratigraphic units may be contained within the fourth mapped allostratigraphic unit. These potential units were not designated as allostratigraphic units because the boundaries between these units are gradational, the primary mappable features are differences in grain size, and the amount of available data decreases with depth below ground surface, making continuity difficult to document.

Hydrostratigraphic Units

Six hydrostratigraphic units were mapped in this investigation. Each of these six hydrostratigraphic unit varies spatially in character. Although the units vary spatially, the relative importance of each of the hydrostratigraphic units in any one location is similar. The morphology of the hydrostratigraphic units are stratiform and are strongly related to the morphology of the alluvial fans. The presence of fine-grained material as a major or minor component, especially when combined with cementation, was found to have a significant impact on ground-water flow to the wells investigated.

Six hydrostratigraphic mapping units are used in this investigation. These are composed of three (3) aquifers and three (3) aquitards. The two lowest mapping units were combined into a single hydrostratigraphic unit of aquiformation rank. The uppermost hydrostratigraphic unit is an aquiformation informally named the Las Vegas Wash Aquitard. This corresponds to hydrostratigraphic mapping unit (HMU) one.

Below this are two aquifers and one aquitard that comprise the three aquimembers of the Las Vegas Springs Aquifer. The uppermost unit is the Las Vegas Creek aquifer. This corresponds to HMU two. Below this is an aquitard informally named as the Twin Lakes aquitard that corresponds to HMU three. Below this is the most permeable unit mapped in this investigation which was informally named the La Madre Mountain aquifer. This corresponds to HMU four.

HMU four, or the lowermost unit in the Las Vegas Springs Aquifer, is the most permeable interval in all wells investigated. In wells that are screened in the saturated part of hydrostratigraphic unit four, a majority of the transmissivity reported for the well can be attributed to this unit. Hydrostratigraphic mapping unit four is about 50 to 75 m thick in most of the area of investigation. HMU two is generally about half the thickness and not as permeable as HMU four.

HMUs five, an aquitard, and six, an aquifer, together comprise the Duck Creek Aquifer. This hydrostratigraphic unit does not outcrop in the area of investigation. Preliminary work on the District's ground-water flow model by the author suggests that this unit may crop out in the south part of the valley.

HMU six is also considered an aquifer because the transmissivity is high enough to be important interval for domestic wells. The transmissivity of this unit appears to be a result of thickness rather than permeability. This unit is at least 300 m thick and may be in excess of 1000 m thick in the eastern part of the area of investigation. HMUs one, three, and five are aquitards separating the aquifers.

Spatial variation

The two most common factors that reduce permeability in the aquifers are cementation and the presence of fine-grained material. The western part of any one hydrostratigraphic mapping unit is generally cemented and the eastern parts generally contain fine-grained material. The boundary between these two facies generally occurs near the subarea boundaries (fig. 5).

The geologic mapping in conjunction with morphological examination of the alluvial fans, slope variations of the potentiometric surface maps, intervals of flow into or away from the wells described during drilling, and aquifer test data, when combined, were good tools to map the nature and boundaries of the hydrostratigraphic units. All of the methods were used because of the inherent limitations of each of the methods.

Hydrologic Characteristics

The absolute value of permeability at any one location was not as important as the relative percentage of the reported transmissivity that could be attributed to individual hydrostratigraphic units, because of inherent and site specific problems associated with calculating values of transmissivity and permeability within the hydrostratigraphic units. If all six HMUs are saturated, and a well is screened in HMUs two, four, and six, about 10 to 20 percent of the reported transmissivity can be attributed to hydrostratigraphic mapping unit two, 50 to 80 percent to HMU four, and 10 to 20 percent to HMU six.

Implications of this investigation

This investigation is a significant revision of the location and nature of the aquifers in the Las Vegas Valley. This revision has important implications for future hydrologic models and a direct economic implication for the operation of wells on the west side of the valley. The west side of the valley contains most of the municipal water supply wells in Las Vegas Valley.

Implications for future models

The area of relatively high permeability was found to be much wider than previously reported (Harrill, 1976, fig. 6, p. 16; Morgan and Dettinger, 1994, fig. 3.3.1-2, p. 69) and elongated to the east and west rather than north and south in the area of investigation. The southern lobe of the Kyle Canyon Alluvial Fan and the zone of coalescence between Kyle Canyon and Red Rock Alluvial Fans (Subarea 1) is a low to moderate permeability area that separates the area of major District and City of North Las Vegas pumpage from areas that may be highly permeable farther to the north. At least one highly permeable area is probably north of Tule Springs in central lobe of the Kyle Canyon Alluvial Fan (K. Brothers, personal communication, 1993). Future hydrologic models should reflect both the orientation and large size of the highly permeable area in the Las Vegas Springs Aquifer.

In Subarea 3, the boundary between the Las Vegas Springs Aquifer and the underlying Duck Creek Aquifers (moderate to low permeability) is at about 135 m above the boundary used in previous hydrologic flow models. Future hydrologic flow models should reflect this relatively high elevation of the boundary between high and moderate permeability units.

The aquimembers of the Las Vegas Springs Aquifer are relatively thin compared to the amount of decline in the potentiometric surface that has occurred since development. Dewatering of highly permeable units can produce significant changes in the hydrologic properties of the alluvium. The magnitude and location of dewatering should be carefully considered when both modeling the hydrologic properties of the alluvium and comparing historic hydrologic data to more recent data.

Economic implications of the hydrostratigraphic units

Wells that produce water only from the Duck Creek Aquifer have specific capacity values that are only 10 to 20 percent of wells completed in both the Las Vegas Springs and Duck Creek Aquifers. The boundary between high and low specific capacity values is sharp because the most permeable aquimember within the Las Vegas Springs Aquifer (La Madre Mountain aquifer) is located at the base of the aquiformation. If the water level declines, the Las Vegas Springs Aquifer may become dewatered decreasing the specific capacities. Conversely rising water levels may rehydrate parts of the Las Vegas Springs Aquifer increasing specific capacities. The potential decrease in the specific capacities that may occur due to declining water levels may result in both a reduction in flow rates and increase drawdown at the well. This would reduce capacity of the well to produce water or increase the pumping cost to lift water from the well.

Unresolved Issues

This investigation covered a relatively large area and was concerned with relatively large scale patterns of sediment distribution. The allostratigraphic units mapped in this investigation were appropriate because they provided a technique to combine lithologically diverse units into one single unit.

Biostratigraphic or radiometric age dating of the subsurface units could test the continuity of the allostratigraphic units. Geophysical techniques have been used to document continuity of caliche horizons similar to the one described in this investigation. The Las Vegas Valley Water District and City of North Las Vegas are expanding the area of wells into the northern and western parts of the area of investigation. As new well data become available the predicted locations of the units in this investigation can be tested.

The units informally named in this investigation are of major stratigraphic rank. The existence of these units throughout the Las Vegas Valley should be investigated.

The subsurface stratigraphic units of this investigation may be exposed at the surface south and east of the area of investigation. The surficial expression of these units would provide insight into the nature and boundaries of the units.

APPENDIX A

TRANSMISSIVITY DATA FROM WELLS

APPENDIX A

Specific Capacity, and Transmissivity Values Used in This Investigation

Well Name	Specific Capacity ℓ/s/m	Transmissivity (T) m^2/day	Effective Aquifers[a]	Method (T values)
W01A	7.5	894	4,6	1
W02A	11.8	1416	4,6	1
W03A	11.2	1350	4,6	1
W05A	12.2	1466	4,6	1
W13	8.3	994	4,6	1
W22A	20.1	1801	4,6	1
W23A	18.4	1658	4,6	1
W24	28.6	2571	4,6	1
W28	15.7	1888	4,6[b]	1
W29	24.8	2981	4,6[b]	1
W33	6.8	1739	4,6[b]	1
W34	10.3	1242	4,6	1
W38	13.2	1590	4,6	1
W45	8.1	969	2,4,6	1
W51	18.6	2236	2,4,6	1
W52	14.3	1714	2,4,6	1
W68	12.2	1464	2,4,6	1
W69	25.3	2038	4,6	2
W70	0.6	41	6[c]	2
W71	0.7	60	6[c]	2
W72	2.3	189	6	2
W73	14.6	1313	4,6	1
W74	N/A	77	2,4,6	2
W75	0.6	79	4,6	1
W76	1.0	93	6	1

Specific Capacity, and Transmissivity Values Used in This Investigation (Cont'd.)

Well Name	Specific Capacity ℓ/s/m	Transmissivity (T) m^2/day	Effective Aquifers[a]	Method (T values)
W77	9.3	936	4,6	3
W78	N/A	949	4,6	2
W79	N/A	548	2,4,6	3
W80	N/A	570	2,4,6	3
W81	N/A	1527	4,6	3
W82	N/A	3609	2,4,6	3
W83	12.6	1508	4,6	3
W84	12.6	2452	4,6	3
W85	12.2	1492	4,6	3
W88	N/A	1947	4,6	2
W89	N/A	1018	4,6	3
N01A	0.2	40	4,6	3
N02B	0.2	21	4,6	3
N03	4.3	857	4,6	3
MAP	0.2	19	6	1

Methods used to generate transmissivity values
1 Estimated from specific capacity (Cs) by the technique of Driscoll (1986)
2 Calculated by the technique of Moench (1985)
3 Calculated by the technique of Papadopulous and Cooper (1967)

Note:

[a] Effective aquifers are; moderately to highly permeable hydrostratigraphic mapping units that are both, saturated at the well, and, directly accessed through perforations or screened intervals in the well case.

[b] Wells are also perforated in the upper aquifer (2) which has been dewatered. Harrill (1976) reported transmissivities of; 1060, 870, and 1740 m^2/day at these wells. Harrill's (1976) data was collected in the 1960's when the upper aquifer was saturated.

[c] These wells are within 100 meters of three wells perforated in the two upper dewatered aquifers (2 and 4). Harrill's (1976) transmissivity estimate of the older, adjacent, wells were; 2110, 1060, and 600 m^2/day when the upper aquifers were saturated.

APPENDIX A PART 2
Location of wells used to estimate transmissivity, and date of test

Well name	X(UTM) meters	Y(UTM) meters	Latitude	Longitude	Date of analysis
W01A	659795	4003155	36°9'42"	115°13'25"	OCT.1991
W02A	658713	4006141	36°11'20"	115°14'6"	OCT.1993
W03A	663541	4006225	36°11'20"	115°10'52"	OCT.1991
W05A	658307	4006198	36°11'22"	115°14'22"	OCT.1993
W13	663009	4004564	36°10'26"	115°11'15"	OCT.1991
W22A	656423	4007453	36°12'4"	115°15'36"	OCT.1990
W23A	656276	4007688	36°12'12"	115°15'42"	OCT.1991
W24	659022	4004524	36°10'27"	115°13'55"	OCT.1993
W28	658774	4010120	36°13'29"	115°14'0"	OCT.1993
W29	658424	4009990	36°13'25"	115°14'15"	OCT.1993
W33	658096	4010162	36°13'31"	115°14'28"	OCT.1993
W34	663180	4004543	36°10'25"	115°11'8"	OCT.1993
W38	658232	4003456	36°9'53"	115°14'27"	OCT.1990
W45	661409	4006986	36°11'46"	115°12'17"	OCT.1992
W51	659583	4007713	36°12'10"	115°13'30"	OCT.1992
W52	659842	4007697	36°12'10"	115°13'19"	OCT.1992
W68	662675	4004116	36°10'12"	115°11'29"	OCT.1992
W69	656412	4009435	36°13'8"	115°15'35"	OCT.1989
W70	656680	4003033	36°9'40"	115°15'29"	OCT.1989
W71	656748	4002860	36°9'35"	115°15'27"	NOV.1989
W72	656400	4009888	36°13'23"	115°15'36"	OCT.1989
W73	658310	4007624	36°12'8"	115°14'21"	OCT.1993
W74	655156	4014736	36°16'1"	115°16'22"	JUN.1990
W75	655464	4015069	36°16'12"	115°16'9"	OCT.1993

APPENDIX A PART 2

Location of wells used to estimate transmissivity and date of test (Cont'd)

Well name	X(UTM) meters	Y(UTM) meters	Latitude	Longitude	Date of analysis
W76	656512	4005194	36°10'51"	115°15'35"	OCT.1992
W77	658914	4006871	36°11'44"	115°13'57"	JUN.1990
W78	652747	4009489	36°13'12"	115°18'2"	SEP.1992
W79	663678	4004642	36°10'28"	115°10'48"	FEB.1992
W80	663536	4004548	36°10'25"	115°10'54"	MAR.1992
W81	663018	4004023	36°10'9"	115°11'15"	DEC.1991
W82	662811	4003740	36°9'60"	115°11'24"	SEP.1991
W83	663011	4003529	36°9'53"	115°11'16"	NOV.1991
W84	663029	4003052	36°9'37"	115°11'15"	FEB.1992
W85	658913	4006584	36°11'34"	115°13'57"	NOV.1991
W88	656929	4008557	36°12'39"	115°15'15"	JUN.1993
W89	658954	4002681	36°9'28"	115°13'59"	JUN.1994
N01A	661193	4016782	36°17'4"	115°12'19"	AUG.1992
N02B	662991	4012870	36°14'56"	115°11'10"	SEP.1992
N03	661590	4010809	36°13'50"	115°12'7"	JAN.1993
MAP	654313	4004077	36°10'16"	115°17'3"	AUG.1981

APPENDIX B

SELECTED WELL LOGS

Key to abbreviations used on strip-logs and cross-sections.

Lithology abbreviations are the United Soil Classification System (USCS) (Pipkin, 1982) with an addition of K, KG, KS, and KM for units described as caliche.	
Abbreviation	Lithologic type (lithologic descriptions assigned to one of the seventeen categories for correlation and consistency)
ML	Silt or clay
ML	Sandy silt or sandy clay
CL	Gravelly silt or gravelly clay
KM	Silt with caliche or strongly cemented clay
SM	Silty sand
SW	Sand
SP	Gravelly sand
KS	Sand with caliche
GC	Silty gravel
GP	Sandy gravel
GW	Gravel
KG	Gravel with caliche
KM	Silty caliche
KS	Sandy caliche
KG	Gravelly caliche
K	Caliche
N/A	Not available, Not applicable
Gravel, and fines (sand, silt and clay) reported as a percentage.	
Degree of cementation reported on a 1 to 5 scale (Hodgson, 1974). 1 = Weak, 5 = Very Strong.	
Roundness (where available) reported on a 0.5 to 5.5 scale (Powers, 1982). 0.5 = Very angular, 5.5 = Well rounded.	

AGI DATA SHEET 26.1

Unified Soil Classification System

Compiled by B. W. Pipkin, University of Southern California

MAJOR DIVISIONS			GROUP SYMBOLS	TYPICAL NAMES
COARSE-GRAINED SOILS More than half of material is larger than no. 200 sieve size.	GRAVELS More than half of coarse fraction is larger than no. 4 sieve size.	Clean gravels	GW	Well-graded gravels, gravel-sand mixtures, little or no fines.
			GP	Poorly graded gravels, gravel-sand mixtures, little or no fines.
		Gravels with fines	GM	Silty gravels, gravel-sand-silt mixtures.
			GC	Clayey gravels, gravel-sand-clay mixtures.
	SANDS More than half of coarse fraction is smaller than no. 4 sieve size.	Clean sands	SW	Well-graded sands, gravelly sands, little or no fines.
			SP	Poorly graded sands, gravelly sands, little or no fines.
		Sands with fines	SM	Silty sands, sand-silt mixtures.
			SC	Clayey sands, sand-clay mixtures.
FINE-GRAINED SOILS More than half of material is smaller than no. 200 sieve size.	SILTS AND CLAYS	Low liquid limit.	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts, with slight plasticity.
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.
			OL	Organic silts and organic silty clays of low plasticity.
		High liquid limit.	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.
			CH	Inorganic clays of high plasticity, fat clays.
			OH	Organic clays of medium to high plasticity, organic silts.
Highly organic soils			Pt	Peat and other highly organic silts.

NOTES:

1. Boundary Classification: Soils possessing characteristics of two groups are designated by combinations of group symbols. For example, GW-GC, well-graded gravel-sand mixture with clay binder.
2. All sieve sizes on this chart are U.S. Standard.
3. The terms "silt" and "clay" are used respectively to distinguish materials exhibiting lower plasticity from those with higher plasticity. The minus no. 200 sieve material is silt if the liquid limit and plasticity index plot below the "A" line on the plasticity chart (next page), and is clay if the liquid limit and plasticity index plot above the "A" line on the chart.
4. For a complete description of the Unified Soil Classification System, see "Technical Memorandum No. 3-357," prepared for Office, Chief of Engineers, by Waterways Equipment Station, Vicksburg, Mississippi, March 1953. (See also Data Sheet 17.)

Pipkin, 1982

Hydrogeologic variation in well W28 (part 1)

LITHOLOGY	THICKNESS	DEGREE OF CEMENTATION	BOTTOM OF INTERVAL
Silt	3.05	1.00	3.05
Caliche	1.22	5.00	4.27
Silt	6.09	2.50	10.37
Caliche	1.83	5.00	12.20
Silt	7.32	2.50	19.51
Caliche	1.52	5.00	21.04
Silt	38.10	2.50	59.15
Gravelly Silt	4.88	3.00	64.02
Sandy Silt	0.91	2.00	64.94
Gravelly Silt	13.71	2.50	77.74
Silty Gravel	12.20	3.00	89.94
Gravel	3.65	2.00	93.60
Gravel	9.45	3.50	103.05
Gravelly Silt	12.80	3.00	115.85
Gravel	2.44	3.50	118.29
Gravelly Silt	6.71	2.50	125.00
Gravel	2.44	3.50	127.44
Gravelly Silt	3.04	2.50	130.49
Gravel	8.23	3.50	138.72
Gravelly Silt	6.71	3.00	145.43
Silty Gravel	1.22	2.50	146.65
Gravelly Silt	10.36	3.50	157.01
Silt	9.75	2.50	166.77
Gravel	11.59	4.00	178.35
Gravelly Silt	21.03	2.50	199.39
Gravel	21.64	3.50	221.04
Caliche	10.67	4.50	231.71
Gravel	1.22	3.50	232.93
Gravelly Caliche	9.45	4.50	242.38
Gravel	17.37	3.50	259.76
Caliche	6.09	4.50	265.85
Gravelly Caliche	23.78	4.00	289.63
Caliche	16.15	4.50	305.79

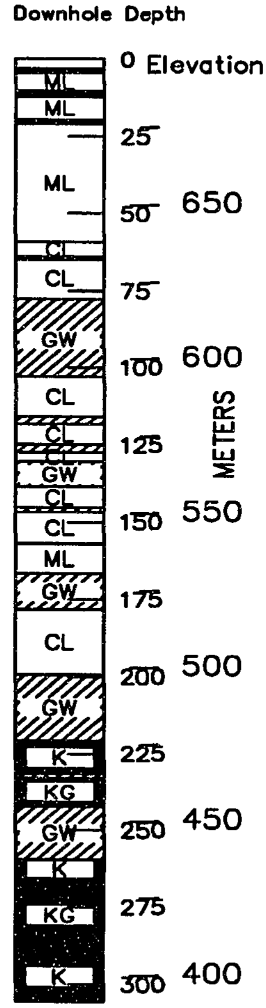
SCREENED INTERVAL	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Closed	93.57	0.00	93.57
Open	9.45	93.57	103.02
Closed	12.80	103.02	115.82
Open	2.44	115.82	118.26
Closed	6.71	118.26	124.97
Open	21.64	124.97	146.61
Closed	20.11	146.61	166.72
Open	11.59	166.72	178.31
Closed	21.03	178.31	199.34
Open	94.79	199.34	294.13
Closed	11.58	294.13	305.71

WATER LEVEL October 1993	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Unsaturated	108.81	0.00	108.81
Saturated	196.90	108.81	305.71

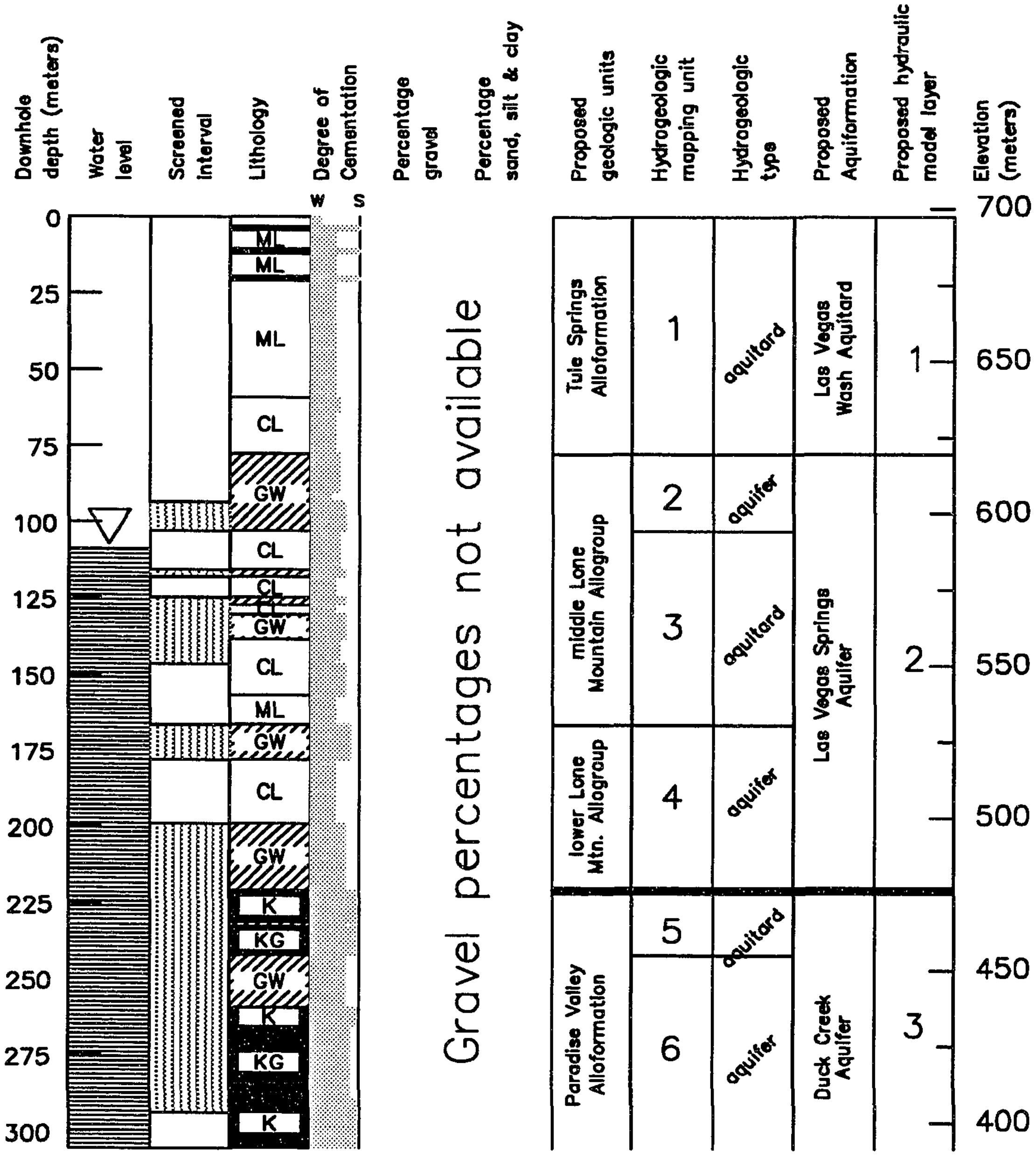
Hatchered intervals are gravel (GW) and sandy gravel (GP).

Solid fill intervals are dominated by cementation and called caliche on drillers' log and here.

All units reported in meters, except degree of cementation.
Degree of cementation is a 1 to 5 scale
1 is weak cementation and 5 is strong cementation.



Hydrogeologic variation in well W28 (part 2)



Cementation, and percentages (where available) increase to the right. Abbreviations W and S above cementation column are weak and strong. 0, 50 and 100 above columns are percentages.

Hydrogeologic variation in well W29 (part 1)

LITHOLOGY	THICKNESS	DEGREE OF CEMENTATION	BOTTOM OF INTERVAL
Gravelly Silt	3.96	2.00	3.96
Silt	13.11	2.50	17.07
Caliche w silt	2.13	4.50	19.21
Silt	31.70	2.50	50.91
Gravel	32.61	2.50	83.54
Sandy Gravel	12.20	2.50	95.73
Silt	6.09	2.50	101.83
Gravelly Silt	4.88	2.50	106.71
Sand	2.44	4.00	109.15
Gravelly Sand	3.66	4.00	112.80
Gravel	7.31	2.00	120.12
Gravelly Sand	4.88	2.50	125.00
Gravel	0.91	2.50	125.91
Sand	2.75	4.00	128.66
Gravel	1.21	4.00	129.88
Gravel	7.32	2.00	137.20
Gravel	3.66	4.00	140.85
Gravel	1.22	2.00	142.07
Gravelly Sand	6.09	2.50	148.17
Silt	8.54	2.00	156.71
Gravel	4.87	2.50	161.59
Gravel	12.20	4.00	173.78
Gravelly Sand	1.52	2.50	175.30
Gravel	4.57	4.50	179.88
Gravel	3.05	2.00	182.93
Gravel	4.88	3.50	187.80
Gravel	4.26	2.50	192.07
Sandy Gravel	6.10	3.00	198.17
Gravel	6.10	4.00	204.27
Gravel	21.33	2.00	225.61
Gravel	12.80	4.00	238.41
Gravelly Silt	2.44	4.50	240.85
Gravel	9.76	4.00	250.61
Gravel	6.09	2.00	256.71
Gravel	7.32	3.50	264.02
Sandy Gravel	1.22	4.00	265.24
Gravel	3.65	3.50	268.90
Gravelly Silt	2.44	4.50	271.34
Gravel	20.73	4.50	292.07
Silt	0.61	2.50	292.68
Sand	1.22	2.50	293.90
Sandy Gravel	1.22	4.50	295.12
Gravel	9.75	4.50	304.88

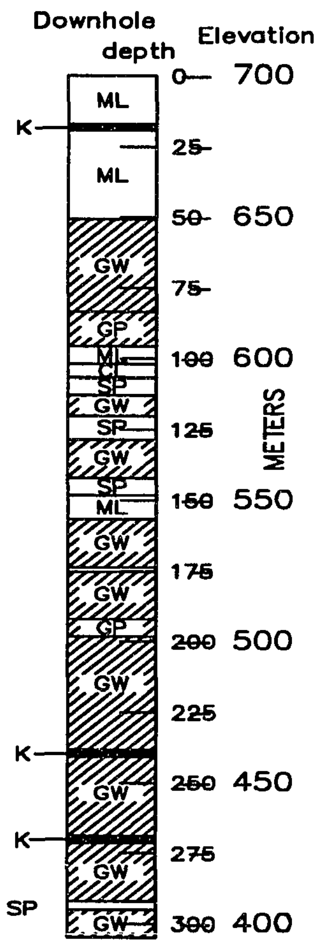
SCREENED INTERVALS	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Closed	53.95	0.00	53.95
Open	40.54	53.95	94.49
Closed	15.24	94.49	109.73
Open	32.31	109.73	142.04
Closed	17.67	142.04	159.71
Open	114.61	159.71	274.32
Closed	30.48	274.32	304.80

WATER LEVEL October 1993	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Unsaturated	99.96	0.00	99.96
Saturated	204.84	99.96	304.80

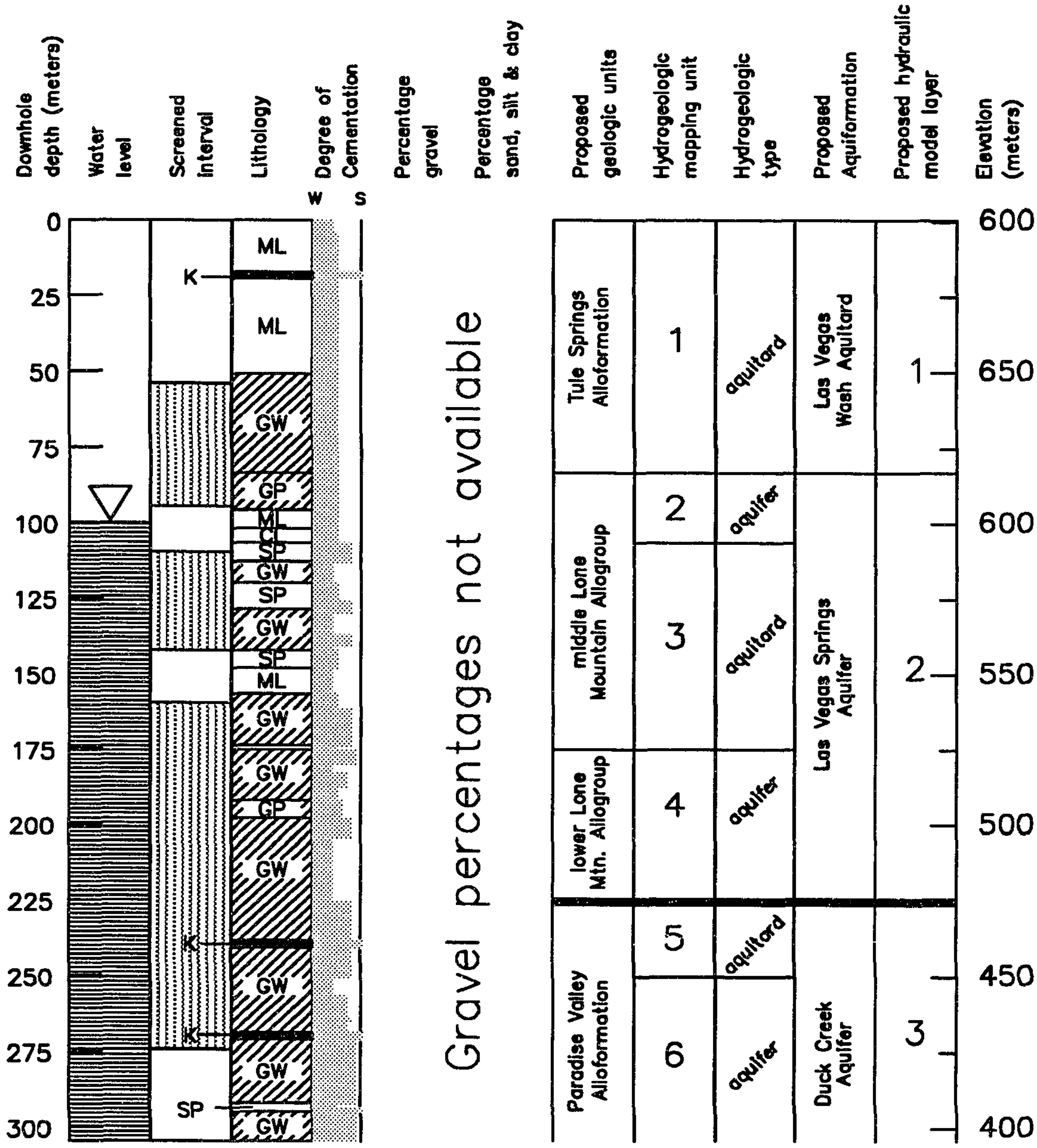
Hatchered intervals are gravel (GW) and sandy gravel (GP).

Solid fill intervals are dominated by cementation and called caliche on drillers' log and here.

All units reported in meters, except degree of cementation.
Degree of cementation is a 1 to 5 scale,
1 is weak cementation and 5 is strong cementation.
Compare with wells W69 and W72



Hydrogeologic variation in well W29 (part 2)



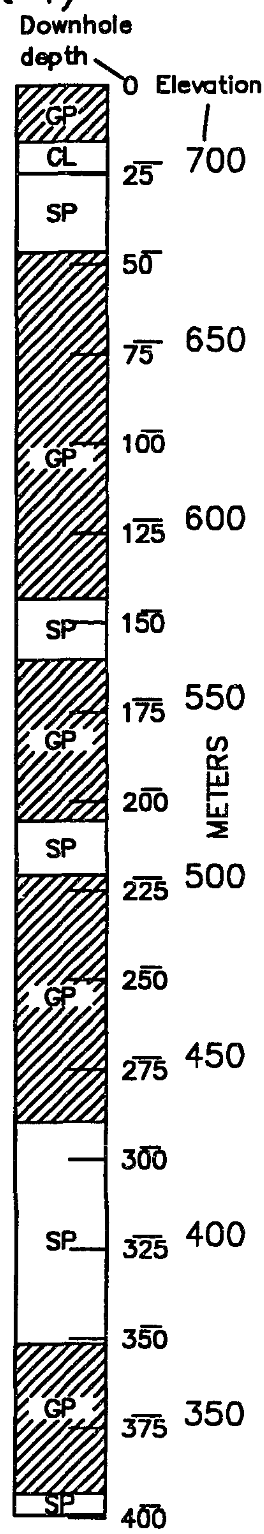
Cementation, and percentages (where available) increase to the right. Abbreviations W and S above cementation column are weak and strong. 0, 50 and 100 above columns are percentages.

Hydrogeologic variation in well W69 (part 1)

LITHOLOGY	THICKNESS	DEGREE OF CEMENTATION	BOTTOM OF INTERVAL
Sandy Gravel	12.19	3.50	12.20
Gravelly Sand	3.35	2.00	15.55
Sandy Gravel	4.27	3.00	19.82
Sandy Silt	4.57	2.00	24.39
Gravelly Sand	22.25	2.50	46.65
Sandy Gravel	40.24	2.50	86.89
Sandy Gravel	7.31	4.00	94.21
Sandy Gravel	19.51	2.00	113.72
Sandy Gravel	29.56	3.00	143.29
Gravelly Sand	17.07	2.00	160.37
Sandy Gravel	45.11	2.50	205.49
Gravelly Sand	15.24	2.00	220.73
Sandy Gravel	15.85	2.50	236.59
Sandy Gravel	9.15	2.00	245.73
Sandy Gravel	27.73	2.50	273.48
Sandy Gravel	2.75	2.00	276.22
Sandy Gravel	13.41	2.50	289.63
Gravelly Sand	26.82	2.50	316.46
Gravelly Sand	35.05	2.50	351.52
Sandy Gravel	30.48	2.50	382.01
Sandy Gravel	11.28	2.00	393.29
Gravelly Sand	5.79	2.00	399.09

SCREENED INTERVALS	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Closed	152.40	0.00	152.40
Open	60.96	152.40	213.36
Closed	13.71	213.36	227.07
Open	114.91	227.07	341.98
Closed	57.00	341.98	398.98

WATER LEVEL October 1993	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Unsaturated	110.95	0	110.95
Saturated	288.03	110.95	398.98

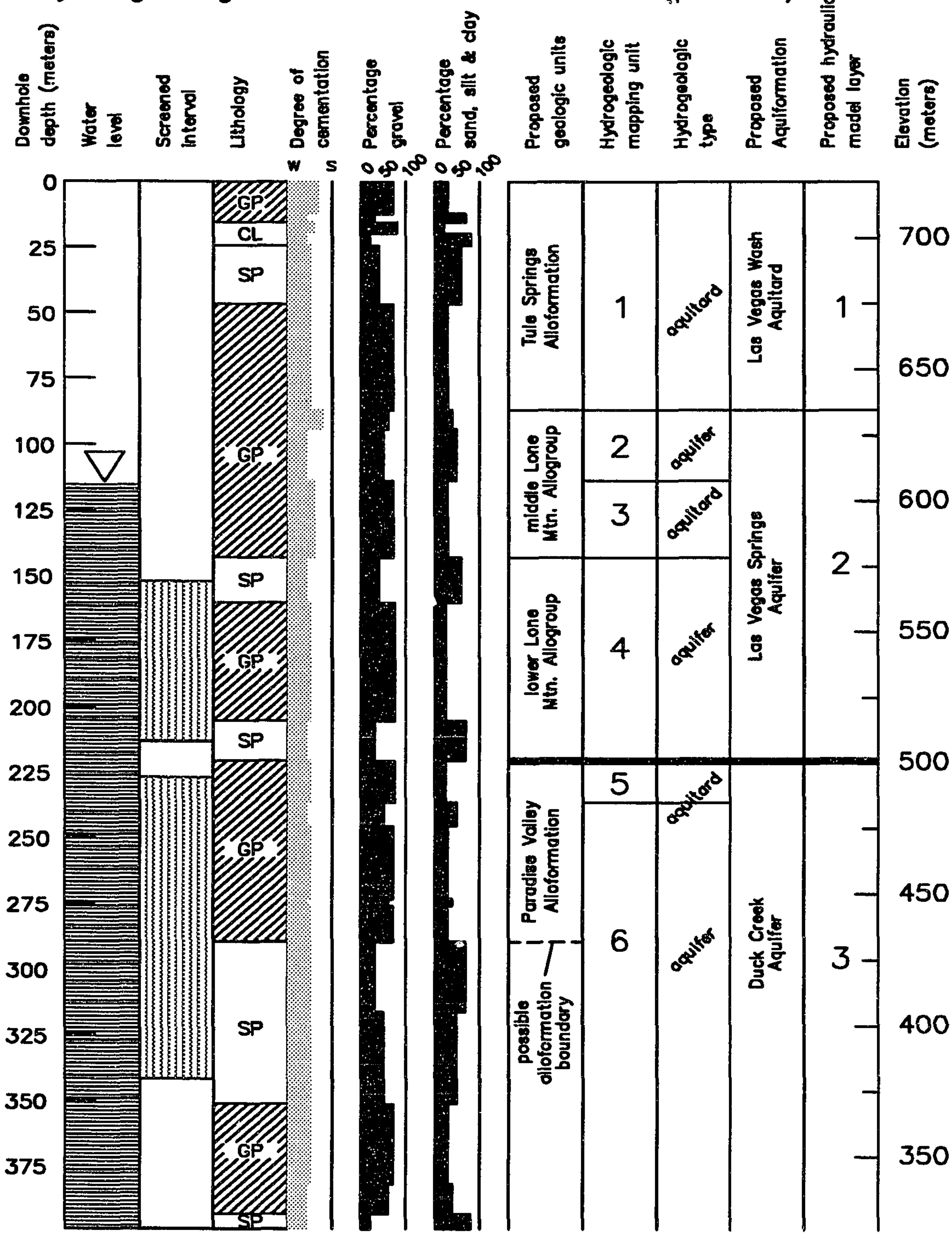


Hatchered intervals are gravel (GW) and sandy gravel (GP).

Solid fill intervals are dominated by cementation and called caliche on drillers' log and here.

All units reported in meters, except degree of cementation. Degree of cementation is a 1 to 5 scale 1 is weak cementation and 5 is strong cementation.

Hydrogeologic variation in well W69 (part 2)



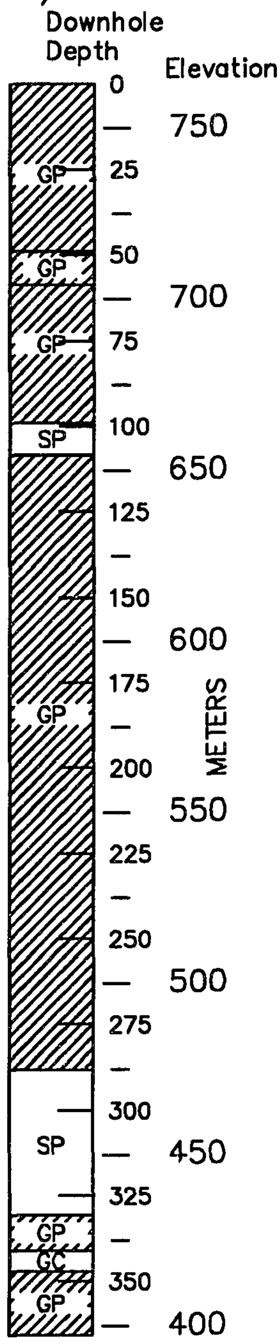
Cementation, and percentages (where available) increase to the right.
Abbreviations W and S above cementation column are weak and strong.
0, 50 and 100 above columns are percentages.
note: plotted at same scale as well W72 for comparison

Hydrogeologic variation in well W70 (part 1)

LITHOLOGY	THICKNESS	DEGREE OF CEMENTATION	BOTTOM OF INTERVAL
Sandy Gravel	14.03	2.50	14.02
Sandy Gravel	24.99	4.00	39.02
Sandy Gravel	10.06	3.00	49.09
Sandy Gravel	9.75	2.00	58.84
Sandy Gravel	20.42	3.50	79.27
Sandy Gravel	16.77	2.50	96.04
Sandy Gravel	3.04	2.50	99.09
Gravelly Sand	29.26	2.50	108.54
Sandy Gravel	35.97	3.50	144.51
Sandy Gravel	10.97	3.00	155.49
Sandy Gravel	41.46	3.75	196.95
Sandy Gravel	30.48	3.50	227.44
Sandy Gravel	18.59	2.50	246.04
Sandy Gravel	25.60	3.50	271.65
Sandy Gravel	16.46	2.25	288.11
Gravelly Sand	18.29	3.50	306.40
Gravelly Sand	24.38	2.50	330.79
Sandy Gravel	10.37	3.50	341.16
Silty Gravel	6.09	2.00	347.26
Sandy Gravel	18.59	3.50	365.85

SCREENED INTERVALS	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Closed	201.17	0.00	201.17
Open	152.40	201.17	353.57
Closed	12.19	353.57	365.76

WATER LEVEL October 1993	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Unsaturated	161.85	0.00	161.85
Saturated	203.91	161.85	365.76

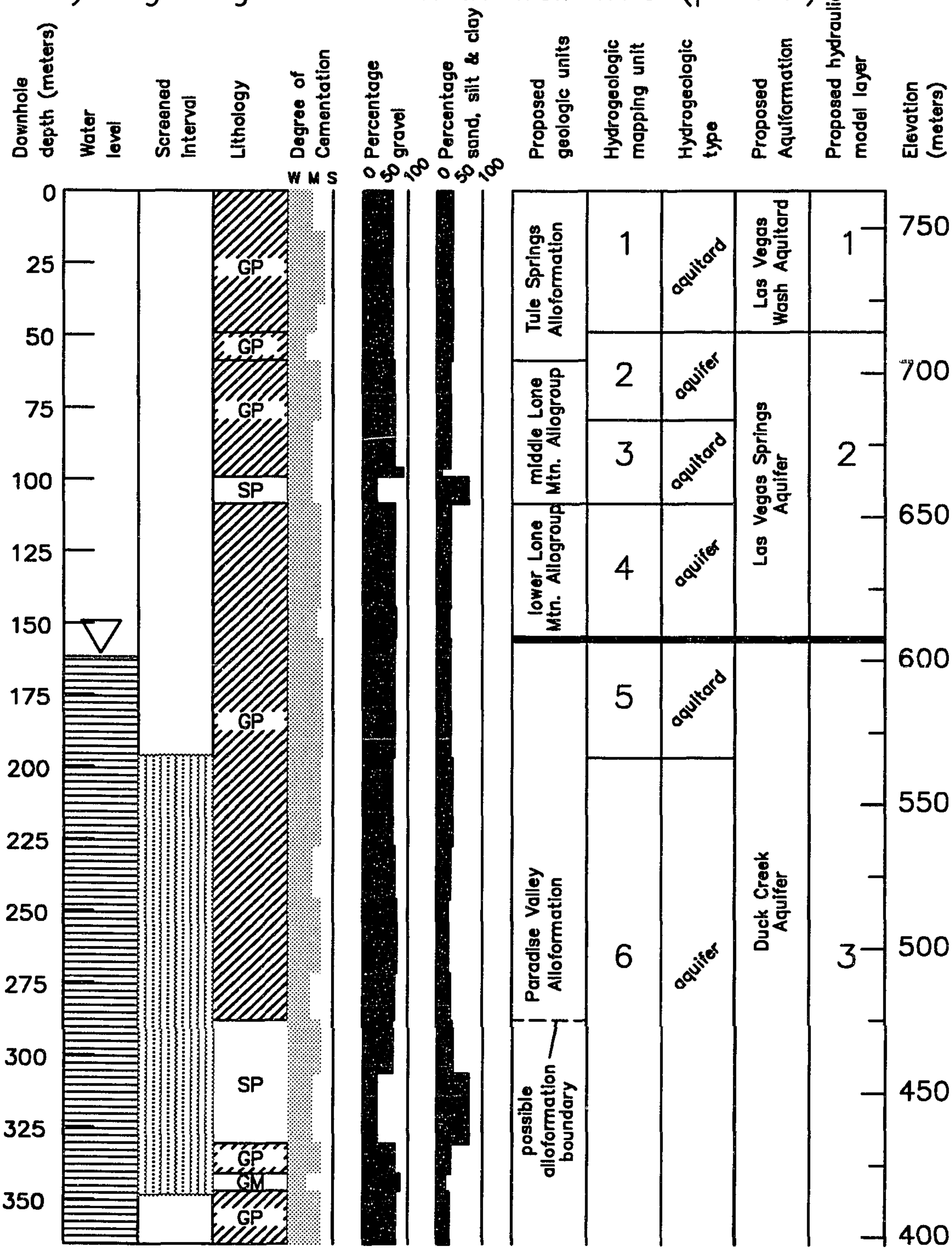


Hatchered intervals are gravel (GW) and sandy gravel (GP).

Solid fill intervals are dominated by cementation and called caliche on drillers' log and here.

All units reported in meters, except degree of cementation.
Degree of cementation is a 1 to 5 scale
1 is weak cementation and 5 is strong cementation.

Hydrogeologic variation in well W70 (part 2)



Cementation, and percentages (where available) increase to the right. Abbreviations W and S above cementation column are weak and strong. 0, 50 and 100 above columns are percentages.

Hydrogeologic variation in well W72 (part 1)

LITHOLOGY	THICKNESS	DEGREE OF CEMENTATION	BOTTOM OF INTERVAL
Sandy Gravel	17.07	2.00	17.07
Gravelly Sand	4.26	4.00	21.34
Sandy Gravel	19.51	2.00	40.85
Gravelly Sand	4.27	2.50	45.12
Sandy Gravel	12.80	3.00	57.93
Sandy Gravel	29.26	3.50	87.20
Sandy Gravel	26.82	3.00	114.02
Sandy Gravel	17.07	2.50	131.10
Sand	10.37	2.50	141.46
Gravel	56.38	2.00	197.87
Gravelly Sand	6.40	1.50	204.27
Sandy Gravel	31.09	4.00	235.37
Sandy Gravel	35.97	2.50	271.34
Sandy Gravel	30.18	2.50	301.52
Gravelly Sand	53.03	3.00	354.57
Sandy Gravel	14.02	2.50	368.60
Gravelly Sand	25.91	2.00	394.51
Sandy Gravel	20.12	2.50	414.63
Sandy Gravel	18.28	4.00	432.93
Sandy Gravel	24.39	3.50	457.32
Sandy Gravel	14.02	3.50	471.34
Gravelly Sand	24.38	4.00	495.73

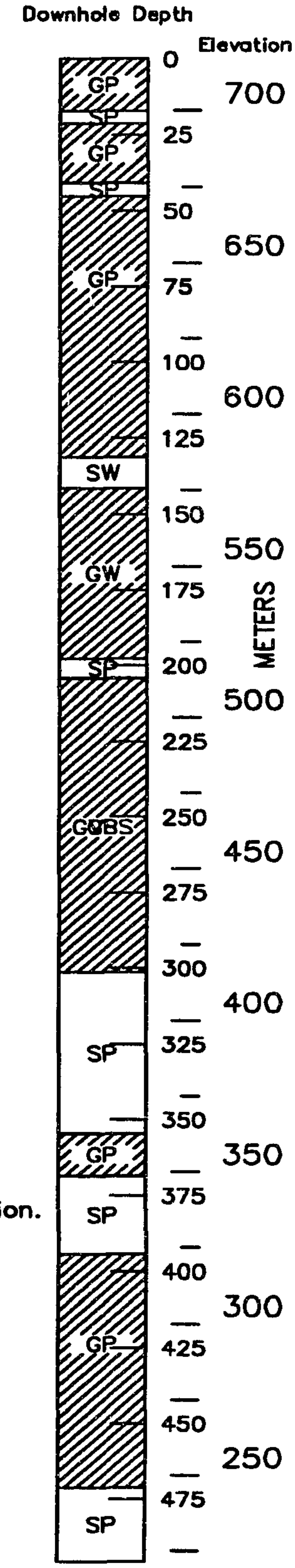
SCREENED INTERVALS	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Closed	260.60	0.00	260.60
Open	97.54	260.60	358.14
Closed	36.57	358.14	394.71
Open	85.35	394.71	480.06
Closed	15.54	480.06	495.60

WATER LEVEL October 1993	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Unsaturated	110.95	0.00	110.95
Saturated	384.65	110.95	495.60

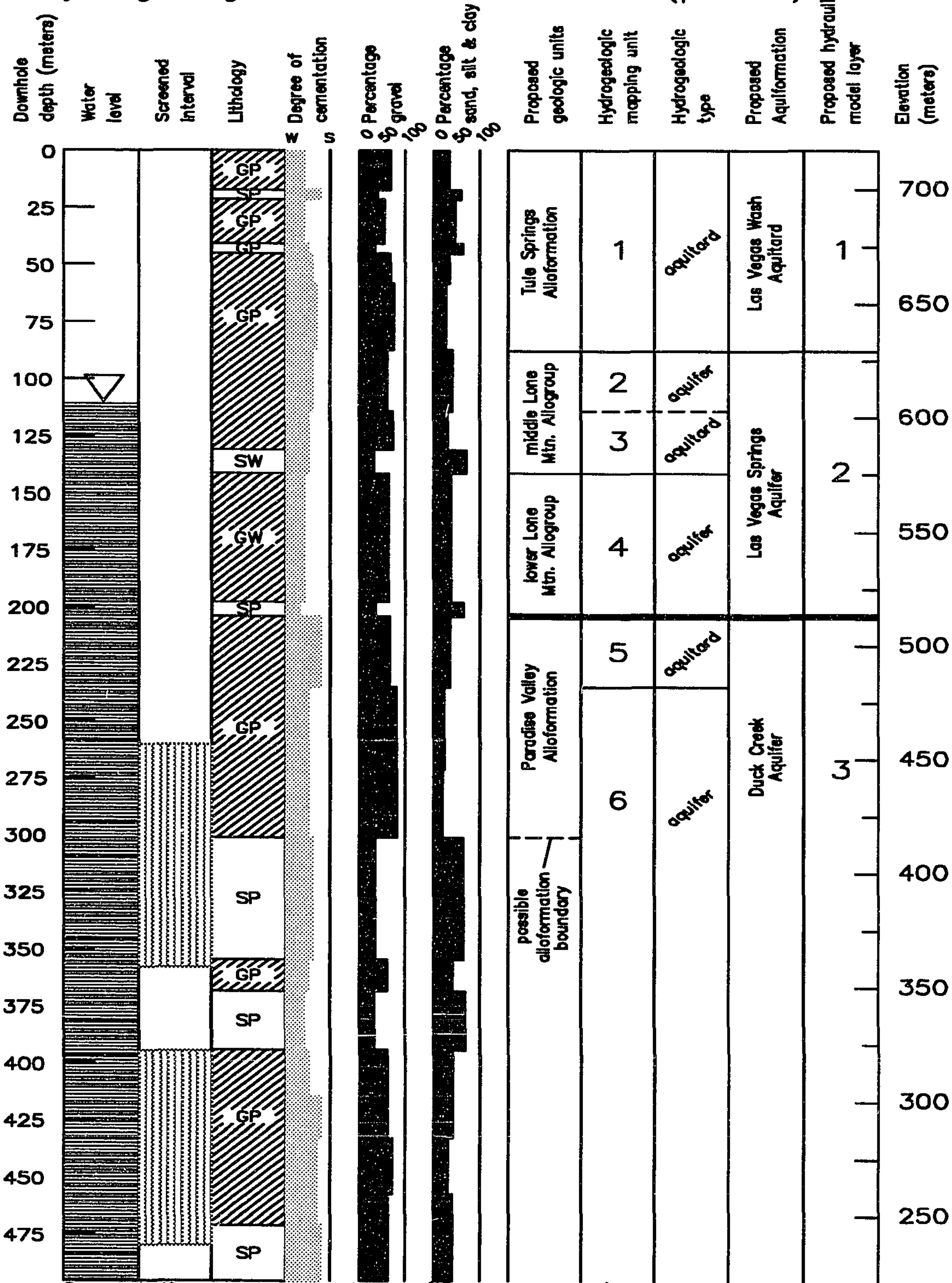
Hatchered intervals are gravel (GW) and sandy gravel (GP).

Solid fill intervals are dominated by cementation and called caliche on drillers' log and here.

All units reported in meters, except degree of cementation.
Degree of cementation is a 1 to 5 scale
1 is weak cementation and 5 is strong cementation.



Hydrogeologic variation in well W72 (part 2)



Cementation, and percentages (where available) increase to the right.
Abbreviations W and S above cementation column are weak and strong.
0, 50 and 100 above columns are percentages.

Hydrogeologic variation in well W78 (part 1)

LITHOLOGY	THICKNESS	DEGREE OF CEMENTATION	BOTTOM OF INTERVAL
Gravelly Sand	2.75	2.00	2.74
Sandy Gravel	12.49	3.00	15.24
Sandy Gravel	13.11	2.00	28.35
Sandy Gravel	36.58	4.00	64.94
Sandy Gravel	35.66	2.00	100.61
Sandy Gravel	12.80	3.00	113.41
Sandy Gravel	5.18	2.00	118.60
Sandy Gravel	8.53	2.00	127.13
Sandy Gravel	53.95	2.50	181.10
Sandy Gravel	32.31	2.00	213.41
Sandy Gravel	36.88	2.00	250.30
Sandy Gravel	4.58	2.00	254.88
Sandy Gravel	4.87	2.00	259.76
Sandy Gravel	17.07	2.50	276.83
Aztec Sandstone	42.67	N/A	319.51

SCREENED INTERVAL	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Closed	213.36	0.00	213.36
Open	85.35	213.36	298.71
Closed	20.72	298.71	319.43

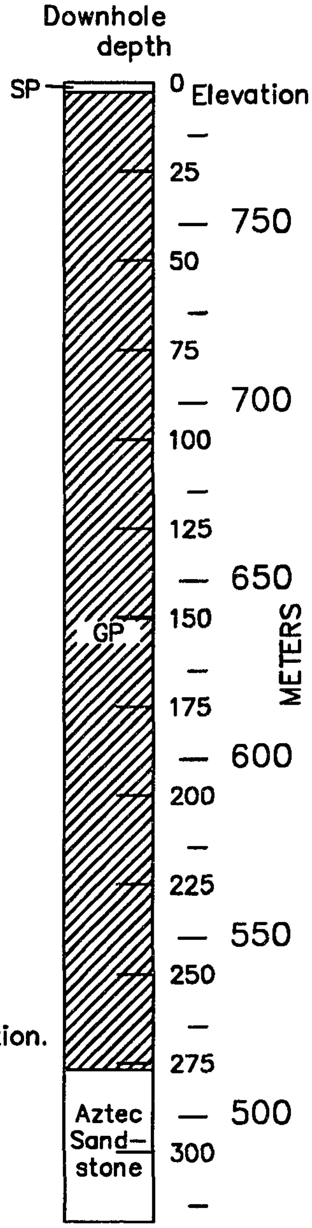
WATER LEVEL October 1993	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Unsaturated	172.00	0.00	172.00
Saturated	147.43	172.00	319.43

Hatchered intervals are gravel (GW) and sandy gravel (GP).

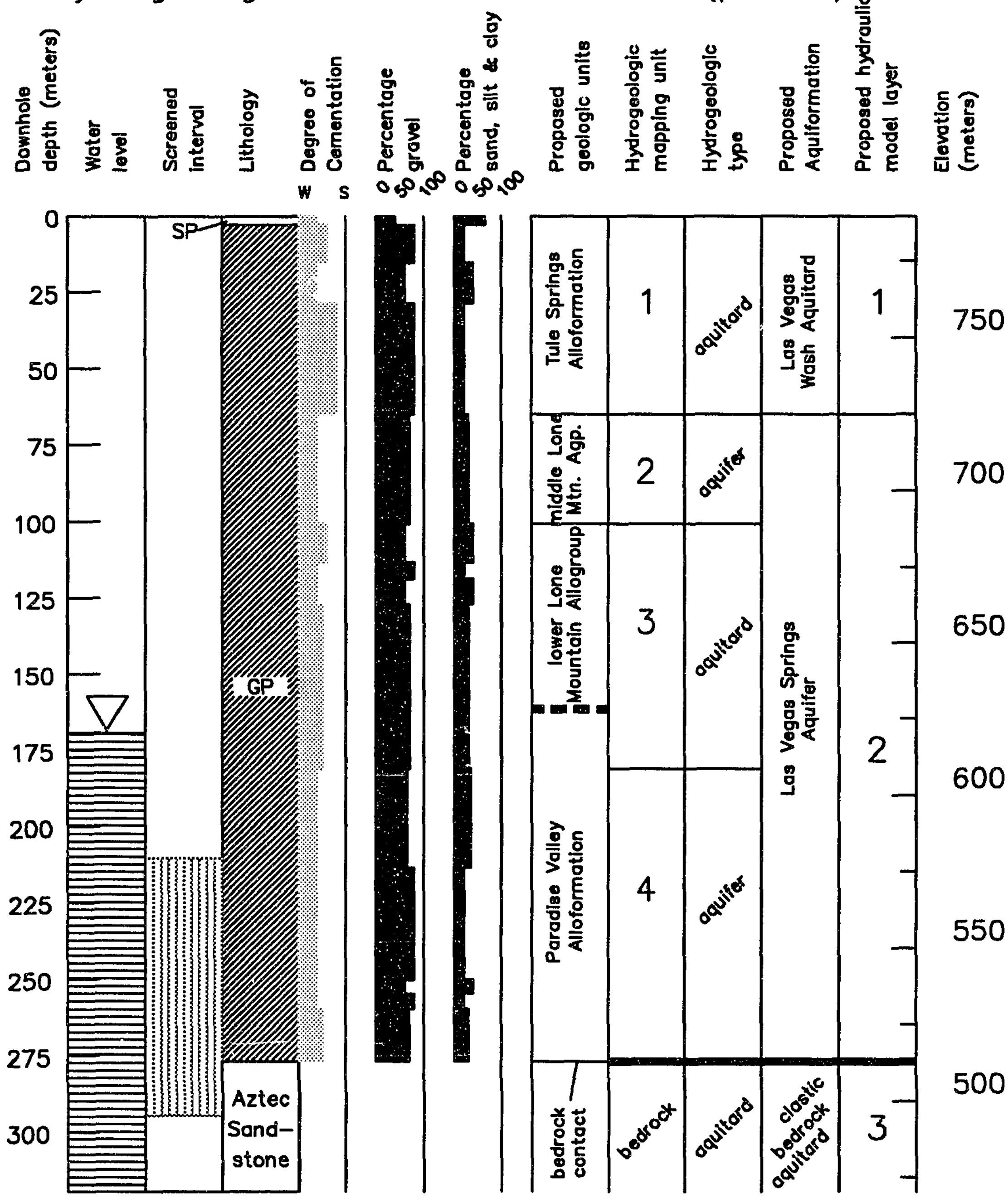
Solid fill intervals are dominated by cementation and called caliche on drillers' log and here.

All units reported in meters, except degree of cementation.

Degree of cementation is a 1 to 5 scale
1 is weak cementation and 5 is strong cementation.



Hydrogeologic variation in well W78 (part 2)



Most permeable zone in this well is the alluvium–bedrock contact. An aquifer test in the bedrock part of this well, produced no significant quantity of water. Lone Mountain Allogroup/Paradise Valley Alloformation boundary infered from well W90.

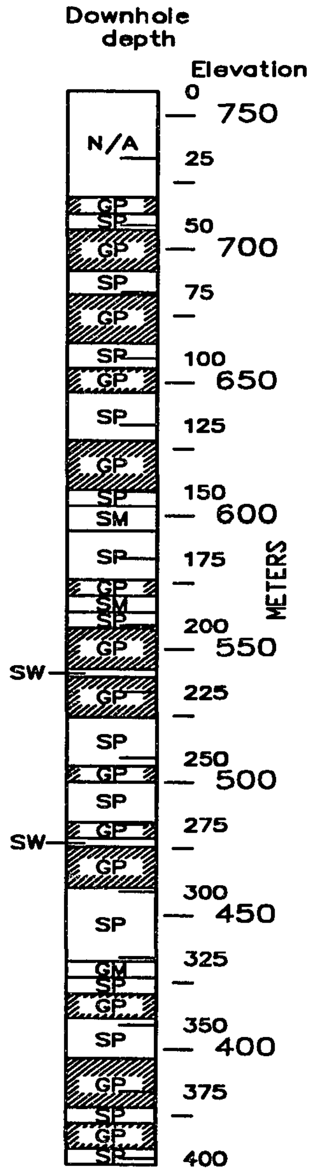
Cementation, and percentages (where available) increase to the right. Abbreviations W and S above cementation column are weak and strong. 0, 50 and 100 above columns are percentages.

Hydrogeologic variation in well W90 (part 1)

LITHOLOGY	THICKNESS	DEGREE OF CEMENTATION	BOTTOM OF INTERVAL
No Data	39.62	0.00	39.63
Sandy Gravel	6.10	3.50	45.73
Gravelly Sand	6.09	3.00	51.83
Sandy Gravel	15.24	2.50	67.07
Gravelly Sand	9.15	3.00	76.22
Sandy Gravel	6.09	2.50	82.32
Sandy Gravel	12.20	2.50	94.51
Gravelly Sand	9.14	3.50	103.66
Sandy Gravel	9.14	2.50	112.80
Gravelly Sand	18.29	3.00	131.10
Sandy Gravel	18.29	1.00	149.39
Gravelly Sand	3.05	1.00	152.44
Sandy Gravel	3.05	3.00	155.49
Silty Sand	9.14	2.00	164.63
Gravelly Sand	3.05	2.00	167.68
Gravelly Sand	3.05	1.00	170.73
Sandy Gravel	3.04	1.00	173.78
Gravelly Sand	9.15	1.00	182.93
Sandy Gravel	6.09	1.00	189.02
Silty Sand	6.10	4.50	195.12
Sand	3.05	1.00	198.17
Gravelly Sand	3.05	1.00	201.22
Sandy Gravel	15.24	1.00	216.46
Sand	3.04	1.00	219.51
Sandy Gravel	15.24	1.00	234.76
Gravelly Sand	18.29	3.00	253.05
Sandy Gravel	6.10	2.50	259.15
Gravelly Sand	6.09	2.00	265.24
Gravelly Sand	9.15	3.00	274.39
Sandy Gravel	6.09	1.50	280.49
Sand	3.05	2.50	283.54
Sandy Gravel	15.24	1.00	298.78
Gravelly Sand	27.43	1.00	326.22
Sandy Gravel	3.05	2.50	329.27
Silt	3.05	2.50	332.32
Sandy Gravel	3.05	3.50	335.37
Gravelly Sand	3.05	3.00	338.41
Sandy Gravel	9.14	2.50	347.56
Gravelly Sand	12.19	3.50	359.76
Silty Sand	3.05	3.00	362.80
Sandy Gravel	6.10	3.00	368.90
Gravelly Sand	3.04	2.50	371.95
Sandy Gravel	9.15	3.50	381.10
Gravelly Sand	6.09	3.00	387.20
Sandy Gravel	9.15	4.00	396.34
Gravelly Sand	3.05	3.50	399.39
Sandy Gravel	3.04	3.00	402.44

SCREENED INTERVAL	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Closed	182.88	0.00	182.88
Open	24.38	182.88	207.26
Closed	12.19	207.26	219.45
Open	42.68	219.45	262.13
Closed	18.28	262.13	280.41
Open	45.72	280.41	326.13
Closed	6.10	326.13	332.23
Open	48.77	332.23	381.00
Closed	21.33	381.00	402.33

WATER LEVEL October 1993	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Unsaturated	137.16	0.00	137.16
Saturated	265.17	137.16	402.33

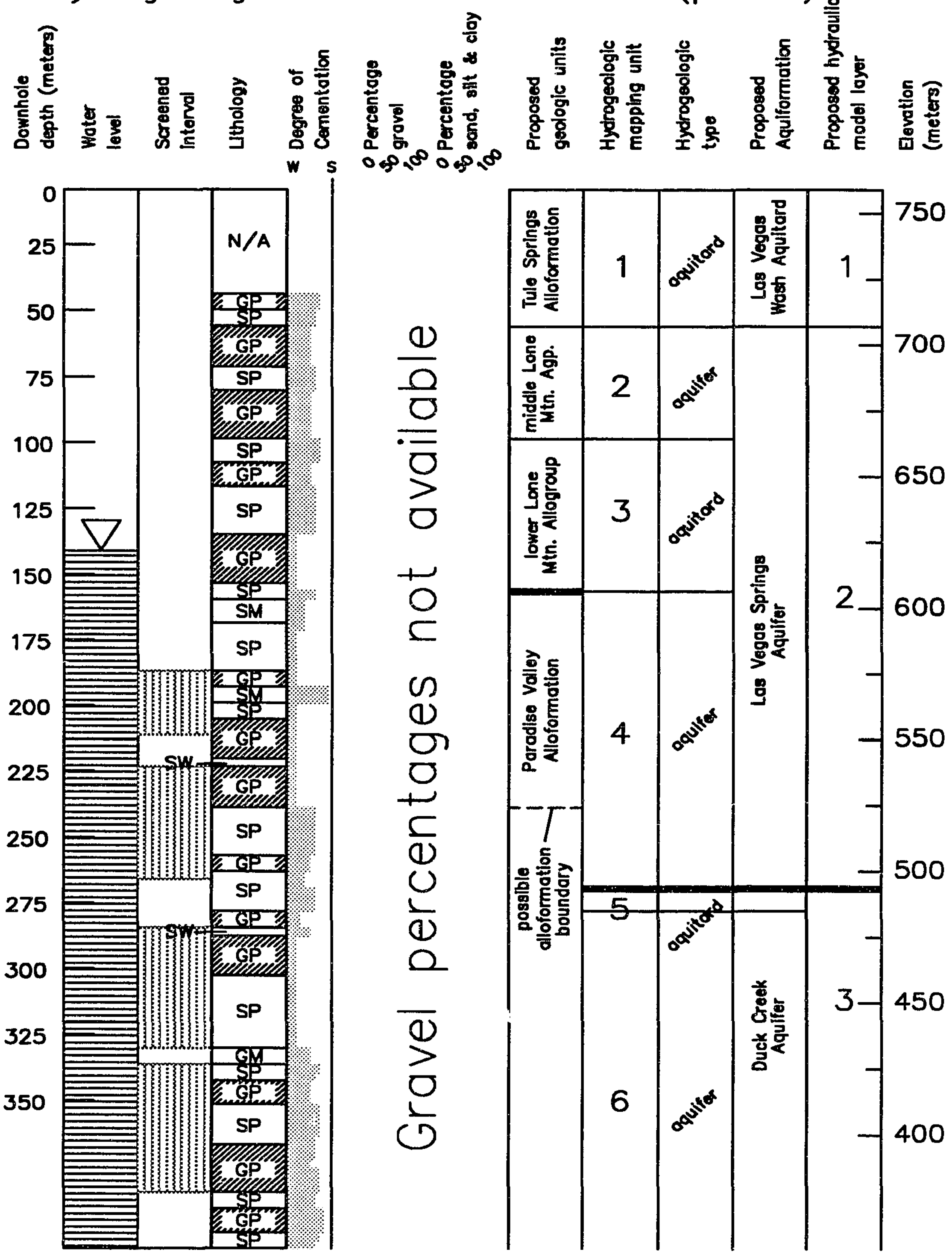


Hatchered intervals are gravel (GW) and sandy gravel (GP).

Solid fill intervals are dominated by cementation and called caliche on drillers' log and here.

All units reported in meters, except degree of cementation.
Degree of cementation is a 1 to 5 scale
1 is weak cementation and 5 is strong cementation.

Hydrogeologic variation in well W90 (part 2)



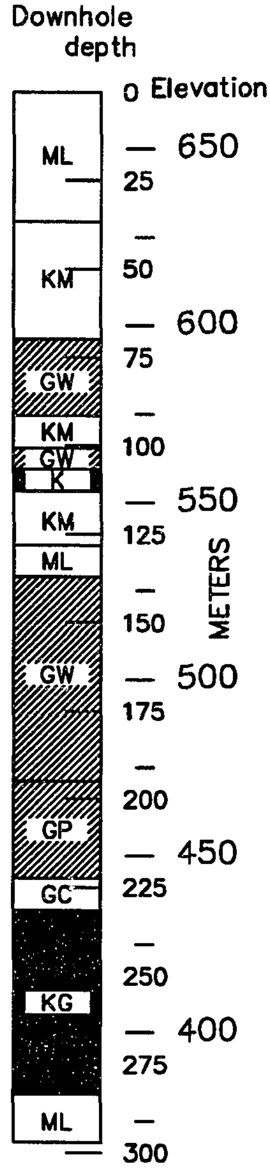
Cementation, and percentages (where available) increase to the right. Abbreviations W and S above cementation column are weak and strong. 0, 50 and 100 above columns are percentages.

Hydrogeologic variation in well NWC (part 1)

LITHOLOGY	THICKNESS	DEGREE OF CEMENTATION	BOTTOM OF INTERVAL
Silt	18.29	2.00	18.29
Silt	6.10	2.00	24.39
Silt	6.09	2.00	30.49
Silt	6.10	2.00	36.59
Silt w Caliche	24.38	3.50	60.98
Silt w Caliche	9.15	3.50	70.12
Gravel	6.09	2.00	76.22
Gravel	15.24	3.50	91.46
Silt w Caliche	9.15	3.50	100.61
Gravel	6.09	2.00	106.71
Caliche	6.10	4.00	112.80
Silt w Caliche	6.09	3.50	118.90
Silt w Caliche	9.15	3.50	128.05
Silt	9.14	2.00	137.20
Gravel	24.39	3.50	161.59
Gravel	6.09	3.50	167.68
Gravel	27.43	3.50	195.12
Sandy Gravel	27.44	2.00	222.56
Silty Gravel	9.14	2.00	231.71
Gravelly Caliche	51.82	4.00	283.54
Sandy Silt	6.09	2.00	289.63
Silt	7.62	2.00	297.26

SCREENED INTERVAL	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Closed	76.20	0.00	76.20
Open	204.22	76.20	280.42
Closed	16.76	280.42	297.18

WATER LEVEL October 1993	THICKNESS	TOP OF INTERVAL	BOTTOM OF INTERVAL
Unsaturated	60.96	0.00	60.96
Saturated	236.22	60.96	297.18

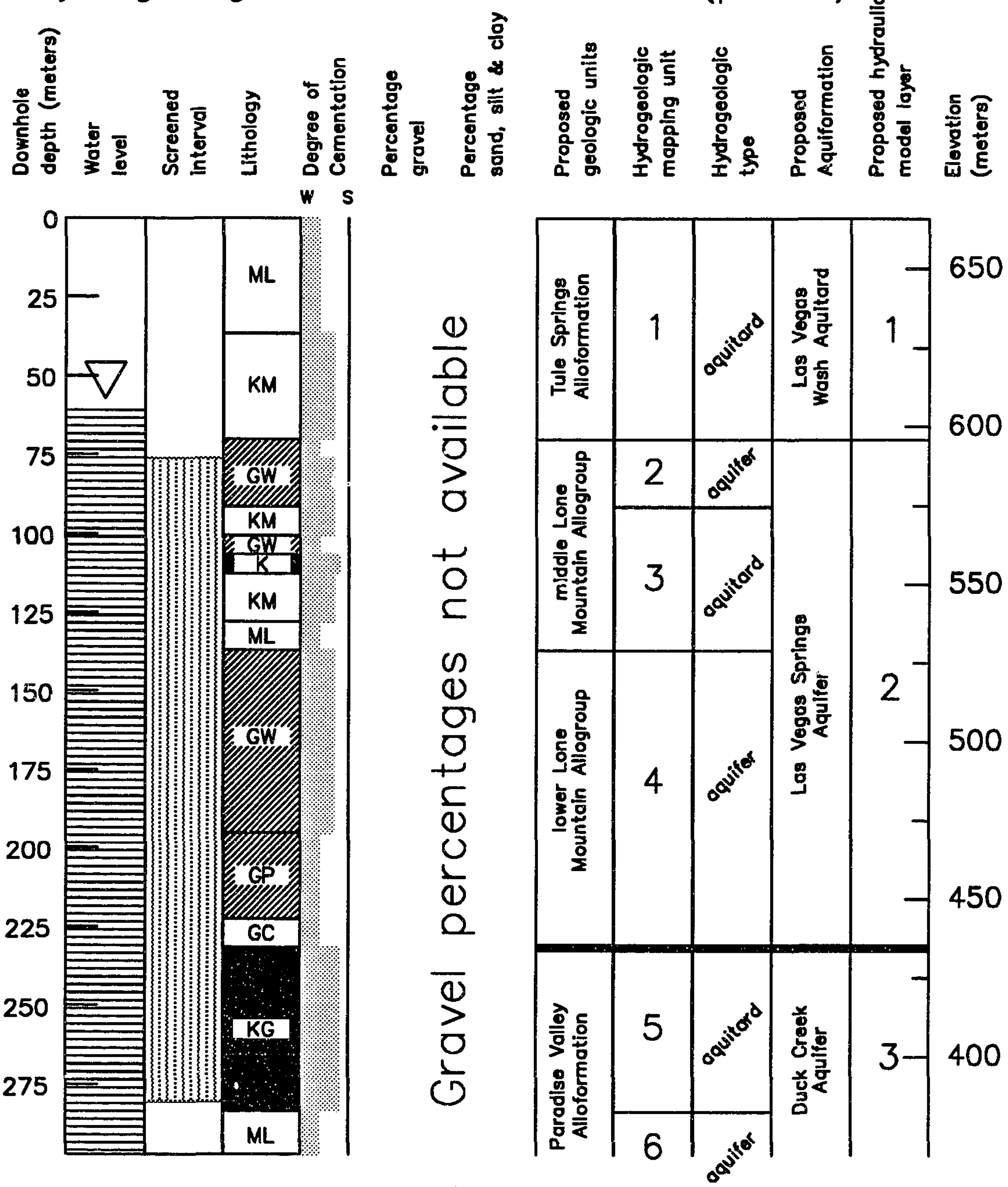


Hatchered intervals are gravel (GW) and sandy gravel (GP).

Solid fill intervals are dominated by cementation and called caliche on drillers' log and here.

All units reported in meters, except degree of cementation.
Degree of cementation is a 1 to 5 scale
1 is weak cementation and 5 is strong cementation.

Hydrogeologic variation in well NWC (part 2)



Cementation, and percentages (where available) increase to the right. Abbreviations W and S above cementation column are weak and strong. 0, 50 and 100 above columns are percentages.

APPENDIX C

DEFINITION OF ALLOSTRATIGRAPHIC UNITS IN THE 1983 NORTH AMERICAN CODE OF STRATIGRAPHIC NOMENCLATURE (NACSN, 1983, p. 865-867)

ALLOSTRATIGRAPHIC UNITS

Nature and Boundaries

Article 58.--**Nature of Allostratigraphic Units.** An Allostratigraphic unit is a mappable stratiform body of sedimentary rock that is defined and identified on the basis of its bounding discontinuities.

Remarks. (a) **Purpose.**--Formal Allostratigraphic units may be defined to distinguish between different (1) superposed discontinuity-bounded deposits of similar lithology (Figs. 7,9), (2) contiguous discontinuity-bounded deposits of similar lithology (Fig. 8) or (3) geographically separated discontinuity-bounded units of similar lithology (Fig. 9), or to distinguish as a single units discontinuity-bounded deposits characterized by lithic heterogeneity (Fig. 8).

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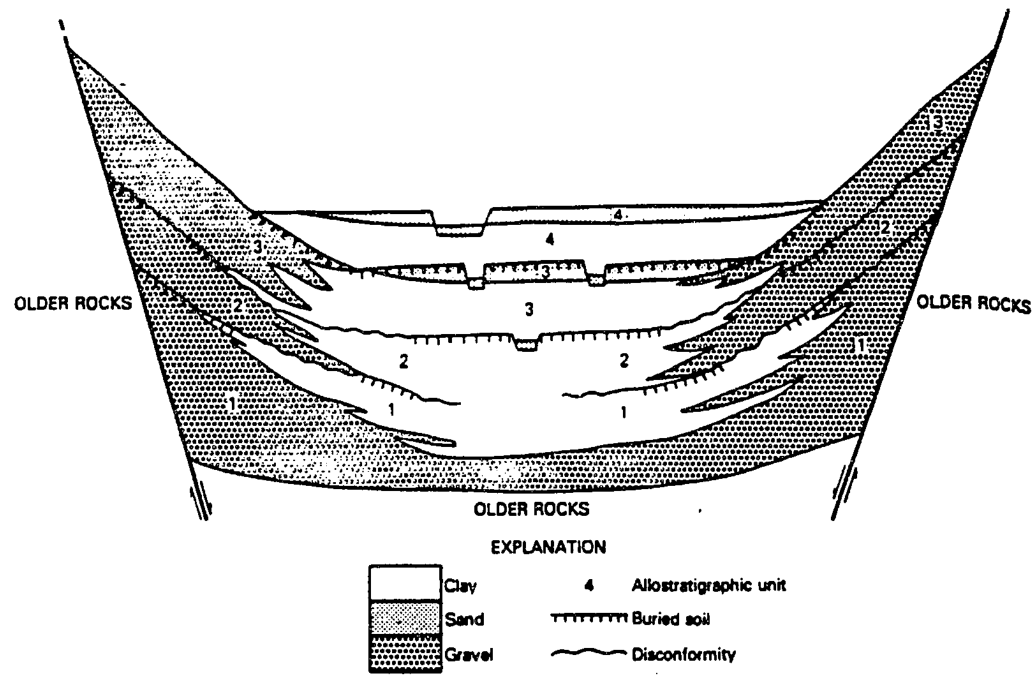

FIG. 7.--Example of allostratigraphic classification of alluvial and lacustrine deposits in a graben.

The alluvial and lacustrine deposits may be included in a single formation, or may be separated laterally into formations distinguished on the basis of contrasting texture (gravel, clay). Textural changes are abrupt and sharp, both vertically and laterally. The gravel deposits and clay deposits, respectively, are lithologically similar and thus cannot be distinguished as members of a formation. Four allostratigraphic units, each including two or three textural faces, may be defined on the basis of laterally traceable discontinuities (buried soils and disconformities).

(b) **Internal characteristics.**--Internal characteristics (physical, chemical, and paleontological) may very laterally and vertically throughout the unit.

(c) **Boundaries.**--Boundaries of allostratigraphic units are laterally traceable discontinuities (Figs. 7, 8, and 9).

(d) **Mappability.**--A formal allostratigraphic unit must be mappable at the scale practiced in the region where the unit is defined.

(e) **Type locality and extent.**--A type locality and type area must be designated; a composite stratotype or a type section and several reference sections are desirable. An allostratigraphic unit may be laterally contiguous with a formally defined lithostratigraphic unit; a vertical cut-off between such units is placed where the units meet.

(f) **Relation to genesis.**--Genetic interpretation is an inappropriate basis for defining an allostratigraphic unit. However, genetic interpretation may influence the choice of its boundaries.

(g) **Relation to geomorphic surfaces.**--A geomorphic surface may be used as a boundary of an allostratigraphic unit, but the unit should not be given the geographic name of the surface.

(h) **Relation to soils and paleosols.**--Soils and paleosols are composed of products of weathering and pedogenesis and differ in many respects from allostratigraphic units, which are depositional units (see "Pedostratigraphic Units," Article 55). The upper boundary of a surface or buried soil may be used as a boundary of an allostratigraphic unit.

(i) **Relation to inferred geologic history.**--Inferred geologic history is not used to define an allostratigraphic unit. However, well-documented geologic history may influence the choice of the unit's boundaries.

(j) **Relation to time concepts.**--Inferred time spans, however measured, are not used to define an allostratigraphic unit. However, age relationships may influence the choice of the unit's boundaries.

(k) **Extension of allostratigraphic units.**--An allostratigraphic unit is extended from its type area by tracing the boundary discontinuities or by tracing or matching the deposits between the discontinuities.

Ranks of Allostratigraphic Units

Article 59.--**Hierarchy.** The hierarchy of allostratigraphic units, in order of decreasing rank, is allogroup, alloformation, and allomember.

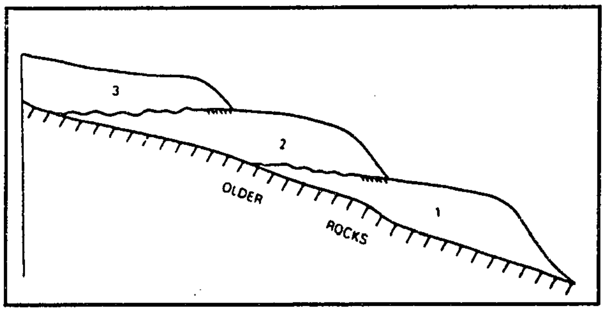

FIG. 8.--Example of allostratigraphic classification of contiguous deposits of similar lithology.

Allostratigraphic units 1, 2, and 3 are physical records of three glaciations. They are lithologically similar, reflecting derivation from the same bedrock, and constitute a single lithostratigraphic unit.

Remarks. (a) **Alloformation.**--The alloformation is the fundamental unit in allostratigraphic classification. An alloformation may be completely or only partly divided into allomembers, if some useful purpose is served, or it may have no allomembers.

(b) **Allomember.**--An allomember is the formal allostratigraphic unit next in rank below an alloformation.

(c) **Allogroup.**--An allogroup is the allostratigraphic unit next in rank above an alloformation. An allogroup is established only if a unit of that rank is essential to elucidation of geologic history. An allogroup may consist entirely of named alloformations or, alternatively, may contain one or more named alloformations which jointly do not comprise the entire allogroup.

(d) **Changes in rank.**--The principles and procedures for elevation and reduction in rank of formal allostratigraphic units are the same as those in Articles 19b, 19g and 28.

Allostratigraphic Nomenclature

Article 60.-**Nomenclature.** The principles and procedures for naming allostratigraphic units are the same as those for naming of lithostratigraphic units (see Articles 7,30).

Remarks. (a) **Revision.**-Allostratigraphic units may be revised or otherwise modified in accordance the recommendations in Articles 17 to 20.

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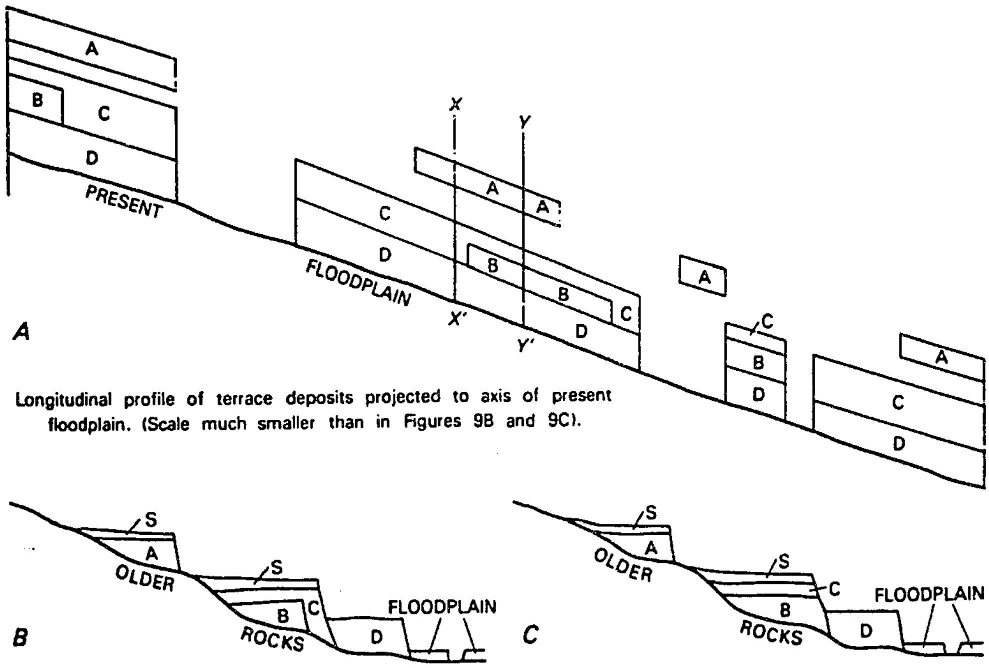

Longitudinal profile of terrace deposits projected to axis of present floodplain. (Scale much smaller than in Figures 9B and 9C).

Transverse lateral cross-section of valley wall at X-X' in Figure 9A.

Transverse lateral cross-section of valley wall at Y-Y' in figure 9A.

FIG. 9.-- Example of allostratigraphic classification of lithologically similar, discontinuous terrace deposits.

A, B, C, and D are terrace gravel units of similar lithology at different topographic positions on the valley wall. The deposits may be defined as separate formal allostratigraphic units if such units are useful and if the bounding discontinuities can be traced laterally. Terrace gravels are of the same age commonly separated geographically by exposures of older rocks. Where the bounding discontinuities cannot be traced continuously, they may be extended geographically on the basis of objective correlation of internal properties of the deposits other than lithology (e.g. fossil content, included tephras) topographic position, numerical ages, or relative-age criteria (e.g. soils or other weathering phenomena. The criteria for such extension should be documented. Slope deposits, and eolian deposits (S) that mantle terrace surfaces may be of diverse ages and are not included in a terrace-gravel dominated allostratigraphic units. A single terrace surface may be underlain by more than one allostratigraphic unit (units B and C in section b and c).

APPENDIX D

DRAFT OF PROPOSED ADDITION TO THE 1983 NORTH AMERICAN CODE OF STRATIGRAPHIC NOMENCLATURE (SEABER, 1992)

Nature and Boundaries

Article 98. -- **Nature of Hydrostratigraphic Units.** A hydrostratigraphic unit is a body of rock distinguished and characterized by its porosity and permeability. A hydrostratigraphic unit may occur in one or more lithostratigraphic, allostratigraphic, or lithodemic units and is unified and delimited on the basis of its hydrologic characteristics and interstices.

Remarks. (a) **Definition and recognition.** -- Hydrostratigraphic units are defined and recognized by observable characteristics of the interstices in any body of rock. they are defined by the number, size, shape, arrangement, and interconnection of the interstices, and recognized on the basis of the nature, extent, and magnitude of the interstices in any body of sedimentary, metamorphic, or igneous rock.

(b) **Purpose.** -- Hydrostratigraphic units are defined to distinguish bodies of rock that may be similar in other material categories on the basis of content or physical limits, but differ in the properties of their interstices. The primary observable rock characteristics of hydrostratigraphic units are their porosity, a rock property based on all rock openings, and permeability, a rock property based on the interconnection of the rock openings. Hydrostratigraphic units may be distinguished and recognized by hydrologic properties other than porosity and permeability, but porosity and permeability shall be the primary observable characteristics that define a hydrostratigraphic units. The interstices in hydrostratigraphic units are the result of the character, distribution, and structure of the rocks, that is, the geologic history of the region. An interstice is any intervening space between the solid rock material, including pores, fractures, and solution openings, or any space not occupied by solid rock material regardless of origin.

(c) **Type and reference localities.** -- The definition of a hydrostratigraphic unit should be based on as full a knowledge as possible of its lateral and vertical variations and its contact relations. For purposes of nomenclatural stability, a type locality and type area must be designated; a composite stratotype or a type section and several reference sections are desirable. The principles and procedures for designating stratotypes are those in Article 8, and Article 22 for lithostratigraphic units, Article 31 for lithodemic units, and Article 58 for allostratigraphic units. The exact relationship of hydrostratigraphic units to other rock material categories based on content and physical limits must be clear and unequivocal Reference to lithostratigraphic, lithodemic, or allostratigraphic units must be made where these units form the solid rock material containing the hydrostratigraphic units. Reference to magnetopolarity, biostratigraphic, and pedostratigraphic units may be made where a clear purpose is served.

(d) **Relation to lithostratigraphic, lithodemic, and allostratigraphic units.** -- Hydrostratigraphic units resemble other categories of units defined on the basis of content and physical limits. They are defined on the basis of objective recognizable properties, but differ fundamentally in that the properties are those of the interstices rather than of the solid rock material. Their boundaries may coincide with those of lithostratigraphic, lithodemic, or allostratigraphic units, or be parallel to but displaced from those of such units, may be crossed by them, or may be part of one or several of these units.

(e) **Independence from inferred geologic history.** -- Concepts based on inferred geologic history play no part in the definition of a hydrostratigraphic unit. Nevertheless, considerations of well-documented geologic history properly may influence the choice of vertical and lateral boundaries of a new unit. The Law of Superposition may or may not apply to hydrostratigraphic units. Hydrostratigraphic units generally conform to the Law of

Superposition where the rocks are lithostratigraphic units, and generally do not conform to the Law of Superposition where the rocks are lithodemic units.

(f) **Independence from lithic characteristics.** -- The nature of the interstices of the rock depend on the character and structure of the solid rock material. Concepts based solely on the lithic nature of the solid rock play no part in the definition of a hydrostratigraphic unit. Nevertheless, considerations of the lithic nature of the rock properly may influence the choice of vertical and lateral boundaries of a hydrostratigraphic unit A hydrostratigraphic unit may be contained within the limits of one lithic rock type, repetitions of two or more lithic types, or extreme lithic heterogeneity, but is fundamentally defined by the porosity and permeability of the rock, not its lithic content. Porosity and permeability may be distinctively represented by electrical, radioactive, seismic, or other properties, but these properties by themselves do not describe adequately the interstitial character of the unit. It is desirable that hydrostratigraphic units should, where, feasible, correspond to formational boundaries based on lithic characteristics, stratigraphic position when contained in lithostratigraphic units, or to lithodemes based on rock characteristics to facilitate an understanding of the geology of the region. Rarely will hydrostratigraphic units correspond to boundaries of allostratigraphic, biostratigraphic, magnetopolarity, or pedostratigraphic units.

(g) **Independence from time concepts.** -- Inferred time spans, however measured, are not used to: define a hydrostratigraphic unit. However, age relationships may influence the choice of the unit's boundaries.

(h) **Relation to genesis.** -- Genetic interpretation is an inappropriate basis for defining a hydrostratigraphic unit However, genetic interpretation may influence the choice of its boundaries.
Primary porosity and permeability, which are initial properties of the rock, and secondary porosity and permeability, which result from such phenomena as secondary solution or structurally controlled regional fracturing, properly play a significant role in influencing the choice of vertical and lateral boundaries of a hydrostratigraphic unit, and may aid in the recognition of similar hydrostratigraphic units far removed from the type locality.

(i) **Relation to geomorphic surfaces.** -- A geomorphic surface may be used as a boundary of a hydrostratigraphic unit. Erosional morphology or secondary surface form may be a factor in the recognition of a hydrostratigraphic unit, but should properly play only a minor role in its definition. Surface expression is a mapping aid for hydrostratigraphic units, as it is for lithostratigraphic, lithodemic, and allostratigraphic units.

(j) **Instrumentally defined units.** -- In subsurface investigations, as for lithostratigraphic units (see Article 22h), certain bodies of rock have their interstices interpreted from geophysical data. Where other considerations do not prevail, the boundaries of subsurface hydrostratigraphic units should be defined so as to correspond to useful geophysical markers; nevertheless, units defined exclusively on the basis of remotely sensed physical properties, although commonly useful in hydrogeologic analysis, stand completely apart from the hierarchy of formal hydrostratigraphic units and are considered informal.

(k) **Economically exploited units.** -- Some hydrostratigraphic units are, in general, informal units even though named. Some such units may be recognized formally because they are important in the elucidation of the regional geology, including structure, stratigraphy, geomorphology, and geologic history. Informal terms are appropriate for casually mentioned, innovative, and some economic units, those defined by unconventional criteria, including those used for ground-water flow modeling, and those that may be too thin to map at usual scales.

(l) **Relation to hydraulic flow system and fluid content.** -- Inferred flow systems and fluid content have no place in the definition of a hydrostratigraphic unit, which must be based on a body of rock defined by its porosity and permeability. Both flow systems and fluid content are ephemeral in a geologic sense. Confinement (artesian) or unconfinement (water table) have no place in the definition of a hydrostratigraphic unit Saturation or the type of fluid content play no role in the definition of hydrostratigraphic units. Whereas the flow system and fluid content relate to the present position of the unit and do not directly affect the rock properties, they are extremely useful in aiding recognition of similar hydrostratigraphic units. It is advisable where other factors do not countervail, to define hydrostratigraphic boundaries so as to coincide with hydrologic changes evidenced by mappable flow systems. However, saturation or nonsaturation, as well as the nature and chemistry of the enclosed fluids shall not play a part in the definition of a hydrostratigraphic unit. Such units, if defined on these bases, are economic units and informal.

(m) **Nature of porosity and permeability.** -- The porosity of a rock is its property of containing interstices and may be expressed quantitatively as the ratio of the volume of its interstices to the total volume of solid rock or the percentage of rock that is not occupied by solid rock material. With respect to the movement of fluids, only the system of interconnected interstices is significant and is termed effective porosity. Intrinsic permeability is a measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is a property of the medium alone and is independent of the nature of the liquid and of the force field causing movement Intrinsic permeability is measured in units of length squared. Intrinsic permeability and porosity are the preferred units used for the definition of hydrostratigraphic units. Definitions must be based on descriptions and measurements of actual rock materials.

(n) **Internal characteristics.** -- A hydrostratigraphic unit should possess some degree of internal homogeneity in porosity and permeability, and, if possible, some degree of distinctive lithic features.

(o) **Mappability and thickness.** -- Practicability of surface and subsurface mapping is an essential characteristic of a hydrostratigraphic unit (see Article 24d). A formal hydrostratigraphic unit must be mappable at the scale practiced in the region where the unit is defined. Regional validity must be demonstrated for all such units. Thickness is not a determining parameter in dividing a rock succession into hydrostratigraphic units. Some thin units, however, or those of only local significance, may be informal and termed water-bearing zones.

Article 99. -- **Boundaries.** Boundaries of hydrostratigraphic units are placed at positions of change of the porosity and permeability. Boundaries are placed at distinct contacts or may be fixed arbitrarily within zones of gradation. Both vertical and lateral boundaries are based on the changes in porosity and permeability that provide the greatest unity and practical utility.

Remarks. (a) **Relation to boundaries of other stratigraphic units.** -- When the rocks are of a lithostratigraphic nature, the same principles and procedures as stated in Articles 10 and 23 should be followed. When the rocks are of a lithodemic nature the same principles and procedures as stated in Article 32 should be followed. Boundaries of hydrostratigraphic units may have little or no relation to boundaries of magnetopolarity, biostratigraphic, pedostratigraphic, or allostratigraphic units.

(b) **Boundaries within gradational zones.** -- Where a hydrostratigraphic unit changes through gradation into, or intertongues with, a rock mass with marked different porosity and permeability it is usually desirable to propose a new unit. It may be necessary to draw an arbitrary boundary within the zone of gradation. When the area of intergradation or intertonguing is sufficiently extensive, the rocks of mixed character may constitute a third unit

(c) **Boundaries based on regional flow systems.** -- Flow systems, while useful in determining the boundaries of hydrostratigraphic units, in themselves play no proper part in determining the boundaries of hydrostratigraphic units.

(d) **Extension of hydrostratigraphic units.** -- A hydrostratigraphic unit may be extended from its type area by tracing the bounding discontinuities of porosity and permeability and defining the porosity and permeability between such discontinuities. Water level and other hydrologic information, as well as geophysical, geochemical, and geologic data may be utilized for this purpose.

Ranks of Hydrostratigraphic Units

Article 100. -- **Hierarchy.** The hierarchy of hydrostratigraphic units, in order of decreasing rank, is aquigroup, aquiformation, aquimember, and aquibed.

Remarks (a) **Aquiformation.** -- The aquiformation is the fundamental unit of hydrostratigraphic classification. It may be an aquifer, aquitard, or aquifuge. An aquiformation may be completely divided or partly divided into aquimembers, if some useful purpose is served, or it may have no aquimembers.

(b) **Aquimember.** -- An aquimember is the formal hydrostratigraphic unit next in rank below an aquiformation. It may be an aquifer, aquitard, or aquifuge.

(c) **Aquibed.** -- An aquibed is the smallest formal hydrostratigraphic unit. The designation of an aquibed as a formally named hydrostratigraphic unit generally should be limited to certain distinctive beds whose recognition is particularly useful and of more than local economic significance.

(d) **Aquigroup.** -- An aquigroup is the hydrostratigraphic unit next in rank above an aquiformation. It may consist of any combination of aquifers, aquitards, or aquifuges. An aquigroup may be established if it is essential to elucidation of the hydrogeology of a large regional ground-water body. An aquigroup may consist entirely of named aquiformations or, alternatively, need not be composed entirely of named aquiformations. Aquigroups are defined to express the natural relationships of associated aquiformations. The aquiformations making up the aquigroup need not necessarily be everywhere the same.

(e) **Changes in rank.** -- The principles and procedures for revision and abandonment of formal hydrostratigraphic units are the same as those in Articles 17, 18, 19 and 20.

Hydrostratigraphic Nomenclature

Article 101. -- **Nomenclature.** The principles and procedures for naming hydrostratigraphic units the same as those in Article 7 and for naming lithostratigraphic units in Article 30 and lithodemic units in Article 39. For most categories, the name of the unit should consist of a geographic name combined
with an appropriate rank or descriptive term with the descriptive term preferred.

Remarks (a) **Unit Description.** -- The principles and procedures for unit description are the same as those in Article 9.

(b) **Use of simple ground-water terms.** -- The ground-water part of the term should indicate the predominant or diagnostic interstitial space characteristic, even if subordinate interstices are included, An aquifer is a porous and permeable geologic unit that can transmit significant quantities of fluid under ordinary hydraulic gradients. An aquitard is a permeable and porous geologic unit that is incapable of transmitting significant quantities of fluid under ordinary hydraulic gradients. An aquifuge is a nonpermeable and nonporous geologic unit that, for all practical purposes, contains no interconnected openings or interstices, and, therefore, neither absorbs nor transmits water. The above three terms are equivalent to the compound part of the name used as descriptive lithic terms is for lithostratigraphic nomenclature (See Article 30) and for lithodemic nomenclature (See Article 40). The definitions of aquifer, aquitard, and aquifuge are purposely imprecise with respect to porosity and permeability so that the terms may be used in a relative sense. The use of aquifer, aquitard, and aquifuge is preferred over the rank term.

(c) **Compound character.** -- The formal name of a hydrostratigraphic unit is compound and follows the principles used in Article 7 and for lithostratigraphic units in Article 30 and lithodemic units in Article 40. It consists of a geographic term combined with a descriptive ground-water term (,see b) or with the appropriate rank term, or both. Initial letters of all words used in forming the names of formal hydrostratigraphic units are capitalized.

(d) **Informal usage of identical geologic names.** -- The application of identical geologic names, whether based on content, physical limits, geologic age, topographic position, or other similar terms is considered informal and is discouraged. Informal units should not be capitalized. The use of formation names, or any formal stratigraphic name, and geologic age terms to designate hydrostratigraphic units is considered informal and is discouraged.

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