A PRELIMINARY EVALUATION OF GROUND WATER IN UPPER DRY VALLEY AND LITTLE LONG VALLEY CARIBOU COUNTY, IDAHO

By Kenneth Albert Sylvester

Prepared in cooperation with the Surface Environment and Mining Division of the U. S. Forest Service.

Idaho Bureau of Mines and Geology
Acting Director John G. Bond
Moscow, Idaho

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BIOGRAPHICAL SKETCH OF THE AUTHOR

Kenneth A. Sylvester was born in Bangor, Maine on August 22, 1949. In 1954 he moved with his family to Phoenix, Maryland, where he attended public schools. In September of 1967 he enrolled in the College of Engineering at the University of Maryland. He received his Bachelor of Science degree in Geology there in June of 1971.

In September of 1973, after two years of working for the U. S. Geological Survey, he enrolled in the Graduate School at the University of Idaho. In February of 1975 he completed the requirements for a Master of Science degree in Hydrology, of which this thesis is a part.
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This report is a slightly condensed version of a more detailed report (Sylvester, 1975) that was prepared as a master's thesis for the University of Idaho.
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Ground water occurs in valley fill and bedrock flow systems in Upper Dry Valley and Little Long Valley, Caribou County, Idaho. The bedrock flow systems develop in consolidated sedimentary rocks as the result of fractures and solution openings in the rock units. The valley fill flow systems occur wherever alluvial and colluvial materials are thick enough to have aquifers within them. Faults displace the hydrogeologic units and create recharge and discharge areas where they might not otherwise be expected.

The hydrogeologic study in the Dry Valley-Little Long Valley area utilized existing geologic data with the aid of remote sensing and field reconnaissance. Oblique color and infrared aerial photography was particularly useful in delineating geologic control on ground water movement. Data from test drilling were used to substantiate the results of surface studies. Theoretical models were used to develop ground-water flow systems.

Little Long Valley is characterized by a relatively large ground-water flow system on the east ridge and by a smaller ground-water flow system on the west ridge. Preliminary interpretations of hydrogeologic data suggest that planned surface mines along the west ridge of the valley would not intercept the major ground-water flow system. Upper Dry Valley is characterized by an extensive alluvial-colluvial valley fill. Aquifer tests show higher hydraulic conductivities in this material than in bedrock aquifers in Little Long Valley. If surface mines are planned in the valley fill material, some dewatering might be necessary.
INTRODUCTION

Ground water is becoming increasingly important to the development of the phosphate mining area of southeastern Idaho. New deposits of phosphate rock are being developed to replace the mined out deposits and to supply increasing demands for fertilizer and other phosphate products. Many of these new areas are in less favorable locations with respect to ground water than the old areas. New, deeper open pit mining operations, both on the ridges and in the valleys probably will encounter ground-water problems more frequently than the shallower operations that have been largely confined to the ridges. It is necessary to have an understanding of the ground-water flow systems and the hydrogeology of those areas in order to deal effectively with the ground-water problems, and to plan for the impact of mining activities on the total water resource system.

Dry Valley and Little Long Valley in Caribou County, Idaho are two areas within the phosphate region that have experienced mining activity in the past. More mining activity is planned for the future. The valleys represent two different types of geologic and hydrologic conditions that are representative, in many respects, of the conditions in other valleys in the phosphate region.

Phosphate mining was first recorded in southeastern Idaho in 1906 (Service, 1966, p. 3). Since that time many reports have been written that deal with various phases of the geology and mining. However, the hydrogeology and the water resources of the area have not been analyzed in detail. Until recently ground water has not been considered unless problems occurred with mining activity. Now, with stricter environmental controls, increased government regulation, and larger
mining operations, there is a need to understand the ground-water resources.
PURPOSE, OBJECTIVES, AND METHOD OF STUDY

The purpose of this study is to provide ground-water information that can be used in land use planning and in the planning of mining operations. The general objectives of this study are to provide hydrogeologic data and results from an integrated analysis of two ground-water systems in the phosphate mining area of southeastern Idaho. This will be done by first reviewing the geology and the geography of the phosphate region. Such a review is necessary to define regional geologic and climatic characteristics. Next, the stratigraphy, structure, and topography of Dry Valley and Little Long Valley will be reviewed in detail. This will be used to define geologic controls on ground-water movement within the two valleys. Lastly, a hydrogeologic framework, with recharge-discharge areas and hydraulic properties of the aquifers, will be proposed. This will be followed by conclusions for this portion of the study.

The specific objectives of this study are to:

1) Compare Dry Valley and Little Long Valley to other basins in the area, with respect to the geography, geology, and hydrology.

2) Show how infrared and color oblique aerial photography can be used with geophysical data and drill hole information, in a hydrogeologic reconnaissance.

3) Describe ground-water flow systems in portions of the two valleys, with particular emphasis on recharge-discharge areas and aquifer units.
About two months were spent in the field during the summer of 1974. Part of this time was spent monitoring mine drilling programs and collecting mining company geologic data. A project drilling program was initiated and several piezometer tubes were installed to monitor water level measurements. Four aquifer tests were carried out on two different aquifers and analyzed. Finally, color infrared and color oblique aerial photographs were taken of Dry Valley and Little Long Valley.
LOCATION AND EXTENT OF THE AREA

Dry Valley and Little Long Valley are in the eastern part of Caribou County, Idaho (Fig. 1). The area covered by these two valleys is about 45 square miles (117 sq. km.). Of this, 42 square miles (109 sq. km.) are in Dry Valley and 3 square miles (8 sq. km.) are in Little Long Valley. Both areas are located in Townships 6 S, 7 S, 8 S, and 9 S, and Ranges 43 E, 44 E, and 45 E, with reference to the Boise Base Line and Meridian.

Dry Valley is bounded on the west by Slug Creek valley and on the east by Diamond Creek valley. Little Long Valley is bounded on the west by Wooley Valley and on the east by Rasmussen Valley. The low-lying lands in all of these valleys are bordered by ridges of the Preuss, Webster, Grays, and Wooley ranges. These ridges serve as geographic divides, but not necessarily as surface water or ground-water divides, between the valleys.

The portions of Dry Valley and Little Long Valley that are in Caribou National Forest are part of the U. S. Forest Service phosphate planning unit. The Dry Valley-Little Long Valley area, as referenced throughout this report, includes Dry Valley, Little Long Valley, Rasmussen Valley, Slug Creek valley and Diamond Creek valley.
Figure 1. Location map of Dry Valley and Little Long Valley, Caribou County, Idaho.
PREVIOUS INVESTIGATIONS

Many geologic and mining reports, both published and unpublished, have been written on the phosphate mining area of southeastern Idaho. The most comprehensive report on the entire region was that of Mansfield (1927). He covered many aspects of the geography and geology of the area and included a short, descriptive section on the water resources. More detailed geologic mapping has been done by Cressman and Gulbranssen (1955), Gulbranssen and others (1956), Cressman (1964), and Montgomery and Cheney (1967). Special interests, such as the search for commercial deposits of phosphates, have led to many detailed reports on various phases of the geology of the area. A summary of many of these reports is contained in the Fifteenth Annual Field Conference Guidebook of the Intermountain Association of Geologists (1967). Service (1966) gives a summary of the Idaho phosphate mining activities.

Detailed geologic and geophysical work has been done in both Dry Valley and Little Long Valley. Much of the detailed geologic and geophysical work is mining company data and is kept confidential. Mining company leases change hands fairly often. Since exploration data is not always transferred with the lease, data for a particular area might be held by several different companies. Mining companies with current exploration programs or mining activity in Dry Valley and Little Long Valley include Washington Construction Company, International Minerals and Chemical, PNC Corporation, and Triangle Mining Company. Seismic investigations were performed in Dry Valley by Cooksley (1962, 1967) and by Olsen (1974).

The ground-water hydrology of the area has not been studied in
much detail. General hydrogeologic descriptions of the area have been made by Stearns and others (1938) and Mundorff and others (1964). More detailed hydrologic studies have been done in adjacent areas. Those by Walker (1965) in the Upper Star Valley and Dion (1969) in the Bear River Basin are useful for regional considerations. Summaries and inventories of the water resources in the area can be found in the Inventory of the Water Resources in Idaho (Water Resources Research Institute, 1968) and in Water Resources, (Pacific Northwest River Basins Commission, 1969).

A rough draft of a hydrologic report on the U. S. Forest Service phosphate planning unit was prepared by Kelly (1974). A detailed summary of the water balance for various land types was presented in his report. Other environmental analyses and land use reports have also been completed by the U. S. Forest Service (1974 a and 1974 b).
WELL NUMBERING SYSTEM

The well numbering system used in this report is the same as that used by the U. S. Geological Survey in Idaho (Fig. 2). It gives the location of the wells within the official rectangular subdivisions of public lands, with reference to the Boise Base Line and Meridian. The first two segments of the number indicate the township and range. The third part of the number gives the section, and this is followed by two letters and a numeral. The two letters indicate the quarter section and the forty acre tract, respectively. They are lettered a, b, c, and d in counter clockwise order from the northeast corner. The final number is the serial number and indicates the order in which the wells were visited within the tract.

As an example of how the well numbering system works, the Last Chance stock well in Upper Dry Valley is numbered 9S-44E-13db1. This could be described as occurring in the NW ¼ of the SE ¼ of Section 13 of Township 9 S, Range 44 E. It was the first well designated within that tract (Fig. 2).

For this investigation several piezometer tubes have been installed to monitor water levels. These piezometers are numbered by the same system as wells. However, mining company drill holes that do not have piezometers are referred to by the mining company numbering systems.
Figure 2. Well numbering system.
The Dry Valley-Little Long Valley area has distinct geographic, geologic, and hydrologic features. The topographic, drainage, vegetative, and cultural patterns have similar characteristics throughout the area. The geologic history of the Dry Valley-Little Long Valley area includes several depositional and erosional periods. The area was involved in a major orogenic phase and also in more recent faulting. The climatic features of the Dry Valley-Little Long Valley area are dominated by three distinct periods of precipitation. Storms in the winter months leave relatively heavy accumulations of snow on the area. Rain and melting snow combine to produce a high spring runoff. Rains during the summer months are infrequent and widely scattered over the area.

Geographic Features

Dry Valley and Little Long Valley are in the western part of the Middle Rocky Mountain physiographic province. The mountains in this area are part of several north and northwest trending ranges of the Idaho-Wyoming chain. They have been named the Peale Mountains (Mansfield, 1927, p. 24). These mountains were involved in the folding and thrust faulting of the Laramide orogeny, but their present relief is due to normal faulting in more recent times. This means that the mountains in this area have characteristics of both the Rocky Mountain, and the Basin and Range, physiographic provinces.

The major subdivisions within the Dry Valley-Little Long Valley area are Preuss Range, Webster Range, Grays Range, and Wooley Range.
(Fig. 3). The Preuss and Webster ranges are separated from the Grays and Wooley ranges by the Blackfoot River. Preuss Range can be subdivided into its three northern extensions, Aspen Range, Schmid Ridge, and Dry Ridge.

The topography in the Dry Valley-Little Long Valley area is dominated by the mountainous ridges and the relatively flat valley floors. Elevations range from 6300 feet (1920 m) above sea level along the Blackfoot River Valley to over 9000 feet (2743 m) above sea level along some of the higher peaks. Local relief variations are between 600 and 2000 feet (183 and 610 m).

The Dry Valley-Little Long Valley area is drained by the Blackfoot River, which is part of the Columbia-Snake river system. The Columbia-Great Basin drainage divide is on the southwest edge of the area (Fig. 3). Major tributary streams to the Blackfoot River generally follow the northwest structural trends. Diamond Creek, Lanes Creek, Angus Creek, and Slug Creek are major tributary streams in the area (Fig. 3).

Vegetation patterns in the Dry Valley-Little Long Valley area vary according to elevation, exposure, and soil conditions. Mountain brush and sagebrush vegetative types, which are characteristic of the Great Basin area, occur in many of the valleys. This type of vegetative cover intergrades with the conifer-aspen type forests that are characteristic of the Northern Rocky Mountains (U. S. Forest Service, 1974 a, Vegetation). Southwest exposures on the northwest trending ridges are subjected to the direct radiation of the afternoon sun and the drying influences of the southwest winds. Therefore, they are
Figure 3. Geographic features in the Dry Valley–Little Long Valley area.
usually much dryer than the corresponding northeast exposures. Southwest exposures are often covered with sagebrush-grass or mountain brush vegetation, while northeast exposures are typically timbered with conifers and quaking aspen (U. S. Forest Service, 1974 a, Vegetation).

Cultural features in the Dry Valley-Little Long Valley area are dominated by the phosphate mines and the Caribou National Forest (Fig. 3). The region is sparsely populated, with only a few yearlong residents. A large demographic shift occurs during the summer months. During this time, increased mining, grazing, and recreational activities bring a relatively large number of people temporarily into the area. These people often have temporary living quarters that are scattered widely throughout the valleys.

Soda Springs, Idaho is the major population center closest to the Dry Valley-Little Long Valley area. It is located about 15 miles (24 km) southwest of the area. Soda Springs has a 1970 population of about 3000 people and is served by the Union Pacific Railroad and by U. S. Route 30 and Idaho Route 34. Railroad spurs extend into Dry Valley and Wooley Valley. These lines are utilized mainly for hauling phosphate ore from the mines to the processing plants.

Roads in the Dry Valley-Little Long Valley area are mainly loose surface all-weather roads and dirt, dry-weather roads. Many of these roads provide access to the mining company plants and to the mining operations. Other roads provide access to parts of the Caribou National Forest. Roads are sometimes abandoned or relocated, as mining or grazing activity shifts from one part of the area to another.

Large, open pit mining operations and the resulting waste piles, ore piles and disturbed areas are significant features of the landscape.
The land surface is altered throughout a mining operation and the topography is usually changed permanently after mining activity ceases. The subsurface layers are also disturbed. Exploration programs leave trenches, drill holes, drill pads, and roads.

Grazing activities in the Dry Valley-Little Long Valley area are confined mostly to the summer months. Pasture land in the higher elevation valleys, which are largely on National Forest land, is used for both sheep and cattle. Lower elevation valleys have some permanent ranches, most of which raise cattle. Grazing activities create the need for roads and stock wells, and cause altered vegetation patterns, all of which have some effect on the land.

Geologic Setting

The geologic material in the Dry Valley-Little Long Valley area is of two different age groups that are separated by a major orogenic phase (Fig. 4). The consolidated sedimentary rocks consist of limestone, shale, sandstone, and siltstone that are Paleozoic and Mesozoic in age. These are overlain unconformably by alluvial and colluvial valley fill material that is Tertiary and Quaternary in age. The younger deposits are largely unconsolidated and consist of varying thicknesses of gravel, sand, silt, and clay. Recent alluvium, colluvium, and alluvial fans are still being deposited.

The Dry Valley-Little Long Valley area was the site of geosynclinal deposition from the Cambrian through the Jurassic (Cressman, 1964, p. 85). The stratigraphic record is dominantly marine and thus indicates progressive subsidence of the sediments. Numerous strati-
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Figure 4. Generalized geologic history of the Dry Valley – Little Long Valley area.
graphic breaks and variations in the character of the sediments show
that there were interruptions in the deposition and also erosion (Mans-
field, 1927, p. 173).

Environments of deposition for the various stratigraphic units
were variable throughout the subsidence (Fig. 4). These have been
described in Mansfield (1927, p. 173-206), McKelvey and others (1959,
p. 23-27), and Cressman (1964, p. 85-90), and will only be highlighted
here. Some units, such as the Madison Limestone, were deposited in
tranquil water. This is evidenced by dark color, fine grain size, and
thin, even bedding. Abundant, light colored crinoidal limestone, and
well-sorted, fine-grained sandstone suggests an above wave base, inner
sublittoral environment of deposition for the overlying Brazer Lime-
stone (Cressman, 1964, p. 86). The Meade Peak Phosphatic Shale Member
of the Phosphoria Formation was deposited below wave base in a bathyal
marine environment (Cressman, 1964, p. 87). The Rex Chert Member of
the Phosphoria Formation resulted from the accumulation of siliceous
skeletal remains and the partial diagenetic reorganization of the silica
(Mckelvey and others, 1959, p. 27). This deposition probably took
place in a sublittoral environment. The Triassic and Jurassic rocks
in this area indicate both marine regressions and transgressions occu-
red. Sedimentation varied from deep water, shelf deposits of shale to
subaerial and shallow water, lagoonal deposits.

The depositional environment in the Dry Valley-Little Long Valley
area ended sometime in the late Mesozoic (Fig. 4). At that time, rocks
of post-Devonian age, east of the area, were thrust over the newly
deposited Jurassic rocks. During this orogenic phase the beds of the
upper plate were folded and faulted. This Laramide orogeny was of considerable duration and involved several thrust complexes. The Meade (Bannock) thrust and its associated faults and folds was the major crustal dislocation in the Dry Valley-Little Long Valley area (Eardley, 1967, p. 37).

A period of erosion followed the Laramide orogeny. This led to the deposition of a red Eocene conglomerate across the area (Cressman, 1964, p. 89). In middle and late Tertiary time, a period of normal faulting and warping produced the present basins and ranges in the Dry Valley-Little Long Valley area. These crustal movements interrupted the drainage and caused lakes to be formed. This led to the deposition of the Salt Lake Formation (Cressman, 1964, p. 89). Quaternary deposition in the area consisted of pediment gravels, terrace gravels, and alluvial fans. This material was derived from both the erosion of the mountain ranges, and of the Salt Lake Formation. Periods of normal faulting continued throughout the Quaternary (Cressman, 1964, p. 82). Recent deposits consist of alluvium, alluvial fans, and colluvium.

Climate and Hydrology

The Dry Valley-Little Long Valley area receives climatic influences from both the Pacific Ocean and the continental interior. Summers generally have warm days and cool nights. They are generally dry, with some convectional rain showers. Winters are generally cold with large amounts of snow. Spring and fall usually have transitional climates. They can reflect either the dominant winter or summer climate, or be a combination of both.
Long term climatic records are available for Conda, Idaho. Its elevation, 6200 feet (1890 m), and its proximity to the Dry Valley-Little Long Valley area make it fairly representative of conditions throughout the area. Kelly (1974) used the records at Conda to calculate the temperature and evapotranspiration for the Forest Service planning unit. Figure 5 gives long term averages of temperature and precipitation at Conda. This illustrates the climatic pattern that can be expected in the Dry Valley-Little Long Valley area.

Moisture producing air masses usually come into the Dry Valley-Little Long Valley area from the south or southwest. This is determined by upper air movements at the 850 millibar pressure surface (Lahey, 1973, p. 43). Surface winds are caused by a variety of factors and may or may not reflect the upper air movement.

Precipitation results when air masses are lifted and cooled below their dew point. This lifting can take place by three different mechanisms. Cyclonic storms result in frontal lifting with a warm air mass being lifted over a cooler air mass. Orographic lifting occurs when air is forced to rise over a mountain range. Convective lifting occurs when warm air is lifted through cooler air by convective processes. In the Dry Valley-Little Long Valley area orographic lifting often takes place simultaneously with convective or frontal lifting. This results in higher precipitation on the mountainous areas than on the adjacent valley floors.

Precipitation varies widely in the Dry Valley-Little Long Valley area. It ranges from less than 20 inches (51 cm) annually along the Blackfoot River and lower Slug Creek valleys to over 35 inches (89 cm)
Figure 5. Climatic regime for Conda, Idaho
20 years of record, elevation 6200 ft (1890 m).
annually at the south end of Dry Ridge (Water Resources Research Institute, 1968, M6). These records were based on an isohyetal analysis prepared by the U. S. Weather Bureau River Forecast Center, that used adjusted climatological data (1930-1957), and values derived by correlation with physiographic features (Water Resources Research Institute, 1968, p. 23).

Winter and late fall climates in southeastern Idaho are dominated by cold, dry continental air and by cyclonic storms that pass through periodically. Mean temperatures at Conda are below freezing from November through March. Precipitation averages 8.3 inches (21.0 cm) during that same time period. These conditions result in relatively heavy snowfalls. Total seasonal amounts of snowfall average over 100 inches (254 cm) in Conda. Snow packs tend to build up on the mountainous ridges more than in the valleys in much of the Dry Valley-Little Long Valley area. The snow pack on Slug Creek divide, at an elevation of 7225 feet (2202 m), increases in both depth and water content throughout the winter. It reaches an average depth of 48 inches (122 cm) and an average water content of 16 inches (41 cm) by the end of the winter (Pacific Northwest Basins Commission, Meteorology Committee, 1969, p. 247). West and southwest surface winds cause the snow to drift and accumulate on the northeast (lee) side of the ridges. These drifts have been reported to be nearly three miles (4.8 km) long and thirty feet (9 m) deep in Little Long Valley (U. S. Forest Service, 1974 b, p. 16).

Spring climates in the Dry Valley-Little Long Valley area are usually dominated by a low pressure area to the south. Precipitation results from this system, when cool marine air flows above an unstable
surface layer, and convective lifting occurs (Lahey, 1973, p. 45). This precipitation, which is heaviest in May, and the melting winter snow packs combine to cause high spring runoff and ground-water recharge potential.

Summer climates in the Dry Valley-Little Long Valley area are dominated by continental air masses. Precipitation is at a distinct minimum during July and August (Fig. 5). During this time, moisture is brought into the area by high level winds from the south. This causes some thundershower activity. The showers are usually isolated and can soak one area while leaving a nearby area completely dry. Thunderstorm activity is influenced by orographic lifting, but the resulting rainfall differences are not as significant as they are with cyclonic storms (Pacific Northwest Basins Commission, 1969, p. 352). Intense rainfall can be associated with the convectional storms but it is usually limited in areal extent. The runoff and ground-water recharge that results from these storms is, therefore, largely local. Temperatures during the summer have 38° F (21°C) of diurnal variation.

Potential evapotranspiration estimates were calculated by Kelly (1974, Climate). He estimated that potential evapotranspiration in the Forest Service Planning Unit ranged from 14 to 17 inches (36 to 43 cm) annually. On a monthly basis these estimates showed highest potential evapotranspiration in July and August, and no potential evapotranspiration through the winter months. In all cases, annual precipitation exceeded annual potential evapotranspiration.

Water yield is calculated by adjusting the records of annual runoff per unit area for altitude differences (Rosa, 1968). It is only a
rough estimate of excess water for an area, and it does not take into account many local variations in topography, plant cover, soil, and precipitation. It also does not take ground-water flow into consideration. Nevertheless, water yield estimates for various land types in the Dry Valley-Little Long Valley area range from 5 inches (13 cm) to 20 inches (51 cm) annually (Rosa, 1968). The higher water yield areas are generally at higher elevations while the lower water yield areas are at lower elevations. Kelly (1974, Hydrology) estimated the percentage of precipitation that appears as runoff to range from a low of 25 percent on nontimbered toeslopes to a high of 60 percent on high elevation ridgeland.

An active streamflow station is located on the Blackfoot River just south of Henry, Idaho. Here, seventeen years of records indicate an average annual runoff volume of 187,000 acre-feet (Robertson, 1967, p. 1-3). The annual runoff from Angus Creek is about 4200 acre-feet (U. S. Forest Service, 1974 b, p. 23). This means that Angus Creek contributes approximately 2.2 percent of the annual streamflow volume to the Blackfoot River at Henry. This does not take into account subsurface flow.

Presently, there are no permanent stream gaging stations located in the Dry Valley-Little Long Valley area. However, several miscellaneous streamflow measurements have been made on both Angus Creek and Dry Valley Creek (Decker and others, 1970, p. 89, 90). The Angus Creek records show that the peak flow usually occurs in early May. The flow volume drops considerably on the day after the peak flow. The Dry Valley Creek records show that Maybe Creek loses water after it
flows out of Maybe Canyon. Maybe Creek is the principal tributary to Dry Valley Creek.
GROUND-WATER GEOLOGY

The stratigraphic, structural, and surficial geology of Dry Valley and Little Long Valley have been reported on by many investigators. However, these reports have been mainly concerned with either the search for phosphate or with regional geologic interpretations. For the purposes of this investigation the geology is important in that it governs the occurrence and distribution of ground water. Therefore, the geology will be dealt with in a hydrogeological perspective. Lithologic, structural, and surficial features will be used to define hydrogeologic units that contain and transmit water similarly.

The capacity of a material to contain water is measured by its porosity. Primary porosity is developed during the formation of a sedimentary rock, while secondary porosity is developed later, by geologic processes acting on the rock. In unconsolidated material, the porosity depends on the packing of the grains, their shape, arrangement, and size distribution (Davis and DeWiest, 1966, p. 160). In consolidated material the porosity depends largely upon the degree of cementation, the state of solution, and the amount of fracturing in the rock.

The permeability of a rock unit is its capacity for transmitting a fluid. This depends largely upon the size and shape of the pores and their interconnections. In consolidated sedimentary rocks, the permeability normal to the bedding is often less than the permeability along the bedding. This is because stratification produces some anisotropy in the vertical direction as compared with the horizontal direction (Davis and DeWiest, 1966, p. 365). In nonindurated sediments the
permeabilities are closer to being equal.

The permeability and porosity of the various geologic formations can be used to classify them as hydrogeologic units. Some geologic units contain and transmit ground water. These are called aquifers. Other geologic units may contain water, but do not transmit significant amounts. These are known as aquicludes. A geologic unit which neither transmits nor stores water is known as an aquifuge.

Lithology

The geologic material in Dry Valley and Little Long Valley is all sedimentary. A sediment is a deposit of solid material on the earth's surface from any medium (air, water, ice) under normal temperatures and pressures. A sedimentary rock is the consolidated or lithified equivalent of a sediment (Krumbein and Sloss, 1963, p. 93). Sediments can have both a detrital fraction and a chemical fraction. Detrital fractions, such as sand and mud, are brought to the site of deposition from a source area, while chemical fractions such as calcite and gypsum are formed at the site of accumulation.

Sediments in Dry Valley and Little Long Valley are in various stages of induration or hardness. They range from fully lithified rocks, such as limestone and sandstone, to loose, unconsolidated deposits such as sand and gravel. A general hydrogeologic breakdown can be achieved by considering indurated and nonindurated sediments as two different types of material (Fig. 6). In this area, rocks deposited before the Laramide orogeny are generally indurated, while those that were deposited after are generally nonindurated. The unconsolidated
<table>
<thead>
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<th>Sedimentary Material</th>
<th>Porosity$^{(0)}$</th>
<th>Permeability</th>
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</thead>
<tbody>
<tr>
<td>Consolidated rocks</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 - 10%</td>
<td>low</td>
</tr>
<tr>
<td>Fine-grained clastic rocks (siltstone, shale)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse-grained clastic rocks (arkose, sandstone)</td>
<td>10 - 20%</td>
<td>low to high</td>
</tr>
<tr>
<td>Chemical precipitates (limestone, chert)</td>
<td>1 - 10%</td>
<td>low to high</td>
</tr>
<tr>
<td>Gravel</td>
<td>30 - 40%</td>
<td>high</td>
</tr>
<tr>
<td>Nonindurated sediments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>30 - 40%</td>
<td>high</td>
</tr>
<tr>
<td>Clay</td>
<td>45 - 55%</td>
<td>low</td>
</tr>
</tbody>
</table>

Figure 6. Hydrogeologic classification of sedimentary lithologies.

($^{(1)}$ Todd, 1959, p. 16)
material usually lies above the older consolidated rocks with profound unconformity.

Nonindurated sediments can be classified, for hydrogeological purposes, into gravels, sands, and clays (Fig. 6). This is primarily a size classification, but many variables can affect the way they contain and transmit water. Size distribution, incipient cementation, packing, and shape should all be considered when analyzing nonindurated sediments. If a mixture is poorly sorted (small grains in the voids of larger grains) it will have a lower permeability than a well sorted one. If the nonindurated sediment has a cementing material present, such as clay, it will also be rendered less permeable. Packing, as affected by the mode of deposition and the depth of burial, can alter the water-bearing properties of nonindurated sediments. Intergranular movements in deeply buried, fine-grained sediments can cause a pore reduction (Davis and DeWiest, 1966, p. 376). The shape of the sediments alters their permeability. Angular particles are held apart by irregular corners and are consequently more permeable than rounded particles of similar size.

Gravels have porosities of 30 to 40 percent (Todd, 1959, p. 15), and have high permeabilities. This is because of relatively large intergranular spaces. Gravels are generally good aquifers. Sand also has a porosity of 30 to 40 percent, but has slightly lower permeability. This is because of generally smaller grain sizes and intergranular spaces. Sand can still be considered as an aquifer. Clays usually have porosities of 45 to 55 percent, but have low permeabilities. The small platy grains in clays tend to hold large amounts of water cohe-
sively. This further cuts down on the already small intergranular openings. Clays generally act as aquicludes, but have the capacity for storing large amounts of water.

Most consolidated sedimentary rocks can be classified, for hydrogeological purposes, into three basic lithologies. These are fine-grained clastic rocks, coarse-grained clastic rocks and chemical precipitates (Fig. 6). Clastic rocks are composed mainly of detrital fragments which have been lithified by compaction and cementing material. They have a clastic texture which is dependent upon grain size, rounding, sorting and cementing material. Chemical precipitates are precipitated out of solution at or near the site of deposition. This causes a crystalline texture to form. Both clastic rocks and chemical precipitates can be greatly altered from their original texture by fracturing, solution, reprecipitation, and cementing fluids.

Primary porosity in fine-grained clastic rocks may be high, but permeability is generally low. However, secondary porosity, formed by joints and faults, can increase the permeability. Fine-grained clastic rocks, such as siltstone and shale, will generally act as aquicludes. However, they can act as poor aquifers in zones of extensive fracturing or coarser sediments. Some fine-grained clastic rocks can store large quantities of water because of high porosity. They are, therefore, important in water resource evaluations.

Coarse-grained clastic rocks, such as sandstone and arkose, have original porosity that is dependent upon the texture of the rock. Their textural characteristics make them less porous than fine-grained clastic rocks, but usually more permeable. Cementation is probably
the most important variable in the porosity and permeability of coarse-grained clastic rocks. Differences in the cementing process can make the porosity and permeability of coarse-grained clastic rocks quite variable from one section to the next (Davis and DeWiest, 1966, p. 350).

A silica cement can make a hard, insoluble orthoquartzite. Silica grains tend to interlock with each other and form a quasi-crystalline texture. In this type of rock, porosity and permeability is usually low unless secondary porosity has been introduced by fracturing. Other common types of cementing materials are calcite, iron, and clay. A calcite cement might be easily removed by later leaching, while a clay cement tends to make a weak rock. The addition of clay would, however, increase the porosity of the material. Porosities and permeabilities in coarse-grained clastic rocks are normally one to three times lower than the porosity and permeability of their unconsolidated counterparts. This is because of closer packing and the addition of cement between the grains.

Chemical precipitates can be carbonate rocks, such as limestone and dolomite, or they can be made of other minerals, such as chert or salt. If they are massive and dense when they are formed they will be relatively impermeable, unless fractured. Carbonate rocks are particularly susceptible to solution processes. Zones of original porosity and permeability are quickly modified by compaction, solution, reprecipitation, and dolomitization processes. These processes, along with fracturing, induce zones of secondary porosity that make the rocks more permeable. Postdepositional changes from calcite to dolomite can add up to 13 percent more pore space (Davis and DeWiest, 1966, p. 353). If
these pores are further enlarged by solution activity, extensive permeability can be developed.

Hydrogeologic interpretations cannot be made on the basis of lithology alone. Only by considering structural, surficial, and lithologic units, along with recharge-discharge characteristics can meaningful generalizations be made for a particular area.

**Structure**

Structure is probably the most important consideration in a hydrogeological analysis of Dry Valley and Little Long Valley. Fractures have a direct influence on the movement of water within a geologic formation. Folds affect the attitude of the various permeable units and are responsible for their outcrop patterns. Rocks in Dry Valley and Little Long Valley were subject to folding and faulting in Laramide times and to block faulting in more recent times (Fig. 4). This resulted in a series of northwest trending folds and several major sets of faults. The folds and the early faults are often offset by subsequent faultings.

The folds in Dry Valley and Little Long Valley are sometimes overturned and sometimes plunging. An overturned fold is one in which both the limbs dip in the same direction, usually at different angles. A plunging fold is one in which the axis is inclined. Alternately resistant and weak sedimentary strata have been eroded to produce three types of ridges and valleys; anticlinal, synclinal, and homoclinal. The attitude of the rocks in anticlinal structures is convex upward, with older rocks in the center of the curvature. Synclinal
structures are folded convex downward, with younger rocks in the center of the curvature. Homoclinal structures dip in one direction only. They usually represent one limb of an anticline or syncline, the rest of which has been eroded away.

The fracture systems in Dry Valley and Little Long Valley are complex and highly variable. They range from major faults with large displacements to joints with no displacements. The faults can be either normal or reverse and can strike and dip in almost any direction. However, the dominant direction of strike is to the northwest, and most of the faults are steeply dipping.

Fractures affect the ground-water flow systems in many ways. Ground-water recharge results from the downward movement of water from the ground surface. This involves vertical leakage of water through various types and thicknesses of geologic material. In consolidated sedimentary rocks, fractures provide the main avenues for this leakage. Fractures are also responsible for the secondary porosity and permeability in many types of rocks. Lastly, faults can affect ground-water discharge by acting as either a barrier or as a conduit for ground-water movement.

Fractures are breaks in a mass of rocks. They are caused by stresses which are greater than the strength of the rock. If there has been differential movement on either side of the plane of fracture, it is known as a fault. If there has been extremely little or no movement the fractures are called joints. Joints are some of the most common structural features exposed at the surface of the earth. The size and distribution of joints within a rock mass are extremely impor-
tant to a hydrogeological investigation.

Joints can develop at all ages in the history of a rock. They have been reported in young unconsolidated sediments (Price, 1966, p. 129) as well as in older sedimentary rocks. There is no easy method to determine if a particular joint was developed during a phase of tectonic activity or whether it developed at a much later time, by a different mechanism.

In the attitude, measured by the strike and the dip, of a group of joints is parallel, then it is known as a joint set. The spacing of the joint planes within a joint set is a measure of the joint frequency. This might range from hundreds of feet to only a fraction of an inch. The size of joints, as measured along the strike and dip is also variable. It ranges from hundreds of feet down to microscopic sizes.

The occurrence and density of jointing in a rock mass is partially controlled by lithological characteristics such as brittleness, mineralogy, and cementation. More brittle, lithic types generally show better development and higher concentrations of fractures than do more ductile rock types. This is because ductile beds have a greater tendency to fail by plastic flow than do more brittle beds, under similar stress conditions. The more brittle rocks will fail by fracturing, under compressional forces, unless sufficient confining pressure and temperature are present to favor flowage. Rocks such as siliceous dolomites, limestones, and quartzites commonly show the highest fracture density, while friable quartz sandstones and soft ductile shales often show the lowest fracture density (Harris and others, 1960, p. 1860).
A rock unit that does not fracture readily may show little or no fracture development even in an area where structural conditions favor fracturing.

In sedimentary rocks an inverse relationship exists between joint frequency and bed thickness (Harris and others, 1960, p. 1869). The concentration of fractures is in approximate inverse proportions to the thicknesses of the individual units. In other words, a dolomite bed one foot thick might have ten fractures per square yard, while a similar, nearby dolomite bed ten feet thick might have only one fracture per square yard. This fracture density relationship holds true for both total fractures and for individual fracture sets.

This phenomenon can be explained in terms of frictional forces which exist between adjacent beds (Price, 1966, p. 145). In Figure 7 it is assumed that we have a competent bed of length $L$ and width $z$, and a uniform tensile stress $\sigma T$ acting throughout the layer. This tensile stress is opposed along both bedding planes by a frictional shearing stress of $t$. A A represents a joint surface where the horizontal stress in the bed is zero. The total force acting along the bed is the tensile stress times the width of the bed or $F = \sigma T \cdot z$. This force gradually increases away from the joint plane A A. Tension is relieved by small amounts of bedding plane slip until at some distance $L$, the tensile force is equaled by the frictional traction resisting the bedding plane slip. At this distance a second tension joint may form. If the bed was twice as thick, the total force resulting from $\sigma T$ would be doubled, because $F = \sigma T \cdot 2z$. The normal stress and the coefficient of friction between the beds remains unchanged so the
Figure 7. Process of joint formation in layered rock (after Price, 1966, Fig. 54).
frictional traction is the same. This means that the traction must act over a distance of $2 \cdot L$ in order to balance the total force and form another joint. Thus, a bed that is twice as thick will, under the same tensional force, require twice the distance to form joints.

Price (1966, p. 147) reported that cohesion, friction and tensile strength will vary according to minor changes in lithology. Normal stress will be influenced by depth of cover, orientation of the rock unit, and for inclined beds, lateral compression. Nevertheless, field observations, as have been reported, generally support the inverse relationship between the concentration of joints and the thickness of beds.

The relationships between joint density and lithology and between joint frequency and bed thickness are useful when trying to analyze complex ground-water conditions such as those in Dry Valley and Little Long Valley. These relationships allow meaningful generalizations to be made about fracture patterns within the area. The fracture patterns control the secondary porosity and hence the permeability of many of the rock units. It should be noted that most interconnecting fractures tend to close at depth because of the weight of overlying material. This means that there will be a regular reduction in the supply of water from fractures at a certain depth, usually less than 500 feet (152 m) (Legget, 1962, p. 137).

Faults in Dry Valley and Little Long Valley affect the position and distribution of aquifers and aquicludes. Differences in depth of the faults, amount of displacement, and lateral extent, along with the character of the fault gouge make each faulted area a separate problem.
Faults can displace alternating permeable and impermeable beds so that the permeable ones face impermeable ones. If the fault is open or if the gouge is permeable, then water can migrate along the fault until it finds either another permeable zone or is discharged at the surface. If the fault is tight it can act as a ground-water barrier. An intricate system of interconnecting and intersecting faults, such as those in the Dry Valley-Little Long Valley area can serve to concentrate ground water into particular zones. Springs can occur where these zones intersect the surface.

Structural factors are directly responsible for the ground-water flow system in many of the consolidated sedimentary rocks in the Dry Valley-Little Long Valley area. In the unconsolidated sediments they are not generally of primary importance, but can have profound local influences. An understanding of the faults, joints, and folds is, therefore, a necessary prerequisite to an understanding of the ground-water systems. Only when structure and lithology are considered together, can potential aquifers be defined.

**Surface Features**

Landforms in Dry Valley and Little Long Valley include both erosional and depositional features. Mass wasting, or the movement of earth material downslope under the influence of gravity, is a very common process in mountainous areas. Alluvial deposits such as alluvial fans and alluvial plains are also common. Erosional processes loosen and wear away earth material and are responsible for much of the relief in the area. Surface features are not usually as important to the
water-bearing potential of a geologic unit as are the structure and lithology. However, they are important to infiltration characteristics and thus also to ground-water recharge.

The soils in the Dry Valley-Little Long Valley area are of three basic types: alluvial, colluvial, and residual. The alluvial soils were formed by recent stream deposits and occur mainly in and along stream valleys. The colluvial soils result from mass wastage deposits and occur along the lower sideslopes of the valleys. Residual soils are formed in place from the disintegration and decomposition of the underlying rock. They occur mainly on the upland areas. Any of these basic soil types can either be mixed with other types, or eliminated by both natural processes and man-related activity.

Infiltration rates are the rates at which water actually enters the soil. They are quite variable and depend on many things. Character and depth of the soil, intensity and duration of the rainfall, vegetal cover, antecedent soil moisture, and subsoil permeability are all factors that influence the infiltration rate. A good vegetal cover can increase infiltration rates from three to seven times by protecting against raindrop impact and by contributing organic matter to increase soil permeability. Shallow rooting systems also help to keep the soil open. Only when soil moisture requirements are satisfied and subsurface geologic conditions are favorable will excess moisture recharge the ground-water aquifers.

The soils in Dry Valley and Little Long Valley are characterized by moderate permeability in the surface horizon to moderately slow permeability in the subsoil (U. S. Forest Service, 1974 a, Soils).
Alluvial soils usually consist of permeable loam in the surface layers. Subsoil layers can consist of either a permeable gravel-loam mixture or a relatively impermeable clay loam mixture. These soils are underlain by alluvium or by an alluvial-colluvium mixture. Soils developed on the colluvium generally have loam surface layers with scattered cobbles. The subsoil consists of a clay loam with low permeability. These residual soils are generally loam in the surface layers and loam or clay loam in the subsoil. They are underlain by consolidated sedimentary rock.

Alluvial fans occur at the mouth of some of the canyons in the dry Valley-Little Long Valley area. These are both actively accumulating alluvial fans (Cressman, 1964, p. 61) and older fan type deposits. These fans occur when heavily loaded streams emerge from the mountains onto a lowland. The sudden change in gradient results in a deposition of alluvium which apexes at the point of emergence and spreads out in a fan-like shape in the lowland. The material in a fan grades from coarse gravel and boulders at its head to finer material down its slope (Fig. 24). If a series of alluvial fans coalesce they will form a bajada or alluvial slope down the face of the mountain.

Alluvial fans are formed during high runoff events. During the rest of the year surface water in the stream channels will sink into the coarse material at the apices of the fans. From there the water moves down the fan under hydrostatic head. If the fans are large enough or if bajada surfaces have been formed they can provide excellent ground-water potential (Thornbury, 1969, p. 174). Significant
ground-water recharge to the alluvial aquifers probably takes place through alluvial fan deposits in Upper Dry Valley.

Landslides and earth flows are fairly common in the Dry Valley-Little Long Valley area. They can locally affect the ground-water system by altering the recharge-discharge areas. In Little Long Valley, areas that are covered by landslide debris have considerably thicker overburden than adjacent areas. This can result in higher soil moisture storage and potential for ground-water recharge for a local area. The overall significance of landslide debris to the ground-water flow system is probably minimal.

Hydrogeologic Units in Little Long Valley and Upper Dry Valley

The sedimentary rocks in Dry Valley and Little Long Valley have been thoroughly classified in time-stratigraphic units. Mansfield (1927), Cressman and Gulbrandsen (1955), Cressman (1964), and Montgomery and Cheney (1967), among others, all give detailed stratigraphic, lithologic, and structural descriptions of the various rock units in Dry Valley and Little Long Valley.

It is impossible to make a meaningful hydrogeologic classification on the basis of existing time-stratigraphic boundaries. This is because the geologic formations in this area are thousands of feet thick and contain repeated sequences of different lithologies. For a hydrogeological investigation, the age of a rock sequence is not as important as its textural, compositional and structural characteristics. Layered rock sequences, separated by millions of years in age can be very similar in their hydrogeologic properties. Therefore an attempt
will be made to take the geologic units that have been described by others and classify them according to the way they contain and transmit water.

The major structures in Little Long Valley are an anticline and a syncline. The topography is reversed, with the syncline occupying a position above the anticline. Both folds plunge to the northwest (Fig. 8). The structure is directly responsible for the drainage patterns that have developed. Weak, fractured rocks along the axis of the syncline have been eroded to form a topographic low. A series of fault zones occur transverse to the synclinal axis. Surface drainage follows the synclinal axial trace in the direction of the plunge, until it reaches a fault zone. It then takes a right angle bend down to the main drainage in the valley bottom (Fig. 8).

The geologic material in Little Long Valley can be divided into three major hydrogeologic units (Fig. 8). These are: 1) thin, interbedded siltstone, shale, and limestone; 2) massive sandstone and sandy limestone; and 3) interbedded mudstone, shale and chert. Each of these groups has similar lithologic, structural and topographic characteristics, and therefore some generalizations are possible.

The thin, interbedded siltstone, shale and limestone occur on the northeastern ridge of Little Long Valley (Fig. 8). They have been folded into an anticlinal and synclinal structure. Fractures are associated with the more brittle lithic units, such as calcareous siltstones and silty limestones. It is probable that the joint frequency increases in areas of thin bedding, because of the relationships described earlier. In addition, the joints are enlarged by solution
Figure 8. Hydrogeologic sketch map of the southeast end of Little Long Valley.

(all structures and contacts are approximately located.)
processes. This results in a well-defined interconnecting fracture system in certain layers. These layers act as aquifers.

In contrast, the southwest ridge of Little Long Valley is composed of massive sandstone and sandy limestone (Fig. 8). It is a homoclinal ridge without major folds. The quartz sandstone is often weak and fine-grained. The thick beds, the friable nature of the rock, and the lack of folds, combine to keep the total number of joints few. Thus, an interconnecting fracture system probably does not form. However, the massive sandstone can act as an aquifer in areas where it is coarse-grained and where the calcareous cement has been dissolved.

The interbedded mudstone, shale, and chert occur in the bottom of Little Long Valley (Fig. 8). They are in fault contact with the massive sandstones, and are dipping nearly vertical. These rocks are not good aquifers. Numerous zones of massive, unweathered chert and argillaceous material probably block the transfer of water from one layer to the next. Aquifers can occur where the chert is thin bedded and fractured, or where there are zones of coarse-grained material.

Upper Dry Valley is in the eroded core of a major anticline, the axial trace of which is on the east side of the valley (Fig. 9). Dry Ridge is a homoclinal ridge formed from resistant rocks on the east limb of the anticline. Alluvial-colluvial valley fill material is variable in thickness. It ranges from 0 feet (0 m) at several bedrock highs in the valley to over 300 feet (91 m) in structural troughs. Drill hole and seismic data indicate that the bedrock surface is irregular because of large fault blocks. The valley fill is generally deepest in the northeast edge of Upper Dry Valley. It gradually thins to the south.
and to the west.

The geologic material in Upper Dry Valley can be divided into four major hydrogeologic units (Fig. 9). These are: 1) interbedded siltstone, shale, and limestone; 2) massive sandstone and sandy limestone; 3) interbedded mudstone, shale and chert; and 4) alluvial-col-luvial valley fill. The three bedrock units contain and transmit water similarly to the bedrock units in Little Long Valley. The synclinal structure in the interbedded siltstones, shales, and limestones (Fig. 9) is probably an aquifer. Also, permeable zones in the massive sandstone and limestone transfer some ground water to the valley. The alluvial-col-luvial valley fill is the most important hydrogeological unit in this area. Water is directed from the higher elevation bedrock areas to the more permeable valley fill material by both direct runoff and ground-water flow.

The main aquifers in the valley fill material are coarse-grained deposits of gravel and sand. They are usually interbedded with deposits of clay that act as aquicludes. Lateral variations in the unconsolidated sedimentary deposits are very important when analyzing the occurrence and distribution of ground water in Upper Dry Valley. Differences in depositional processes have caused layers, lenses, and stringers of gravel and sand to occur irregularly in the deposits. These aquifers sometimes thicken or thin, or else give way abruptly to clays, as they are followed laterally across the valley. This contrasts with the relatively uniform conditions found in some of the consolidated sedimentary aquifers. Drill holes 9S-44E-11ba2 and 9S-44E-3da1 (Fig. 9) illustrate the rapid change that can be expected.
Figure 9. Hydrogeologic sketch map of the north end of Upper Dry Valley. (all structures and contacts are approximately located.)
Here, a relatively shallow water-bearing unit of sand and gravel rapidly gives way to a continuous sequence of moist clay. As a general rule, sediments are finer and thinner at increasing distances from the source of the sediments.

In Little Long Valley and Upper Dry Valley, each area must be examined individually to make a detailed hydrogeologic classification. Ground water will generally be transmitted and stored according to the broad guidelines that have been presented. However, faults and lateral variations can drastically alter the hydrogeologic units in both the bedrock and the valley fill areas. Examples of this in Upper Dry Valley and Little Long Valley will be given in a later section.
GROUND-WATER HYDROLOGY

The location and extent of recharge and discharge areas, and the direction and velocity of flow are essential factors in the evaluation of the ground-water resources. At the present stage of this investigation, too little is known about the geohydrology in the Dry Valley-Little Long Valley area to quantify sufficiently the ground-water flow systems. What is presented here is a qualitative analysis of two representative flow systems; one in the consolidated sedimentary rocks of Little Long Valley and one in the unconsolidated sediments of Upper Dry Valley. These analyses are made by using both real data and theoretical models. They are highly interpretive and are subject to revision as more data become available. Nevertheless, the interpretations are based on sound hydrogeologic principles and offer a method for classifying the very complex ground-water flow systems in this area.

Ground water in the Dry Valley-Little Long Valley area exists in both confined and unconfined conditions. The unconfined water is in direct contact with the atmosphere through open spaces in permeable material. In an unconfined system, water in a well will not rise above the zone from which it is obtained. The confined (artesian) water is separated from the atmosphere by impermeable material. In an artesian well, the water level will rise above the zone from which the water is obtained. The division between confined and unconfined water is entirely gradational (Davis and DeWiest, 1966, p. 45).
Surface Methods

Methods for analyzing the occurrence and distribution of ground water include both surface and subsurface techniques. Surface techniques that yield valuable hydrogeologic information include geological, hydrological, geophysical, and remote sensing investigations. Test drilling and logging are subsurface methods that can be used. Information gathered from surface and subsurface investigations usually leads to a tentative appraisal of the ground-water system in an area. This is a necessary starting point for more intensive investigations and a more detailed analysis.

A first step in a hydrogeological investigation is to analyze both geologic and hydrologic data from the area. In Dry Valley and Little Long Valley, this information was available from published reports and from unpublished mining company and government data. The results from this phase of the investigation provided a basic knowledge of geologic and hydrologic conditions in the area. The fundamental relationships between geologic material and ground water and between precipitation and ground-water recharge were presented earlier in this report.

A field reconnaissance is essential to a hydrogeological investigation in complexly folded and faulted terranes such as Dry Valley and Little Long Valley. Surface observations of the character of rock outcrops and character of the soil proved to be useful in making hydrogeological interpretations for a particular area. Fracture patterns in the geologic material were observed and measured wherever possible.
These fractures were particularly important for ground-water movement in the consolidated sedimentary rock areas. Folds and faults were outlined in the field wherever found. In Little Long Valley, previously unmapped structures were of major hydrogeological importance. Ground-water discharge zones, such as springs and seepage, were observed in detail. Their appearance and their relation to the surrounding terrain often give clues as to their origin. Vegetation patterns and drainage patterns were also considered in the field reconnaissance. They were significant to ground-water recharge and discharge, and to direct runoff.

Remote sensing data can be used to supplement the field reconnaissance. In Little Long Valley, unmapped folds and faults were first located on vertical aerial photographs. They were then measured and observed more closely in field investigations. Terrain characteristics such as vegetation, land forms, and drainage patterns were also delineated by stereoscopic study of photo pairs. These were used in outlining areas favorable for ground-water supply.

Oblique color and color infrared, aerial photography was used in conjunction with vertical aerial photographs and ground reconnaissance to study certain areas in Dry Valley and Little Long Valley. The photographs were taken by a party led by the author, specifically for this investigation. These photographs were taken from a single-engine light aircraft along successive flight lines at altitudes ranging between 2000 and 3000 feet (610 and 914 m) above land surface. They were taken by hand-held 35 millimeter Minolta and Nikon motor-driven cameras. Stereoscopic pairs were obtained for many of the views by
first taking a picture of one scene, then lagging the next picture of the same scene by enough time to get a slightly different angle. The amount of time lag needed depends on both the distance to the object and the speed of the airplane. It usually ranges between one and three seconds.

The oblique aerial photography was used to help outline recharge-discharge contacts, and to spot geologic features that influence the ground-water system in Dry Valley and Little Long Valley. Certain parts of this investigation were particularly helpful and could be used in other areas. The infrared photography proved to be a useful tool when used in conjunction with other data.

Infrared radiation occurs in the electromagnetic spectrum between visible light and radio waves. It covers the wavelength range from about 700 nanometers to about 1,000,000 nanometers. The primary source of infrared radiation is the sun. As the sun's energy falls on the surface of the earth, it is either reflected or absorbed. Reflected infrared radiation is similar to reflected visible radiation. It can be recorded by standard photographic processes at wavelengths of up to 900 nanometers (Fig. 10). Objects that absorb radiation tend to increase in temperature, then re-emit this energy, mostly in the far infrared portion of the spectrum (Cantrell, 1964, p. 917). This "heat" radiation can be recorded by thermal detectors. The crossover point where emitted infrared radiation becomes dominant over solar, reflected, infrared radiation is at approximately 3,000 nanometers (Suits, 1960, p. 765).
Figure 10. Idealized spectral reflectance curves for healthy trees.
A loss of reflected infrared radiation is often the first indication of a loss of vigor in plant growth. This loss of vigor can be due to many factors, including soil condition, water content, age of leaf, and disease. If the other factors are kept constant, or are in some way accounted for, then water content of the soil will become the dominant factor in the amount of reflected infrared radiation present. This is the basis for many hydrogeological interpretations of the photographs.

The infrared film used was Kodak, Ektachrome Infrared Film Type II. This film is sensitive to wavelengths from 360 to 900 nanometers. The film was exposed with a yellow filter which attenuated wavelengths shorter than 500 nanometers. The processing results in a false-color image which is subject to the following guidelines. Infrared-reflective objects come out as red; green objects that are not infrared-reflective appear as blue-green; and brown or red objects register as yellow or brown. Since blue light is eliminated, blue objects appear as black. For plants, the spectral reflectance of infrared dominates that of the other colors (Fig. 10). Hence, vegetal covers usually show up red on infrared photographs. The shade of red depends on many things, among them the type of plant and the vigor of its growth. If a tree loses its infrared reflectance, the photographic reproduction is less red and more blue-green.

In Dry Valley, infrared photographs proved particularly useful in locating alluvial fans. The slightly different spectral response of vegetation on the fan surfaces made them stand out as triangular shaped features (Fig. 11). The infrared photographs were also useful
Figure 11. Color oblique (a) and color infrared oblique (b) views of alluvial fans in Upper Dry Valley
in delineating spring discharges and wet spots on the valley floor. These showed up as dark spots on an otherwise light colored terrain. Anson (1969, p. 197) observed that intermittent drainage lines are readily observable on Ektachrome infrared, since the presence of moisture contrasts with highly reflective dry soil.

In Little Long Valley, the infrared photographs were useful in interpreting the geologic control on ground-water movement. Water-bearing zones in certain geologic units stood out as lineaments on the infrared photographs. Figures 12 and 14 show zones of ground-water discharge that can be interpreted from infrared photographs. Streams with base flow also contrasted with inactive drainages on the photographs. In Figure 13, infrared-reflective vegetation in Angus Creek shows up as red while unhealthy vegetation in the dry drainages in the upper, right part of the picture shows up as yellowish-brown.

The greatest value of large scale aerial photography in an area such as this, is that of minimizing time and cost of field investigations. In some cases, problem areas can be spotted and outlined on the photographs before field investigations are started. In other cases, the photographs give a different perspective on complex field problems. Sometimes, information that is obtained from the photographs cannot be obtained any other way. Babcock (1971, p. 3189) located active faults in an alluvial plain by using infrared photography. Slight differences in soil moisture along the fault traces affected the vigor of plant growth. These differences were recorded on infrared film. Other investigators (Garofalo and Webber, 1973, p. 46) found large scale photographs to be useful in studying surface mining areas.
Figure 12. Color infrared view of Little Long Valley

Figure 13. Color infrared view of part of Angus Creek drainage in Little Long Valley
Figure 14. Color infrared views of east ridge in Little Long Valley showing ground-water discharge zones.
The terrain information recorded on color and false color films made it possible to monitor many environmental effects of surface mining, by an integrated analysis of photographs.

For hydrogeological investigations, color aerial photography is another tool, which, when used within its limitations, provides useful information on soils, rocks, vegetation, and streams. This information can then be used along with information gathered from other surface and subsurface methods to make hydrogeological interpretations.

Refraction seismology is another surface method that can be used in a hydrogeological analysis. When used in conjunction with drill hole data it can give valuable information on the depth of valley fill and on the location of water-bearing units. When used without drill hole data it is, at best, only a crude estimate of subsurface conditions.

The interpretation of seismic data assumes that there are homogeneous, subsurface layers which are bounded by sharp interfacial planes (Todd, 1959, p. 228). When these conditions are not met, the data is often difficult to interpret. Water in the unconsolidated valley fill material makes its seismic velocities similar to those of weathered or fractured bedrock (E. P. Olson, written commun., 1974). Hence, the actual presence of ground water is difficult to determine without supplemental data.

Used together, geologic reconnaissance, remote sensing data, and geophysical data can provide valuable hydrogeologic information. However, they are all surface methods and provide only indirect indications of the ground-water systems. In order to substantiate surface
interpretations, supplemental data is required from subsurface investigations.

**Subsurface Methods**

Test drilling is the most common subsurface method used in hydrogeologic investigations. Geologic logs obtained from drill holes are helpful in delineating water-bearing units. Geophysical logs can be used to supplement the geologic data. Finally, piezometer tubes or small diameter wells can be installed to monitor water levels and to use for aquifer tests.

Phosphate mining companies have been drilling exploration holes for many years in Dry Valley and Little Long Valley. These drill holes provide valuable subsurface information, which is detailed and exact in phosphate ore zones. However, the mining company exploration holes have several drawbacks for use in a hydrogeological reconnaissance. Important ground-water areas are often away from the phosphate ore zones, and mining company data either does not exist or is incomplete. Also, information on water-bearing units is sometimes not recorded on mining company logs. In addition, many of the exploration holes are drilled with water as a circulating fluid. This makes it extremely difficult to determine when a water-bearing unit has been penetrated. Finally, mining company drill holes are usually abandoned soon after they are drilled. The weak, fractured sedimentary rocks and the loose unconsolidated sediments will usually cave quickly and plug the hole. This makes the drill hole useless for further data collection.
A test drilling program was initiated as part of this study. Geologic logs were kept for these holes and particular attention was paid to the water-bearing units. In addition, five piezometer tubes were installed in order to make water level measurements and aquifer tests. The results from this part of the investigation are still very preliminary. Nevertheless, they do aid in regional analyses, and will be included where they are significant.

Figure 15 presents geologic logs from selected drill holes in Dry Valley and Little Long Valley. These logs can be used to illustrate certain features that are representative of the hydrogeology in the two valleys. Hole 20, RMC Corporation, illustrates the possible depth and complexity of the valley fill material in Dry Valley. This hole was located in middle Dry Valley, approximately 2 miles (3 km) northwest of Figure 9. Numerous zones of clay, alternating with more permeable material make it likely that a multiple aquifer system exists in this area. Zones of consolidated rock, such as limestone and sandstone are sometimes interbedded with the unconsolidated sediments. This adds to the complexity of the flow system.

Hole 78-43E-3ad1, of the test drilling program, is in consolidated material. The ground-water potential of the consolidated sediments varies from place to place, depending upon the lithologies and the structure. In this particular hole, the main water-bearing beds are dark, hard, calcareous siltstones or silty limestones. Numerous clay seams and mudstone layers alter the water-bearing properties of the aquifer in certain zones. The water level rose above the zone from
Figure 15. Geologic logs of selected drill holes in Dry Valley and Little Long Valley.
which it was first obtained, suggesting artesian or confined con-
ditions. The alluvium and colluvium in this particular area is thin and
discontinuous, and is probably not a major factor in ground-water
supply.

Holes 9S-44E-3dal, 9S-44E-2dcl, and 9S-44E-11ba2, all construc-
ted as part of the project test drilling program are in the unconsol-
dated alluvial sediments of Upper Dry Valley. They were drilled to
determine the character of the upper alluvial aquifer. The water-
bearing zones in these sediments are generally sands and gravels. Where
these zones are overlain by a clay layer the water exists in artesian
conditions. Since the clay in the soil substratum is not continuous,
it is likely that unconfined conditions are also present in places.
Hole 9S-44E-3dal shows a continuous sequence of clay instead of alter-
nating layers of clay, sand, and gravel. The thick clay serves as a
barrier to the movement of ground water through Dry Canyon.

Hydraulic Properties of the Aquifers

On September 29, 1974, two aquifers were tested by the "slug"
method, in order to compare the hydraulic conductivities of the water-
bearing units in the two representative flow systems. The first test
was in an alluvial aquifer in Upper Dry Valley. The second test was
in a consolidated sedimentary aquifer in Little Long Valley. The
piezometer tubes used for the tests were 9S-44E-2dcl in Dry Valley and
7S-43E-3ad1 in Little Long Valley (Fig. 15). Both aquifers were under
artesian conditions.

The "slug" method can be used to obtain an estimate of the
hydraulic conductivity ($K$) and transmissivity ($T$) of an aquifer. The hydraulic conductivity (coefficient of permeability) is a measure of a material's ability to transmit water. A medium has a hydraulic conductivity of unit length per unit time, if it will transmit, in a unit time, a unit volume of ground water at the prevailing viscosity, through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow (Lohman, 1972, p. 6). The transmissivity is a measure of the ability of an aquifer to transmit water through its entire thickness. It can be defined as the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman, 1972, p. 6). In a confined situation the transmissivity ($T$) is equal to the hydraulic conductivity ($K$) multiplied by the saturated thickness ($b$).

To apply the "slug" method, a known volume or "slug" of water is injected suddenly into a well. The post-injection decline in water level is monitored at repeated time intervals. Data from these measurements is used to calculate the transmissivity. The hydraulic conductivity is then figured by dividing the transmissivity by the thickness of the water-bearing material.

Since the duration of a "slug" test is usually very short, the transmissivities determined from the test will be representative only of the water-bearing materials close to the well (Ferris and others, 1962, p. 104). This means that errors could result if the transmissivity value is extended throughout the aquifer. Lohman (1972, p. 27) suggests that the slug method is only applicable to fully penetrating
wells in confined aquifers with transmissivities less than 650 m²/day. The transmissivity value obtained for partially penetrating wells applies only to the portion of the aquifer that is screened or open.

In the Dry Valley and Little Long Valley "slug" tests, water was injected into the piezometer tube by pouring from a five gallon drum. This method was not instantaneous, and water leaked into the aquifer during the time interval when the slug was being injected. Measurements of residual head were made with a chalked steel tape. This method, while being reasonably accurate, is slow, with measurements being recorded at one to two minute intervals. This introduced another source of error. Since the decline of the water level was greatest during the first few minutes of the test, all of the data points fell at the tail end of the curve on which they plotted.

The data from each test was analyzed by two different methods. Both of these methods make numerous assumptions and are described by Cooper and others (1967, p. 263-269) and by Ferris and Knowles (1963, p. 299-304). Basically, the Cooper and others method uses an equation for non-steady radial flow, that describes the response of a finite diameter well to an instantaneous slug of water. The Ferris and Knowles method uses an equation derived by Theis for an instantaneous vertical line source or sink. Both methods are based on the nonequilibrium formula derived by Theis and are subject to the following assumptions given by Ferris and others (1962, p. 93): a) the aquifer is homogeneous and isotropic; b) the aquifer has infinite areal extent; c) the well penetrates or receives water from the entire thickness of
the aquifer; d) the coefficient of transmissivity is constant at all
times and at all places; e) the well has an infinitesimal diameter;
and f) water removed from storage is discharged instantaneously with
decline in head.

Table 1 gives the results of the "slug" tests on the two aquifers.
The hydraulic conductivity of the alluvial material surrounding the
Upper Dry Valley test well fell in the lower range of a good aquifer.
The hydraulic conductivity of the consolidated, sedimentary material
surrounding the Little Long Valley test well fell in the upper range
of a poor aquifer (Davis and DeWiest, 1966, p. 164). The results of
the Upper Dry Valley test are probably more reliable than results of the
Little Long Valley test. This is because the construction of the well
and the nature of the material being tested, in Dry Valley, came closer
to meeting the ideal conditions for the test. For an aquifer test,
consolidated sedimentary rocks exhibit homogeneous characteristics only
if sufficiently large volumes of material are involved in the test
(Todd, 1959, p. 90). The "slug" test in Little Long Valley dealt with
only a small volume of consolidated material, and therefore, is prob-
ably not representative of the aquifer.

Because of the restrictive assumptions, outlined earlier, and
the numerous sources of error, the results of the "slug" tests are
only semi-quantitative descriptions of the aquifer material. Also,
the estimates of hydraulic properties can be applied only in the imme-
diate vicinity of the test wells. However, when used within these limi-
tations, and in conjunction with other hydrogeologic data, the "slug"
test results are useful in helping to broadly classify the aquifers.
Dry Valley - unconsolidated sediments

<table>
<thead>
<tr>
<th>Transmissivity (T)</th>
<th>Hydraulic Conductivity (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooper and others method</td>
<td>( \frac{m^2}{day} \left( \frac{180 \text{ gpd}}{ft} \right) )</td>
</tr>
<tr>
<td>Ferris and Knowles method</td>
<td>( \frac{m^2}{day} \left( \frac{140 \text{ gpd}}{ft} \right) )</td>
</tr>
</tbody>
</table>

Little Long Valley - sedimentary rocks

<table>
<thead>
<tr>
<th>Transmissivity (T)</th>
<th>Hydraulic Conductivity (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooper and others method</td>
<td>( \frac{m^2}{day} \left( \frac{140 \text{ gpd}}{ft} \right) )</td>
</tr>
<tr>
<td>Ferris and Knowles method</td>
<td>( \frac{m^2}{day} \left( \frac{150 \text{ gpd}}{ft} \right) )</td>
</tr>
</tbody>
</table>

Average values of K after Davis and DeWiest (1966, p. 164)

<table>
<thead>
<tr>
<th>Aquifer Class</th>
<th>( \frac{m}{K \text{ day}} )</th>
<th>( \frac{\text{gpd}}{ft} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>( 8.64 \times 10^{-2} - 8.64 \times 10^{-4} )</td>
<td>( 2.12 \times 10^{4} - 2.12 \times 10^{6} )</td>
</tr>
<tr>
<td>Good Aquifers</td>
<td>( 8.64 \times 10^{-1} - 8.64 \times 10^{2} )</td>
<td>( 2.12 \times 10^{4} - 2.12 \times 10^{6} )</td>
</tr>
<tr>
<td>Poor Aquifers</td>
<td>( 8.64 \times 10^{-4} - 8.64 \times 10^{-1} )</td>
<td>( 2.12 \times 10^{2} - 2.12 \times 10^{4} )</td>
</tr>
<tr>
<td>Aquiclude</td>
<td>&lt; ( 8.64 \times 10^{-4} )</td>
<td>&lt; ( 2.12 \times 10^{2} )</td>
</tr>
</tbody>
</table>

Table 1. Results of aquifer tests using "slug" method
The unconsolidated sediments, as expected, had higher hydraulic conductivity than the consolidated rocks. The ground water was also closer to the surface in the alluvial area. This would indicate that larger amounts of ground water would occur at shallower depths in Upper Dry Valley as opposed to Little Long Valley.

The Little Long Valley well is thought to be in a major valley aquifer. The water-bearing material was fairly uniform in the section that was penetrated by the drill hole. This aquifer probably extends up Little Long Valley as a regional structure. It is quite possible that ground water discharges into Angus Creek through this aquifer. Further drilling is necessary to substantiate these ideas.

Theoretical Methods

Several theoretical methods have been developed for analyzing ground-water flow systems. These methods can be used to investigate ground-water movement as it occurs in idealized situations. They make use of electrical analogs, scale models, and mathematical models. In Dry Valley and Little Long Valley the hydrogeology is not yet well enough understood to obtain quantitative results from theoretical methods. However, a qualitative application of the theories greatly aids in the understanding of the ground-water flow. It will be used to describe the flow systems and to help tie together some of the practical data that has been generated thus far.

Toth (1963, p. 4795-4812) constructed a mathematical model for a small drainage basin. He assumed that ground-water motion could be
treated as unconfined flow through a homogeneous medium, down to depths at which basin-wide layers of contrasting, low permeability are found. He also assumed that water table highs and lows followed topographic highs and lows. Under these conditions, three types of flow systems were outlined; local, intermediate, and regional (Fig. 16 A, B). A local system has its recharge area at a topographic high and discharge area at an adjacent topographic low. This system is most affected by seasonal recharge and discharge, and accounts for the majority of ground-water flow. As a result of local systems, the origins of water found at closely related places may not be the same. An intermediate system receives recharge in a topographic high and has discharge in a topographic low, further away. A regional system receives recharge at the ground-water divide and has discharge at the bottom of the basin. Intermediate and regional systems have smaller recharge areas than local systems and are, therefore, much less influenced by climatic variations. They also have smaller amounts of recharge and longer flow paths. The resulting slow motion of the ground water increases the chances of it becoming mineralized.

Toth also discussed the effects of topographic variations on ground-water flow systems. A general increase in the slope of the valley flank will result in increased lateral flow toward the bottom of the valley. Local systems will degenerate or vanish and allow new intermediate and regional systems to form. On the other hand, if topographic relief is increased, new and deeper local systems will form. Intermediate and regional systems may vanish in areas of high topographic relief. Under extended flat areas, ground-water movement is
Figure 16.
retarded and neither regional nor local systems will develop. In this case ground water will only be discharged by evapotranspiration, and water-logged areas may form.

Freeze and Witherspoon (1967, p. 623-634) used digital computer solutions of hypothetical models to explain the effects of water table configuration and subsurface permeability variations on the ground-water flow systems. They introduced nonhomogeneous and anisotropic conditions into their models. Their study covered only a fraction of the possible combinations of water table configurations and subsurface permeability variations that may exist in a basin. Freeze and Witherspoon (1967, p. 633) said, "there is very little generalization possible regarding the effect of irregular geologic configurations. It is safe to say, however, that the introduction of discontinuities (partial layers, lenses, and sloping beds) will result in the formation of small sub-basins that did not exist in the homogeneous case".

Figure 16 (C, D, E) gives some examples of ground-water flow systems that are affected by geologic discontinuities. In 16 C the upper beds are underlain by a more permeable layer. This has the effect of making the vertical components of flow in the upper layer much more pronounced than they were in 16 A. The recharge area of the upper bed also increases. Freeze and Witherspoon (1967, p. 633) state that, "The effect of introducing a high-permeability aquifer into the system is to create a highway for ground-water flow such that the percentage of flow traversing the entire basin increases".

If the high permeability bed is pinched out (Fig. 16 D) recharge
and discharge areas are created where they would not be anticipated. Almost all of the flow that had entered in the upper half of the basin is discharged in the middle of the slope. Under strictly topographic control, this would be impossible (Freeze and Witherspoon, 1967, p. 629).

If sloping layers are introduced into the ground-water system, further variations in flow are observed. Figure 16 E shows a high permeability bed that is dipping into the slope of the valley. This causes ground-water discharge to occur where the aquifer crops out and also in the valley bottom. In this case, ground-water moves up the dip of the aquifer.

It must be remembered that these mathematical models were developed for hypothetical basins under idealized conditions. In nature, an infinite variety of ground-water situations can be found. However, an understanding of the theoretical models is necessary to describe the ground-water flow systems.

Flow Systems in Little Long Valley and Upper Dry Valley

Upper Dry Valley and Little Long Valley can be divided into ground-water flow systems. A ground-water flow system includes all flow lines from a recharge area to a discharge area. The boundaries of a flow system depend upon lithologic, structural, and surficial features which affect ground-water flow through geologic material. These boundaries can be, but are not necessarily, at topographic divides. The amount of ground-water available within an area depends on both the character of the geologic material, and the amount of ground-water recharge that takes place. Ground-water discharge can take place
by springs, seepage, and evapotranspiration, or artificially, through wells.

For this report, the ground-water flow systems that are being analyzed in detail are in; 1) the folded and faulted consolidated sedimentary rocks in the southeast end of Little Long Valley (Fig. 17); and 2) the unconsolidated sediments in Upper Dry Valley (Fig. 18). These flow systems are representative of the two basic types of ground-water conditions found over the entire area. However, the geologic conditions vary greatly from one geographic area to another. Therefore, each area must be studied in detail in order to define the specific ground-water flow systems within it.

Little Long Valley is in a consolidated sedimentary rock area. Ground-water movement occurs primarily through permeable zones developed from fractures and solution cavities in the rock. The alluvial-col-luvial valley fill material is thin and discontinuous, and is not a major factor in ground-water flow. Landslide debris causes locally thick deposits of unconsolidated material, but probably does not affect the regional ground-water flow systems.

The geology of Little Long Valley is exceedingly complex and the ground-water flow systems are correspondingly complex. Figure 19 shows some of the stratigraphy and the structure in the east wall of Triangle's phosphate mine in Little Long Valley. The faults can displace permeable beds and block the flow of water, or they can transfer water from one permeable bed to another, or to the surface. Figure 20 shows the synclinal and anticlinal structures that affect the ground-
Figure 17. View of Little Long Valley

Figure 18. View of flat alluvial-colluvial valley fill in Upper Dry Valley
Figure 19. View of east wall of Triangle's phosphate mine in Little Long Valley

Figure 20. Stereogram of Little Long Valley
water flow in Little Long Valley. Transverse faults offset the axis of the syncline in several places.

Figure 21 is an idealized cross section showing a possible ground-water flow system in Little Long Valley. This figure will be used to help illustrate various factors that influence the occurrence and distribution of ground water in the consolidated sedimentary terrain. Ground-water flow is generally from the ridge tops to the valley bottom. This takes place by local, intermediate, and regional systems. The main valley aquifer is thought to be the fractured calcareous siltstone that was penetrated in drill hole 7S-43E-3ad1 (Fig. 15) and was tested by the "slug" method (Table 1).

Ground-water recharge to the main valley aquifer takes place both at the synclinal axis in the east ridge of Little Long Valley and at the anticlinal axis outside of the valley. Fractures and longitudinal faults in the axes of these folds increase vertical permeability. The faults are believed to transect all of the geologic formations and allow the passage of water from one layer to another. The water then spreads laterally into the more permeable layers under confined conditions.

In order for ground-water recharge to occur certain other conditions must be met. Soil moisture requirements must be satisfied before recharge can take place. The anticlinal and synclinal axial traces are forested and have relatively thick soil. In addition, the synclinal axial trace occupies a topographic low (Fig. 21). The loose soil and abundant forest litter combine to give high infiltration rates and high
Figure 21
Idealized hydrogeologic section (A), and hypothetical ground-water flow diagram (B), of Little Long Valley.
soil moisture storage potential to the axial areas.

Ground-water recharge in Little Long Valley probably occurs during the spring snowmelt. During this time the snow pack becomes saturated and cannot hold any more water. As a result, spring rains percolate through the snow and saturate the underlying soil. Excess water either runs off the soil or moves down into the ground-water system under the influence of gravity. The lack of any well defined stream channels in the recharge areas suggests that much of the rain and melting snow infiltrates into the soil.

As was indicated earlier, snow tends to blow off the southwest facing slopes and accumulate on the northeast facing slopes. Thus, large snowdrifts accumulate over both of the recharge areas. These drifts are at a high elevation and are protected from the direct rays of the sun by both their northeast exposure and the forest cover. Therefore, meltwater from these drifts keeps the soil moisture requirements satisfied, and continues to recharge the ground water longer than in other areas. Later in the year, summer rains are not frequent enough to keep the soil saturated. This results in the termination of ground-water recharge and the beginning of soil moisture utilization. During the late summer months, soil moisture in the recharge areas is discharged by evapotranspiration processes. Ground-water recharge is thus an intermittent and irregular process and does not occur throughout the year.

The vertical movement of water in the recharge areas is probably blocked at some depth by either the closing of the fractures with depth, or by an impermeable boundary. A thick, massive unit of chert acts as
an impermeable boundary in parts of Little Long Valley. Water was observed issuing directly from the contact between the chert and the overlying material, close to the Angus Creek Spring (Fig. 8). As was described earlier, the tight massive chert is being used for a hydrogeologic classification, based on lithology and structure. It does not include the entire Rex Chert Formation, which is a time-stratigraphic unit. The unfractured, massive chert, used here in its hydrogeological sense, is just one rock unit that may be repeated many times in the Rex chert formation. Other rock units in the formation may be of different lithologies and have different structural characteristics. Therefore, they would have different hydrogeological properties and would be defined as such.

Discharge areas along the east ridge of Little Long Valley, occur at both the valley bottom and along the sideslopes (Fig. 21). These discharge zones are related to permeable layers within the consolidated rock sequence. Some of the discharge zones are seepage and can be traced laterally along the slope of the valley, while in others the discharge is concentrated in the form of springflow (Fig. 14). The concentration of discharge is believed to be related to the transverse system of faults that crosses the ridge. Ground water moving under confined conditions down the plunge of the structures is transferred to the surface through the more permeable fault zones.

Other ground-water discharge occurs along the thrust faults that are common in this area. Water moving in the permeable layers is blocked by more massive, impermeable beds of another unit. The water then moves up the fault zone and discharges at the surface (Fig. 21).
Even where there is no seepage or springflow, ground-water discharge occurs as evapotranspiration. Wherever the capillary fringe nears the surface, the root systems of plants provide a direct route for ground water to get to the surface by transpiration processes. Direct evaporation from the soil surface is an effective means of ground-water discharge in the upper three feet (.9 m) of sandy soils and in the upper 10 feet (3.0 m) of clay soils (Davis and DeWiest, 1966, p. 19). However, direct evaporation is generally not as important a discharge mechanism as is the use of water by plants.

The west ridge of Little Long Valley is not as important, as a source of ground-water recharge to the valley aquifers, as is the east ridge. The lack of interconnected fractures to induce vertical permeability and the tree covered dip slope probably combine to keep ground-water recharge at a minimum. Although melting snow and spring rains probably infiltrate into the soil, they are blocked from entering the ground-water system by clay subsoil and unfractured bedrock. Excess water is, instead, directed by surface runoff and interflow into the valley. This is shown by well defined runoff channels that originate on the west ridge (Fig. 13). These channels are dry except during times of high runoff.

Some ground-water recharge does take place where permeable units crop out at the surface. This water can be discharged further downslope by evapotranspiration processes or else in a fault zone, as shown in Figure 21. Because of its southwest exposure and steep slope, it is unlikely that ground-water recharge takes place on the Wooley Valley
side of the ridge. There, snow would be blown off the ridge, and snow-melt would not be a major factor.

It is possible that some ground-water recharge takes place in the phosphate rock zones in Little Long Valley. This is because of their position on a topographic bench right above the final break in slope, and because of the coarse oolitic texture of the phosphorite. However, the small areal extent of the deposits and the character of the surrounding material make it unlikely that this recharge is significant to the valley aquifer.

Upper Dry Valley is in an area of unconsolidated sediments. The alluvium and colluvium lie unconformably on consolidated, sedimentary bedrock. The floor of the valley is relatively flat and consists of alluvial material (Fig. 18). The first slope in the east side of the valley wall consists of colluvial material and alluvial fans (Fig. 11 and 22). From the first slope, to the top of the ridge, and also behind the ridge, is all consolidated sedimentary rock (Fig. 22 and 23).

An idealized hydrogeologic section of Upper Dry Valley will be used to help illustrate various factors that influence the occurrence and distribution of ground water in the nonindurated sediments (Fig. 24).

As was mentioned earlier, alluvial fans are a good area for ground-water recharge. In Upper Dry Valley, alluvial fans occur both as new, recently formed deposits and as older, partly eroded material. Most of the surface water, that originates from rainfall and melting snow on Dry Ridge, seeps into the permeable fan deposits before it reaches the valley floor (Fig. 24). Where the alluvial fans are not present, there is a constant slope of colluvial material. This slope
Figure 22. View of alluvium, colluvium, and consolidated sedimentary rock contacts, in Upper Dry Valley.

Figure 23. Stereogram of Dry Ridge and Upper Dry Valley.
Figure 24. Idealized hydrogeologic section of Upper Dry Valley (A), and hypothetical ground-water flow system through a section of valley fill (B).

**EXPLANATION**
- ☑️ gravel
- ☑️ sand
- ☑️ bedrock
- ☑️ clay
- ➡️ flow line
- ➡️ mudflow
is usually covered with deep-rooted trees. It also acts as a regional ground-water recharge zone to the valley aquifers (Fig. 16 A).

The main aquifers in Upper Dry Valley are coarse-grained, non-indurated deposits such as gravel and sand. They occur in multiple layers which are separated from each other by thick zones of clay. This results in confined conditions under much of the valley. However, unconfined conditions are also present where a confining layer has not been deposited or has been eroded away. The small depression shown in Figure 24 B would have an unconfined situation in the upper aquifer. It is likely that the water table would be at the surface during times of high spring runoff. This would result in a wet spot on the valley floor, that would gradually dry up as the water table lowered, towards the end of the summer.

Not all of the sediments in Upper Dry Valley are unconsolidated. Some early deposits have been partly or fully indurated (Fig. 15). Many of these partly consolidated sedimentary rocks have been tilted and displaced by episodes of normal faulting and are sometimes brought close to the surface by structural highs (Fig. 24). Ground-water flow characteristics in these zones are similar to those in the consolidated sedimentary rocks, that were outlined earlier.

The effects of faulting and fracturing in the unconsolidated valley fill are not as noticeable as they are in consolidated rocks. The younger the material, the less faulting it has been subjected to. The folds and the faults associated with the Laramide orogeny occurred before any of the valley fills were deposited. Also, many of the normal
faults in the area have affected only the older valley fill material. Even when faulting does offset the more recent deposits, surface traces of the faults are quickly obscured by active alluvial and colluvial processes. The effects of faults are still present, however, and they can alter the ground-water flow systems. Faults can displace or eliminate permeable units and create recharge and discharge areas where they would not be anticipated.

It must be emphasized that the ground-water flow systems that have been described in Dry Valley and Little Long Valley are based on idealized hydrogeologic sections and on hypothetical flow diagrams. Nevertheless, they illustrate many aspects of the ground-water conditions that are found in consolidated sedimentary rocks and in nonindurated sediments in the phosphate area. Although the geologic conditions will vary from place to place, the hydrogeologic principles will remain constant. On this basis, the flow system concept, described in these analyses, can be extended to include other valleys in the phosphate area.
DRY VALLEY AND LITTLE LONG VALLEY
AS REPRESENTATIVE HYDROGEOLOGICAL AREAS

Rasmussen Valley, Slug Creek valley, and Diamond Creek valley all have geological, geographical, and climatological characteristics that are similar to those in Dry Valley and Little Long Valley. The hydrogeological characteristics are also similar.

The entire five valley area is underlain by folded and faulted sedimentary rocks of late Paleozoic and early Mesozoic age. These rocks were involved in the Mead thrust of the Laramide orogeny. They were compressed into a series of north and northwest trending folds. Some of the folds plunge and some are overturned. All of the folds have been eroded to expose underlying rocks.

Normal faults and crustal warps produced most of the present relief in the area. Aspen Range, Preuss Range, Schmid Ridge and Dry Ridge are all fault-block mountains with normal faults along their western margin (Cressman, 1964, p. 80). A valley fill of alluvial and colluvial material has been deposited unconformably on the older rocks in some of the valleys. Normal faulting has been continuous through recent times and has tilted and displaced some of the layers of valley fill material.

Dry Valley, Rasmussen Valley, Slug Creek valley, and the northern part of Diamond Creek valley all have extensive deposits of valley fill material. The southern part of Diamond Creek valley and Little Long Valley have thin and discontinuous deposits of valley fill material. The higher elevation valleys of tributary streams often have no extensive
alluvial or colluvial deposits.

Surface drainage in the five valleys usually follows the north-west structural trends. Exceptions occur where transverse faults have created weak zones in the ridges. Here the drainages make right angle bends toward adjacent valleys. This creates a water gap and allows surface water to flow from one valley to another. Angus Creek flows from Little Long Valley to Rasmussen Valley in this manner. Surface water in Upper Dry Valley drains into Slug Creek through two water gaps in Schmid Ridge. Ground-water flow does not necessarily follow surface water flow.

The precipitation patterns in the five valleys vary according to the elevation. The ridge tops receive more total precipitation and more snowfall than the valley floors. However, the elevation of the valley floors and the ridge tops increases toward the southern and western parts of the area. This results in the highest relative amounts of precipitation on the southern end of the Dry Valley and Diamond Creek valley areas.

Upper Dry Valley is representative of the hydrogeological system present in the valley fill type material. This system is present in any area where alluvial and colluvial deposits are thick. Rasmussen Valley, northern Diamond Creek valley, and Slug Creek valley probably have these systems.

Little Long Valley is representative of the hydrogeological system that is present in the bedrock areas. The alluvium and colluvium is thin and discontinuous and probably not a major factor in the
ground-water flow system. Southern Diamond Creek valley and the higher elevation, tributary stream valleys, probably have these systems.
GROUND WATER AND LAND USE PLANNING

Ground water in Upper Dry Valley and Little Long Valley is an important consideration in land use planning. Several conclusions can be reached from hydrogeologic investigations, regarding the impact of mining on ground water, and the impact of ground water on mining. These conclusions are interpretive. They are based on an analysis of the hydrogeologic units and of the ground-water flow systems in the two valleys. Test drilling and further hydrogeologic investigations will be needed to substantiate the results.

A large area of ground water within 50 feet (15 m) of the surface can be expected in the bottom of Little Long Valley (Fig. 25). Open pits in this zone would probably intercept significant quantities of ground water and make pumping necessary. This area is being recharged by a massive flow system that has developed on the northeast ridge. Surface disturbances in this area would probably affect the valley aquifer. A surface mine in the ore zone along the southwest side of Little Long Valley (Fig. 25) would probably not intercept large quantities of ground water. However, some diffuse ground-water flow could be expected along the fault zone and along some coarse-grained sandstone aquifers. A surface disturbance in this area would probably not affect the main valley aquifer. This is because of the small ground-water flow system that has developed along the southwest ridge and because of the hydrogeologic characteristics of the mudstone, shale, and chert. Direct runoff during times of spring snowmelt would be an important consideration on the southwest ridge.
Figure 25. Ground water recharge sketch map for the southeast end of Little Long Valley.
A large area of ground water within 50 feet (15 m) of the surface can also be expected in Upper Dry Valley (Fig. 26). Open pits in this area would probably intercept significant quantities of ground water in the valley fill material, and make pumping necessary. Flow volumes, as indicated by the aquifer tests, would be larger in Upper Dry Valley than in Little Long Valley. Also, it is likely that more than one aquifer system would be encountered, as indicated by the test drilling. Recharge areas for the Dry Valley aquifers would be in the valley fill close to the bedrock contacts (Fig. 26). Alluvial fans would be especially important recharge areas. Surface disturbances in the recharge areas would probably affect the valley aquifer. The bedrock areas in Upper Dry Valley direct water to the valley aquifers by both ground-water flow and direct runoff. This should be considered if surface disturbances are planned for the bedrock areas.
Figure 26. Ground-water recharge sketch map for the north end of Upper Dry Valley.
CONCLUSIONS

1. Geologic and hydrologic factors control the occurrence and distribution of ground water in the Dry Valley-Little Long Valley area. Geologic factors, such as structure, lithology, and surface features, can be used to describe the hydrogeologic units that will contain and transmit water similarly. Hydrologic factors, such as precipitation, snowmelt, evapotranspiration, and runoff can be used to estimate the amount of water that is available for ground-water recharge. Together the geologic and hydrologic factors can be used to define a ground-water flow system.

2. Two basic types of ground-water flow systems can be described. These flow systems are in: a) the consolidated sedimentary rock, and b) the alluvial-colluvial valley fill material. Aquifers in the valley fill material will generally have larger hydraulic conductivities than those in the consolidated rock.

3. These two basic types of ground-water flow systems are representative of other flow systems found throughout the Dry Valley-Little Long Valley area. The flow systems in the valley fill material occur wherever extensive alluvial or colluvial sediments have accumulated, such as in Upper Dry Valley. The flow systems in the consolidated sedimentary rocks usually occur in the higher elevation areas where valley fill is not present, such as in Little Long Valley.

4. The hydrogeology of an area in the phosphate region can be studied by several methods. Surficial methods, such as geologic mapping, remote sensing, and geophysical exploration, give indirect indications
of the ground-water system. Subsurface methods, such as test drilling and aquifer tests, substantiate the surface interpretations. Theoretical methods tie together the practical data and allow flow systems to be delineated. Only after an integrated analysis of all the data, can maps and cross sections be drawn to show the hydrogeologic units and the ground-water flow systems.

5. The hydrogeologic units and the ground-water flow systems in the southeast end of Little Long Valley can be delineated. Three general groups of consolidated sedimentary rocks control the ground-water flow. Most of the water in the main valley aquifer originates on the northeast ridge. It flows in confined conditions through thin-bedded, fractured siltstones. Large amounts of ground-water recharge occur in the axes of folds. Spring flow occurs where transverse fault zones displace the aquifers and where a massive chert unit blocks the flow of water. The southwest ridge of Little Long Valley is not an important recharge area for the main valley aquifer.

6. The hydrogeologic units and the ground-water flow systems in northern Upper Dry Valley can be delineated. The higher elevation bedrock areas direct water to the more permeable valley fill material. The alluvial-colluvial aquifers are recharged through coarse-grained material at the bedrock-valley fill contact. Significant recharge takes place through alluvial fan deposits. A multiple aquifer system probably exists in the valley fill. These aquifers are in sand and gravel and are often not continuous.

7. Ground-water data from a study such as this can be used to
make interpretations for land use planning. The effect of proposed mining activity on the ground-water system and the effect of ground water on proposed mining activity can both be qualitatively evaluated. The proposed surface mine along the west ridge of Little Long Valley will probably have little impact on the flow system in the main valley aquifer. Significant quantities of ground water might be intercepted by surface mines in the valley fill material in Upper Dry Valley.
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