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GEOLOGY
OF THE
BIG VALLEY GEOTHERMAL PROSPECT,
LASSEN, MODOC, SHASTA AND SISKIYOU COUNTIES,
CALIFORNIA

for

AMAX EXPLORATION, INC.

by

GeothermEx, Inc.

October 1975

CONTENTS

ILLUSTRATIONS

After Page

Figures

Plates

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CONCLUSIONS

1. Big Valley lies to the east of a zone of Holocene volcanism and tectonic activity that extends from Lassen Peak northward through Fall River Valley and Medicine Lake Highland into Oregon. The area from the Big Valley Mountains eastward to the Warner Range shows less evidence of Quaternary volcanism and tectonism, and therefore is less attractive as a geothermal target.

2. Big Valley has not been active tectonically since middle Pleistocene time, except for minor crustal adjustments. No late Pleistocene or Holocene scarps and unconformities were observed.

3. There is no evidence of young volcanism within Big Valley, either in the form of eruptions or intrusions. Some Pleistocene basalt flows are found in the mountains to the south and west of the valley. A radiometric age-date of 6.7± 2.5 million years before present was obtained for the youngest-appearing rhyolite tuff at the southeast boundary of Big Valley.

4. Earlier geological studies of the Big Valley were found to be unreliable in details of stratigraphy, lithology and tectonic history. New map units and a new stratigraphic sequence are proposed. These include Miocene basalt and andesite flows, tuffs and breccias; Pliocene basalt flows, tuffaceous lacustrine sediments, and silicic tuffs and minor intrusions; probable Pleistocene basalt flows; and Quaternary fluviatile, lacustrine and alluvial sediment.

5. Hot springs in the area do not indicate a magmatic heat source by their chemistry and geological relationships. Surface temperatures of Little Hot Spring, Bassett Hot Spring and Kellog Hot Springs are about 80°C. All are probably associated with north-to-northwest-trending faults. Chemical contamination of the hot water by shallow ground water is possible, but less likely than the hypothesis that these waters have risen directly from depths of 1 or 2 kilometers with little cooling or mixing.

6. Geophysical information and well data indicate a horst of Miocene rocks in Big Valley in the vicinity of the hot springs. Geophysical evidence does not appear to support the alternative of a shallow, mafic intrusive body, either within Big Valley or to the south in the vicinity of the youngest silicic rocks.

7. Temperature gradients at 1-meter depth give evidence of northwest or north-south fracture control over surface discharges at Kellog Hot Springs. This supports the concept of deep circulation along fractures, and is in agreement with data from field and photogeology. No magmatic heat source is required to explain the geothermal phenomena.

8. Fractured basalt flows and silicic to intermediate-composition pyroclastic rocks probably occur at varying intervals from less than 2,000 feet in Big Valley to depths in excess of 10,000 feet. Fractured metasedimentary rocks may occur at greater depths. These rocks have the potential for serving as reservoirs of geothermal fluid.

9. There is a large amount of water in storage and a good recharge system in the Big Valley. Aquifer conditions and water chemistry are known only for the shallow aquifers, less than 2,000 feet in depth. Deeper aquifers, to about 2 kilometers, are suspected to contain saline hot water at temperatures of 120°C to 150°C. There is no evidence of a vapor-dominated system.

10. Experience in a similar geologic regime at Kelly Hot Spring supports the hypothesis of 150°C water at about 2 kilometers in depth. This experience includes drilling two holes, each to about 1 kilometer in depth.

11. The only target that is identified in Big Valley is a shallow objective near Kellog Hot Springs. A hole less than 3,000 feet deep, and probably no deeper than 2,000 feet, would test the concept of a convecting cell of geothermal water at 120° to 130°C at 1 kilometer, and perhaps at 150°C at 2 kilometers.

RECOMMENDATIONS

1. Do not continue exploration of the Big Valley area.
2. In the event it is decided to continue activities there, perform additional work as described below.
3. Obtain about 4 more K/Ar radiometric age-dates on grey tuffs associated with the youngest dated acidic eruptions and intrusions, and on the youngest-appearing basalts of the area.
4. Process existing gravity and magnetic data in search of possible magmatic intrusions beneath Big Valley and the area to the south near Hayden Hill.
5. Consider performing an active seismic experiment in Big Valley, to determine depth and configuration of high-velocity basement.
6. Drill one or more intermediate depth holes to no more than 3,000 feet in depth, in the vicinity of the Kellog Hot Springs. Log and obtain fluid samples from these holes.

INTRODUCTION

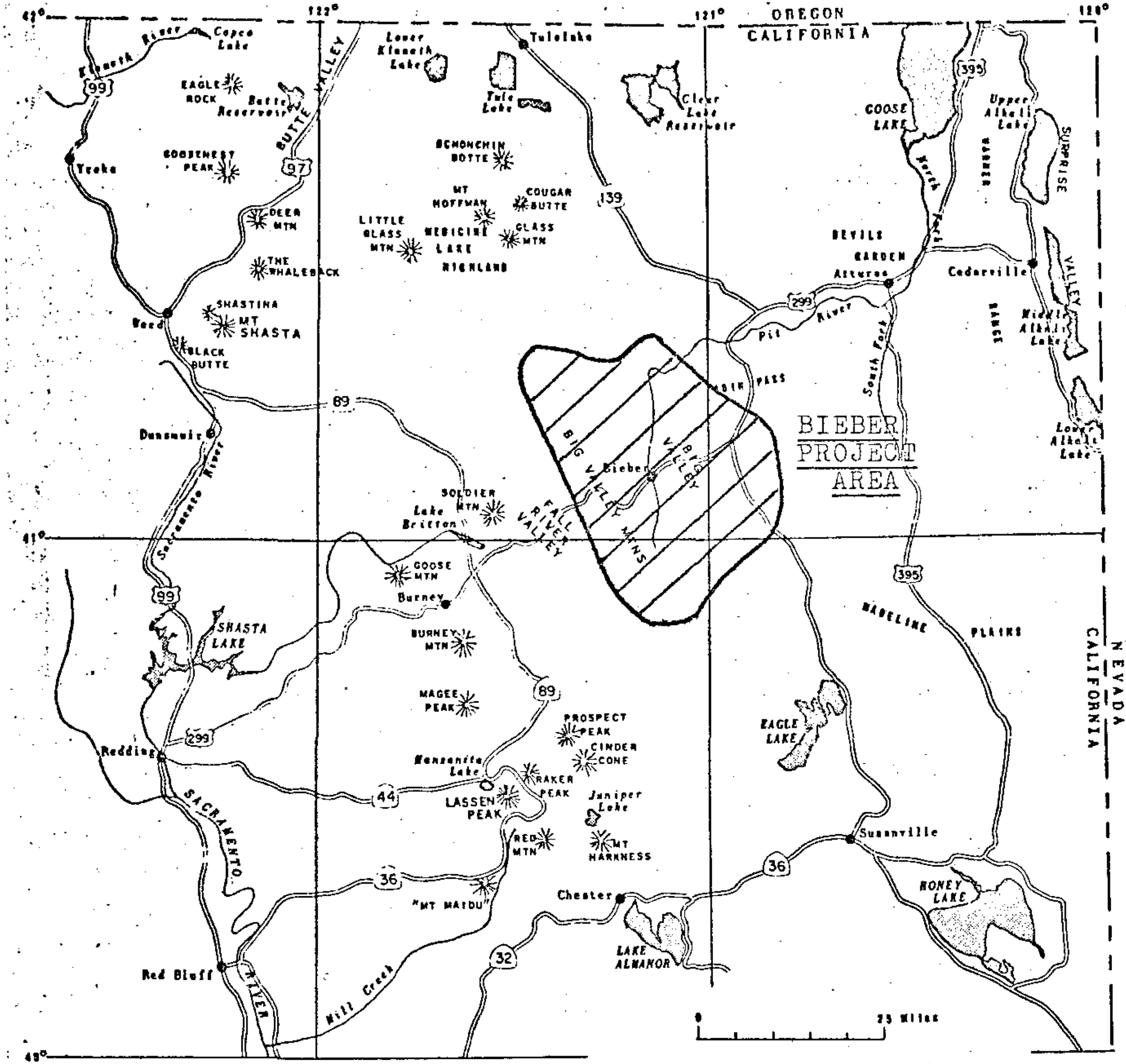
Location.

Bieber is a village in Big Valley, located on the west side of the Modoc Plateau of northeastern California. Both Bieber and Big Valley have been used informally as the title of this project. However, the latter is preferred, as the area under study includes an extensive area of Big Valley in northeastern Lassen County and southwestern Modoc County, and extends into Shasta and Siskiyou Counties (figure 1). It extends from the northern boundary of T. 36 N. to the northern boundary of T. 39 N., and from the center of R. 5 E. to the east side of R. 9 E. The project area includes part or all of the Bieber, Adin, Canby, Clark Mountain, Whitehorse, Fall River, Jellico, Little River and Hayden Hill 15-minute topographic quadrangles of the U. S. Geological Survey. The area falls on parts of the Alturas and Westwood 1:250,000-scale topographic sheets.

Purpose and Scope.

Geologic mapping was authorized in April 1975 by AMAX Exploration, Inc., with the objective of assessing the geothermal potential of Big Valley and specifically of the leaseholds available on option to AMAX in the valley. Geological goals have been to attempt to determine:

1. the existence and location of a heat source;
2. the depth to and configuration of the impermeable basement;
3. the thickness of potential reservoir rocks in Big Valley;
4. the origin and tectonic history of the valley; and
5. the nature of thermal fluids in storage beneath the valley.



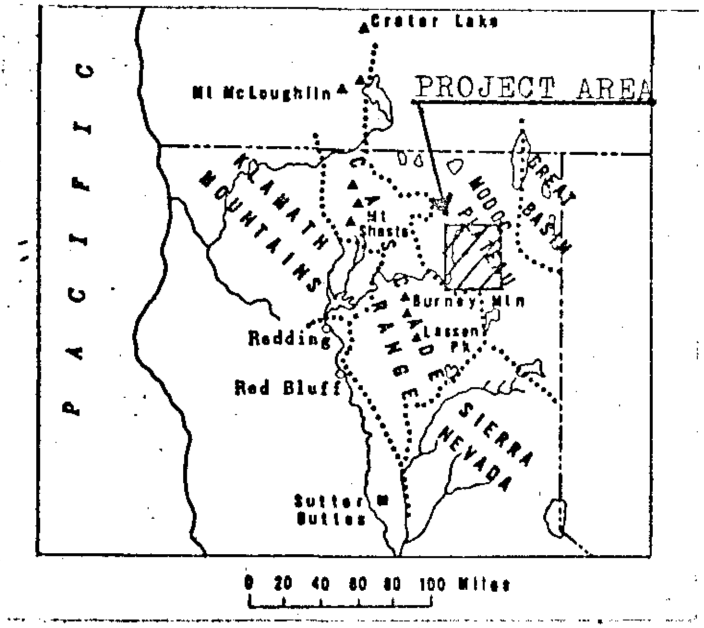


Figure 1. Big Valley project area, northeastern California

Specifically, the study focused on the lithologic sequences and the succession of deformation and volcanic events that took place during Miocene to Holocene epochs. It was anticipated that detailed knowledge of the geology of Big Valley would allow comparison with adjacent areas of the Modoc Plateau and Cascade Range, where Holocene volcanism has been evident.

Published and unpublished data were reviewed as the first phase of the project. Thereupon, geologic mapping and photogeology were carried out. A geologic map with accompanying cross-sections has been prepared (plate 1 and 2) for about 530 square miles. The area has been divided into inner and outer zones, in which the detail and precision of work varies. An inner area, consisting of about 110 square miles, is centered around leases held by Eason Oil Company in the southern part of Big Valley. Geological work here consisted of detailed field mapping and photo-geologic investigation. The area surrounding this central core was mapped by reconnaissance level field work and semi-detailed photo-geology (figure 2). Photograph scale varied from 1:15,840 to 1:60,000. Twenty thin-sections were made and analyzed, and two K-Ar age-dates were obtained. About 300 rock samples were collected.

Major emphasis was placed on identification of faults and joint systems in bedrock, and lineaments of possible structural origin in alluviated areas of Big Valley. Further emphasis was placed on the study of rock alteration and the identification of volcanic and intrusive centers. In addition, reservoir potential of various stratigraphic units was evaluated in hand-specimen and thin-section. Hydrological interpretation is based upon data provided by Frank Dellechaie and upon a review of published materials, as well as inspection of surface features. Aeromagnetic and gravimetric information was supplied by AMAX Exploration, Inc.

Prior Work.

Reconnaissance geologic studies of the area were published by the California Department of Water Resources (Ford et al., 1963), and the California Division of Mines and Geology, both as part of the state geologic map (Gay and Aune, 1958), and within the general geologic survey of

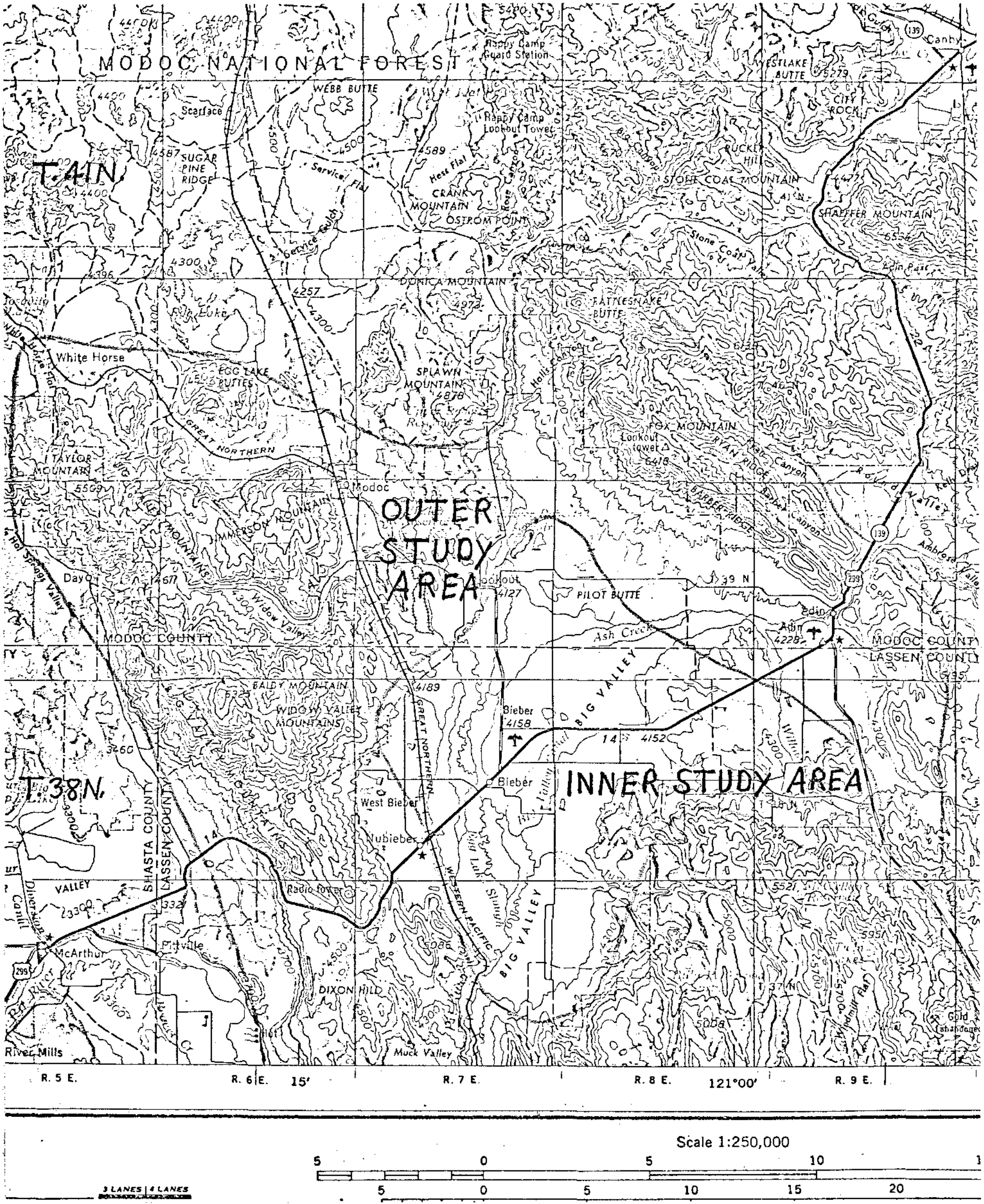


Figure 2. Topographic setting of the Big Valley area

northern California (MacDonald, 1966). The only detailed report on the area concerns the engineering geology of Allen Camp Dam Site, covering a few square miles at the northern edge of the project (California Department of Water Resources, 1964).

Regional geophysical reports covering the project consist of reconnaissance gravity and magmetic surveys (Eaton, 1966; LaFehr, 1965; Chapman and Bishop, 1968).

Outside of the project boundaries, important geological and geophysical work has been done around major Cascade Range volcanic centers. Among these are studies of the Mount Shasta region to the northwest (Williams, 1932, 1949), and Mount Lassen to the southwest (Pakiser, 1964; Williams, 1932; MacDonald, 1963, 1964, 1965). An area adjacent to the northwest boundary of the outer zone was studied in reconnaissance as part of a dissertation (Gardner, 1964, unpublished).

PHYSICAL AND ECONOMIC GEOGRAPHY

Physical Geography.

The Modoc Plateau geomorphic province is characterized by linear, northwest- or northward-oriented fault block mountains, separated by broad valleys floored with fluvial and lacustrine sediments or by basalt lava flows. Small to medium-sized basalt and andesite eruptive centers are scattered widely over the area. All of these landforms are relatively young and have undergone only minor modification by erosion. The relatively flat intermontane basalt flows gave rise to the term "plateau" for this topographically diverse region.

The boundary between the Modoc Plateau and Cascade Range province to the west is indefinite. Physical characteristics, structures and volcanic rock types of the two provinces are similar to some extent (Gardner, 1964 and MacDonald, 1966). To the east, the boundary between the Modoc Plateau and the Basin and Range province also shows a gradational character. Physiography, structures and rock types differ more in degree than in kind.

The project area consists of two fault-bounded mountain ranges and the valley between them. From east to west these topographic units are (1) Barber Ridge and Ryan Ridge, and unnamed hills on trend to the southeast of Adin; (2) Big Valley and an unnamed upland area extending across its southern end between Willow Creek and the Pit River, referred to here as the Juniper Creek Hills; and (3) the Big Valley Mountains (figure 2).

Barber and Ryan Ridges are narrow and parallel, and trend in a north-northwesterly direction across the east side of the project area. The maximum elevation of the double ridge is 6,394 feet at Fox Mountain, and decreases southeastward to elevations of 5,000 feet or less in the vicinity of Adin. Both sides of Barber Ridge are steep. The southwest face is more precipitous than the northeast face, and is a fault-line scarp developed from a major buried fault system bounding the east side of Big Valley. The ridge is cut by the Pit River at its north end and by Ash Creek at Adin.

Big Valley is a bilobate basin, the eastern part of which trends northwesterly. The western half of the valley trends almost due north. The valley as a whole is terminated on the south by the Juniper Creek Hills. It extends about 15 miles north, to the edge of a volcanic tableland. The valley has a maximum east-west extent of 14 miles, from Barber Ridge to the volcanic slopes and fault-line scarps of the east side of the Big Valley Mountains.

The elevation of the valley floor is about 4,200 feet. Relief in the valley is low, consisting of broad knolls rising a few tens of feet above the general level of the valley floor. The soil cover on these knolls is generally less than 5 feet thick. Two basalt-capped mesas, Roberts Butte and Pilot Butte, occur at the north end of the valley.

Three streams of significant size flow into the valley. Willow Creek enters from the southeast to join Ash Creek, which enters from the northeast, near Adin. The combined streams then flow west to Big Swamp. This swamp drains into the nearby Pit River in periods of high water. The Pit River enters the valley at its north side and flows due south. It leaves the valley through a steep-sided gorge as much as 250 feet deep, cut in Pleistocene basalt flows. In general, the meandering and swampy course of the Pit in Big Valley, combined with the gorge cutting at the south end, indicates that the river has not had time to adjust fully to the impediments of uplifted fault blocks and lava flows which developed across its course in Quaternary time (Hail, 1961).

The Big Valley Mountains, to the west of Big Valley, have a northwesterly trend within the project area, but this topographic trend changes to a more westerly direction several miles to the north. The ridge basically is a fault block uplift, with a major fault system along its west face and minor faulting along the east flank. This simple fault block is surmounted by large basaltic eruption centers, of probable early Pleistocene age. The eruptive centers are located at Jimmerson Mountain and in the complex of peaks at Widow Mountain. Small drainages within the range have a strong northwest orientation, controlled by faults and joints. In the areas dominated by eruptive centers, both the initial radial drainage and the northwesterly fracture-controlled drainage can be seen.

Elevations in the Big Valley Mountains range from 6,321 feet at Widow Mountain to 4,500 feet in the pass on U. S. Highway 299. The mountain uplift merges into flat-lying flood basalts at both its north and south ends. No drainage systems cut completely across the range, and Widow Valley is the only relatively large valley with a permanent stream invading far into the ridge.

The Juniper Creek Hills are an unnamed, dissected basalt plateau, capped by a few small eruptive centers, extending across the south side of the project area from the Pit River Canyon on the west to Willow Creek on the east. Elevations in the upper part of this hilly region generally are around 5,550 feet. The maximum elevation is 6,067 feet at the Bald Mountain eruptive center. The upland area has been dissected by numerous shallow, parallel drainages having a strong northwest strike. This drainage pattern appears to be controlled by a major system of northwest-trending joints or small faults. There are extensive poorly drained faults between the linear drainages, so that the area still appears to be in the youthful stage of the erosional cycle.

Economic Geography.

The total population of Lassen County in the 1970 census was 16,796. That of Modoc County was only 7,469. Slightly over 1,200 of these 24,000 persons live in towns and on farms in Big Valley. These include the small farming and lumbering communities at Adin in Modoc County (population 500); and Bieber (250 persons), Nubieber (200), and Lookout (100) in Lassen County. The surrounding mountains are essentially unpopulated.

Agriculture, logging and lumber processing are the chief economic activities of the region. Gold mining at Hayden Hill was formerly of some importance, and yielded $2,500,000 in gold and accessory silver from veins in rhyolitic tuff and breccia. Quarrying of volcanic materials for road construction is carried on intermittently.

The most important economic activity in the region is hay farming and grazing. Water for these activities is obtained from surface runoff retained in ponds and dams; directly from the Pit River and its few permanent tributaries; or from ground water (Ford et al., 1963). In general, more arable lands exist in the valley than can be irrigated with existing developed sources of surface and subsurface water.

Population of the region has been static, or has declined, through most of the past 50 years. Long-term economic outlook is somber, and will depend mostly on the prices paid for lumber, hay and beef.

The climate of the project area is characterized by low precipitation, warm dry summers and cold dry winters. The temperature ranges from summer highs in excess of 100°F, to winter lows reaching as low as -30°F. The valleys are usually frost-free from June until late September. This provides an unusually short growing season.

Mean annual precipitation in Big Valley varies from 10 to 18 inches. The year-to-year variation is considerable. At Bieber, the average annual precipitation is almost 17 inches. The precipitation in the upland area, exclusive of the mountain ranges surrounding the valley, ranges from 18 to 22 inches per year. The moisture falls as snow and rain in the period from October through April (Ford et al., 1963).

The area is crossed by two state highways. One of these, Highway 139, connects Bieber and Adin with Susanville, approximately 70 miles to the south. Highway 299 leads west to Redding, 90 miles from Bieber, and northeast about 50 miles to Alturas. Lines of the Burlington Northern and Western Pacific Railroads extend southward through the area from Klamath Falls, Oregon, with connections to Reno on the southeast and the Sacramento Valley on the southwest. Nubieber was built around the important rail junction between the Burlington and Western Pacific systems.

The floor in Big Valley is criss-crossed by a network of secondary roads and farm lanes, except within Big Swamp in the center of the valley. Barber Ridge and Big Valley Mountains are accessible through logging and Forest Service roads, although the higher and steeper portions of the ranges offer difficult passage.

Electric-power service is offered by Pacific Gas and Electric Co. in the southwest and by Pacific Power and Light Company in the northeast sectors of the region.

REGIONAL SETTING AND GEOLOGIC HISTORY

Rocks of the Modoc Plateau province are Oligocene to Holocene volcanic and sedimentary formations. However, the nearby Klamath Mountains, Basin and Range, Great Valley and Sierra Nevada provinces all contain older rocks, elements of which may project under the Modoc Plateau lavas. These rocks record a history of deposition and tectonism extending into Mesozoic and Paleozoic time.

During Paleozoic and Early Mesozoic time the entire region appears to have been the site of eugeosynclinal marine deposition. The oldest dated sedimentary rocks in adjacent regions are Ordovician slate, chert and limestone in the eastern Klamath Mountains to the west (Irwin, 1966). Similar sections, which include varying amounts of greywacke, tuff and metamorphosed rhyolite, andesite and basalt (Silurian through Early Mesozoic) are exposed in both the Klamath Mountains and northern Sierra Nevada province. Similar rocks of Late Paleozoic and Early Mesozoic age occur eastward in the Basin and Range province.

These assemblages contain immense thicknesses of slightly to moderately metamorphosed rocks. For instance, as much as 40,000 to 50,000 feet of Paleozoic and Mesozoic metasedimentary and metavolcanic strata are present in the northern Sierra Nevada province, about 65 miles due south of the project area (McMath, 1966).

Several periods of deformation are recognized for Paleozoic and Early Mesozoic time, culminating in the Nevadan Orogeny. The main part of this deformation took place prior to the intrusion of most of the magmas comprising the Sierra Nevada batholith. Radiometric age-dates on minerals produced during this plutonic activity indicates that it extended intermittently over a period from 210 million years before present (mybp) to about 80 mybp in various parts of the huge intrusive complex (Bateman and Wahrhaftig, 1966).

As a result of Late Mesozoic deformation and intrusion, these rocks crop out at present in four roughly parallel bands in the western Great Basin, northern Sierra Nevada and Klamath Mountains areas. From west to east, these are a zone of mainly Early Mesozoic rocks, a central area of Paleozoic rocks, a belt in which the largest of the Late Mesozoic intrusions is concentrated and an eastern zone in parts of northwestern Nevada of Early Mesozoic rocks.

The trend of these linear belts is northerly in the northern Sierra Nevada province, as far as the south edge of the Modoc Plateau and Cascade Range provinces, where the trends change to northwesterly, striking toward parallel structures in the Klamath Mountains (Bailey, 1966). Projections of these trends beneath the project area suggest that either the Sierra Nevada intrusive belt or the eastern zone Early Mesozoic slate, marble and metavolcanic rock would be present at some unknown depth below the surface.

While it is hazardous to speculate on the structures present in pre-Tertiary rocks beneath the project area, a northerly and/or northwesterly trend is present in the pre-Tertiary faults mapped in the northern Sierra Nevada (Bailey, 1966; Lydon et al., 1960). Although the faults cutting pre-Tertiary rocks belong to an older and different structural system, their trend is similar to that of many normal faults cutting Tertiary-Quaternary rocks on the Modoc Plateau. It appears that the old trends may have localized release of strain resulting from Tertiary stress fields in the younger materials.

Rocks post-dating the main orogenic and plutonic activity in northern California include Cretaceous clastic marine and Early Tertiary fluvial deposits, which are exposed in the Great Valley province, the western edge of the Sierra Nevada province, and parts of the eastern Klamath Mountains. Cretaceous marine rocks exposed in the western foothills of the Sierra Nevada and the eastern Klamath Mountains generally are referred to as the Chico Formation and Hornbrook Formation in their respective areas. These Cretaceous outcrops are the eastern edge of a great wedge of clastic sediment that thickens westward across the Great Valley into the Coast Ranges. Their extent eastward beneath the Cenozoic lavas of the Cascade Range and Modoc Plateau provinces is unknown, because of a lack of surface exposures and deep subsurface well data. Where last exposed in the Sierra Nevada foothills near Chico, the Cretaceous rocks are about 2,800 feet thick (Bateman and Wahrhaftig, 1966). However, in the outcrops of Mesozoic rocks closest to the project area, in the Big Bend of the Pit River, about 50 miles west of Bieber, Cretaceous rocks are absent.

The Early Cenozoic history of the region is unknown, and no pre-Oligocene rocks are known in the Modoc Plateau. In the Big Bend of the Pit River, mentioned above, fluvial gravels and carbonaceous non-marine shale and sandstone of a probable middle Eocene age are present in a section with a reported maximum thickness of 2,600 feet. These sediments are referred to as the Montgomery Creek Formation (Sanborn, 1960). Conceivably, non-marine deposits of this type could be present under the project area.

The Oligocene and later history of the Modoc Plateau region is dominated by the extrusion of immense volumes of volcanic rock and the accumulation of associated non-marine volcaniclastic fluvial and lacustrine sediments. Rocks of this type extend for hundreds of miles north and east of the project area, into Oregon and Nevada. The thickness of volcanic and volcaniclastic rocks present in these areas appears to presuppose the development of a major regional downwarp to receive the material. The Warner Range, about 60 miles northeast of Bieber, contains the most complete section of the lower part of the Cenozoic section thus far reported in the Modoc Plateau. As much as 7,500 feet of middle Oligocene to late Miocene are rocks are exposed there (Russell, 1928).

The Cedarville Formation consists of ash-fall and ash-flow tuffs, tuff breccias, lahars, agglomerates and associated lava flows and sediments. Andesitic materials predominate, but basalt flows are present and rhyolite or dacite is represented in the pumice-tuffs and in minor intrusive bodies (MacDonald, 1966). Lithologic equivalents of the Cedarville Formation were not recognized in the project area. However, a thick sequence of andesite tuff breccias, flows and lithic tuffs, and basalt flows on Barber Ridge may be their temporal equivalent, in part (figure 3).

In late Miocene or early Pliocene time the Modoc Plateau experienced the earliest significant stage of block-faulting. It is uncertain in this area whether arching was associated with deformation, as has been suggested in geologically similar areas in southern Oregon (Walker, 1963; Peterson and McIntyre, 1970). From middle Pliocene to Holocene time, large lakes formed in the graben valleys, contemporaneous with extrusions of basalt. Lake-basin sediments throughout a large area of northeastern California and southern Oregon are characterized by diatomite, siltstone, and fine- to coarse-grained basaltic tuff, basalt-derived clastic rocks and basalt flows. Variable amounts of acidic tuff occur and small intrusions of andesite to rhyolite composition also are present locally (MacDonald, 1966).

Building of large basalt shield volcanoes and andesite cones appears to have begun in Pliocene time and to have continued almost to the present, in both the Modoc Plateau and adjacent Cascade Range. Whereas basic magmas are the most widely distributed, Quaternary rhyolite and dacite are present in significant quantity at the Lassen Peak and Medicine Lake eruptive centers. Flood basalts filled the lowland areas, particularly late in the period. Deformation in later Pliocene and Quaternary time consisted of the continuation of northwest-oriented block faulting. Some faulting of this type has continued up to recent time in parts of the Modoc Plateau province, as for example along Hat Creek.

Details of this general history are illustrated in the project area. Events began with andesite-dominated volcanism in Miocene(?) time, followed by the extrusion of a thick sequence of upper Miocene basalts interbedded with more acidic pyroclastic rocks. These are seen in the Barber Ridge fault block. Faulting may have begun to define broad uplifts and basins in the region by this time.

A basin of deposition occupied most of the project area following this early episode of basaltic volcanism. This basin is believed to have extended far beyond the present limits of Big Valley and to have included part of the present Fall River Valley and Big Valley Mountains. Contemporaneous with basin development and deposition of lacustrine and fluvial sediments in it, large basalt piles were built on the site of the central Big Valley Mountains. To the south of Big Valley, intrusion and extrusion of acidic volcanic rocks and pyroclastics took place at Hayden Hill and probably other areas. These products acidic volcanism filled the lake basin in its later stages. They are believed to be of Pliocene age.

Erosion followed the basin filling, and extensive flood basalts were extruded over the basin deposits. A major period of faulting followed the deposition of these basalts. At this time the Big Valley Mountains were uplifted and outlines of the present-day topography began to emerge.

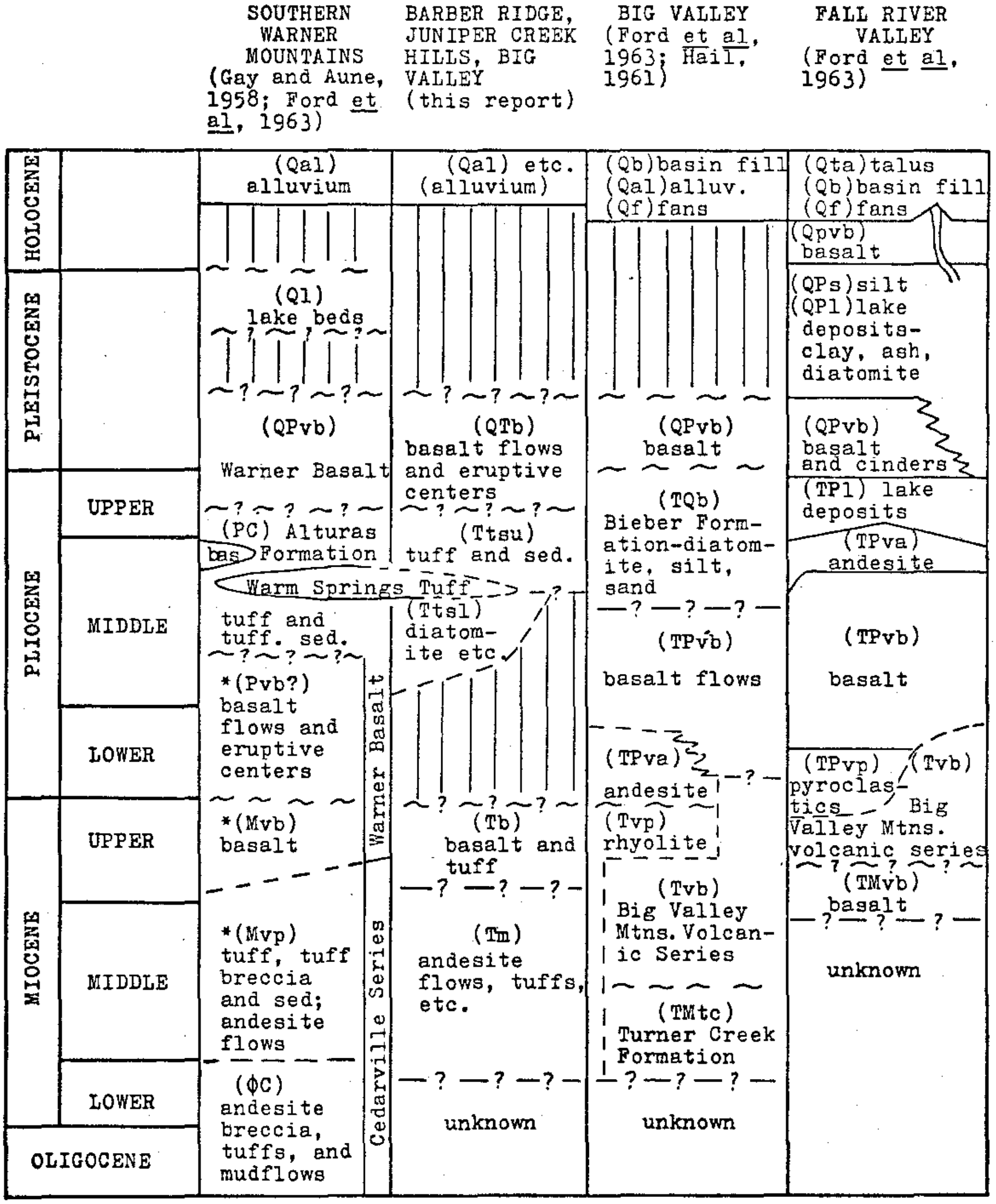
Further erosion in Big Valley was followed by the emplacement of additional thin flood basalts at lower topographic levels than the earlier flows. These in turn were eroded, and the valley reduced essentially to its present level.

In Fall River Valley, although not in Big Valley, construction of large basalt eruptive centers, extrusion of flood basalts, and normal faulting have continued into the Holocene epoch.

STRATIGRAPHY

Stratigraphic units present within the Bieber project area are shown in figure 3, and their relationships to regional stratigraphy are shown in figure 4. Geology is shown on plate 1; cross-sections (plate 2) accompany it.

Stratigraphic usage by Ford _et al_. (1963) could not be applied satisfactorily in every case. Therefore, descriptions of several units have been revised for use in this report, and none of the earlier formation names has been used. Correlation between the units used in this report and those of other workers in the region is tentative, as there are no regional stratigraphic studies for reference.



*identification, age, and stratigraphic position of units in the southern Warner Mountains is uncertain

Figure 4. Regional stratigraphic correlation chart, northeastern California

Miocene.

Miocene Volcanic and Volcaniclastic Rocks.

A thick sequence of lava flows and tuffs and tuffaceous sediments is exposed in fault-block ridges along the east side of Big Valley. The thickness of these rocks, exposed in incomplete, faulted sequences in Barber Ridge, may exceed 11,000 feet. Individual units in the section are lenticular; however, two thick members have been distinguished. Descriptions of these members are given below. In addition, detailed petrographic descriptions are presented as Appendix 1.

No identifiable fossils were found in the Miocene rocks during this study, but a middle Miocene flora has been reported from tuffs which may be part of the interval in the mountains east of Adin (MacDonald, 1966). A potassium-argon radiometric age date of 13.8 ± 2.4 mybp was reported by Teledyne Isotopes (see Appendix 2) for a sample of basalt from the upper part of this unit. This corresponds to an upper Miocene age. The lower part of the unit may extend back in time to middle or even lower Miocene epoch.

These Miocene rocks were part of the "Turner Creek Formation" of Ford et al. (1963). That formation never was described and defined adequately. Therefore, it was not used in the present study.

Andesite and Tuff (Tm).

This member of the Miocene volcanic sequence is the oldest stratigraphic unit exposed in the project area. Its most extensive area of outcrop is along the west side of Barber Ridge, between Howell Canyon and the Pit River: more than 2,000 feet of strata are exposed south of Black Butte. Neither the top nor the bottom of the unit is exposed. Its only contact with the overlying unit (Tb) appears to be a fault.

The unit is poorly exposed and details of the lithology are known only in small areas. It tends to form smooth, moderately steep slopes where tuffs predominate. Areas underlain by lava flows are characterized by poorly defined ledges. Dip slopes and ridge crests usually are underlain by flows also.

Individual strata appear to be lenticular, but there are some overall characteristics which distinguish the unit. From the scattered surface data, it is estimated that about 65 percent of the member is pyroclastic in origin, consisting of tuff breccia and air-fall tuff. About 15 percent is made up of tuffaceous sediments and about 25 percent consists of flows and flow breccias of andesite or basalt.

The most characteristic rock type is red, porphyritic andesite, containing phenocrysts of plagioclase and hornblende. The vesicles are filled with zeolite minerals, calcite or chalcedony. Calcite veins are common. A typical exposure of this lithology is in the southeast quarter of section 1, T. 40 N., R. 7 E.

Some of the tuffaceous rocks of this unit are green, apparently due to alteration. Fine-grained, tuffaceous sediments and lignite are reported from this member also, with petrified wood float associated with it. In general, unit (Tm) is distinguished by its abundance of andesite flows as compared to the predominantly basalt character in the overlying (Tb) unit. The degree of alteration and fracturing distinguish it from other, younger andesite units.

Basalt Flows, Breccias and Lithic Tuff (Tb).

This assemblage of interbedded basalt flows, flow breccias and lithic ash-flow tuffs is exposed on Barber Ridge, Ryan Ridge and in the hills southeast of Adin, along the east side of Big Valley. No complete section of these materials was found in the project area. Partial sections are present in several areas. In Turner Canyon, an estimated thickness of 3,500 feet of the unit is present, without either top or base being exposed. Local thickening of basalt flows and breccias may occur near buried vents.

Typical basalts of this unit are dark grey and fine-grained, with small (<2mm) phenocrysts of olivine and plagioclase. The olivine characteristically is altered to iddingsite, an important factor in distinguishing these flows from younger basalts.

Pyroclastic rocks, which make up the largest part of the member, consist of massive tuff breccias containing basalt fragments, and lapilli tuff with abundant white pumice fragments. These tuffs show a moderate to high degree of induration. Glass in the characteristic white pumice fragments appears to be devitrified, at least in surface outcrops. The pyroclastic units seem to increase in abundance upward in the section. Relatively good exposures can be seen along Ash Creek, immediately south of Adin.

The base of the (Tb) unit has not been recognized in or near the project area. In the hills south of Adin it is overlain by tuffs and tuffaceous sediments of the Pliocene (Tts) section. Because the contact is poorly exposed, conformability or lack of it could not be determined.

No fossils were found in the (Tb) unit. However, a thick section of similar basalt flows and breccias in Rush Creek (west-center of T. 40 N., R. 10 E.) is overlain by the middle Pliocene Alturas Formation of Warm Springs Valley. On the basis of this relationship, the (Tb) unit was considered to be of late Miocene age. A basalt sample from Barber Ridge (NE/4, Sec. 33, T. 40 N., R. 8 E.) was aged-dated by potassium-argon method. The 13.8 ± 2.4 mybp date supports the conclusions from field relationships.

Pliocene.

Several stratigraphic units in the project area are assigned to the Pliocene on the basis of radiometric age-dating, stratigraphic position or gross lithologic similarity to dated deposits in the region. No fossils were found in this part of the section.

The two main lithologic assemblages assigned to the Pliocene epoch on these bases are tuffaceous lacustrine and fluvial sediments (Tts) and basalt flows and eruptive centers (Tpb).

Tuffaceous Lacustrine and Fluvial Sediments, Ash-Flow Tuffs, and Minor Acid Intrusive Rocks (Tts).

Three main aspects of the (Tts) section were recognized in different parts of the project area: the section in the Juniper Creek Hills-Hayden Hill area; the surface and subsurface section in Big Valley proper; and the section exposed in the northwestern part of Big Valley Mountains. The relationships between the rocks in these different areas is not clear, due in part to facies changes in the assemblage.

The section in the Juniper Hills-Hayden Hill area is relatively well-exposed on forest roads in various locations. It consists of thinly bedded tuffaceous siltstone, which may be diatomaceous; poorly consolidated cross-bedded sands and pebbly sands; beds of massive, light-colored ash-flow tuff, with large, fresh pumice fragments; two, or possibly more, massive units of dark gray ash-flow tuff characterized by large fragments of black pumice, dacite glass and basalt; and at least two thin, glassy basalt flows showing evidence of extrusion into water. The massive tuffs appear to be thickest and most coarsely textured in the Hayden Hill area and in the hills to the east of Highway 139. The thin-bedded, fine-grained water-laid materials increase northward, toward Big Valley.

Small bodies of altered dacite or rhyolite intrude the tuffs near Hayden Hill (Sec. 26, T. 37 N., R. 9 E.). Altered andesite dikes intrude the unit at Little Gold Hill. The largest of these intrusions is only a few acres in extent. In both of these areas the surrounding tuffs have undergone silicification, kaolinization and zeolitic alteration. A gold mining district was developed at Hayden Hill in mineralization related to these intrusives. The intrusives are younger than the upper member tuffs which they penetrate, but they appear to be similar in composition to the tuffs and probably are essentially contemporaneous with them. This assemblage has been designated as (Ttsu) on the geologic map.

The section described herein is at least 1,000 feet thick. It appears to overlie (Tb) in the hills southeast of Adin, and it seems to grade laterally into and to overlie finer-grained tuffaceous and diatomaceous sediment of Big Valley. It is overlain by basalt flows of the (Tpbu) and (QTb) units along an erosional unconformity. Available attitudes are inconclusive as to whether this represents a low-angle unconformity.

The old erosional surface developed at this horizon is notable for the presence of scattered, well-rounded quartzite pebbles and cobbles. The origin of these quartzite clasts presents an unsolved problem in regional geomorphic history, because no quartzite horizons are known in the pre-Tertiary rocks in this region. Elsewhere in the Pacific northwest, such clasts in Tertiary rocks are thought to have been derived from ancient miogeosynclinal quartzites. Their presence at depth beneath the Big Valley area or its hinterland is problemmatic.

The (Ttsu) unit is the most recent product of acidic volcanism in the project area. Therefore, its age is important. To establish this age, a sample of welded tuff from near the top of the section in the Hayden Hill area (NW/4, Sec. 35, T. 37 N., R. 9 E.) was submitted for potassium-argon dating. A middle Pliocene age-date was obtained (6.7 ± 2.5 mybp). This is in accord with observed field relationships. Additional confirming evidence of the age of this sequence is found in the distribution of the unusual dark grey lithic tuff containing black pumice, occurring about 200 feet stratigraphically below the top of the section in the west half of Sec. 26, T. 37 N., R. 9 E. Tuff of this appearance also is present in two massive beds in the middle Pliocene Alturas Formation, in Warm Springs Valley, about 25 miles northeast of Adin, and in several other areas east of the Juniper Creek Hills. However, the various exposures of grey lithic tuff may be of different ages, reflecting different eruptive events.

The (Ttsu) unit appears to grade laterally and downward from Juniper Creek Hills into the diatomaceous and tuffaceous sediments (Ttsl) of Big Valley. No clear structural separation of the hills from Big Valley could be established. Therefore, the topographically high Juniper Creek Hills section is interpreted as part of a continuous sequence extending between the valley subsurface and the hills.

The rocks here called (Ttsu) were part of the section mapped as "Miocene-Pliocene(?) Turner Creek Formation" by Ford _et al_. (1963). We propose an alternative interpretation, in which the tuffaceous rocks of the Juniper Creek Hills are included within the Pliocene basin-filling deposits, rather than being a part of the time-transgressive Miocene-Pliocene(?) undifferentiated complex.

Fine-grained sediments seen in weathered outcrops and wells in Big Valley have been designated on the map as (Ttsl). Surface exposures of (Ttsl) are limited to a few tens of feet of section in any one locality. The characteristic lithologies are white, tuffaceous diatomite in beds up to 10 feet or more thick, and thin-bedded grey sandstone containing basalt fragments. Typical examples of these lithologic types can be seen in SW/2, Sec. 2, T. 38 N., R. 8 E.; NE/2, Sec. 20, T. 39 N., R. 6 E.; and in NE/4, Sec. 24, T. 39 N., R. 8 E. Cross-bedded fluvial sands are present locally. Thin scoriaceous basalt flows were extruded into the lacustrine beds in the northern and northwestern parts of the area. There is an exposure of these flows in a road cut in the center of Sec. 23, T. 40 N., R. 7 E. These may be the distal ends of flows originating in eruptive centers in the northern Big Valley Mountains or the Egg Lake Butte region.

Much more complete sections of (Ttsl) have been encountered in water wells drilled in Big Valley, where it is estimated that more than 1,200 feet of fine-grained lacustrine sediment are present (California Department of Water Resources well BV-2, located in SE/2, NW/4, Sec. 26, T. 39 N., R. 7 E.). Gravity data indicate that this well is in a structural low within the valley. This depression appears to contain the thickest (Ttsl) accumulation in the valley. By analogy, another area in which a thick section of (Ttsl) may be present is within the gravity low centered in the southeast corner of T. 38 N., R. 7 E.

No detailed logs are available, but Hail (1961) described the subsurface section as consisting of poorly-consolidated pebble gravel, pumiceous sandstone, volcanic sandstone, siltstone and diatomite. He interpreted the record to indicate that about 50 percent of the unit is made up of diatomite, occurring in beds from 2 feet to nearly 200 feet in thickness. Of the other lithologic types reported, siltstone predominates. It occurs in beds up to 100 feet thick. Gravel beds average about 10 feet thick, but may range up to 40 feet. They make up less than 10 percent of the section. Various types of sandstone occur in beds up to 60 feet thick. These clastic beds are believed to be lenticular.

The relationship of the (Ttsl) unit to older rocks is not exposed in any field locality, and none of the well logs in Big Valley provides information on the materials underlying it. On the west side of the valley, general field relationships suggest that the basalt flows of the southern Big Valley Mountains (Tpbl) are older than (Ttsl) and underlie the unit at least locally. Farther north, along the west side of the valley, the large basalt eruptive centers of Widow Mountain and Jimmerson Mountain appear to be either contemporaneous with or slightly younger than (Ttsl). Evidence for this relationship comes from Widow Valley, where (Ttsl) diatomite appears to be overlain by basalt (Tpbu) of the Jimmerson Mountain-Widow Mountain eruptive complex (center of T. 39 N., R. 6 E.).

Along the east side of Big Valley, (Ttsl) sediments appear to be in fault contact with Miocene volcanic rocks (Tb) along a concealed fault bounding the west-southwest side of Barber Ridge.

In most of Big Valley, (Ttsl) either is exposed at the surface or is overlain by youthful swamp deposits, stream sediment or fans. However, at the north end of the valley (Ttsl) is covered by flood basalts of the (QTb) unit.

The (Ttsu) unit has been deformed by faulting, with attendant tilting. Dips up to 20° are seen occasionally near probable faults, although in general the dips are low. There is no outstanding difference between the degree of deformation of (Ttsl) in Big Valley and the (Ttsu) of the plateau to the south.

No fossils were found in (Ttsl) sediments during the present study. Similar deposits in other parts of the Modoc Plateau and adjacent areas in Oregon have yielded diatoms, megafloras, non-marine gastropods, and a few vertebrate remains, which have given ages varying from middle Pliocene to Pleistocene (MacDonald, 1966). Obviously, not all diatomaceous lakebed sediments accumulated at the same time in this broad region.

Ford et al. (1963) included two important outcrop areas of our unit (Ttsl) in their Miocene volcanic assemblage, "Turner Creek Formation." One of these areas is at the northern end of Big Valley, around Splawn Mountain and Donica Mountain. The rocks exposed there are diatomite, grey tuffaceous sandstone with basalt fragments, and vesicular intralacustrine basalt flows. This assemblage is similar in appearance to the typical Pliocene assemblage in the region. In the absence of precise dating these deposits have been included in (Ttsl) in our report.

A second important area mapped as Miocene by Ford et al. (1963) extends along the northeastern side of Big Valley, west of Barber Ridge, from Adin to Rattlesnake Butte. There are only a few outcrops in this area, and these are diatomaceous and basaltic sediments which have a typically (Ttsl) aspect. Further, the boundary between these sediments and the basalts (Tb) of Barber Ridge is a fault along which the valley sediments have dropped down relative to the basalts. In the interpretation of Ford et al. (1963), the diatomites underlie the basalts, an impossible relationship in view of the fault separating them.

The remainder of the (Ttsl) unit in Big Valley was called the "Bieber Formation" by Ford et al. (1963). The name "Bieber Formation" never was described adequately and has not been used here.

Ford et al. (1963) vaguely referred to a Miocene flora in the diatomites west of Barber Ridge. No location was given in that report, but it appears that this flora is the basis of classifying the diatomites in the northern part of Big Valley with the Miocene volcanic section. Perhaps more than one diatomite horizon is present, and a Miocene age is correct for part of the diatomite accumulation. However, in view of their similarity to the Pliocene and Pleistocene diatomaceous sediments rocks of the region, their lack of similarity to well-defined Miocene deposits, and the structural inconsistency brought about by assigning a Miocene age to them, they have been mapped as Pliocene herein.

The third important area containing (Ttsl) sediments and tuffs is in the northwestern end of the Big Valley Mountains, adjacent to Little Hot Spring Valley, north of the village of Day. The section exposed here is estimated to be about 1,200 feet thick. The lower one-third of the section contains significant, thick units of diatomite, while the remainder is characterized by grey basaltic tuffs and basalt-derived sandstones. These rocks are strikingly similar in lithology to (Ttsl) sediments seen in outcrop in Big Valley and are believed to be correlative with them. Isolated diatomite outcrops in Widow Valley (center of T. 39 N., R. 6 E.) confirm the lateral continuity of these units.

Southward, along the west side of the Big Valley Mountains, the section consists of basalt flows and cindery agglutinate within which minor amounts of basaltic tuff are interbedded. These volcanic rocks, designated (Tpbl), are believed to be contemporaneous with parts of the (Tts) sequence of sediments and tuffs.

The base of the (Ttsl) sequence in the Big Valley Mountains is not exposed. Rocks overlying the sediments in the northern part of the range are basalt flows of the (Tpbu) interval.

Basalt Flows of Pliocene Age.

There are several assemblages of basalt flows and eruptive centers in the project area. These include at least two generations of eruptives in the Big Valley Mountains, and an isolated flow sequence capping the Juniper Creek Hills between Willow Creek and the Pit River. These basalts are distinguishable from younger flows of the (Qb) assemblage on the basis of the amount of deformation and erosion effecting them and by their apparent relationships to Pliocene-age sediments (Tts). Some of these have been called the "Warner Basalt" by previous workers (MacDonald, 1966; Gay and Aune, 1958). However, that term has been defined so inadequately that confusion can be avoided only by rejecting the name. The map units loosely defined by Ford *et al*. (1963) also were found to be unsatisfactory for use in the present study.

These basalts have been grouped into two main suites, an upper unit (Tpbu) and a lower designated (Tpbl).

Lower Unit (Tpbl).

Basalts included in this suite occur in the southern Big Valley Mountains and appear to extend northward under the younger Widow Mountain eruptive center in the northern part of that ridge. In part, these flows are equivalent to the "Big Valley Mountains Volcanic Series" of Hail (1961).

The (Tpbl) sequence is made up mostly of light grey plagioclase-rich holocrystalline basalt, with a range of textures including slightly porphyritic and diktytaxitic variations. Locally, near eruptive centers, the rock is a red, cindery breccia. The flows average 15 to 20 feet in thickness. Adjacent flows are often separated by a foot or two of red, cindery soil. A representative exposure can be seen along Highway 299 in Sec. 28 and 34, T. 38 N., R. 6 E.

The base of the section is not exposed. The unit is overlain by the eruptive pile around Widow Mountain in the central part of the Big Valley mountains and by flood basalts of the (Tpbu) and (QTb) assemblage in the Pit River gorge area. In these areas, no sediments of the (Tts) sequence are present between the older and younger basalts. Absence of (Tts) sediments may reflect lack of depositional basins in the vicinity of the eruptive centers.

The (Tpbl) unit is distinguished from petrologically similar, younger, plagioclase-rich basalts by its weathering characteristics. Most of the original scoriaceous surfaces have been destroyed, soils are well-developed, and the interior parts of flows often are weathered into rounded boulders.

Upper Unit (Tpbu).

These basalts, like those of the older (Tpbl) unit, are light to medium grey and plagioclase rich. Large eruptive centers, such as Widow Mountain and Jimmerson Mountain, and the flood basalts capping the Juniper Creek Hills, are included herein.

The flows forming the surface of the Juniper Creek Hills vary considerably in total thickness, from 100 to more than 600 feet, depending on their proximity to eruptive centers, and on the relief developed on the underlying surface.

These flows rest on an erosional unconformity in older rocks. It is difficult to determine whether an angular unconformity is present, as the dip is low both above and below the zone of non-conformity. The amount of faulting seen in (Tpbu) rocks appears to be about the same as that in older rocks, and is much greater than that present in younger basalts (QTb) or (Qb). This characteristic further assists us in distinguishing those otherwise-similar units. The age of the (Tpbu) unit is unknown, except that it overlies (Tts) rocks that have been age-dated and correlated stratigraphically as Pliocene. These basalts may, therefore, be of late Pliocene or possibly Pleistocene age. A late Pliocene age is preferred, on regional considerations of erosion, faulting and time sequence.

Pliocene-Pleistocene(?).

Basalt Flows (QTb).

Of the several basalt flow sequences of different ages, one is assumed to span the Plio-Pleistocene interval, based on stratigraphic relations, and amount of weathering, disection, and deformation. They have been termed (QTb). They are light grey, plagioclase-rich flows, as are all the others in this general group. They are less faulted than adjacent older flows, as can be readily seen in comparing (QTb) and (Tpbu) in T. 37 N., R. 8 E., on aerial photographs.

(QTb) flows appear to cover an eroded surface developed on (Tts) rocks, similar to the position held by certain (Tpbu) units. They form a continuous plateau in the northern part of the mapped area, north of Lookout. Isolated erosional remnants of flows also are present in the northern Juniper Creek Hills and elsewhere. These may not all be part of a formerly continuous sheet, but they occupy a generally similar position in the stratigraphic sequence of the area.

The thickness of the isolated basalt caps in the southern part of the region amount to a few tens of feet. Thickness appears to increase northward from Lookout.

Quaternary.

Quaternary Basalt (Qb).

The most-recent-appearing volcanic rocks in the area are extensive basalt flows and shield volcanoes of the Fall River Valley. Several different ages of eruption can be distinguished, but all of them have been included in the single unit (Qb) for the purposes of this report. Individual flows have been separated in mapping by Anderson (1941) and Gardner (1964) in the southern Medicine Lake area and western Fall River Valley-Hambone areas, respectively.

The rocks in this assemblage are mainly dark grey, fine-grained, holocrystalline intersertal basalt. Many of the flows are highly vesicular. The principle mineral constituents are plagioclase, pyroxene, olivine, glass and iron oxide. Plagioclase makes up 45 to 55 percent of the rock. The amounts of other constituents vary widely (Powers, 1932).

Thickness of the (Qb) basalts varies from several hundred feet near eruptive centers to a few tens of feet at a distance from these centers. The flow surfaces are so fresh that scoriaceous tops and the original very rough topography of the surfaces are preserved. Little soil is developed on these flows. Surface drainages remain deranged or impeded. However, despite the recency of this volcanic activity, some of the flows have been subjected to faulting, for example in the Hat Creek area north of Lassen Park.

It is notable that, in the project area, these young basalts appear to occur only to the west of the Big Valley Mountains. Eruptive igneous activity of this age did not occur in Big Valley.

Quaternary Sediment.

Several types of unconsolidated sediments occur in Big Valley. Those distinguished during the present mapping project are discussed below.

Older Valley Fill (Qol). Small areas around the margins of Big Valley are covered with a lag of basalt rubble and by periglacial mounds. These surfaces appear to be developed on thin slope-wash deposits which have been preserved from erosion since at least the last glacial period. A typical example of this material is present in the center of the south half of Sec. 12, T. 39 N., R. 9 E.

Lake and Swamp Deposits (Ql). Shallow, undrained depressions occur on the surfaces of flat-lying basalt flows and in other areas of impeded drainage. These depressions contain thin deposits of peat, sand, silt, organic mud and probably some diatomite and volcanic ash. Egg Lake, at the northern edge of the mapped area, is an example developed on lava flows. Big Swamp, in the center of Big Valley, is an area of impeded drainage which may be impounded behind a slight structural uplift lying across the valley.

Fan Deposits (Qf). Large, low, coalescing fans occur on the east slope of the Big Valley Mountains, west of Bieber. Other fans are developed along the steep west slope of this range. All are composed of basalt debris.

Undifferentiated Alluvium (Qal). This map unit consists of deposits in the valleys of presently active streams. The largest area is in the western part of Big Valley, associated with the present-day meanders and abandoned channels of the Pit River. Water-well data indicate that these deposits may average about 150 feet in thickness, but may reach a local maximum of 250 feet (Hail et al., 1961). They are made up of fine sand, clayey silt and organic mud. Some lenticular beds of gravel are present along the channel of Pit River.

Above the level of the regional flood plain, alluvium in Big Valley is thin. Road cuts and other excavations reveal (Ttsl) bedrock at a depth of 5 feet or less. In these areas, bedrock has been shown on the geologic map, rather than alluvium (Qal).

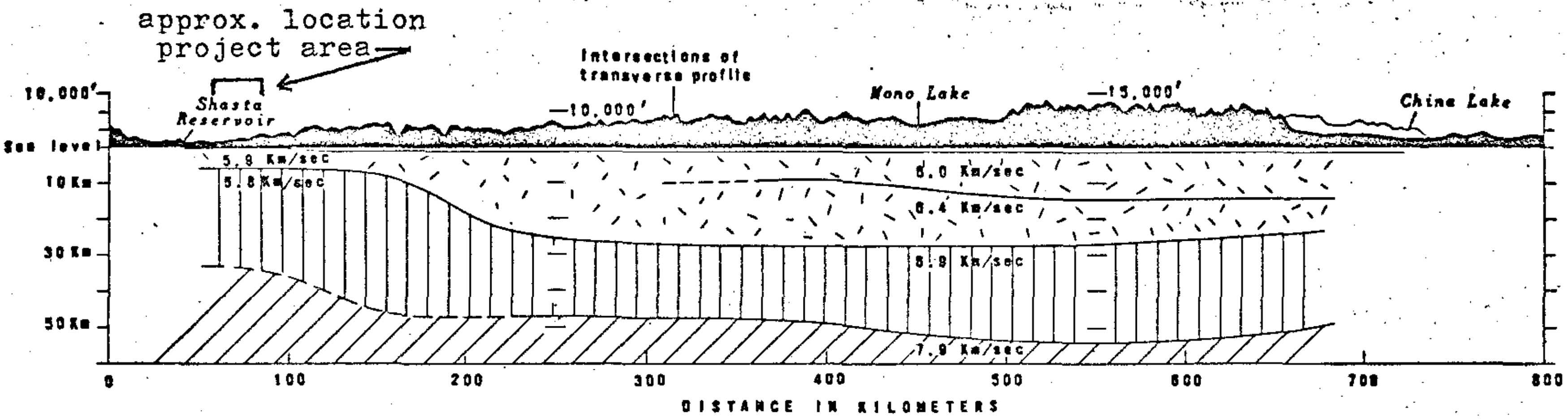
STRUCTURE

Normal faults are the dominant structural features of the Modoc Plateau province (plates 1 and 2). These faults divide the region into horst ridges and graben valleys. The wide distribution of these tensional structures, combined with the large volumes of andesitic and basaltic eruptives, indicates that the crust in this area has been extended significantly and is thinned.

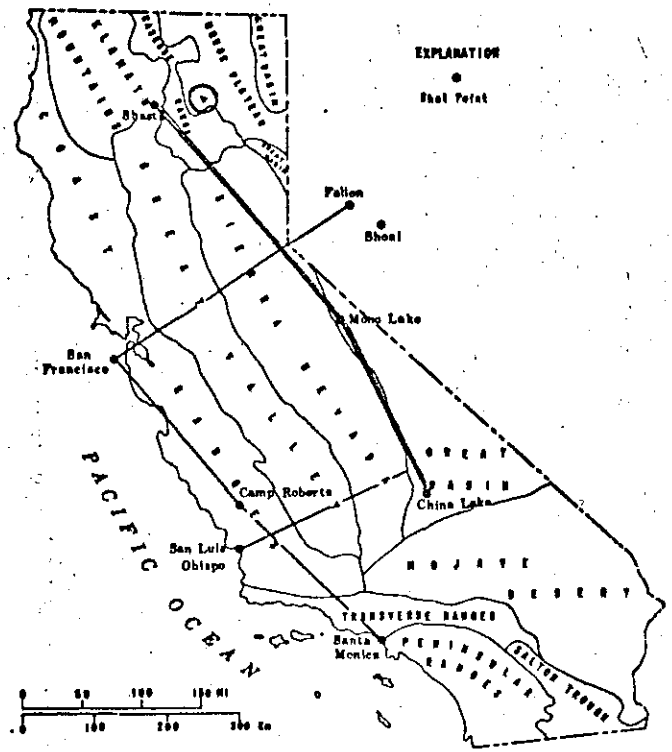
This assumption is corroborated to some degree by seismic studies carried out in the Vela Uniform program (Eaton, 1966; Prodehl, 1970). These show shallow crustal velocities of 5.9 km/sec. to a depth only of about 6 km, and deeper crustal velocities of 6.8 km/sec. to about 30 km, whereupon velocities increase to 7.9 km/sec. (figure 5). The nearest observing station was 50 miles southwest of the Big Valley area. Therefore, velocity data do not necessarily apply directly to Big Valley and vicinity.

Prodehl (1970) re-interpreted the Vela Uniform seismic-refraction studies. He noted that for this region there is no velocity zone corresponding to the "intermediate crust" of the Basin and Range province. Also, the high-velocity layer (mantle) is shallower by several kilometers than beneath the adjoining Sierra Nevada.

Most importantly, he noted that velocities are dependent not only upon rock densities, but upon thermal



Longitudinal seismic cross section through the Sierra Nevada from near Shasta Reservoir to China Lake.



Map showing shot points and seismic refraction profiles made by the U.S. Geological Survey in the northern and central part of California.

Figure 5. Deep crustal structure from a seismic refraction profile (Eaton, 1966)

character of those rocks. Therefore, he concluded that the "intermediate" layer beneath the northern Basin and Range was heated rock of mantle affinity. Further, he revised the velocity values of Eaton (1966) slightly, and noted a velocity inversion from about 6.4 to 6.0 at approximately 7 km beneath the Lassen Park area. This he attributed to either a low-density mass of hot batholithic intrusions or a volcano-tectonic collapse feature filled with low-density debris. It would be extremely interesting to compare the Lassen data with new seismic data from Big Valley and Fall River Valley. Lacking these, we can only note that:

> Under the southern Cascade Mountains in northern California, upper crustal material is probably thin or lacking, as indicated by volcanic surface material that consists mainly of pyroxene andesites and basaltic andesites and by correspondingly higher seismic velocities of 6.5 to 6.6 km/sec. at 7 km depth. . . . The gravity highs under the . . . southern Cascade Mountains . . . correspond with a thin upper and a thick lower crust (Prodehl, 1970).

The "lower crustal" layer may be very hot, mafic in composition, and consisting in part of mantle material, upwelling as sheets, dikes and/or diapirs beneath and into the thinned upper crustal layers. A relatively thin upper crust would allow hotter materials from the lower crust and upper mantle to reach closer to the surface. This would help explain the regional thermal anomalies of the Cascades and the Modoc Plateau: the entire region may be abnormally hot without the necessity for plutons to be present in the upper 6 or 7 km.

Major faults in the project area trend northwesterly. Subordinate faults are numerous within the ridge blocks, and probably are present also under alluvial cover in the valleys, where they are suggested by photogeologic lineaments. Trends of these subordinate faults are predominantly northwesterly, but there are significant numbers with a northeasterly or a northerly trend. Taken together, the faults in the region exhibit a conjugate pattern of northwest- and north-trending fractures.

Most of the larger faults are downdropped on their southwest sides, although some exceptions occur. Strata within the Big Valley Mountains and Barber Ridge uplifts generally dip to the northeast. Folding prior to faulting may have contributed to the dip, but it cannot be distinguished from tilt attributable to rotation during faulting.

No fault planes were observed in the project area. In other parts of the Modoc Plateau, and in structurally similar areas of southern Oregon, exposed fault planes are visible along the fronts of some of the largest blocks. In these areas, fault plane dip ranges from 55° to 70°. In the absence of other data, it appears reasonable that similar dips occur on the planes of major faults in the project area. There is no direct evidence of lateral or reverse movement on any of the larger faults in the project area. However, both left- and right-lateral offset is reported from historic earthquakes in the Basin and Range province of northern Nevada, along what appear to be similar range-bounding faults with hundreds to thousands of feet of vertical throw. Further, a few feet of reverse movement can be seen on some minor faults. Examples of this can be seen in the cuts along Highway 299, at the center of the west boundary of Sec. 36, T. 40 N., R. 9 E.

There appears to be a general difference in age between faults in Fall River Valley and Little Hot Springs Valley, compared to those in the Big Valley Mountains and to the east. Topographic evidence and the youthfulness of basalt flows which are offset in Fall River Valley suggest geologically recent movements in this area. The lack of topographic expression of some inferred faults in Big Valley, and the amount of erosional modification of the west slope of Barber Ridge, suggest that the fault activity, though probably continuing into the Quaternary period, has not occurred in Holocene time.

Evidence of older faults sometimes is derived from alignments of eruptive centers. Jimmerson Mountain and Egg Lake Butte may suggest such a fracture-controlled trend but, in general, the project area does not contain enough eruptive centers to permit patterns to be distinguished.

For the purposes of detailed discussion, several structural units have been defined. There are the Big Valley Mountains block, Big Valley block with subunits, the Juniper Creek Hills block and the Barber Ridge block (see overlays to plate 1 for supporting gravity and aeromagnetic data).

Big Valley Mountains Block.

This block is divided into two segments. On the west side, from its south end at the Pit River to the settlement of Day, the ridge axis and bounding faults trend about N. 20° W. From this point, the strike changes to about N. 60° W., thereby defining the second segment. The southwest side of the ridge is bounded by two series of normal faults arranged en echelon. The eastern series, along a line lying east of Little Hot Spring Valley, through Crum Reservoir, Dixon Flat and the west side of Fourth Butte, shows the larger displacement. Topographic relief along this zone indicates offset in excess of 1,500 feet, and the stratigraphic offset may be considerably larger. A second fault set lies parallel to this, roughly two miles to the west. This trend has a displacement of 500 feet or more, based on the height of the topographic scarp.

The eastern side of the range appears to be bounded by en echelon faults from the settlement of Pit River on the south, northward to Sec. 30, T. 38 N., R. 7 E. Topographic evidence of faulting can be seen clearly only in the southern part of the trend, but Bouguer gravity data offer support for extension of the zone to the northwest.

At the northern end of this fault zone, near Nine Springs Reservoir, the range broadens, apparently as the result of a large complex of eruptive centers (Tpbu) built before faulting began. This is also the point of intersection between the buried Bassett uplift (see below) and the Big Valley Mountains. Gravity data suggest that faults which bound the range are offset here about three miles to the northeast. However, evidence of range-bounding faults in the northeast part of the Big Valley Mountains remains ambiguous.

Displacements on faults bounding the east side of Big Valley Mountains seem smaller than those on the west side. Rock attitudes in the range generally are about 20°E, probably as a result of rotation of the mountain block between the zones of unequal displacement.

Most of the faults within the Big Valley Mountains block show the characteristic northwesterly strike. Although the time of their initiation is unknown, movement on the faults has continued, so that they cut the (Tpbu) basalt flows and associated Widow Mountain and Jimmerson Mountain eruptive centers, which are the youngest bedrock units in the range.

Big Valley Block.

Topographic relief is low and outcrops are scattered in Big Valley. Therefore, inferences concerning structure depend on projection of trends from surrounding bedrock areas, on the interpretation of photogeologic lineaments and drainage patterns, and on gravity and magnetic data. On the basis of these data, it appears that the valley can be subdivided into the Bieber basin, the Bassett uplift, the Big Swamp basin, the Cemetary uplift and the Albaugh Road basin (plate 1).

The Bieber basin is an asymmetrical gravity low bounded on the southwest by the faulting at the front of the Big Valley Mountains, and on the northeast by a gravity gradient change which suggests a rather small fault. This gravity-indicated fault forms the common boundary between the Bieber basin and the Bassett uplift. The deepest part of the basin appears to be on the west, adjacent to the Big Valley Mountains. It appears to contain a relatively thick section of lacustrine sediments (Tts) and alluvium of the Pit River (Qal).

The Bassett uplift trends northwest beneath the surface of Big Valley, between Bieber and Big Swamp. The presence of the uplift is indicated by gravity data, and appears to be corroborated by the existence of a shallow bedrock feature. Big Swamp may have developed as the result of impedence of the Ash Creek drainage course by the slight topographic effect of the uplift. On the basis of the gravity data, the uplift appears to be bounded by faults on the northeast and southwest sides. The smaller gravity gradient on the southwest suggests that the displacement here is the lesser of the two and that strata within the block may be tilted to the southwest.

Faulting or jointing in bedrock within the uplift is suggested by short lineaments seen on aerial photographs. These lineaments have a predominant northeast trend, although northwest strikes are also present. Bassett Hot Springs (Sec. 12, T. 38 N., R. 7 E.) is located on the summit of the Bassett uplift, approximately one-half to three-quarters of a mile to the southwest of the postulated northeast boundary fault. Poorly defined air-photo lineaments were noted near the springs, suggesting that local fracturing is present in bedrock. The Bassett uplift also is underlain by a magnetic high. This may mean that a mafic igneous unit has been uplifted.

Lake beds (Ttsl) are exposed in a number of road cuts and shallow excavations on the uplift. However, it is believed that these sediments are likely to be thin here. Unfortunately, sample descriptions from water wells are not sufficiently detailed to provide data on the thickness or nature of underlying rocks. Magnetic data suggest that basalt (Tb) may be present at a relatively shallow depth (magnetic and gravity overlays to plate 1).

Gravity data indicate that a major basin trends about N. 70° W. beneath Big Valley, northeast of the Bassett uplift, for a distance of about 14 miles. The strike of this depression is somewhat more westerly than typical for structures in this region. The center of the gravity low underlies Big Swamp, for which the basin is named.

Both sides of the Big Swamp Basin appear to be faulted. On the southwest the boundary is the fault postulated from gravity data along the edge of the Bassett uplift. The northeast boundary is defined by a steep gravity gradient which probably reflects an important buried fault aligned with a surface drainage lineament in Willow Creek to the southeast.

Several lines of evidence indicate the presence of minor structures along the southeast side of the Big Swamp basin. Small faults and joints are common in the hills south of Kellog Hot Springs. These faults and joints trend both northeast and northwest, toward the valley. In addition, a number of air-photo lineaments have been detected in the valley where alluvial cover over (Ttsl) is thin. These show northeast, northwest and north trends. Finally, the gravity map indicates a significant northwest-trending fault between the SE/4, Sec. 22 and the center of Sec. 6, T. 35 N., R. 8 E. This feature is based on a marked change in strike of the gravity contours, and is supported by the surface drainage lineament in Hot Spring Slough. This feature is of particular interest because it trends toward Kellog Hot Springs.

A well was drilled to a depth of 1,850 feet by the California Department of Water Resources near the center of the Big Swamp basin (well BV2, SE/4, NW/4, Sec. 26, T. 39 N., R. 7 E.). The log of this well has been interpreted to show about 150 feet of river alluvium and 1,750 feet of (Ttsl) sediments, most of which were diatomite, clay or silt. No rocks older than the lake beds were encountered (Hail, 1961).

The Cemetery uplift lies northeast of the Big Swamp basin, adjacent to the Barber Ridge fault block. The existence of the uplift is suggested by incomplete gravity data. It is bounded on the southwest by the steep gravity gradient which flanks the Big Swamp basin, and on the northeast by the steep topographic slope along Barber Ridge, which is interpreted to be a fault line scarp. In addition to the topographic evidence for faulting here, the gravity gradient near Adin strongly supports the presence of a fault.

Gravity data are too incomplete to suggest the internal structure of the uplift. Photogeologic mapping has detected a few northeast-trending lineaments of unknown structural significance.

The Cemetary uplift is in an area of low surface relief, and outcrops are poor. However, the evidence available indicates that (Ttsl) diatomite and tuffaceous sandstone are present near the surface. Their total thickness is not known, but was reported to exceed 400 feet in a water well in the NE/4, Sec. 13, T. 39 N., R. 8 E.

A small, structurally low area is suggested at the southwest end of the Cemetery uplift, herein called the Albaugh Road basin. It is bounded on the northeast by faults along Barber Ridge and probable faulting along Butte Creek. On the west, it is defined by a spur of the buried Cemetery uplift which separates this depression from the Big Swamp basin. At the surface, this basin is topographically part of Big Valley. There are limited outcrops of (Ttsl) sediments at the surface. Their thickness in the subsurface is unknown.

Juniper Creek Hills.

The dissected plateau-like area lying to the south of Big Valley, between Willow Creek and the Pit River, is charactertized by strong northwest- and northeast-trending joints and faults of small displacement. Although attitudes are difficult to obtain in the basalt, both surface mapping and photogeologic data indicate that dips are low. Erosional windows in the basalt expose tuffaceous rocks of the (Ttsu) sequence.

The northwest edge of this plateau is irregular in outline, and does not suggest a fault boundary between the plateau and Big Valley. In effect, the Juniper Creek Hills appear to be merely an elevated and dissected extension of the Big Valley block, within which intra-block faults have diminished in displacement.

Barber Ridge Block.

This is the westernmost part of a range bounding the east side of the Big Valley block. Although Barber Ridge topographically is restricted to a single ridge north of Adin, the term Barber Ridge block is applied to all of the hills bounding the east side of Big Valley and east of Willow Creek.

The block is characterized by the oldest rocks in the project area, with dips that exceed 30° to the northeast in the area north of Adin and that generally are somewhat lower, in the same direction, to the southeast of town. The structurally highest part of the block is north of Adin: it plunges southeastward. The presence of a boundary fault along the west side of the ridge is indicated by both topography and gravity data. It has been noted earlier that this fault may be older than some of the other faults in the region, based on the erosional slope recession that appears to have taken place along the ridge front. Southeast of Adin, topographic evidence of faulting diminishes somewhat, but the straight course of Butte Creek suggests that it is controlled by a continuation of this fault system. East of the Barber Ridge block, beyond the project area, there is a major fault zone from Dutch Flat, through Round Valley, to Upper Ash Creek.

There is a number of small faults within the uplift. One of the most important of these trends northeasterly across the ridge, in Howell Canyon. This fault separates a block of older Miocene rocks (Tm) from the late Miocene basalts (Tb).

GEOPHYSICS

Gravity Surveys.

A gravity survey of Big Valley was carried out by United Geophysical Company for the California Department of Water Resources, in 1959. This survey map was included in an unpublished report by Hail (1961). The survey was conducted on a grid with a station spacing of approximately one-half mile. Although relief is low in the survey area, terrain and rock density corrections were made. The survey is of considerable value in interpreting the buried structure in Big Valley. Interpretations have been discussed in the section of the report covering structural geology. Bouguer gravity profiles are shown on plate 2.

Magnetic Survey.

An aerial magnetic survey of Big Valley was purchased by AMAX in 1974. The flight-lines were oriented in a northeasterly direction, at right angles to the structural strike. The distance between flight lines was one-half mile and the flight altitude was 1,000 feet above ground level. The patterns of high and low magnetic intensity values are much more difficult to relate to surface geology than is the gravity survey covering the same area. The various alternative explanations for the magnetic anomalies have not been discussed here. Selected aeromagnetic profiles are shown on plate 2.

GEOHYDROLOGY

Hydrological conditions in Big Valley and eastern Fall River Valley are the product of lithology, structure, glaciation, Holocene volcanism and climatology, as is the hydrochemistry.

The surface drainage network in the valley areas is very poorly developed, except for a few major streams, certain of which are antecedent. Impermeable, fine-grained sediments alternate with highly permeable, fractured, basalts at the ground surface. Added to this, low and inconsistent topographic gradients, Quaternary volcanic activity and alpine glaciation, and fault-block drainage barriers have led to an immature regime of surface drainage. The permanent water table ranges in altitude from about 4,000 to 4,100 feet throughout much of the Modoc Plateau region. The Pit River, master stream of the area, is influent above 4,000 feet, but is effluent below 4,000 feet (MacDonald, 1966). Both surface and ground water move generally southward from the Medicine Lake Highland, Tule Lake and Clear Lake Reservoir, and southwestward from Goose Lake and the Warner Range, toward the Sacramento Valley.

Surface Water.

The Pit River and its tributaries are the surface drainage for Big Valley. It has dissected the southeastern margin of the Plio-Pleistocene lava plateau located at the northwestern edge of the Big Valley, and has cut a gap through the older lava flows at the southwestern end of the valley. This gap provides the main exit for surface and ground water through the Big Valley Mountains fault block, into lower-elevation Fall River Valley.

In Big Valley, the Pit River is a turbid stream of calcium-sodium bicarbonate water, with T.D.S. averaging 155 ppm. Its tributaries Ash Creek and Rush Creek are sodium-magnesium bicarbonate waters.

According to Hail (1962), the Pit River has barely been able to keep pace with uplift of the barrier formed by resistant basalts in the Big Valley Mountains block. Resistant basalt outcrops in the channel of the Pit River downstream from the valley exit were considered by Hail (1962) to be evidence of the natural dam formed by the basalt. Apparently, the Pit River has not yet eroded through to the Miocene flows and pyroclastic rocks that underlie Pliocene and younger basalts of the range. This is not surprising, because the Big Valley Mountains has been uplifted more in its northern part than to the south. This is similar to Barber Ridge.

The low gradient of the Pit River in its course through Big Valley results in a large, flat, poorly drained central marsh and swamp. This area apparently was the site of an intermittent lake until relatively recent time.

Tributaries to the Pit River in Big Valley are Ash Creek, Juniper Creek, Horse Creek, and many intermittant streams. Fall River, Horse Creek and Beaver Creek enter the Pit River in the northern and eastern parts respectively of Fall River Valley.

Ash Creek drains Round Valley, a basin northeast of Adin, and enters Round Valley through a notch in Barber Ridge, similar to the way the Pit River cuts through the Big Valley Mountains. Round Valley apparently was the site of a lake (Hail, 1961) during the period when Ash Creek was dammed by Barber Ridge.

Fall River Valley also is a structural basin, probably younger by as much as 2 million years than Big Valley. Fall River and Pit River drain the northern and eastern parts of the valley, respectively. The two streams join at the southwestern corner of the valley and flow through a deep cut in Hogback Ridge where it abuts Hanney Mountain. It has been suggested (Hail, 1962) that the Fall River Valley was drained to the north prior to buildup of the Medicine Lake Highland during the Pliocene and Pleistocene epochs. Fall River and its tributary, Tule River, are the only perennial drainage courses in the northern part of Fall River Valley. There is a very gentle slope northward from the Pit River in Fall River Valley, and spring-fed marshes and lakes have formed at the distal southern edges of the Holocene lava flows. The Pit River has a steep course, 1,200 feet in about 25 miles (average 50 feet per mile) through the Fall River Valley.

The upland areas bordering Big Valley, Round Valley and Fall River Valley are characterized by an immature drainage system. There are numerous intermittent streams which do not reach the major perennial streams throughout the Big Valley Mountains, Barber and Ryan Ridges, and the hill area south of Big Valley. The intermittent streams infiltrate rapidly through permeable hillside rubble and basalt flows, reaching the shallow ground-water aquifers, and emerging as springs at lower elevations.

Annual runoff of precipitation from the areas considered by this report is very large. Fall River Valley, with an area of 1,218 square miles, has 910,000 acre-feet of water runoff. Big Valley, inclusive of Round Valley, yields 180,000 acre-feet of runoff from an area of 1,243 square miles. (This includes the recharge areas bounding the valleys.) The tremendous amount of runoff in Fall River Valley is attributed to underflow from Clear Lake and Tule Lake, 50 miles north of the Pit River, and 1,000 feet higher in elevation. The Medicine Lake Highland, 25 miles north of the valley, at an elevation of more than 7,000 feet, is also believed to be a source of large volumes of infiltration water. As a result, springs at the heads of Fall River, Spring Creek and the Tule River discharge a total of nearly 1,000 second-feet of water (over 400,000 gallons per minute) into the streams. Not surprisingly, this accounts for the majority of flow in these streams. Maximum surface runoff occurs during the snowmelt period.

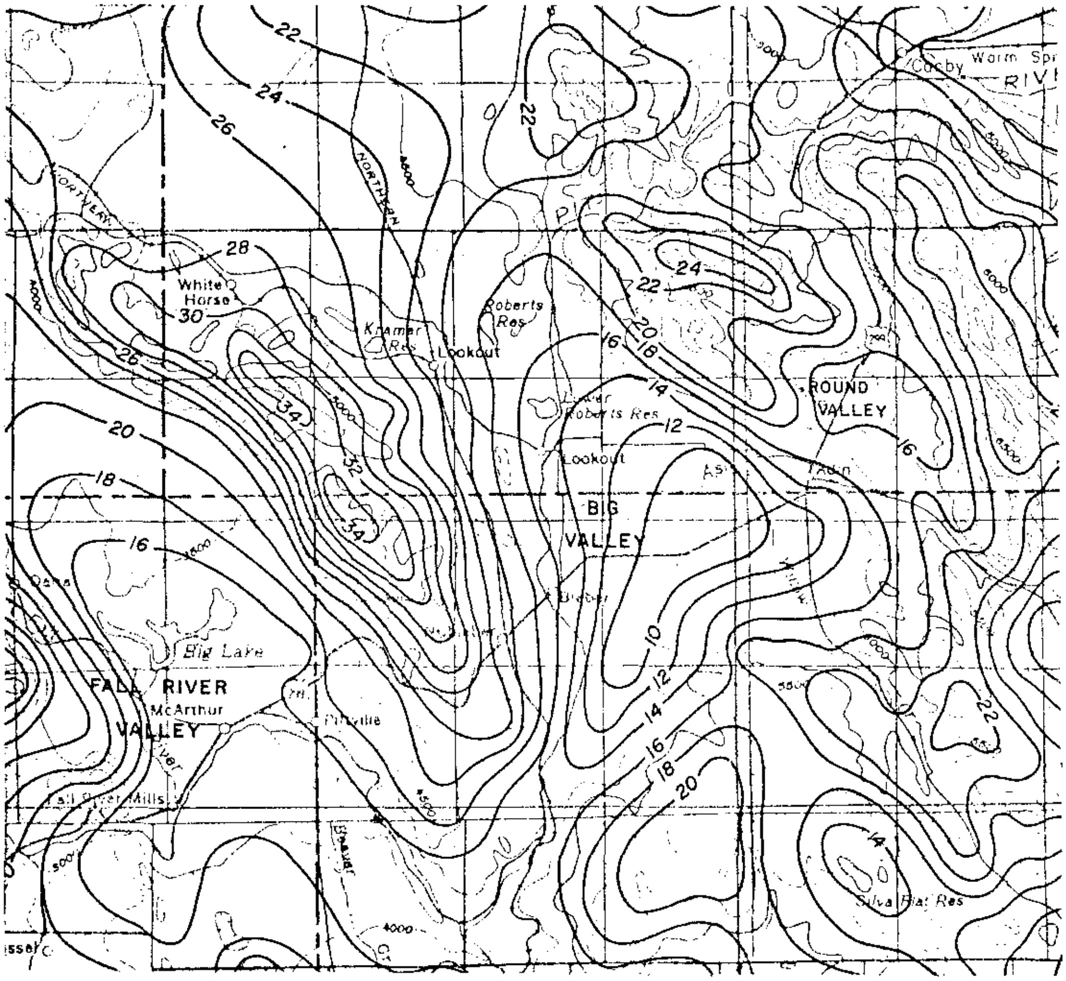
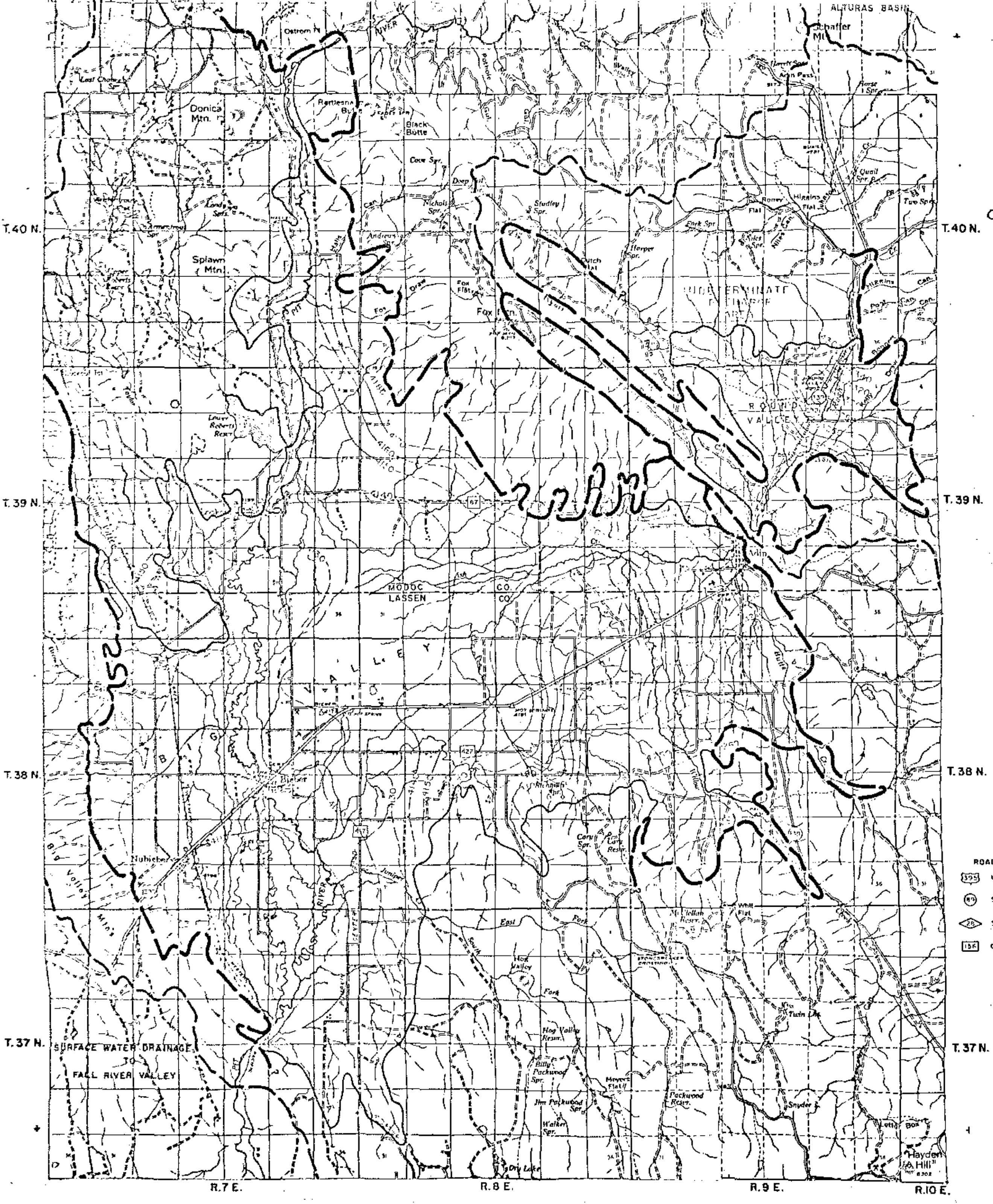


Figure 6. Distribution of precipitation, Big Valley and vicinity. Contours are lines of equal mean annual precipitation in inches (Ford *et al*, 1963).



KEY TO PLATES

LEGEND

GENERALIZED LINES OF EQUAL ELEVATION OF WATER IN WELLS IN NEAR-SURFACE AQUIFERS, DASHED WHERE INFERRED

UPLAND RECHARGE AREAS

AREA FOR WHICH LINES OF EQUAL ELEVATION OF WATER IN WELLS IN CONFINED AQUIFERS IS SHOWN (See Plate 12).

GROUND WATER BASIN BOUNDARY

SURFACE WATER DRAINAGE BOUNDARY

VALLEY FLOOR AREA BOUNDARY (WHERE DIFFERENT FROM GROUND WATER BASIN BOUNDARY)

NOTE GROUND WATER EXISTS IN THE NEAR-SURFACE AQUIFERS IN CONDITIONS RANGING FROM UNCONFINED TO CONFINED

ROAD SYMBOLS

395 U.S. HIGHWAY

89 STATE SIGN ROUTE

28 STATE HIGHWAY ROUTE

156 COUNTY ROAD

Figure 7.

STATE OF CALIFORNIA
THE RESOURCES AGENCY OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
NORTHERN BRANCH

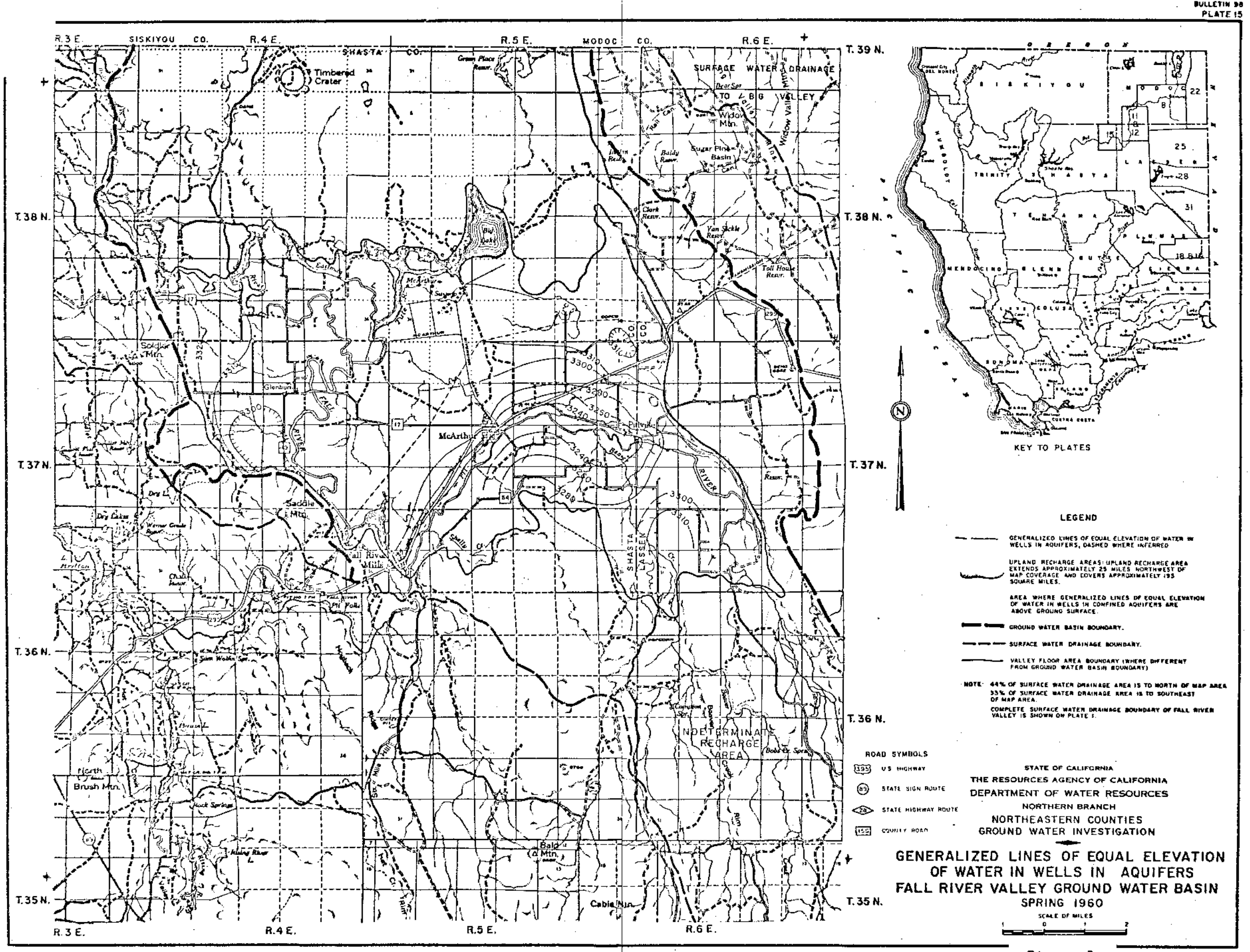
NORTHEASTERN COUNTIES
GROUND WATER INVESTIGATION

GENERALIZED LINES OF EQUAL ELEVATION OF WATER IN WELLS IN NEAR-SURFACE AQUIFERS BIG VALLEY AND ROUND VALLEY GROUND WATER BASINS

SPRING 1960

SCALE OF MILES

Figure 8.

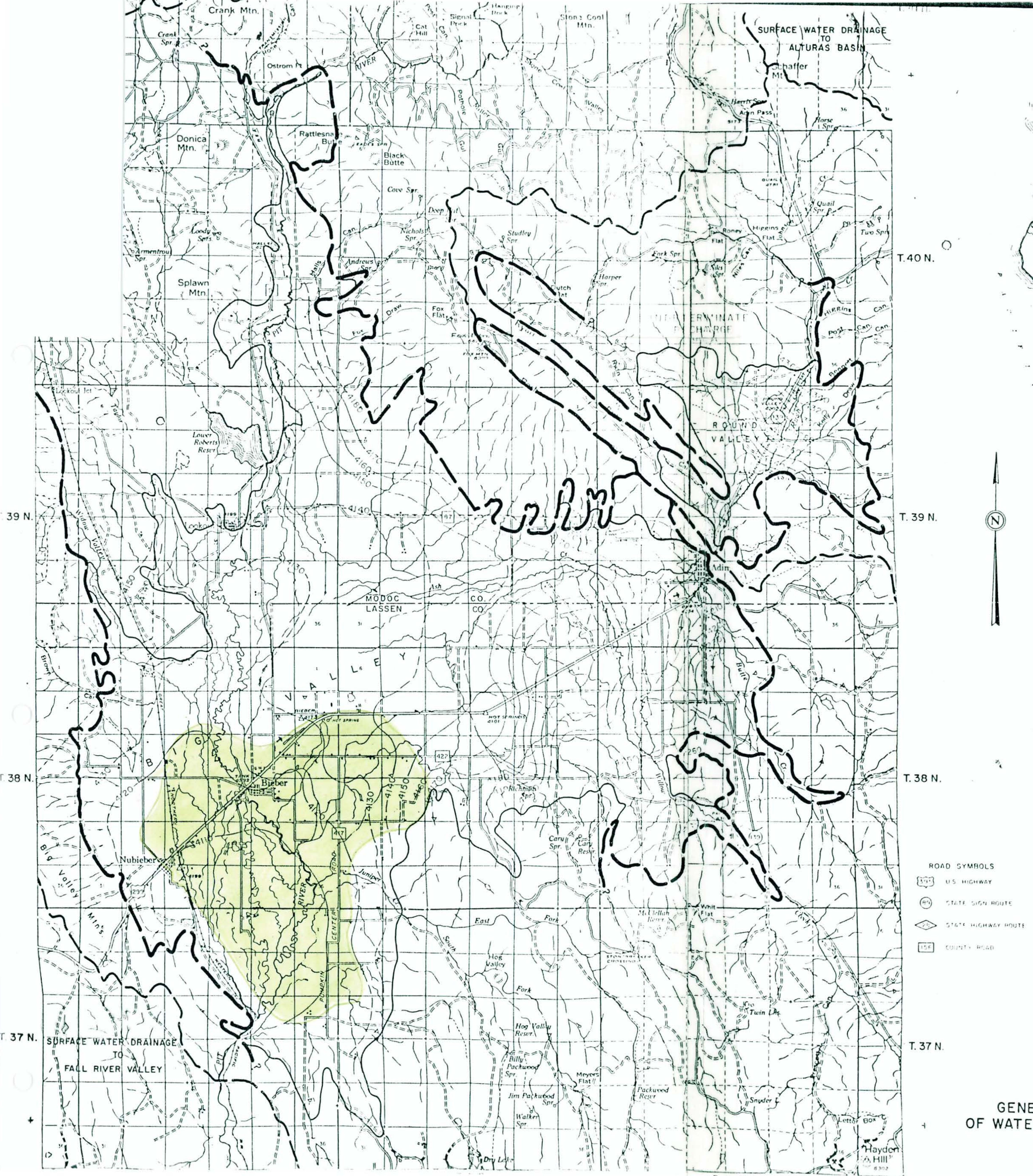


STATE OF CALIFORNIA
THE RESOURCES AGENCY OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
NORTHERN BRANCH
NORTHEASTERN COUNTIES
GROUND WATER INVESTIGATION

GENERALIZED LINES OF EQUAL ELEVATION OF WATER IN WELLS IN AQUIFERS FALL RIVER VALLEY GROUND WATER BASIN

SPRING 1960

Figure 8.



KEY TO PLATES

LEGEND

- GENERALIZED LINES OF EQUAL ELEVATION OF WATER IN WELLS IN NEAR-SURFACE AQUIFERS, DASHED WHERE INFERRED
- UPLAND RECHARGE AREAS
- 🟩 AREA FOR WHICH LINES OF EQUAL ELEVATION OF WATER IN WELLS IN CONFINED AQUIFERS IS SHOWN (See Plate 12)
- GROUND WATER BASIN BOUNDARY
- SURFACE WATER DRAINAGE BOUNDARY
- VALLEY FLOOR AREA BOUNDARY (WHERE DIFFERENT FROM GROUND WATER BASIN BOUNDARY)

NOTE GROUND WATER EXISTS IN THE NEAR-SURFACE AQUIFERS IN CONDITIONS RANGING FROM UNCONFINED TO CONFINED

Figure 7.

STATE OF CALIFORNIA
THE RESOURCES AGENCY OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
NORTHERN BRANCH

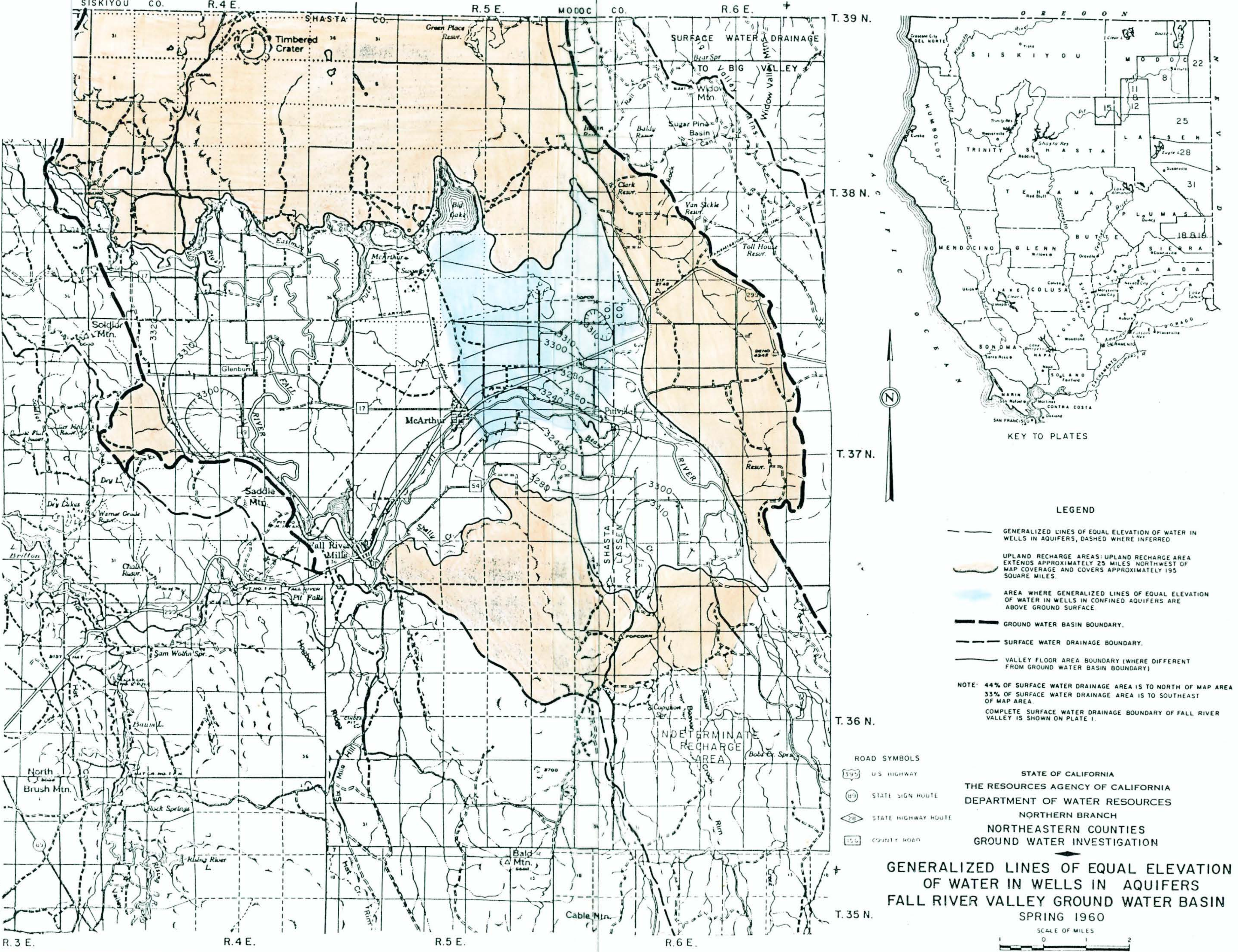
NORTHEASTERN COUNTIES
GROUND WATER INVESTIGATION

GENERALIZED LINES OF EQUAL ELEVATION OF WATER IN WELLS IN NEAR-SURFACE AQUIFERS BIG VALLEY AND ROUND VALLEY GROUND WATER BASINS

SPRING 1960

Figure 8.

BULLETIN 98
PLATE 15



STATE OF CALIFORNIA
THE RESOURCES AGENCY OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
NORTHERN BRANCH
NORTHEASTERN COUNTIES
GROUND WATER INVESTIGATION

◆

GENERALIZED LINES OF EQUAL ELEVATION OF WATER IN WELLS IN AQUIFERS FALL RIVER VALLEY GROUND WATER BASIN

SPRING 1960

Figure 8.

Mean annual precipitation ranges from a low of about 10 inches near the floor of Big Valley, to 17 inches in the vicinity of Bieber (elevation 4,170 feet), over 20 inches in the bounding upland areas, reaching 34 inches at the crest of the Big Valley Mountains and 42 inches at Medicine Lake Highland. Precipitation decreases eastward in general, so that even areas of higher elevation do not match the precipitation levels of the Big Valley Mountains. This is shown in figure 6. Therefore, spring flow even from storage areas far to the north of Big Valley becomes important in determining the water budget of the area.

Stream gauging stations now exist throughout the Pit River basin. In the area of interest, gauging stations are or have been maintained for significant periods at Adin, on Ash Creek; near Bieber, on the Pit River; and at Fall River Mills, on the Pit River. At Adin, in 1968, discharge via Ash Creek totaled 36,630 acre feet, much of which occurred from runoff from winter snowmelt and rain, from a drainage area of 249 square miles. The Pit River west of Fall River Mills averages more than 2 million acre-feet of runoff annually, from 4,000 square miles of drainage area.

Groundwater.

Wells and flowing springs are the principal sources of water supply for Big Valley and Fall River Valley. Additionally, they provide considerable information on the nature, distribution and quality of groundwater in the upper 1,000 feet of the hydrologic system. The deeper parts of the system are not known, except for a few isolated wells. Unfortunately, most of the deeper wells are not cased, or are cased through a wide interval and thus provide a mixture of water from several aquifers.

Water is present both in unconfined and confined aquifers in the valleys. Knowledge of the confined groundwater regime is restricted to small areas near Adin and Bieber. Big Valley is a broad, almost equidimensional plain, about 200 square miles in area. The average elevation of the valley floor is 4,200 feet. The water table within the valley stands at elevations of 4,120 to 4,260 feet, with elevations at the valley margins of about 4,300 feet. This generally is less than 100 feet below ground surface, and in many locations is less than 10 feet below surface. Plates 11 and 12 from Ford et al. (1963) are reproduced herein as figures 7 and 8. They show the elevation of unconfined and semi-confined groundwater within Big and Round Valleys, and the potentiometric surface for groundwater in the shallow confined aquifer system of the two valleys. They also show directions of flow for the near-surface groundwater.

In Big Valley, unconfined groundwater near Adin moves westward toward Ash Creek. To the west of the confluence of Ash Creek and Willow Creek, the direction of ground water is toward the Pit River. From north of Lookout, movement in shallow groundwater regime also is toward the Pit River. Between Lookout and Bieber, a portion of the groundwater is discharged into stream channels, while another part continues southward toward Bieber, with a quite flat gradient.

Confined groundwater near Adin, as determined from a few wells, also flows westward. Near Bieber, confined water generally moves westward, apparently in permeable basalt flows and sands in the otherwise-impermeable "Bieber Formation" (part of our (Ttsl) unit).

Shallow groundwater in Round Valley flows in part toward Ash Creek, and in part discharges into surface streams. The (Tb) unit and/or fault planes along Ryan Ridge forms a barrier to groundwater moving through Barber Canyon. The only area of hydraulic continuity appears to be through the Ash Creek narrows at Adin.

Groundwater Chemistry.

Several government agencies, as well as AMAX Exploration, Inc., have sampled surface waters and groundwater in Big Valley and vicinity. Multiple analyses show that bicarbonate waters predominate in the regional system. Sodium and calcium are the principal cations. Exceptions to the general geochemistry are the hot springs in Big Valley basin, which have a strongly sodium sulfate character. Several wells show wide variations in their calciums, sodium and magnesium concentrations, perhaps as a function of length of time of travel and storage of groundwater. Groundwater inflows to Big Valley from Round Valley also are sodium-calcium bicarbonate type.

Details of groundwater chemistry are obtained from Hail (1961), Scott (1958), Swanson (1962) and Stetson (1964), as well as from unpublished work done for AMAX in 1975 (see Table 1). It is not the purpose of this report to duplicate these efforts. F. Dellechaie of AMAX has provided us with computer-drawn plots

Table 1. Selected chemical analyses of spring and well water,
Big Valley region, California
(From Hail, 1961 and Swanson, 1962)

Well	depth,	T		constituents in ppm											TDS,	Remarks
number	feet	°F	pH	Ca	Mg	Na	K	CO_3	HCO_3	SO_4	Cl	F	B	SiO_2	ppm	(see Notes, below)
37N/7E-2D	400	58	7.6	11	5.8	21	4.5	0	116	5.4	3.8	0	0	62	171	a,c
-13B	158	57	7.7	12	8.4	21	4.5	0	118	0	6.0	0	0	64	185	c
8E-6M	120	64	7.8	9.6	4.4	21	4.8	0	104	5.8	2.0	0	0	61	161	Artesian; c
-7A	60	60	7.8	10	6.1	20	4.5	0	109	2.5	2.5	0.2	0.1	51	156	a,c
10E-28E	-	78	8.0	10	4.0	19	4.4	0	100	1.5	2.4	0.1	0	45	136	Willow Creek Warm Spring; e
38N/6E-24A_1	197	75	7.1	20	16	8.2	2.5	0	164	1.9	2.0	0	0	47	179	d
A_2	-	57	7.0	14	7.5	7.7	3.6	0	100	1.9	1.0	0	0	62	147	spring; d
7E-2P	218	65	7.5	29	16	44	13.	0	228	5.2	40	0	0	78	344	a,c
-11F	90	64	6.9	14	11	12	2.6	0	96	13	8.6	0.3	0.1	72	182	c
-12K	-	180	8.7	31	0.1	216	5.2	13	11	362	96	2.4	2.4	72	805	Bassett Hot Spring; a
-14G	60	59	6.8	21	13	18	3.0	0	100	41	17	0.4	0.1	69	232	c
-17L	58	55	7.4	8.3	6.6	10	2.1	0	80	3.8	2.5	0	0	54	127	a
-23D	451	65	7.1	16	10	28	3.0	0	151	7.1	8.1	0.3	0	64	211	c
-23R	80	50	8.0	109	75	155	12	0	90	525	204	0	0.9	62	1,200	a,c
-24A	95	52	7.1	31	20	34	5.6	0	235	18	9.9	0.2	0.3	65	317	a,c
-27J	375	50	7.0	7.4	7.4	31	3.1	0	143	0.8	2.2	0.2	0.1	65	188	a,c
-28G	65	54	7.1	27	19	29	3.3	0	231	5.9	6.9	0.2	0.1	57	263	a
-29R	150	56	7.1	7.8	9.1	17	3.8	0	117	0.8	0.7	0.2	0.1	68	166	a,c
-32A	339	-	6.9	7.0	6.7	14	3.6	0	90	6.7	1.0	0	0	67	150	a,c
-33C	321	51	7.2	25	17	39	3.5	0	196	45	10	0.2	0.1	61	298	a,c
-34J	606	48	7.3	58	36	45	3.7	0	362	46	29	0.1	0.1	49	445	a,c
-36J	1,040	64	7.9	6.6	2.6	19	4.5	0	82	2.0	2.9	0.1	0.1	50	128	a,c
8E-14N	-	186	8.7	31	0.1	241	7.6	14	12	392	116	2.8	3.1	88	902	Kellog Hot Spring; a
-14P	60	170	8.6	31	0	241	7.2	10	18	403	117	2.8	3.1	87	911	a,c
-17K	175	58	7.2	14	12	14	2.8	0	130	6.4	2.8	0.1	0	64	180	c

Table 1. (continued)

Well number	depth, feet	T °F	pH	constituents in ppm											TDS, ppm	Remarks (see Notes, below)
				Ca	Mg	Na	K	CO$_3$	HCO$_3$	SO$_4$	Cl	F	B	SiO$_2$		
38N/8E-23F	-	63	6.7	27	11	17	4.9	0	179	6.7	0.2	0	0	58	213	spring; c
-30D	295	62	7.4	3.2	1.8	62	7.1	0	167	4.2	14	0.3	0.1	72	248	c
-30R	200	54	7.5	21	18	25	5.1	0	124	13	22	0.1	0	55	265	a,c
-31D	90	53	7.6	8.5	5.4	20	4.6	0	104	1.6	4.1	0.3	0.1	53	149	c
9E-8E	1,100	63	8.1	27	11	21	5.4	0	152	6.9	13	0.2	0	69	244	c
-8G	221	57	7.9	17	8.6	13	2.8	0	103	17	2.6	0.3	0	66	179	c
-10C	85	58	8.0	9.6	4.4	35	4.7	0	123	6.2	8.6	0.6	0	63	193	a,c
-21L	200	71	8.0	16	4.9	47	8.3	0	199	7.7	5.5	0	0	84	272	a
10E-4F	-	49	6.9	14	6.4	5.5	1.0	0	85	2.9	2.0	0.2	0	40	116	spring
-28R	-	49	7.7	11	5.0	19	5.3	0	114	1.9	2.0	0.1	0.1	50	151	spring
39N/7E-11A	535	60	7.4	12	6.3	27	4.4	0	125	1.6	4.5	0.1	0.1	60	190	a,c
-11B	332	64	7.5	8.6	4.7	20	2.9	0	100	2.1	0.5	0.1	0.1	57	151	a,c
-13Q	216	56	7.0	9.3	2.2	31	2.0	0	104	8.7	4.7	0.3	0	60	176	c
-14R	25	56	8.0	95	49	100	1.6	0	454	76	105	0.4	0.1	52	774	a
-22A$_1$	50	60	7.2	30	17	20	2.1	0	124	11	17	0.3	0.1	61	268	b
-22A$_2$	155	56	6.6	33	18	9.8	2.9	0	131	11	11	0.2	0.1	69	274	b
-22G	80	56	6.9	26	16	18	2.3	0	158	14	18	0.3	0.1	65	239	a
-26N$_1$	45	53	7.2	19	12	24	2.4	0	176	5.1	3.5	0.1	0.1	59	212	a
-26N$_2$	135	53	7.4	16	14	32	2.6	0	197	0.8	2.5	0.2	0.1	55	221	a
-27A	450	56	9.0	6.9	3.2	55	2.0	26	163	4.3	7.6	0.2	0.1	44	203	a,c
-28B	80	52	7.3	16	7.0	15	2.1	0	115	1.0	3.9	0.2	0	55	157	a
-30A	57	51	7.6	18	7.0	18	2.1	0	133	0	2.8	0.1	0	38	152	b
8E-7B	254	59	7.3	5.0	2.9	35	7.3	0	118	8.6	5.5	0	0	63	186	c
-14R	370	59	7.3	11	8.3	18	5.0	0	99	12	6.2	0	0	72	184	c
-22D	22	58	6.9	10	6.1	36	2.7	0	106	21	3.8	0.3	0.1	70	218	a
-23A	370	56	7.2	11	9.6	18	4.8	0	103	21	2.1	0.4	0.1	65	185	c
-26J$_1$	30	53	7.0	58	25	53	5.7	0	133	43	45	0.4	0	65	538	c
-26J$_2$	72	56	7.0	12	4.4	33	2.2	0	108	16	14	0.3	0.1	56	192	c
9E-2P	12	61	7.3	20	10	11	5.7	0	142	1.0	0.8	0	0	54	176	a
-9A	205	68	8.0	14	7.8	18	6.3	0	128	0	1.2	0.1	0	54	165	c

Table 1. (continued)

Well number	depth, feet	T °F	pH	constituents in ppm											TDS, ppm	Remarks (see Notes, below)
				Ca	Mg	Na	K	CO_3	HCO_3	SO_4	Cl	F	B	SiO_2		
39N/9E-10A	138	56	7.5	11	9.1	27	7.4	0	155	0	3.7	0.3	0.1	55	190	a,c
-12P	131	56	7.6	10	5.6	25	4.8	0	121	1.2	4.6	0.2	0.1	60	172	c
-16J	85	53	7.6	20	10	11	2.6	0	117	1.2	5.6	0.3	0	62	185	a,c
-16N	108	58	8.0	11	9.8	14	4.9	0	119	0	3.0	0.1	0.1	53	156	e
-19K	200	58	7.6	8.9	7.5	14	5.1	0	94	3.1	3.3	0.3	0	64	157	a,c
-20F	106	59	7.3	13	8.0	12	2.9	0	89	6.7	7.5	0	0	68	170	a,c
-21P	48	-	7.1	18	8.0	33	9.3	0	160	9.6	9.0	0.2	0.1	59	233	a
-21Q$_1$	-	70	7.8	13	6.9	14	5.5	0	113	1.9	2.1	0.1	0	56	156	warm spring; a,e
-21Q$_2$	120	65	7.8	18	6.8	10	4.4	0	118	0.6	2.1	0.1	0.1	51	152	a,e
-21Q$_3$	55	65	7.1	12	9.7	12	5.4	0	114	8.6	0.7	0	0	54	158	artesian; a,c
-28C	174	70	8.0	8.4	1.9	21	6.0	0	89	0.3	3.5	0.2	0	53	140	a,c
-28F	108	64	7.3	7.2	4.4	18	5.2	0	88	3.8	1.7	0.2	0	70	154	a,c
40N/7E-24R	-	76	8.2	12	4.7	15	7.4	0	104	2.3	1.6	0.2	0	63	157	warm spring; c
-27H	-	56	7.4	19	8.9	8.9	2.6	0	80	38	2.2	0.1	0	73	192	spring; a
8E-30E	?	55	7.4	15	5.2	21	13	0	112	14	14	0	0	57	194	a
9E-12P	-	55	6.9	14	4.7	13	2.2	0	96	4.8	1.2	0.2	0	39	126	spring
41N/8E-29H	-	61	7.0	21	11	11	3.9	0	145	6.7	0.2	0	0	63	188	spring
Fall River Valley																
37N/5E-1A	500	-	8.4	32	14	20	3.9	8	206	2.9	3.0	0	0	56	241	a,b
-1C	347	60	8.1	18	6.3	17	2.9	0	124	3.8	6.6	0.1	0	47	163	a,b
-2G	415	63	8.1	17	1.8	19	2.4	0	100	9.1	4.0	0	0.1	26	130	a,b
-3N	65	64	7.1	12	6.6	8.0	2.6	0	72	5.8	20	0.1	0	64	147	a
-9J	140	58	8.5	22	22	84	6.3	16	331	1.9	32	0.1	0	60	414	a
-9N	155	57	8.4	29	33	146	8.8	7.1	587	0	27	0.2	0.3	56	600	a
-9P	120	58	7.9	50	28	157	7.0	0	663	3.8	25	0.2	0.2	65	669	a
-10L	90	-	8.4	31	12	10	2.4	1	160	4.8	4.8	0.2	0.1	55	204	a
-11G	360	-	8.1	15	6.0	20	2.4	0	111	12	6.0	0	0.1	36	153	a,b
-11K	78	-	7.7	47	25	17	5.0	0	276	1.9	8.5	0	0.1	71	334	a

Table 1. (continued)

Well number	depth, feet	T °F	pH	constituents in ppm											TDS, ppm	Remarks (see Notes, below)
				Ca	Mg	Na	K	CO_3	HCO_3	SO_4	Cl	F	B	SiO_2		
37N/5E-11Q	350	59	8.2	14	5.6	20	5.4	0	104	9.0	5.6	0.1	0.1	30	142	a,b
-12D	280	60	8.2	18	6.0	18	2.9	0	125	3.8	6.8	0	0	46	164	a,b
-13M	96	59	8.2	21	9.0	17	3.6	0	131	3.5	2.8	0.1	0.1	43	172	a
-14R	280	56	9.0	2.5	0.1	39	1.0	13	75	4.3	2.9	0.1	0.1	34	101	a,b
-15F	135	57	8.2	17	4.3	22	2.9	0	110	13	7.0	0	0.1	39	160	a,b
-15G	302	61	8.2	6.0	0.1	30	1.8	0	73	11	6.0	0	0.2	46	139	artesian; a,b
-16F	124	57	8.5	35	19	46	4.6	11	230	12	15.5	0.3	0.4	62	318	a
-17J	80	58	8.2	19	8.6	12	2.4	0	109	4.6	1.0	0.3	-	59	173	a
-19P	225	58	8.2	21	16	54	5.6	0	250	0	0	1.1	-	64	334	a
-20L	100	62	8.2	18	11	8.0	4.2	0	122	6.9	0	0.2	-	56	167	a
-21R	64	58	7.3	24	12	8.0	3.4	0	146	1.6	3.0	0.5	0	66	197	a
-22F	430	64	8.1	10	0.1	33	3.2	0	100	4.1	7.5	0.1	0.1	36	143	a,b
-23K	12	52	8.2	35	23	28	9.2	0	202	16	6.5	1.2	0	53	332	
-24F	200	59	8.2	12	6.4	22	2.4	0	116	2.5	0.9	0.1	-	34	143	a,b
-29D	110	58	8.2	22	11	10	4.6	0	137	6.2	0.5	0.3	0.1	54	179	a
-30Q	108	-	8.5	33	22	12	7.0	9	205	5.8	10	0	0	55	271	a
6E-6L	300	58	7.5	22	18	12	2.0	0	184	0.3	3.5	0.3	0	39	188	a,b
-6M	63	56	7.3	40	44	31	3.0	0	353	9.7	12	0.5	0	62	411	a,b
-17L	80	62	7.4	53	34	20	6.2	0	320	16	14	0.3	0	52	379	
-18E	-	62	7.4	14	11	11	3.2	0	118	1.5	3.0	0.3	0	40	142	spring
-19L	96	61	7.3	20	5.3	9	3.2	0	92	3.0	2.0	0.2	0	46	155	a
-29B	50	64	7.3	29	0.1	12	4.0	0	61	4.9	6.0	0.3	0	52	184	a
-30N	530	63	8.3	7.2	1.9	43	2.4	2	139	1.9	4.2	0	0	56	188	a,b

Notes:

Units encountered in drilling:

a = young alluvium, alluvial fans and lacustrine deposits (aquifer)
b = Quaternary basalt flows (aquifer)
c = tuffaceous and lacustrine sediments (Tts1) (occasional aquifer)
d = Tertiary basalt flows (occasional aquifer)
e = other Tertiary volcanic rocks (aquitard)

of selected cation and anion values and various cation and anion ratios for wells and springs in Big, Round and Fall River Valleys, based on analytical results from samples collected by Dellechaie and his associates. It might be valuable to utilize older analyses available from the California Department of Water Resources (see REFERENCES) in preparing computer contour-plots, because there are many areas of less than 1 analysis per 10 square miles in the AMAX survey. These would not alter the gross features of the plots, but would add some subtle details and would smooth certain gradients, and should balance the water-quality effects of the hot springs, from which area many samples were obtained. Most of the more than 400 wells drilled in Big Valley are meaningless as sampling points, because they are very shallow and clustered in limited areas.

Not surprisingly, almost all anion groups show maxima in the hot springs, although not every thermal water is high in every major constituent. The exceptions are magnesium and carbonate-bicarbonate, both of which decline in the thermal waters. This probably reflects low-temperature fixation of magnesium carbonate. Carbonate and bicarbonate do have a single anomalous high near the Henson warm well, with 150 ppm, whereas both Kellog and Bassett hot springs have only 27 ppm of bicarbonate. On the other hand, warm wells in northern Round Valley have bicarbonate values of about 95 ppm.

Sulfate and chloride anomalies about the hot springs are well defined. Both Kellog and Bassett Hot Springs have sulfate values in excess of 350 ppm. The normal content of each at the basin margins is only 1 or 2 ppm. A less-intense high appears at Bieber, where a well has 150 ppm of sulfate. Chloride values at Kellog and Bassett Hot springs are 86 and 94 ppm, respectively. However, there are chloride concentrations of 60 to 70 ppm at cold wells in the vicinity of Lookout. Chloride to sulfate ratios show no significant trend.

Values at the eastern margin of Fall River Valley are similar to those in Big Valley. At Little Hot Spring, bicarbonate concentration is 40 ppm, chloride is 90 ppm and sulfate is 400 ppm. At the much cooler Dixon Flat (Vestal) warm spring, there are only 2.3 ppm of chloride and 4 ppm of sulfate, whereas there is 75 ppm of carbonate.

Fluorine and boron are found in anomalous patterns very similar to chlorine and sulfate. High fluorine values of 1.8

and 2.2 ppm are found at Bassett and Kellog Hot Springs, respectively. Two distinct anomalies occur at the springs, separated by a value of about 0.2 ppm, which appears to be the normal background concentration of fluorine for the region. Boron values reach 2.3 and 2.16 ppm at Bassett and Kellog Hot Springs, respectively. These anomalies are separated by a 0.1 ppm low, which again appears to be the normal background concentration for boron in the region. At Little Hot Spring, in the Fall River Valley, fluorine concentration is 3.2 ppm and boron concentration is 2.3 ppm.

Data from Hail (1961) and Swanson (1962) are similar to analyses from elsewhere on the Modoc Plateau and adjoining areas in Oregon. Cool, near-surface groundwater contains $Ca>Mg \sim Na>K$, and $HCO>SO_4 + Cl$, except where surface evaporation is intense, or where unusually soluble sediments are present. With increased trend or residence time, or with elevated temperature, the waters evolve to $Ca \sim Na>Mg \sim K$, and $HCO_3>SO_4>Cl$. Truly elevated temperatures yield $Na>Ca>K>Mg$ and $SO_4>Cl \sim HCO_3$ or even (as at Klamath Falls, Oregon) $SO_4>Cl>HCO_3$. Big Valley and vicinity fits this general pattern.

Dellechaie has plotted the qualitative temperature indicators, carbonate plus bicarbonate:boron, and chloride:boron. For the ratios of the carbonate group to boron, values of 27 and 11 were obtained at Bassett Hot Springs and 10 at Kellog Hot Springs. Highest ratios obtained were at the Henson well (150) and Dixon Flat Warm Spring (75). Little Hot Springs was 12. For chloride to boron, there was a range in ratios of 45 to 80 at Bassett Hot Springs, and a ratio of 45 at Kellog Hot Springs.

There is an anomalous concentration of SiO_2 in cool waters of Big Valley and vicinity (table 1). Even dilute waters commonly carry 50 to 65 ppm of SiO_2, and values in excess of 70 ppm are not rare. This may be caused by devitrification of siliceous glass and diatomite, or may be a ghost of thermal conditions at depth. Because of the widespread nature of this anomaly, the former idea is preferred.

A computer plot of silica values shows no significant additional anomaly at the hot spring areas. Local anomalies occur at the two hot spring areas, but they are not clearly above background for the valley. Calculations by Dellechaie of base temperatures, based upon silica as quartz, show maxima of about 125°C, at the hot spring groups in the Big Valley and at Little Hot Springs in Fall River Valley. Dellechaie is in process of plotting reservoir base temperatures using the sodium/potassium/calcium method of Fournier.

Hydrochemistry of the area does not serve to substantiate directions of ground-water flow, because of the distorting influence of the hot springs on the computer plots. All values are influenced strongly by the hot springs. It is unknown whether the springs represent rapid flow from depth, and the high mineralization represents deep hot water, or whether the springs represent relative slow ascent from depth, with contamination by reactions of the thermal fluid with the thick sections of pyroclastic rocks and lakebed sediments in the most stagnant part of the basin's groundwater system. Rapid movement from depth is favored, considering the availability of faults as channelways, and the relatively high temperature of discharge of the springs.

Hydraulic Characteristics of Rock Units.

Ford *et al.* (1963) and Hail (1961, 1962) noted several rock units as having "water-bearing" significance. Their formation names are not endorsed in this report. However, a correlation of their water-bearing units with our lithologic units is possible:

Ford et al. (1963)	This report
Basin deposits	Ql
Intermediate alluvium	Qal
Alluvial fans	Qf
Pleistocene basalt	Qb
Bieber Formation	Ttsl
Pliocene basalt and andesite	Tpbu
Rhyolite	Ttsu
Big Valley Mountains volcanic series	Tts, Tpbl
Turner Creek Formation	Tb, Ttsu, Tm

From oldest to youngest unit, the water-bearing properties of the rocks have been determined to be as follows:

(Tb, Ttsu, Tm). Although not considered to be a good aquifer as a whole, it has some excellent aquifers in lenticular, shoe-string, channel sandstones and conglomerates. Fractured lava flows, between pyroclastic members, also are quite permeable locally. Even within the rather impermeable pyroclastic rocks, highly fractured zones are both laterally and vertically permeable. Diatomite is impermeable except where fractured. The few deep wells that penetrate the "Turner Creek Formation" in Big and Round Valleys have obtained "moderate" amounts of ground water. The formation may be considered to have considerable water in storage. Altered zones, fault gouge, and the bulk of the pyroclastic units are aquitards. Ford et al. (1963) assumed that groundwater issuing from outcrops of the "Turner Creek Formation" recharges the northern part of Big Valley.

(Tts, Tpbl). These extensive and thick units ("Big Valley Mountains volcanic series") have not been tested sufficiently to evaluate storage and yield characteristics. Fractured flows probably transmit considerable amounts of water toward the Big Valley. Ford et al. (1963) qualitatively judged the unit as having low overall permeability.

(Tpbu). These Pliocene volcanic rocks include basalts and andesites on the margins of Big and Round Valleys. Andesite is restricted to the northern margins, in the vicinity of Stone Coal Mountain, and is considered impermeable and unlikely either to transmit recharge groundwater or to store water in the valley areas. Pliocene basalt is present on all sides of the valleys. It is permeable in numerous scoriaceous and vesicular zones, as well as along joints and faults. The basalt therefore has large storage capacity and probably serves as an important recharge horizon. It is probably not present at depth beneath Big Valley.

(Ttsl). This unit (Ford et al.'s "Bieber Formation") contains many different lithologies, and comprises more than 2,000 feet of section. Therefore it exhibits many differing hydrologic characteristics.

Pumiceous white sands and black sands are very permeable and porous. Poor sorting and fine grain size makes the other lithologic types less permeable. Aquitads within the (Tts1) unit cause confinement of some aquifers and create artesian conditions. The "older lake deposits," as described by Hail (1961) before the name "Bieber Formation" was used by Ford et al. (1963), are at least 2,000 feet thick in those parts of Big Valley characterized by the deepest gravity lows. These fine-grained aquitards could provide confinement for a deeper geothermal reservoir.

(Qb, Qf, Qal, Ql). These units do not serve as reservoirs for thermal fluid, because in most cases they do not extend to any significant depth. Further, the Pleistocene basalts are very permeable and transmit water rapidly to underlying formations. In some areas however, baked zones at the base of flows are aquitards. In areas such as near Juniper Creek, artesian conditions occur. Bouldery clay soils are developed on the basalt in some areas and provide impervious tops upon which water ponds and evaporates.

Pleistocene alluvial fans are surface and near-surface features with limited areal extent and average thicknesses of 10 to 100 feet. The fans are poorly sorted, but are composed of mainly coarse materials and are locally highly permeable. They may, therefore, serve as conduits of recharge.

Alluvium of Holocene age occurs in the streams in Big, Round and Fall River Valleys. A large delta has been formed where the Pit River enters Big Valley. Sandy parts of the alluvium are very permeable. Some clay and evaporite crusts were reported from drill holes by Hail (1961).

Basin deposits of Holocene age consist of fine sand, clayey silt, organic muck and alkali crusts that are distributed over the broad, flat, poorly drained parts of Big Valley, the center of Round Valley and Fall River Valley. These deposits are as much as 250 feet thick, cause stagnant conditions to arise locally in the surface water regime of Big Valley, and may contribute significantly to local chemical anomalies in warm spring hydrochemistry. Similar lacustrine, swamp and marsh deposits probably formed at prior periods in these basins, when eruptions of volcanic rocks and structural adjustments caused blockages of drainage systems.

Groundwater Storage and Movement.

Hydraulic conditions are known quantitatively only for Ford *et al*.'s (1963) "Bieber Formation" (our Ttsl) in Big Valley and Round Valley. The data for the hydraulic analyses come from 5 wells which were tested by Hail (1962), 2 in Big Valley and 3 in Round Valley. All produce from "older lake deposits" of the "Bieber Formation" (our Ttsl). The average permeability is 17.6 gallons/day/square foot.

Groundwater storage capacity to a depth of 1,000 feet was calculated for Big Valley from 21 well logs and 2 test holes. The total capacity was estimated to be about 3,750,000 acre-feet, based on specific yield of just over 5 percent, below 11 feet depth and a diminishing surface area. For Round Valley, based on 4 well logs, groundwater storage capacity to a depth of 200 feet is 120,000 acre-feet.

The deep section, which would provide any thermal aquifer, is unknown hydraulically. At target depths between 4,000 and 8,000 feet, it is assumed that the lower part of the "Turner Creek Formation" (Tb, Ttsu, Tm) or its age-equivalents would be found. Fractured basalts in these formations could provide suitable reservoir rocks, unless strongly altered. Altered andesitic and basaltic flows and especially pyroclastic units would serve as aquitards. Horsts of less permeable, older pyroclastic rocks beneath the surface of Big Valley may be the reason that circulation of groundwater and surface drainage of the valley is restricted, leading to development of swamps and stagnant zones. The horsts are proposed principally on the basis of gravity and magnetic data, and are supported indirectly by the shallow depth to bedrock in this region.

The eastern part of the Fall River Valley has a hydrological system almost equivalent to that of the Big Valley.

Formations are lithologically and temporally the same, and water storage and permeability apparently are the same. Both unconfined and confined groundwater occurs. Pliocene lake deposits were believed (Swanson, 1962) to be present at depth beneath Fall River Valley, and to provide a permeable section of several hundred feet in thickness. Wells in the eastern part of the valley produce water from a thick section of Pleistocene basalts.

The most permeable section in Fall River Valley consists of interbedded Pleistocene lakebed aquitards, composed of semi-consolidated sandy silt, silt and clay, together with highly permeable basalt flows, fine sand, volcanic ash and diatomite. This sequence has been tested to less than 500 feet depth, and is thought to be at least 700 feet thick.

Very youthful basalt flows border Fall River Valley with low rims on its north and south margins. These (Qb) basalts are very permeable, through vertical joints. The basalt section is 30 to more than 500 feet thick. Much groundwater is transmitted and stored by these flows: they are the conduit for runoff from the Medicine Lake Highland to the great springs at the head of the Fall and Tule Rivers, as well as for recharge to the basin sediments and older flow rocks at depth. The southern set of Quaternary basalts have the same high permeability as the northern basalts, but are not as significant to the groundwater regime of the basin. They are not marked by great spring discharges, but are a recharge unit to the valley. A recharge zone on the eastern boundary of the valley is comprised of older basalts in the Big Valley Mountains.

Alluvial fans, intermediate alluvial deposits, interrelated with thin basalt flows, and basin deposits, talus, and other materials of very limited vertical and areal extent, are found in Fall River Valley, but are of little influence on a deep reservoir system.

Although wells in Fall River Valley are shallow, there are enough wells to provide evidence of numerous northwest-trending, en echelon, normal faults that have been masked by basin fill. The faults break the interior basin of the valley into four main blocks. A northwest-trending graben occurs between McArthur and Fall River Mills, apparently increasing the depth to water bearing rocks in the central part of the valley. There is a second fault step up to the east near Pittville. Where these fault zones intersect volcanic flows and breccias, open fractures may provide significant increase in permeability. Permeability is reduced where the faults intersect clay-rich sedimentary rocks and pyroclastic deposits. Little Hot Springs, in the northeastern part of Fall River Valley, appears to occur at the intersection of several nearly parallel faults bounding the Big Valley Mountains.

Hydraulic conditions in the eastern part of Fall River Valley are based on yield data from only 11 wells. Deeper wells, intercepting basalt flows between depths of 200 and 400 feet, have permeability between 107 and 775 gallons/day/square foot (gds). The average permeability is 357 gds, based on data from 6 wells in the valley's central portion. Saturated thicknesses of 83 to 397 feet were found.

An estimated groundwater storage capacity of nearly 1,000,000 acre-feet was calculated for the interval from surface to 400 feet in depth, by assigning specific yield values to descriptive information in driller's logs. A diminishing surface area was used to calculate the storage capacity, which may minimize the figure. The amount of water in storage in this interval is only of interest in that it indicates water available for recharge to a potential reservoir at greater depth.

GEOTHERMAL REGIME

Thermal Manifestations.

The principal thermal manifestations in Big Valley are Bassett and Kellog Hot Springs. Additionally, there is a number of warm wells in the valley. In the eastern part of Fall River Valley, Little Hot Springs and Dixon Flat Warm Spring are present.

Kellog Hot Springs, described by Waring (1915) as Stonebreaker Hot Springs, is in Sec. 14, T. 38 N., R. 8 E. It consists of two main groups of springs, about 0.2 miles apart on an east-west line. The springs are at the southeast edge of Big Valley, in a flat meadow of alluvium. Lacustrine deposits (Ttsl) crop out less than one-half mile east and west of the springs. Pyroclastic rocks (Ttsu) crop out in hills less than one-half mile south and north of the springs.

Waring (1915) described 6 pools and springs in the main group. These were dispersed over a distance of 275 yards in a north-south direction. About 300 yards east of the southernmost of the springs of the group he found 4 other hot pools. Waring estimated that flow from the main, hottest spring was 125 gallons per minute. The highest temperature he measured was 165°F (75°C). He deduced that the springs probably issued from "tuffaceous sandstone" that underlies the meadow alluvium. He decided also that the rocks cropping out in the hills north and south of the springs was tuffaceous sandstone, rather than altered tuff. In 1973, J. B. Koenig measured a temperature of 88°C (190°F) at the base of a cistern into which the main spring was flowing. Frank Dellechaie measured temperatures as high as 89°C (192°F) in the main western spring of the group in 1974 and 1975. Dellechaie estimated that flow was 50 gpm at the western springs and 20 gpm at the eastern springs.

A one-meter-deep temperature survey was made of Kellog Hot Springs area on a 100-foot (30-meter) rectangular grid as a part of this project, in August, 1975. A solid-shaft, metal, 1-meter-long thermometer was used. A 5/8-inch pilot hole was driven with a pipe to about 80 cm depth; the temperature-sensitive point of the thermometer was then forced down the remaining 20 cm, so that the thermometer would not be in contact with air. Air temperatures ranged from 18° to 25°C through the 2-day operation. The hole sites were revisited and measured at different times of the day to be sure that soil temperature rather than ambient air temperature was being measured.

The results of the survey are plotted on plate 3. The lowest temperature recorded was 16°C. Temperatures were contoured at 25°C, coincidentally at the maximum air temperature, thereby defining an area of more than 10,000 square feet, with a distinct north-northwest trend. The zone within the contour is more than 800 feet long by about 150 feet wide, and is divisable into three segments, of which one is half the length of the zone, whereas each of the other two is about one-fourth of the zone. The northernmost half trends N. 30° W., and includes the main orifices of the western hot springs. The central fourth of the thermal zone trends north-south. The southern fourth trends N. 30° W.

As defined by the 25°C contour, the eastern group of hot springs are in the center of a 300-foot-long and 75-foot-wide zone trending north-south. About 500 feet of distance separates the two warm zones, with ground temperatures below 25°C.

The east and west parts of Kellog were sampled by AMAX in 1974. Analyses and interpretations show (see table 1):

pH = 9
F = 2.5 ppm
Na(240) > Ca(35) > K(5.6) > Mg(0.1)
SO_4(400) > Cl(86) > HCO_3(27)
$T_{SiO_2} = 124°C$
$T_{Na-K-Ca} = 75.5°C$

Note: ( ) = value in ppm

Indicated reservoir temperatures are not high at depth, unless considerable mixing with near-surface, cold waters has contaminated the chemistry of the thermal spring water. The spring water is very similar chemically to hot springs in the Fall River and Alturas-Canby areas. This breadth of chemical similarity suggests that chemistry is a valid indicator of reservoir conditions. In particular, SiO_2 concentration appears to be a reasonable guide to reservoir base temperatures. It is possible that identical mixing and dilution has occurred in each case, because the springs pass through similar lithologies and are in similar structural settings. However, this is less likely, on grounds of conservatism.

Bassett Hot Springs is located in Sec. 12, T. 38 N., R. 7 E., about 2.5 miles northeast of Bieber. The springs were visited by Waring (1915) in 1909 and samples were collected for chemical analysis. At that time a main spring that issued from altered tuff, which Waring called tuffaceous sandstone, in the (Ttsl) lacustrine deposits. There are no conspicuous structures and outcrops in the area.

Waring estimated total flow to be 175 gpm at a temperature of 79°C (173°F). Dellechaie also estimated flow of 175 gpm and measured a temperature of 78°C in 1974. Chemical analyses performed in 1909 (Waring, 1915), 1961 (Hail, 1961) and 1974 (Dellechaie, 1974) are remarkably similar. The most recent analysis shows:

pH = 9.1
F = 2.4
Na(220) > Ca(36) > K(3.2) > Mg(0.1)
SO_4(350) > Cl(94) > HCO_3(27)
SiO_2 = 72 ppm
T_{SiO_2} = 121.7°C
$T_{Na\text{-}K\text{-}Ca}$ = 58.9°C

Note: ( ) = value in ppm

These data and interpretations are very similar to those from Kellog Hot Springs, and the same conclusions may be drawn.

A temperature of 64°C was reported by Dellechaie from an artesian well located about 0.2 miles north of Bassett Hot Springs. From the analysis of a sample which he collected, the hot well is similar to Bassett Hot Springs and probably is drawn from the same ultimate source. Cl, SiO_2 and Ca content are less than for Bassett Hot Springs. All other ions are present in essentially the same concentrations.

Several other mildly warm wells and springs have been reported in the Big Valley-Round Valley area. Henson warm well, in Sec, 25, T. 38 N., R. 7 E., located about 2.5 miles southeast of Bassett Hot Springs, has a temperature of 31°C. It is notable for having a relatively high silica content (81 ppm). As noted earlier, it also has high potassium content, low sodium content and low calcium content. Therefore, base temperature calculations of 125°C and 186°C were obtained for T_{SiO_2} and $T_{Na\text{-}K\text{-}Ca}$, respectively. pH is low, 7.35, as is Cl (60 ppm) and sulfate (2.0 ppm); F content is only 0.25 ppm. The well produces 250 gpm from the (Ttsl) lacustrine sediments ("Bieber Formation").

Tyrrell warm well (Sec. 35, T. 40 N., R. 9 E.) produces 100 gpm of 30°C water. Silica content is only 45 ppm, in a mildly alkaline solution of pH 8.3. Only 1 ppm each of sulfate and chloride is present. There is no geological evidence that the well produces from a major thermal reservoir; however the calculated $T_{Na\text{-}K\text{-}Ca}$ is 365°C. This value is abnormally high, and probably meaningless.

Willow Creek Spring, in Sec. 28, T. 37 N., R. 10 E., flows 200 gpm of water at a temperatue of 28°C. It is located in a canyon southeast of the mapped area, probably along a fault located at the boundary between the rhyolites of Hayden Hill (Ttsu) and pyroclastic rocks in the southern part of the Barber Ridge volcanic series (Tm). Like Tyrrell warm well, Willow Creek Spring has low T.D.S., and manifests no chemical evidence to indicate anything other than circulation of ground water along a fault. It is mildly carbonate (78 ppm), with about 1 ppm each of chloride and sulfate.

Dutch Flat Warm Spring, at the northwest margin of Round Valley in Sec. 34, T. 40 N., R. 9 E., is a seep with a flow of only 1 gpm and temperature of 25°C. Although SiO_2 content is 64 ppm, the low flow makes the calculated T_{SiO_2} of 114°C suspect. The springs flow from a northwest-trending fracture zone in the Barber Ridge volcanic series (Tm).

Other slightly warm springs and wells are:

Lower McBride Spring, in Sec. 28, T. 37 N., R. 10 E., one-half mile north of Willow Creek Spring, flowing 100 gpm of water at 24°C.

Art Bennett warm well, in Sec. 28, T. 39 N., R. 9 E., producing approximately 20 gpm of water at 23°C. The well may be 174 feet deep, and probably was completed in lake sediemtns (Ttsl?).

Knudson warm well, in Sec. 21, T. 38 N., R. 9 E., producing an unknown volume of water at 22°C. Chemical analyses reported by Hail (1962), and by Dellechaie were very similar. The well produces from a depth of 200 feet, in alluvium. A relatively high SiO_2 content (82 ppm), and a calculated T_{SiO_2} of 126°C make the well interesting, although the water temperature is not exciting. Carbonate is 163 ppm, whereas chloride and sulfate are both about 2 ppm.

According to Hail (1961) a warm spring in Sec. 21, T. 39 N., R. 9 E. was developed by the Edgerton Lumber Company of Adin, and had a temperature of 21°C. Flow was not reported and the spring was not visited in this survey. Hail (1961) reported predominant bicarbonate, with low chloride and sulfate (about 2 ppm each), and 56 ppm of SiO_2.

Hail also reported a spring in Sec. 24, T. 40 N., R. 7 E., that flowed an unknown volume of water at 25°C. The spring is bicarbonate type (104 ppm), with low sulfate and chloride content (about 2 ppm each).

There are two occurrences of thermal water at the eastern margin of Fall River Valley, associated with the western structural boundary of the Big Valley Mountains. These are Little Hot Spring and Dixon Flat Warm Spring.

Little Hot Spring is a well-known thermal area, visited and reported by Waring (1915). The springs are in Sec. 9, T. 39 N., R. 5 E. About 200 gpm of water flows at a maximum temperature of 78°C (172°F), according to J. B. Koenig, after a visit in 1973. Waring reported maximum temperatures of 170°F (77°C) and F. Dellechaie measured a maximum temperature of 75.5°C (168°C). The hot water flows from a northwest-trending fracture zone at the base of a scarp cut on basalt flows and pyroclastic rocks. The scarp represents one of the several faults bounding the Fall River Valley. To the east of the faults are a succession of probably Pliocene pyroclastic rocks and volcaniclastic sedimentary rocks. West of the faults are very young basalt flows (Qb). Farther north, some basalts of this group are believed to be less than 1,000 years old (M. C. Gardner, 1964).

The chemistry of water from Little Hot Springs is very similar to that of hot springs in Big Valley. The analysis, reported by F. Dellechaie, shows the following:

pH = 8.1 (lower than that of Bassett and Kellog Hot Springs)
F = 2.3 ppm
$Na(240) > Ca(40) > K(5.6) > Mg(0.3)$
$SO_4(400) > Cl(90) > HCO_3(40)$
$SiO_2 = 86$ ppm
$T_{SiO_2} = 129°C$
$T_{Na-K-Ca} = 74.6°C$

Note: ( ) = value in ppm

These data and base temperature calculations are almost the same as those for Kellog Hot Spring. Comments made earlier about Kellog apply here also.

Dixon Flat Warm Spring is a weak thermal manifestation in Sec. 27-28, T. 37 N., R. 6 E. It flows an indeterminite, but large, volume of water at a temperature of 28°C into a marsh and creek. The spring is at the base of a youthful fault scarp separating the southern part of the Big Valley Mountains from the Fall River Valley. Basalt flows crop out east of the fault and lacustrine sediments crop out west of the fault. The Pit River flows through the sediments less than one mile west of the springs.

Chemistry of the spring water is comparable to, but somewhat less concentrated than, the principal thermal springs of Big Valley and Fall River Valley. Silica content is only 50 ppm. T.D.S. of the springs is only 171 ppm. There are 2.3 ppm of chloride and 4 ppm of sulfate, whereas there are 75 ppm of bicarbonate. The spring of itself does not provide evidence of a thermal reservoir at depth nearby. Base temperature calculated from SiO_2 is 101°C, and that from Na-K-Ca is 60.4°C.

Heat Source.

There is no compelling evidence that a young, cooling intrusion or magma exists below the Big Valley. Geological evidence specifically offers no support for the presence of a heat source in the vicinity of Bassett and Kellog Hot Springs. Only geophysical evidence indicates that a large, dense body of material occurs in the subsurface of Big Valley near the hot springs. Such a body may be a basaltic intrusion. More likely, it is an uplifted segment of the older basalt flow series (Tb).

Geochemical data do not support a shallow, cooling intrusive and/or magma. Specifically, SiO_2 values appear to be too low for a high-temperature intrusion, and Na-K-Ca ratios usually are even less favorable. The chemistry of the springs indicates that water has circulated to some unknown depth, and then has risen along faults without the introduction of high-temperature constituents such as would be produced by reaction of a magma with crustal rocks of the area. Therefore, a magmatic or intrusive heat source requires that there have been extensive dilution of deep, very hot thermal fluids with cool groundwater. Geochemical support for such a mixed thermal system is permissive at best.

Other gravity and aeromagnetic anomalies occur in the Big Valley, but are not coincident with known geological features that could assist in explaining them. A case in point is the magnetic high over the gravity low in the Beiber and Big Swamp basins. Possibly there are large, strongly magnetic bodies at depth below a thick section of low-density sediments. There is no geological or hydrochemical support for this speculation. Further, even if such a body did exist and were magnetic enough to be discernible through a thick cover of non-magnetic sediment, it would have to be below the Curie temperature, and probably be too cool and/or too deep to be an effective heat source.

The rhyolite tuffs of the Hayden Hills area represent intrusion by silicic magmas during middle Pliocene time, 6.7 ± 2.5 mybp being the age-date of a welded tuff related to such an igneous event. Possibly younger intrusions of silicic composition remain unrecognized in the magnetic and gravity data for that region. The prospect is not encouraging, however. This appears to be the youngest silicic igneous activity likely to provide a heat source in the Big Valley area.

The youngest eruptive rocks of the region are basalt flows and cinder cones. These are widespread along the western boundary of the Big Valley Mountains and in Fall River Valley. Fall River Valley appears to have a more youthful igneous history than Big Valley. It appears that a major series of structural breaks developed in the eastern part of Fall River Valley during the Pleistocene-Holocene epochs, during which time the western margin of the Big Valley Mountains was uplifted differentially, and olivine basalts were erupted from several centers along fissures. Some of the basalts in the Fall River Valley probably are less than 1,000 years old (Gardner, 1964).

Also, it would appear that the extensional forces acting on the thin, upper crustal zone are most recently being resolved in Fall River Valley, after earlier disturbances of the Big Valley. Big Valley is east of this zone of activity.

The area beginning at the Big Valley Mountains, and extending as far east as the Surprise Valley does not appear to have had the same Holocene eruptive and tectonic history.

Convective circulation of groundwater appears to fit the geological data, and is corroborated by interpretation of hydrochemical analysis. Geophysical data are passive, but permit this interpretation. The depth of such convective circulation is unknown, but may extend between 1 and 3, or even 4, kilometers, by extrapolation of simple temperature gradients, and by analogy elsewhere (see below).

Reservoir.

Adequate aquifers may exist for storage and production of thermal fluids at depth in Big Valley. The stratigraphic section at depths between 3,000 and 8,000 feet is believed to be composed of a mixed lithology of pyroclastic, sedimentary and basaltic and andesitic flow rocks. The initial porosity and permeability of the pyroclastic and sedimentary rocks is likely to have been poor, except for limited bodies of coarser river-channel sediments. Poor sorting, welding, and varying degrees of induration are the principal causes of low permeability. Alteration of tuffs and of interflow pyroclastic materials by hydrothermal solutions tends to further reduce permeability. Basalt flows often are very permeable, as a consequence of jointing and development of rubbly and scoriaceous interflow surfaces.

The persistant history of tectonic activity in the area has led to development of a system of macro- and microfractures, represented by faults, shears, joints and cleavage planes. Such a fracture system would be especially effective as a storage and transport mechanism in a reservoir that has come to thermal equilibrium, has undergone significant deposition of silica, calcite, clay or zeolite, and is continuing to undergo stress and fracture by tectonic activity.

If there is a significant geothermal cell beneath Big Valley, the reservoir is most apt to be the section of Miocene to Pliocene pyroclastic, volcaniclastic and flow rocks that may be more than 12,000 feet thick. It is unlikely that a hole drilled on the floor of Big Valley would penetrate into older horizons. Within this Miocene-Pliocene section, basalt flows, fractured pumiceous tuffs and fractured ignimbrites might offer the best targets for reservoir.

Analogy With Kelly Hot Spring.

Kelly Hot Spring is located a mile east of Canby, along a subsidiary branch of the Likely fault, in Warm Springs Valley, some 20 miles northeast of Big Valley. A sequence of Oligocene(?) to Pleistocene volcanic and sedimentary rocks, similar to those of Big Valley, has been mapped in the Warm Springs Valley region. Therefore, tectonically and stratigraphically there is a clear analogue between the two areas.

Kelly Hot Spring has been reported by Waring (1915) and others to discharge several hundred gpm of 94°C (204°F) water from a single orifice. Other thermal springs in Warm Springs Valley discharge water at 25° to 35°C (77° to 95°F).

In 1969, a hole was drilled to 3,200 feet, less than one-quarter mile south of Kelly Hot Spring. To about 1,600 feet the temperature increased steadily. A lost circulation zone at that depth was followed by temperature reversal, and near-adiabatic conditions to the hole bottom. The maximum temperature was about 110°C (230°F).

After ground-noise and electrical resistivity surveys, a new drilling location was chosen 2 miles to the east, on a small, closed resistivity low. A hole was drilled to 3,396 feet in 1974. In this hole, a maximum temperature of about 107°C (224°F) was reached, at hole bottom. However, temperature increased from ambient at the surface to 102°C (215°F) at 1,760 feet, at which point circulation was lost. From there until hole bottom (or until 2,900 feet by another interpretation), conditions were adiabatic, with occasional slight reversals of temperature. Even at hole bottom it was impossible to state with certainty that the increase in temperature would be continuous with increasing depth.

Each hole penetrated a sequence of sedimentary rocks (mudstone, sandstone, siltstone) and igneous rocks (basalt, andesite, latite porphyry, tuff, mudflow breccias and coarser-grained intersive rocks). Neither reached pre-Tertiary basement.

It is uncertain if either hole reached pre-Miocene rocks. Temperatures, lost-circulation zones, gradients and depths were very similar. The second hole may be thought of as an unnecessary duplication of the first.

The gradient in the lowest 400 feet of the second hole approximated 1°F per 75 feet. This is barely "average" for provinces of youthful volcanism and tectonic activity. If projected, it would yield a temperature of about 130°C (265°F) at about 6,500 feet. If the gradient were to steepen with depth to 1°F per 50 feet, which is more typical of the Basin and Range and Modoc Plateau provinces, 140°C (285°F) would be the temperature at 6,500 feet. If adiabatic conditions were to persist well beyond 3,400 feet, even lower bottom-hole temperatures would be encountered at 6,500 feet. Under the more favorable assumptions, even at 10,000 feet the temperature would be in the order of 183°C (360°F). This is scarcely worth contemplating drilling to 3 kilometers in depth.

As with Big Valley, there is no obvious magmatic heat source in Warm Springs Valley. Data do not foreclose that possibility, but the same can be said for millions of acres in northeastern California and adjacent Oregon and Nevada.

Six shallow temperature-gradient holes were drilled to the north, northeast and south of Kelly Hot Springs. Not surprisingly, temperatures and gradients in these 75- to 150-meter-deep holes were attractive. Equally unsurprising, holes drilled nearly due north of the hot springs a distance of one-quarter to one-half mile had the most favorable temperatures and gradients. That is, they defined a north-northwest-trending fracture, buried beneath the unconsolidated sediment of Warm Springs Valley, along which the waters of Kelly Hot Spring reasonably may be assumed to rise.

This, then, is the classic case of deep, convective circulation of hot water along a buried fracture. The circulation cell brings water from 1 or 2 kilometers in depth to the surface. Shallow aquifers are heated along and near the fracture. No magmatic heat source is required or suspected.

Even allowing for errors in measurement of temperature, disequilibrium during measurement, and improperly projected gradients to depth, it is unlikely that temperatures above

150°C (300°F) would be found at 2 kilometers (6,500 feet) in depth. This is in close accord with geochemical indicators.

A similar condition may be anticipated for Big Valley.

PROGRAM

It is our basic recommendation that no further work be done in Big Valley. However, if additional effort is decided upon, the following may prove more productive than other activities:

1. An additional group of perhaps 4 radiometric age-dates should be obtained on grey tuffs associated with the youngest dated silicic intrusives of the Hayden Hill area, and on the youngest-appearing basalt lavas north and south of Big Valley. This may improve understanding of igneous chronology and offer a possibility for finding a magmatic target.

2. Existing chemical analyses of the California Department of Water Resources should be processed mechanically and integrated with analytical data collected by AMAX. This may improve our understanding of circulation in the cool-water and thermal regimes by augmenting the loose network of AMAX sample locations.

3. Existing gravity and magnetic data should be processed by computer, in an attempt to determine depth to and shape of basement, and possible existence of a magmatic body beneath Big Valley and beneath the Pliocene rhyolite tuff of Hayden Hill and vicinity.

4. It may be useful to perform active seismic profiling along a line across Big Valley. This would provide information on the depth to and shape of high-velocity layers,

including a possible mafic intrusion beneath the magnetic high in the center of Big Valley.

5. One or more intermediate-depth holes may be warranted in the vicinity of Kellog Hot Springs. Such holes would test the concept of a convecting geothermal cell with a base temperature of 120° to 150°C at depths of 1 to 2 kilometers. The hole(s) probably would be 1,500 to 2,000 feet in depth, and certainly not deeper than 3,000 feet. If temperatures became isothermal through a distance of several hundred feet, the hole would be abandoned and the convective hypothesis accepted. If, on the other hand, temperatures continued to climb without reversal to 2,000 or especially 3,000 feet, the region would have a significant potential for discovery of a high-temperature resource at perhaps 2 kilometers. The latter is believed to be unlikely.

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APPENDIX 1

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Appendix 1

Petrographic Analyses, Thin-Sections of Rocks From Big Valley and Vicinity

Sample number: B-1

Formation: (Ttsu)

Hand specimen identification: rhyolitic tuff, altered

Thin-section identification: crystal tuff

phenocrysts: 14%
- 10% quartz (0.3 mm), subhedral; most of the grains are broken
- 2% biotite, altered to montmorillonite-group clay minerals
- 2% rock fragments (< 1 mm)
- trace cryptocrystalline quartz or opalite, sericite, and secondary mineral that may be adularia.

ground mass 86%
- 50% devitrified glass, brown
- 20% plagioclase laths (0.2 to 0.5 mm)
- 16% pore spaces

Sample number: B-1 a

Formation: (Ttsu)

Hand specimen identification: quartzite pebble from detrital sand and gravel deposit

Thin-section identification: quartz

specimen consists entirely of sutured quartz grains (0.1 to 1 mm); iron oxide rind to pebble

Sample number: B-4

Formation: (Ttsu)

Hand specimen identification: dark grey, vesiculated basalt, with a felted appearance to the plagioclase phenocrysts

Thin-section identification: glomeroporphyritic olivine-labradorite basalt

phenocrysts: 35%
- 30% plagioclase (core An 62, rim An 60), euhedral (4 mm max); normal zoning; glomeroporphyritic clusters with olivine; clusters range to 4 mm; slight alteration, to montmorillonite(?)
- 5% olivine, euhedral (0.5 to 2 mm); almost totally altered to iddingsite (smectite-chlorite); few unaltered olivine cores

ground mass: 65%
- 20% plagioclase (An 35), subhedral (0.2 to 0.3 mm); felted texture; normal zoning; laths partially altered
- 20% glass, dark, interstitial; contains iron oxide
- 15% vesicles, with sub-dictytaxitic texture
- 5% olivine (0.1 to 0.2 mm), subhedral, interstitial; altered to iddingsite
- 2% augite (0.1 to 0.2 mm), subhedral, interstitial
- 1% iron oxides (<0.1 mm); dispersed widely

Sample number: B-10

Formation: (Tpbu)

Hand specimen identification: basalt; possibly hypabyssal intrusive rock

Thin-section identification: olivine basalt with ophitic augite

phenocrysts: 12%
- 5% plagioclase (An 69), subhedral (2 mm); normal zoning
- 5% augite (1 to 4 mm), poikilitic with plagioclase
- 2% olivine (1 mm), subhedral; partial alteration to iddingsite

ground mass: 88%
- 50% plagioclase (0.5 mm), subhedral
- 25% augite (0.2 to 1 mm), ophitic plates
- 5% iron oxides, black, subhedral, mostly magnetite
- 5% glass, interstitial, badly devitrified to unidentifiable substance

2% alteration products, probably smectite-group clay minerals
1% olivine (0.1 mm), subhedral; partial alteration to iddingsite

no vesicles
sample almost identical to B-30, except for larger grain size hypabyssal mode of emplacement suggested

Sample number: B-14

Formation: (Ttsu)

Hand specimen identification: tuff

Thin-section identification: dacitic crystal-lithic tuff

phenocrysts: 50%
- 40% plagioclase (An 20), oscillatory zoning (1 to 4 mm); grains often broken
- 5% lithic fragments (0.5 mm), volcanic glass, devitrifying to quartz in part
- 2% augite (0.1 mm)
- 2% hornblende
- 1% iron oxide, probably magmetite

ground mass: 50%
devitrified glass, brown, fine-textured, with few identifiable shards

Sample number: B-22

Formation: (Ttsu)

Hand specimen identification: welded tuff

Thin-section identification: welded tuff

phenocrysts: 13%
- 7% plagioclase (An 30), many broken grains (1 to 2 mm)
- 3% rock fragments (1 to 2 mm), almost entirely volcanic; plagioclase of An 60 measured in one fragment; possible vesicular basalt fragment; fragments altered in varying degree
- 2% augite (1 to 2 mm)

1% magnetite

ground mass: 87%
welded glass shards (0.5 mm), ash, collapsed pumice in eutaxitic texture; dense; few seams of non-welded pumice tuff form thin lamellae

Sample number: B-22 b

Formation: (Ttsu)

Hand specimen identification: rhyodacite dike

Thin-section identification: hyalodacite

phenocrysts: 18%
14% plagioclase (core An 45, rim An 27), subhedral (1 to 2 mm); glomeroporphyritic clustering with other plagioclase and with pyroxenes; oscillatory zoning
3% augite (0.1 to 0.3 mm), subhedral, glomeroporphyritic
1% enstatite (0.5 to 1 mm), subhedral
trace magnetite (0.1 mm), subhedral
trace olivine (0.1 mm)

ground mass: 82%
70% glass, interstitial
10% plagioclase crystallines (0.05 mm); may be zoned
2% iron oxide, dusty, fills fractures

Sample number: B-26

Formation: (Ttsu)

Hand specimen identification: altered tuff breccia

Thin-section identification: crystal-rich welded tuff

phenocrysts: 30%
20% plagioclase (core An 45, rim An 32), unbroken phenocrysts (1 to 2 mm)
5% plagioclase (An 23), different from above (0.5 mm); crystallites
5% augite (0.5 to 1.0 mm)

ground mass: 70%
glass, vesicular, flattened; partially devitrified; some areas resemble crushed pumice; fiamme to 8 mm by 20 mm, parallel to eutaxitic fabric of shard-rich matrix

Sample number: B-27 a

Formation: (Ttsu)

Hand specimen identification: rhyodacite (volcanic neck?)

Thin-section identification: pilotaxitic basalt

phenocrysts: 15%
5% plagioclase (core An 50, rim An 34); subhedral (1 to 5 mm); clusters of plagioclase and augite; very slight degree of alteration
5% augite (0.2 mm), euhedral
2% iron oxide, probably magnetite
1% enstatite (0.2 mm), subhedral
1% hornblende (0.2 to 0.5 mm), bordered with iron oxide dust
1% biotite (0.2 to 0.4), outlined with iron oxide dust

ground mass: 85%
48% glass, devitrified, altered in part to montmorillonite-group clay minerals; pilotaxitic texture with plagioclase
35% plagioclase (0.1 to 0.3 mm), probably oligoclase
2% iron oxide (0.05 to 0.1 mm), dusting across entire matrix

Sample number: B-27 b

Formation: (Ttsu)

Thin-section identification: identical to B-27 a, except that An 70 plagioclase phenocrysts (0.2 to 1 mm) make up 20% rock, and that magnetite comprises only 1% of the rock.

Sample number: B-28

Formation: (Tpbu)

Hand specimen identification: volcanic sandstone

Thin-section identification: volcanic sandstone

60% pumice and glass fragments (to 4 mm), altered, devitrified in large part, with palagonite rinds
25% pore space
10% volcanic rock fragments
5% plagioclase fragments
<1% amphibole, pyroxene, olivine fragments; subhedral to euhedral

Sample number: B-30

Formation: (Tpbu)

Hand specimen identification: basalt

Thin-section identification: poikilophitic olivine basalt

phenocrysts: 10%
5% plagioclase (core An 76, rim An 35), subhedral (1 to 2 mm), normal zoning, with abrupt step near crystal rims; glomeroporphyritic clusters with other plagioclase and olivine grains
5% olivine (0.5 to 2 mm), subhedral; rimmed with iddingsite

ground mass: 90%
45% plagioclase (An 30), subhedral (0.2 to 0.6 mm); normal zoning
30% augite (0.1 to 1.5 mm); poikilophitic texture with plagioclase laths
5% glass, dark, interstitial; small crystallites present
5% vesicles, dictytaxitic
3% iron oxides (0.1 mm) subhedral
2% olivine (0.1 to 0.2 mm) subhedral; slight alteration to iddingsite

Sample number: B-39 a

Formation: (Ttsu)

Hand specimen identification: tuff

Thin-section identification: crystal tuff

phenocrysts: 42%
- 30% plagioclase (An 60), subhedral (2 to 4 mm); grains commonly broken
- 10% volcanic rock fragments (2 to 4 mm), contain abundant plagioclase and pumice
- 2% augite (<1 mm)

ground mass: 58%
glass and ash, partially devitrified, sharp, angular

Sample number: B-40

Formation: (Ttsu)

Hand specimen identification: basalt

Thin-section identification: basalt

phenocrysts: 17%
- 10% ovate vugs, lined with unidentified fibrous material
- 5% magnetite
- 2% plagioclase (An 65), subhedral (0.2 to 1 mm)
- traces of muscovite and hornblende

ground mass: 83%
glass, altered, brown, with microlites of plagioclase and pyroxene (0.02 to 0.05 mm) in flow-banded pattern

Sample number: B-50 c

Formation: unknown -- not in mapped area

Hand specimen identification: altered tuff

Thin-section identification: silicified tuff

Extremely fine-grained, partially silicified, possibly recrystallized, with bands of yellow to purple iron oxide minerals.

Sample number: B-56 b

Formation: unknown -- not in mapped area

Hand specimen identification: altered basalt

Thin-section identification: altered porphyritic basalt

phenocrysts: 27%
- 20% plagioclase, subhedral (0.5 to 3 mm)
- 4% iron oxides, probably magnetite
- 3% olivine (to 2.0 mm), altered almost entirely to iddingsite and chlorite

ground mass: 73%
- 35% plagioclase laths
- 30% chlorite, probably replacing olivine and/or augite
- 8% iron oxides, probably magnetite

cut by veinlets of equigranular quartz
calcite occurs as late vein filling and as patchy replacement grains up to 5 mm in diameter

Sample number: B-133

Formation: (Ttsl)

Hand specimen identification: volcaniclastic conglomerate

Thin-section identification: epiclastic volcanic conglomerate

Almost wholly sub-angular to sub-rounded epiclastic volcanic fragments (2 to 8 mm diameter); suggestive of transport from a distance; cemented by fibrous, zoned, authigenic feldspar; multiple sources of mafic volcanic clasts; abundant plagioclase laths in mafic glass matrix; minor pyroxene grains in some clasts; iron oxide and clay mineral alteration products.

Sample number: B-143

Formation: (Tb)

Hand specimen identification: basalt

Thin-section identification: porphyritic, pilotaxitic basalt

phenocrysts: 32%
  25% plagioclase (An 70), subhedral (0.5 to 2 mm); discrete laths and clots with pyroxene
  5% diopside (0.5 to 2 mm)
  2% magnetite (0.5 to 2 mm)

ground mass: 68%
  glass, only slightly devitrified, containing oriented plagioclase microlites and magnitite (<0.1 mm); pilotaxitic texture

Sample number: B-144

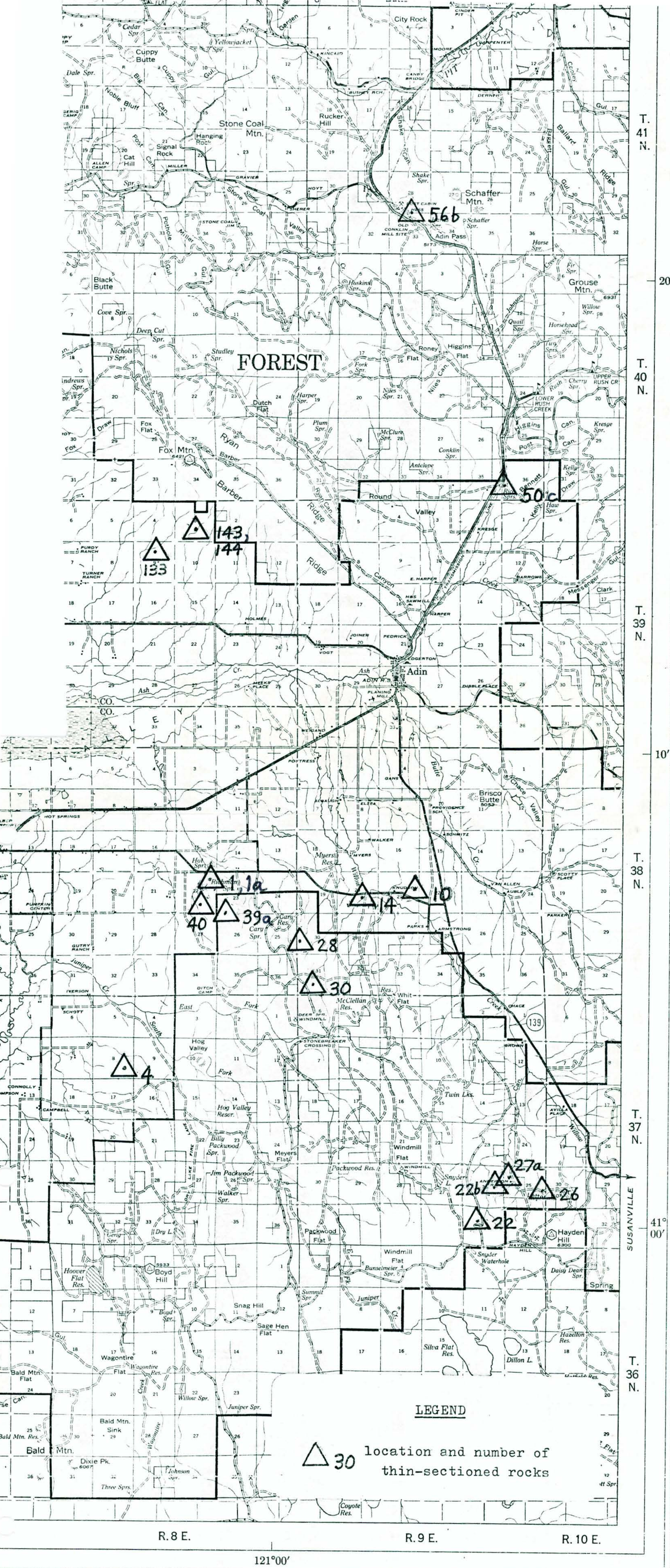
Formation: (Tm?)

Hand specimen identification: basalt

Thin-section identification: altered vesicular basalt

phenocrysts: 27%
  15% vesicles (0.1 to 2.5 mm); some are empty; some lined or filled with chlorite (to 0.5 mm) or chlorite and fibrous, patchy quartz; gives rock distinctive grey-green color
  10% plagioclase (An 80) subhedral (to 1 mm)
  2% augite (0.5 mm)

ground mass: 73%
  glass, brownish, with needles of plagioclase (0.2 mm) in pilotaxitic texture; patches of replacement chlorite (to 0.5 mm)


T. 41 N.
T. 40 N.
T. 39 N.
T. 38 N.
T. 37 N.
T. 36 N.
R. 8 E.
R. 9 E.
R. 10 E.
121°00′
20′
10′
41° 00′
SUSANVILLE
FOREST
Adin
Stone Coal Mtn.
Rucker Hill
City Rock
Schaffer Mtn.
Adin Pass
Grouse Mtn.
Black Butte
Fox Mtn.
Round Valley
Brisco Butte
Hog Valley
Hayden Hill
Boyd Hill
Snag Hill
Bald Mtn.
Dixie Pk.
Windmill Flat
Packwood Flat
Twin Lks.
56b
50c
143, 144
133
1, 1a
40
39a
28
30
14
10
4
27a
22b
26
22
LEGEND
△30 location and number of thin-sectioned rocks

GeothermEx 901 MENDOCINO AVE.
BERKELEY, CA. 94707

JAMES B. KOENIG (415) 524-9242
MURRAY C. GARDNER (503) 482-2605

APPENDIX 2

DONALD F. SCHUTZ
General Manager

TELEDYNE ISOTOPES
50 VAN BUREN AVENUE
WESTWOOD, NEW JERSEY 07675
(201) 664-7070 TELEX 13-4474

23 September 1975

Dr. Murray Gardner
Geothermal Exploration Services
1340 Ponderosa Drive
Ashland, Oregon 97520

W. O. No. 3-4036

Dear Murray,

We have completed the analysis of your samples submitted for K/Ar age determination. The results for the analysis are as follows:

Isotopes Sample #	Your Sample #	Isotopic Age (m.y.)	scc $Ar^{40}Rad/gmx10^{-5}$	$\%Ar^{40}Rad$	%K
KA75-299	BAD-4	13.8 ± 2.4	.055	21.8	1.07
			.062	25.4	1.05
KA75-300	BAD-5	6.7 ± 2.5	.067	15.0	3.45
			.116	54.7	3.43

These analyses were performed on whole rock samples.

The constants for the age calculation are $\lambda_\beta = 4.72x10^{-10}yr^{-1}$.
$\lambda_\varepsilon=0.585x10^{-10}yr^{-1}$ and $K^{40}=1.19x10^{-4}$ atom percent of natural potassium.

The error indicated for the reported ages consists of a summation of all analytical errors. The argon extraction spike calibration against standard biotite limits the accuracy to 5%. Therefore, we have selected 5% as our minimum analytical error for samples with sufficient radiogenic argon. All samples are done in duplicate. The precision of the duplicate analysis is calculated. If the sum of the errors of the potassium and argon measurements exceeds 5%, this summation is reported as the analytical error.

If you have any questions concerning these results, please do not hesitate to contact me.

We look forward to being of further service to you.

Very truly yours,

Don

Donald F. Schutz
General Manager

DFS:hp

cc: J. Koenig

TELEDYNE
ISOTOPES

50 VAN BUREN AVENUE
WESTWOOD, NEW JERSEY 07675
(201) 664-7070 TELEX 134474

29 August 1975

Mr. Murray Gardener
Geothermal Exploration
901 Mendocino Avenue
Berkeley,
California 94707

W.O. No. 3-4016-212

Dear Mr. Gardener:

These are the potassium determinations you requested. Please notify us as to which samples you want argon analyses performed on.

	%K		
Sample No.	Run 1	Run 2	Ave.
BAD-1	0.15	0.14	0.145
BAD-2	0.51	0.49	0.50
BAD-3	0.14	0.14	0.14
BAD-4	1.07	1.05	1.06
BAD-5	3.45	3.43	3.44
BAD-6	2.23	2.25	2.24
BAD-7	0.14	0.15	0.145
BAD-8	0.88	0.91	0.89

If you have any questions concerning these analyses, please contact me. We look forward to being of further service to you.

Very truly yours,

REPerrin
R. E. Perrin
Manager, Analytical Services

REP:pg

Binocular Petrography

(30X binocular microscope)

BAD-4

Location: NW/4, NW/4, NE/4, Sec. 33, T. 40 N., R. 8 E.

Field relationships: flow rock, from ridge to the south of Fox Flat; key to age of uppermost flows of Barber Ridge; from poorly defined flow sequence.

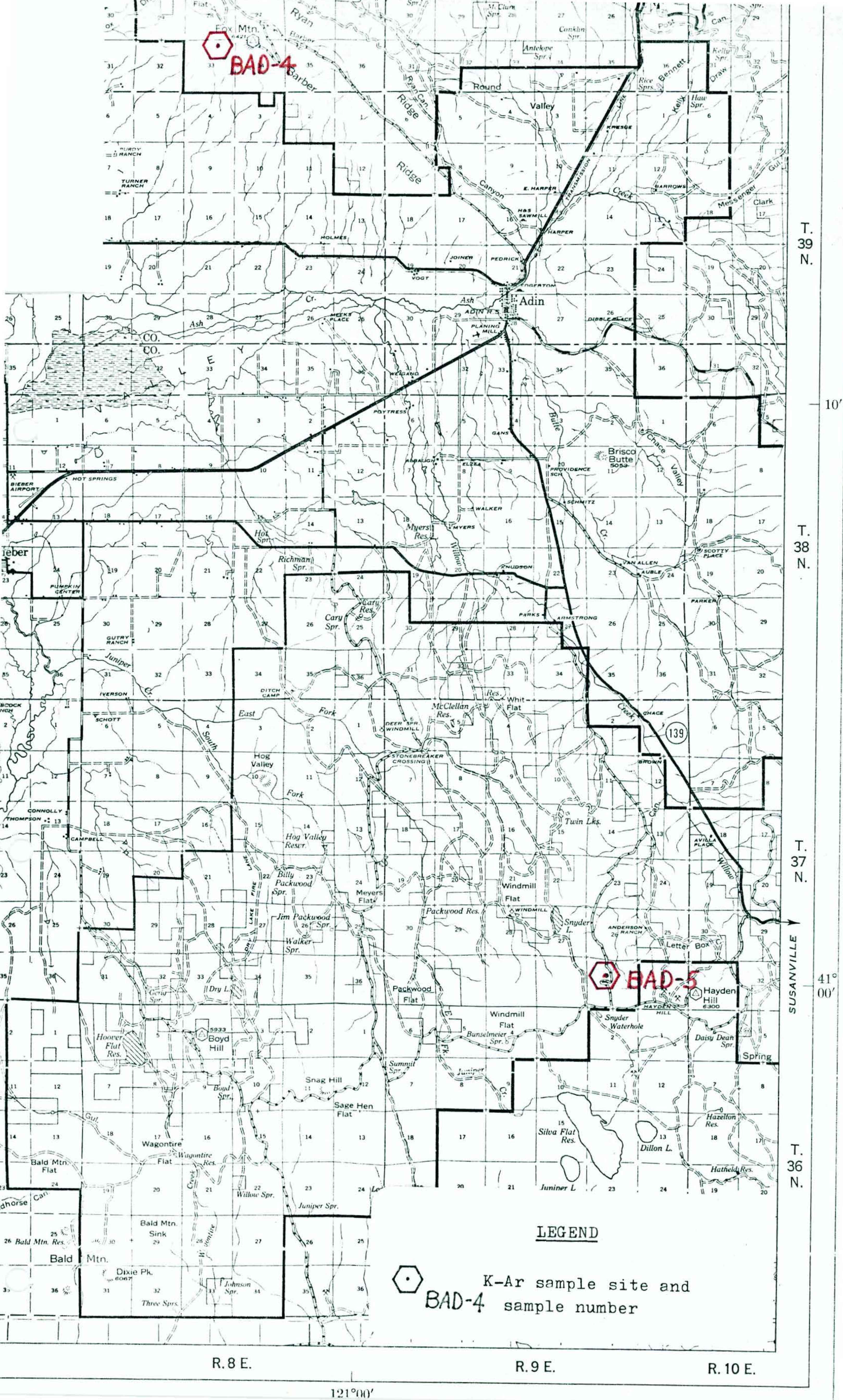
Description: dark grey basalt; less than 5% olivine phenocrysts (maximum 2 mm); olivine partially altered to brown smectite clay; slight platy cleavage noted.

BAD-5

Location: SE/4, SE/4, NW/4, Sec. 35, T. 37 N., R. 9 E.

Field relationships: unit caps series of poorly bedded pyroclastic rocks, and is separated from overlying basalts by an erosion surface; may supply a key age relationship of pyroclastic section to overlying basalts.

Description: light grey welded tuff; petrographic description given for thin-section B-22, Appendix 1.


BAD-4
BAD-5
Fox Mtn.
Round Valley
Adin
Bieber
Brisco Butte 5053
Hayden Hill 6300
Boyd Hill
Snag Hill
Bald Mtn.
Dixie Pk.
Silva Flat Res.
Dillon L.
139
T. 39 N.
T. 38 N.
T. 37 N.
T. 36 N.
R. 8 E.
R. 9 E.
R. 10 E.
10′
41° 00′
121°00′
SUSANVILLE
LEGEND
K-Ar sample site and
BAD-4 sample number