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GEOLOGY OF THE
LA GRANDE-BAKER AREA,
OREGON

by

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for

AMAX EXPLORATION, INC.

DENVER, COLORADO

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ILLUSTRATIONS

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CONCLUSIONS

1. The Grande Ronde Valley is a major, complexly faulted, northwest-trending graben, having maximum vertical displacements of 5,000 feet from west rim to graben center and 6,200 feet from east rim to the graben center (see Plate II, cross-section A-A' and Plate I, Geologic Map). Much of the displacement is taken up by two or three faults on each side of the graben.

2. The surface geology is dominated by platy andesite flows which overlie a 6,000-foot-thick section of Columbia River Basalt. The distribution of the platy andesite is closely associated with the graben and its southward extension, whereas the basalt comprises a major regional feature. Within the project area, the basalt shelves rapidly to the south upon a basement highland that has persisted at least since early Miocene time.

3. Radiometric age dating show that the platy andesite is 12 to 16 million years old and that the basaltic cinder cones are not Pleistocene in age. The cones are inferred to have been erupted 10 to 15 million years ago, despite apparently greater radiometric age-dates. Both of these rock units represent magmatic events far too old to be associated with a shallow geothermal field.

4. Thermal springs and wells are widespread, apparently are structurally controlled, and do not cluster about an obvious heat source or reservoir target. Temperatures and chemical compositions vary significantly, suggesting complex sources, general mixing with shallow ground water, or both.

5. The lower parts of the Columbia River Basalt and highly fractured zones within the basement complex are proposed as reservoir targets. The maximum anticipated reservoir thickness includes the lower 3,000 feet of the Columbia River Basalt and possibly the upper 5,000 to 8,000 feet of basement. Therefore, along cross-section A-A' near the graben axis the drill-target depths range from a minimum of 4,000 feet to an economic maximum of 10,000 feet below the valley surface. The Columbia River Basalt thins rapidly

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southward and the entire volcanic cover becomes insignificant south of the latitude of Telocaset. Exposed pre-Tertiary basement is not considered to be a suitable reservoir target.

6. The relative sparsity and wide dispersion of surface geothermal manifestations is probably the result of the geometry of heat source, reservoir and cap rock. In the Grande Ronde Valley and adjacent areas underlain by platy andesite and Quaternary sediments, at least 500 to 2,000 feet of impermeable to semi-permeable materials overlie the upper aquifers of the Columbia River Basalt, and the depth to potential geothermal aquifers may be considerably greater. The capping units may confine the thermal fluids and allow surficial expression only where geologic structures favor rapid upwelling. In the southern part of the project area, the surface manifestations again are controlled structurally, and thermal fluids issue from basement rocks via fractures and fault-induced permeable zones. Leakage of thermal fluids may be possible only along these fracture zones. If major graben-forming faults have moved significantly during the late Pleistocene epoch, the present structural, hydrologic and geothermal system may still be in the process of equilibration. Another possible alternative is that the proposed heat source(s) is insufficient to drive a major geothermal system, and that the total heat in storage in the area is relatively small.

7. Either of two potential heat sources may be present in the area. The heat may be supplied by a buried and, as yet, undetected intrusive body (or bodies) of mafic or intermediate composition. Or, the Grande Ronde structure may represent an area of abnormally thin crust, wherein hot mantle materials, and therefore higher isotherms are relatively close to the surface. There is no certainty that these heat sources are intense enough to support a major geothermal system.

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RECOMMENDATIONS

1. Gravity data collected by AMAX should be reduced to complete Bouguer anomalies, and interpreted to shed light upon subsurface structures, to determine the depths at which basement is located beneath a cover of Tertiary volcanic and sedimentary rocks, and to locate, if possible, youthful intrusions at depth. Follow-up gravity surveys should be undertaken if the preliminary work indicates that more detail would be helpful.

2. The magnetic survey data should also be interrogated with the aim of answering the questions posed for the gravity work. If necessary, additional, detailed aeromagnetic surveys should be carried out within the southern half of the project area.

3. Ground noise and microseismic data obtained previously by AMAX should be interpreted in light of available geological and other geophysical data. Areas of greater tectonic activity should be selected for additional exploration by other means, so long as these areas can be supported geologically.

4. Deep electrical resistivity and perhaps active seismic surveys should be organized, to provide data on basement configuration, potential permeability at depth, and complexities of structure in those areas of relatively high interest.

5. The geological, geophysical, and hydrochemical data should be interpreted to determine the most suitable locations for several deep temperature-gradient holes. These should be situated so as to penetrate resistivity anomalies, and preferably to penetrate the principal ground-water aquifers of the area.

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INTRODUCTION

Purpose and Scope.

This mapping project was undertaken to fulfill recommendation #2 of the Koenig and Gardner (1974, p. 1) report: to "conduct geological exploration, namely photogeology, field geology and radiometric age dating to define principal structures, and obtain absolute as well as relative igneous and sedimentary rock relationships." The ultimate objective of this exporation was to develop a detailed working model of the size, shape, and internal character of the potential geothermal reservoir. It was also intended to determine the depth, volume, shape, composition, and age of the heat source that is manifested by warm- and hot-water wells and springs in the area.

The project area includes the land indicated by Koenig and Gardner (1974, Fig. 2), plus the tier of four 7.5-minute U. S. Geological Survey topographic quadrangles immediately south of the original plot. The total area mapped exceeds 400 square miles, and is distributed over the following 7.5-minute quadrangles: Cove, Conley, Craig Mountain, Union, North Powder, Telocaset, Medical Springs, Haines, Magpie Peak, Keating NW, Sawtooth Ridge, as well as portions of La Grande SE, Glass Hill, Little Catherine Creek, and Flagstaff Butte.

Previous Work and Acknowledgements.

The regional geologic setting can be pieced together from several sources. The geology of portions of the Wallowa Mountains was summarized by Smith (1938) and Smith and Allen (1941). These works, in conjunction with the Sparta 15-minute geologic map by Prostka (1962), detailed the lithologic sequence and major structural features exposed east and southeast of the present project.

The 30-minute Sumpter quadrangle mapped by Pardee (1941) indicated the relationships between basement and the Tertiary volcanic sequence in the Blue Mountains, southwest of the project area.

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More recent reconnaissance geologic maps at scales of 1:250,000 or smaller exist for areas adjacent to or partially or wholly inclusive of the present project. Included in this group are works by Walker (1973 a, and in preparation); Brooks, McIntyre and Walker (in preparation); Newcomb (1970); Lystrom, Nees and Hampton (1967); and Hampton and Brown (1964). These maps have provided the major structural and lithologic framework upon which the present work was based.

Gilluly's (1937) work on the Baker 30-minute quadrangle, and McIntyre's unpublished work on the Haines, Magpie Peak, Keating NW, and Sawtooth Ridge 7.5-minute quadrangles, have been checked briefly, interpreted, integrated, and adopted with little modification during this study.

The State Forestry Division (La Grande and Salem) and the U. S. Forest Service (La Grande and Union) made available aerial stereo-photo coverage of portions of the project area and provided space in which to use the photos. The Oregon Department of Geology and Mineral Industries (Baker) provided access to McIntyre's maps and to other geological literature pertinent to the project.

Present Work.

Mapping in the area consisted of photogeologic interpretation coordinated with field mapping. The mapping progressed from the south, where the most detailed previous data was available, towards the north, where the greatest geothermal potential was believed to exist. About 175 rock specimens were collected, 12 representatives of which have been thin-sectioned, and five of which have been analyzed chemically and age-dated radiometrically by potassium-argon on whole rocks. Most of this work was undertaken by Knox with supervision and review by Gardner. A total of 49 man-days were devoted to the mapping activities, approximately 15 man-days were spent in review, travel, and field briefing sessions, and 25 man-days were used in the preparation of this report.

The owner of one property of approximately 11,000 acres within the area of high interest (high geothermal potential) would not allow access to any portion of his land. This closed to our exploration a significant portion of the Union and Telocaset quadrangles, except for road traverses. Fortunately, Oregon Highway 237 through Pyles Canyon and "public" dirt roads through Ramo Flat afforded access into the property.

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PHYSICAL AND ECONOMIC GEOGRAPHY

Location.

The project area is located in Union and Baker Counties in north-eastern Oregon. La Grande (pop. 9,645) and Baker (pop. 9,354) are the principal towns. Lesser centers of population include Union (pop. 1,720), Cove (pop. 363), North Powder (pop, 304), Haines (pop. 212), Island City (pop. 202) and Telocaset; each of which is accessible from La Grande or Baker by well-maintained, paved and improved gravel roads, as are the resort-spa of Hot Lake and the country gas station at Medical Springs (see Figure 1).

The major highway traversing the region is Interstate 80N. The principal roads granting access within the project area include U.S. Highway 30 and State Highways 203 and 237. The Union Pacific main line runs southeastward from La Grande to Telocaset and thence southwestward towards Baker. United Airlines maintains regularly scheduled service into Pendleton (52 miles northwest of La Grande). The small municipal airport at La Grande handles general aviation traffic for the immediate area.

Most of the area is accessible to four-wheel-drive vehicles, although road quality varies greatly according to ownership and use. County and forest access routes usually are well-kept gravel roads, whereas most ranching/farming/hunting roads generally are poorly maintained. Because of precipitation and drainage patterns, roads south of Telocaset stay in better condition and need fewer repairs than those to the north.

Topography.

The elevation of the Grande Ronde Valley is approximately 2,700 feet above sea level. The valley is bounded on the east and west sides by an en echelon series of steep fault scarps. Above an elevation of about 4,800 feet on the west and 6,500 feet on the east, the scarps give way to a late youth stage of dissection, and rolling upland topography is present. South of the valley, the topography is characterized by linear, northwest-trending, steep-sided, narrow, flat-bottomed, valleys separated

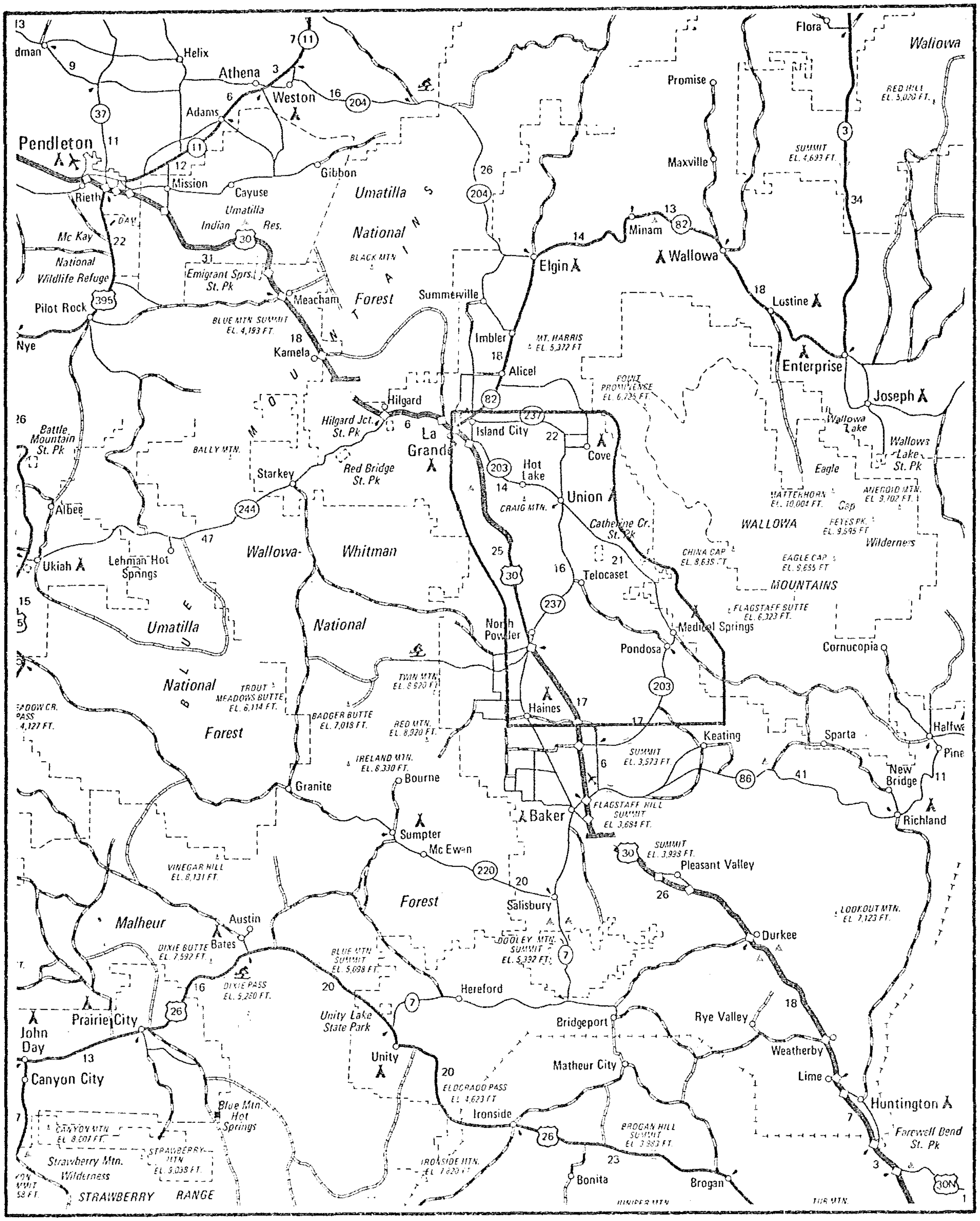

Figure 1.

INDEX MAP OF THE
LA GRANDE - BAKER AREA, OREGON

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by gently rolling to moderately steep-sloped uplands. However, south of Telocaset much of the topography of the area is more subdued and mature in expression; linearity gives way to rolling hills without distinctive trends.

Climate.

The climate of the area is characterized by warm to hot summers and cold winters. Although La Grande has experienced the extremes of -22°F in winter and 108°F in summer, more typical temperatures range from lows of 0° to 20°F in winter, to highs of 85° to 100°F in summer. The mean annual temperature at La Grande is 50°F.

The average annual precipitation ranges from 13.2 inches at Union to 19.7 inches at La Grande, and to 22.9 inches at Cove. This precipitation is distributed with relative uniformity from October to June, with only minor contribution by summer thunderstorms. Two or three winter storms each drop 6 to 15 inches of snow in the valley. Most of this snow melts rapidly and little lingers longer than 2 or 3 days. The mountainous areas surrounding the valley receive much more snow, which provides great amounts of meltwater runoff during Spring. The higher elevations, in addition to receiving greater precipitation, have lower mean annual temperatures and lower daily minima and maxima.

Hydrology.

In response to control by the major northwest-trending fault system, a well-developed rectangular drainage pattern pervades the areas underlain by Tertiary volcanic rocks. In areas of exposed basement rock a modified dendritic pattern, or at some localities a radial pattern, characterizes the drainage.

Spring-flow patterns and water-well productivity records indicate that the Tertiary rocks (especially the Columbia River Basalt) have significantly greater porosity, permeability, and ground-water capacity than the near-surface components of the basement complex. Most springs issuing from the volcanic rocks are perennial, whereas many basement springs are dry in late

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summer and autumn. Wells drilled into basement generally produce significantly less water than those penetrating aquifers in the Columbia River Basalt.

Drainage in the northern part of the project area runs northwest into the Grande Ronde River, which flows northeast to the Snake River. West of La Grande, the Grande Ronde River traverses the Blue Mountains in a deeply incised steep-walled canyon. North of Elgin the river is confined again to a narrow canyon. However, within the Grande Ronde Valley, the river is at grade and meanders widely across the flat valley floor. Therefore, it appears that the floor of the valley may be dropping slowly, relative to the surrounding mountainous regions.

In the southern section the principal drainage is the Powder River, which loops northward from Baker to North Powder and subsequently flows southeast to the Snake River. The Powder River is fed by meltwater runoff in its source area south of Elkhorn Ridge, as well as by springs and minor runoff from the lower elevations. This drainage basin is underlain primarily by rocks of the pre-Tertiary basement complex.

Economic Geography.

Roughly 35,000 persons live in the La Grande - Baker area; most of the population resides in identified towns and villages. The Grande Ronde Valley is a relatively prosperous area that contrasts sharply with much of the rest of eastern Oregon. This prosperity has developed through reliance upon a broad-based agricultural economy which includes cattle-feed and produce farming, cattle ranching, and the forestry-logging-lumber industrial complex (State Forestry Division and U. S. Forest Service offices and Boise-Cascade Corp.). A four-year state college, Eastern Oregon College, with a student population of 2,000, is at La Grande. A small but growing tourist trade also brings money into the local economy. The Union Pacific Railroad maintains facilities, switching terminals, and yards in La Grande.

La Grande is served by a 230 kVe transmission line operated by Bonneville Power Administration (BPA) running southwest from 1,000 kVe Columbia River (McNavy) generating

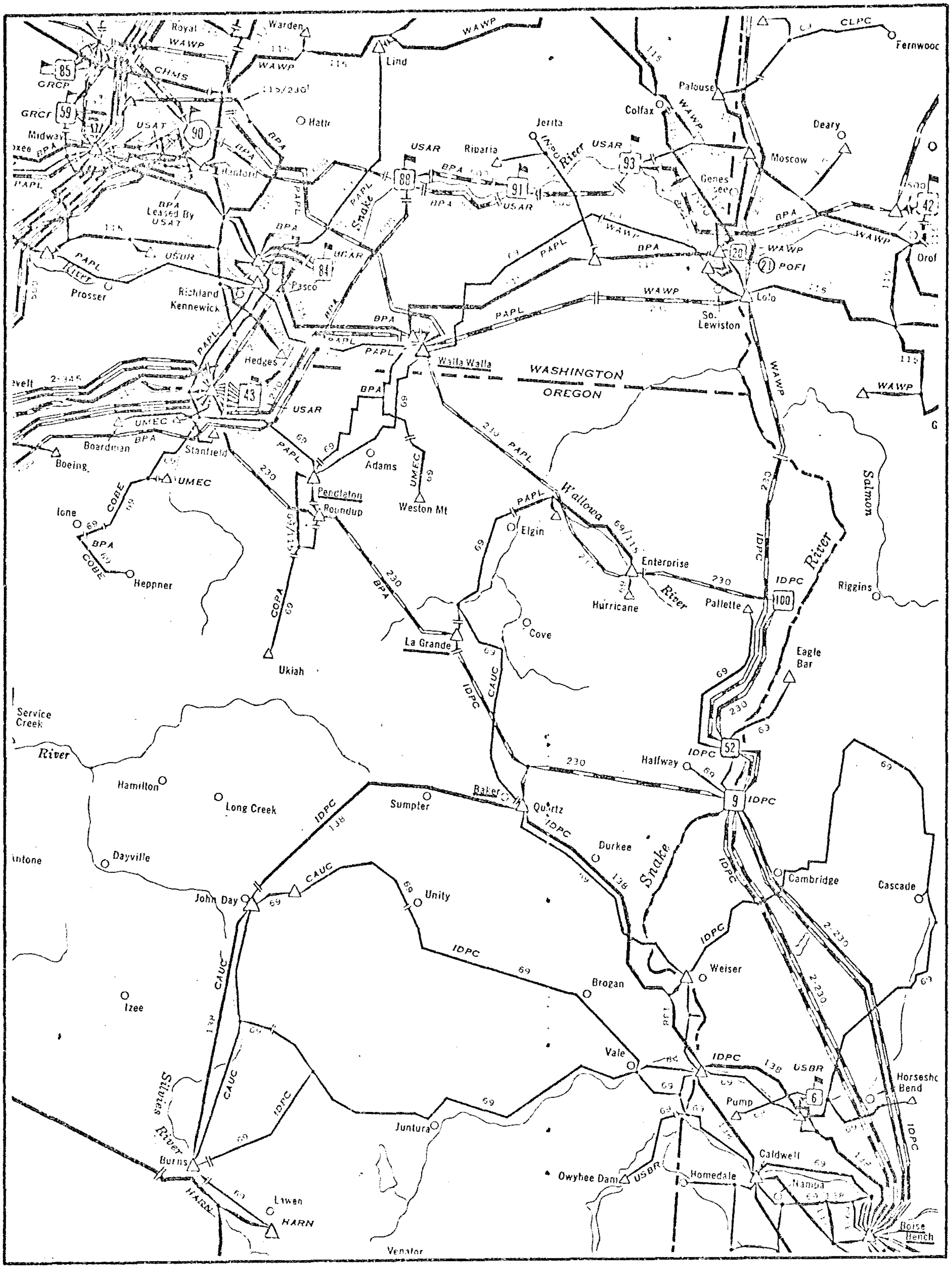

Figure 2.

MAP OF ELECTRIC TRANSMISSION ROUTES IN EASTERN OREGON

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stations. From La Grande, a switching point, distribution is made by Idaho Power Company over a 230 kVe line to the southeast. California-Pacific Utilities Company and Pacific Power and Light Company distribute power via 69 kVe transmission lines to Baker and Elgin respectively (see Figure 2).

REGIONAL GEOLOGY

Regional Stratigraphy.

Regional stratigraphy is characterized by a Paleozoic-Mesozoic basement of metasedimentary, metavolcanic, and intrusive igneous rock, upon which lie continental sedimentary and volcanic rocks of Eocene(?) to Pleistocene age.

The metasedimentary units are composed of chert, conglomerate, limestone, mudstone, greywacke, shale, and argillite. The metavolcanic sequence includes tuffs and basaltic to rhyolitic flows altered to greenstone, spilite, and keratophyre. This diverse lithology has been subdivided into the following formations:

Elkhorn Ridge Argillite (Permian? or early Triassic?),
Clover Creek Greenstone (Permian to Triassic),
"Lower Sedimentary Series" (mid-upper Triassic),
Martin Bridge Formation (mid-upper Triassic),
Hurwal Formation (mid-upper Triassic).

The aggregate original thickness of these units is 15,000 feet or more. The units were described in detail by Prostka (1962 a,b).

In the Pendleton quadrangle, Walker (1973 a) has mapped phyllite, hornfels, schist, and amphibolite, which he tentatively assigned to the most strongly metamorphosed portions of the Elkhorn Ridge Argillite and Clover Creek Greenstone.

Mafic to acidic plutonic intrusions of early Triassic and Jurassic-Cretaceous ages are widespread in the region. The older plutonic complex is composed of gabbro, peridotite and serpentinite, quartz diorite and albite granite, all of which intrude the Elkhorn Ridge Argillite. Mild to strong shearing and slight to moderate hydrothermal alteration is pervasive through much of the complex.

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In the Sparta quadrangle (Prostka, 1962,1963), the Jurassic-Cretaceous intrusions are gabbroic dikes and sills and quartz dioritic stocks. Walker (1973 a) described rocks that are predominantly biotite- and hornblende-quartz diorite, and which included the Bald Mountain Tonalite (dated radiometrically as 99 million years in age) and the Anthony Lakes Granodiorite.

The basement of intrusive and metamorphic rocks is separated from the overlying Tertiary sedimentary and volcanic rocks by a profound unconformity. Altered andesite flows and poorly to moderately well-consolidated sandstone, siltstone, shale, and conglomerate of Eocene(?) to Oligocene(?) age (George W. Walker, 1974, personal communication) rest upon the eroded basement complex. These lower Tertiary units, considered to be equivalent of part of the Clarno Formation, are overlain by the Columbia River Basalt.

The Columbia River Basalt consists of basalts of Miocene age which are typified by the term "flow-on-flow" because the individual flows are separated by weathered zones rather than by sedimentary debris. Several tens of thousands of square miles of Oregon, Washington, and Idaho are covered by and/or underlain to depths of several thousand feet by these flat-lying to moderately deformed basalts.

Platy andesite of Miocene age is known to overlie and in part interfinger with rocks of the upper Columbia River Group in an area adjacent to the north-northwestern part of the Grande Ronde Valley. Walker (1973 b) indicated that north of Elgin the basalt and andesite are separated by a unit of sedimentary rocks, locally as thick as 200 feet. He reports the thickness of the andesite to be only 100 feet. In the present project area, the andesite achieves a thickness in excess of 1,000 feet at Frazier Mountain and at Sawtooth Ridge. Evidence from the area between Sawtooth Ridge and Cove indicates that vents for the andesite were located south and southeast of the Grande Ronde Valley.

Although volcanism continued into Pleistocene time in the Snake River Plain, some one hundred miles to the southeast, there are no Quaternary volcanic rocks in this project area.

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Generalized Geologic History.

The known history of this region began in Permian time with deposition of mud, silt, and minor limestone of the Elkhorn Ridge Argillite. During the early Triassic, these sediments were regionally metamorphosed and intruded by a plutonic igneous complex composed of albite granite, quartz diorite, peridotite, serpentine, and gabbro. Following this intrusion and the accompanying deformation of the sediment, regional uplift and erosion occurred and the intrusions were partially unroofed. A sequence of interbedded and interfingering volcanic and marine sedimentary rocks was deposited upon the erosion surface during the mid-upper Triassic period.

During a subsequent period of regional tectonism and greenschist facies metamorphism, the Permian and Triassic rocks were deformed into open to tight northwest-trending folds. In the Sparta quadrangle, Prostka (1962, 1963) has mapped sheets of Clover Creek Greenstone which were thrust, probably northeastward, over younger Triassic strata during this deformational episode. In the Jurassic and/or Cretaceous periods gabbro dikes and sills and quartz diorite stocks were intruded into the older metamorphosed rocks throughout the region. Extensive contact metamorphic aureoles, including metamorphic grades as high as the epidote-hornblende facies, are associated with the larger intrusive bodies.

Erosion followed, terminating with mild subsidence and the deposition of sediment of Eocene(?) to Oligocene(?) age in several basins of unknown trend or extent on basement. In the Miocene epoch, the Columbia River Basalt floods filled many of the basins to depths of several thousand feet. The basalts probably shelved up against basement "highs" throughout the area (compare geologic cross-sections A-A', B-B', and C-C'). Remaining lowlands (notably near Elgin and North Powder) received sedimentary fill before the youngest Miocene basalts and andesites were extruded from several shield volcanoes (Walker, 1973 b, p. 426).

A series of major east- to northeast-trending open folds developed in the basalts during the Pliocene to Pleistocene epochs. Fold limbs dip 3° to 8° from the axis of the Blue Mountain Anticline, a feature having a known axial trace over 240 miles long. The Grande Ronde Valley and other northwest-trending graben structures developed in response to extensional

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stresses during the Miocene(?) through Pleistocene epochs. The Grande Ronde Valley, which is a deep, narrow, crustal tear, probably developed in response to combined dip-slip and strike-slip motion across most of the faults. The shape of the valley dictates a dominantly left-lateral sense for the strike-slip component. The resulting "hole in the Miocene" is probably an area of thin crust. The Baker Valley and Snake River structural depressions were initiated in about Miocene time also.

Finally, during Plio-Pleistocene time, the Snake River structure was flooded by basaltic lavas. Cycles of extensive erosion and deposition during the Quaternary period have resulted in development of gravel terraces elevated above the present levels of the various flood plains.

Regional Structure.

Four major structural-lithologic provinces or sub-provinces dominate the region surrounding the Grande Ronde Valley. These features include the Columbia Plateau, the Wallowa-Blue Mountains uplifts, the Snake River depression and the Idaho batholith.

The Grande Ronde Valley straddles the northern boundary of the Wallowa-Blue Mountains uplift. The Columbia River Basalt shelves rapidly southward onto this structure, which has persisted at least since middle Miocene time. At that time, surface relief on the basement complex was in excess of 3,000 feet. Since then, tectonic processes have increased the relief on this surface to at least 9,500 feet within the project area and to over 12,000 feet throughout the region. The regional dip of this surface is down to the north and down between the central cores of the Wallowa Mountains and the Blue Mountains.

The Columbia River Plateau and its extensions, the Modoc and Snake River lava plateaus, of late Tertiary to Pleistocene age, cover most of eastern Oregon and Washington, western Idaho, parts of northeastern California and northernmost Nevada. An estimated minimum of 25,000 cubic miles of Tertiary and Quaternary volcanic rock underlie this province (Clark and Stearn, 1968, p. 266). These rocks have been folded into broad, open warps along east-west to northeast-trends and faulted along east-west and northwest to north-south trends.

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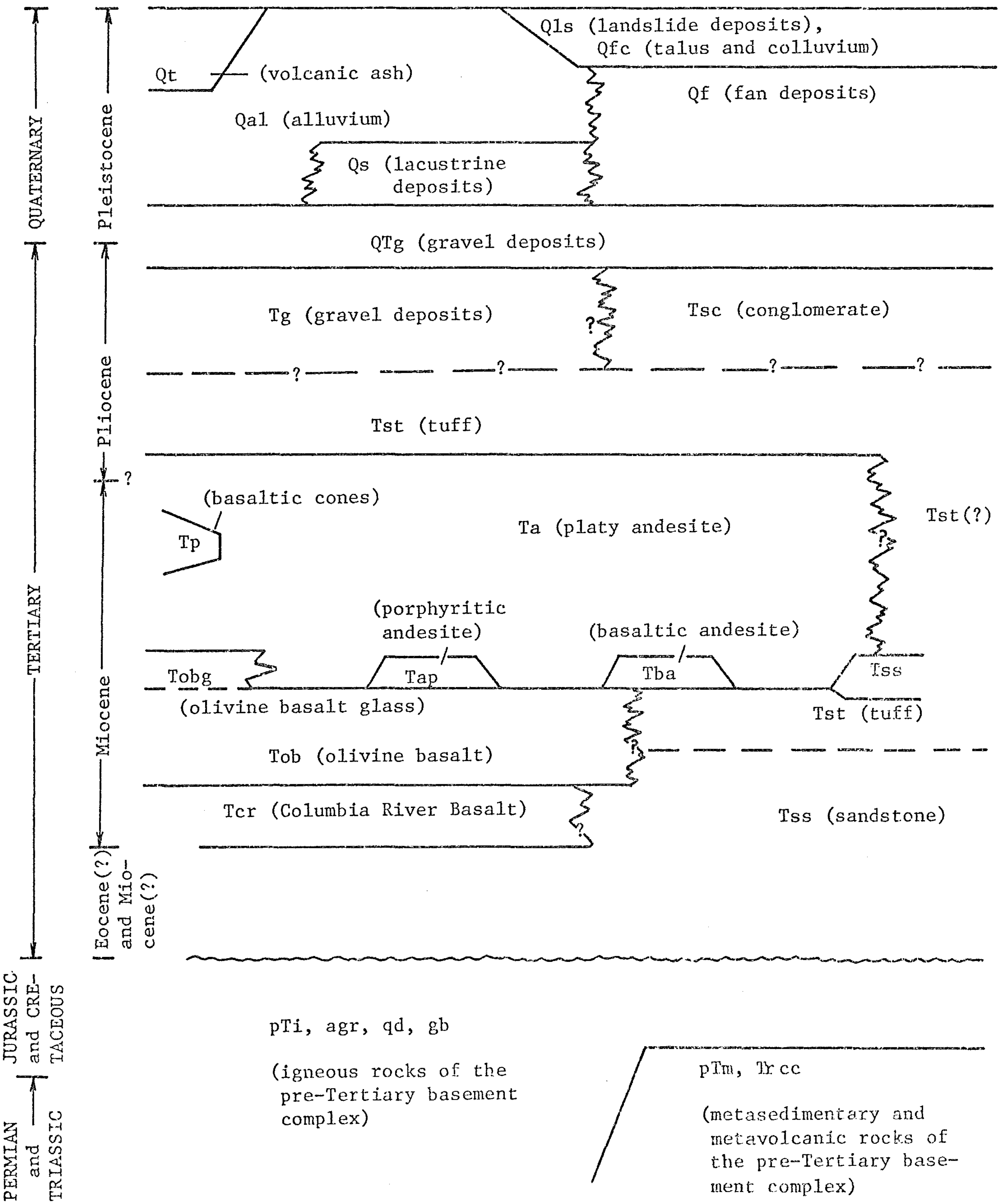
The Snake River depression trends northwest-southeast across the Idaho-Oregon border, bends eastward, possibly at a major structural intersection at the southern end of the Idaho batholith, and trends northeast across southern Idaho. This broad structural depression is filled with several thousand feet of Miocene to Pleistocene sediments and volcanic rocks, forming the Snake River Plateau. The origin of the structure has been attributed by Smith and Sbar (1974, p. 1214) to a mobile mantle plume. However, the structure may be the result of intra-continental sub-plate deformation and rifting. If so, the Grande Ronde graben may represent a northwestward extension of the feature.

The Idaho batholith forms the eastern boundary of the Columbia Plateau in Idaho. The batholith is composed of numerous intrusive bodies ranging in age from late Jurassic to early Tertiary. A series of north-trending normal faults persists along the western margin of the batholith and extends into the Tertiary volcanics of the Columbia Plateau as well. These faults depart from the northwest to east-west trends established throughout the region of interest and probably represent isostatic readjustment along the border of the two provinces.

Within the Columbia Plateau and Wallowa-Blue Mountains uplift area, two major structural grains are apparent. The first is a fault and fold sequence composed of these elements: the northwest-trending Grande Ronde fault swarm developed in the volcanic units; a series of open folds having northwest to east-west axial trends developed in the basement highland west of Baker; and the east-west-trending fault swarm exposed in the volcanic rocks of the John Day country and the Paulina Basin. The fold system and the fault swarms probably required substantially different stress orientations for development, although structures in the basement, related to ancient stress fields, may have influenced all of the fault and fold orientations, including the later Tertiary features. Different lithologies reacted with different modes of deformation, and this is reflected in the magnitude of folds and faults. Northwest-trending features probably are related to the development of the Snake River depression and its extension from a zone of thin crust and deep basement into an area of relatively shallow basement.

The second structural grain is developed north and west of the Grande Ronde Valley. In this region the dominant feature is a series of open folds, with trends varying from northwest to

Figure 4. GENERALIZED STRATIGRAPHIC RELATIONSHIPS LA GRANDE - BAKER AREA, OREGON



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east-west to southwest-northeast. Those having significance to the project area include the Blue Mountains anticline and the Grande Ronde syncline, both of which are discussed below in the section on STRUCTURE.

STRATIGRAPHY

Pre-Tertiary Basement Complex: Metavolcanic, Metasedimentary, and Igneous Intrusive Rocks (pT).

Rocks belonging to the basement complex crop out throughout much of the southern quarter of the project area. North and east of a line connecting Medical Springs and Telocaset, basement is exposed in only a few isolated places in the Catherine Creek area (sec. 2, T. 5 S., R. 40 E.) and on the north flank of Frazier Mountain (sec. 22-28, and 34, T. 5 S., R. 41 E.).

Most exposures of basement are limited to road cuts, float, and small knobby protuberances of the more resistant units (usually diorite). Outcrops are small and unobtrusive, but readily identifiable. The physiographic expression suggests a mature upland topography that has been subjected to recently renewed dissection. The Powder River cuts an impressive 400-to-500-foot-deep gorge (which is partially fault controlled) through basement near Thief Valley Reservoir.

The age assignments, stratigraphic relationships, and nomenclature pertaining to the pre-Tertiary basement complex were discussed briefly in the section on Regional Stratigraphy. For the purpose of this report, it was deemed necessary only to delineate areas of metavolcanic and/or metasedimentary rocks (pTm), mafic and felsic intrusives (pTi), and altered undivided metamorphic and igneous rocks (pTu). Where previous workers, primarily Gilluly (1937), have made stratigraphic correlations within the pre-Tertiary basement complex, their correlations largely have been accepted. These correlations are shown on the geologic map, where the Clover Creek greenstone (Ћcc), albite granite (agr), biotite-quartz diorite (qd), and gabbro (gb) are delineated. Some of Gilluly's contacts have been modified to accommodate more recent work. The generalized rock groupings correspond to recognized formations as follows and as given in Table 1:

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(pTm) = Metasedimentary and metavolcanic rocks, primarily Clover Creek greenstone (Tr cc), but possibly including the Elkhorn Ridge Argillite (Pe), the "Lower Sedimentary Series" (Tr ls) and the Martin Bridge (Tr mb) Hurwal Formations (Tr h). Several small intrusive bodies may be incorporated in this unit.

(pTi) = Early Triassic and Jurassic-Cretaceous intrusive bodies. This include Gilluly's (1937) albite granite (agr), biotite-quartz diorite (qd), and gabbro (gb). However, significant amounts of greenstone and/or metasedimentary rocks also may be included.

(pTu) = Undifferentiated basement rocks, in large part composed of skarn and areas of hydrothermal alteration.

Table 1. CORRELATION CHART OF PRE-TERTIARY ROCKS, EAST-CENTRAL OREGON

This Report		Gilluly (1937) Prostka (1962)	Walker (1973 and in preparation)
pTu	pTi	agr qd gb	KJi
	pTm	Tr h Tr ls Tr mb Pe	Tr sv
		Tr cc	Tr v

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Most exposures of basement in the mapped area north of 45° 00' N are mafic and felsic igneous intrusive rocks, which include the following:

a. diorite--a fine- to medium-grained, hard, resistant, occasionally quartz-bearing, feldspar-pyroxene-olivine rock;

b. gabbro--a medium-grained, dark green to black, pyroxene-feldspar rock;

c. albite granite--a fractured, rust-orange, slightly decomposed or hydrothermally altered, medium- to coarse-grained, quartz-albite(?) rock; and

d. alaskite--a very fresh, hard, resistant, white, medium-grained, quartz-feldspar rock.

Feldspars of the mafic intrusive rocks often exhibit argillization or incipient sausaritization. Many of the mafic minerals have been partially or totally chloritized.

Outcrops and road cuts east of Thief Valley Reservoir, along the northeast flank of Frazier Mountain, in the vicinity of Medical Springs, and along Catherine and Scout Creeks, expose metavolcanic and metasedimentary rocks. Included are: chloritized, black, aphanitic basalt; chloritized, argillized, and calcitized(?), porphyritic volcanic rocks; blue-gray, recrystallized limestone; and altered argillites and chert.

Significant zones of hydrothermal alteration, contact metamorphism, and mineralization within the undifferentiated basement complex (pTu) are found west of Thief Valley Reservoir, at a locality east of Medical Springs and at a locality south of the Sawtooth Ridge shield. Prospects and small workings near the reservoir indicate fairly widespread hydrothermal leaching, accompanied by localized, very low-grade mineralization. Small bodies of skarn occur near the reservoir and near Medical Springs. The age of the mineralization and alteration is unknown, but it probably pre-dates the extrusion of the Miocene volcanic rocks. No Tertiary rocks exhibiting comparable alteration were found.

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The basement complex has a rotted appearance in hand specimens. It is pervasively fractured, and most of the metavolcanic and intrusive rocks break into blocky rubble. Two through-going faults and a few small faults have been mapped; undoubtedly many more exist beneath the slope wash and colluvium.

The water-bearing character of the pre-Tertiary basement rocks has not been determined. Lystrom et al. (1967) concluded that, despite fracturing, the crystalline rocks have not developed sufficient porosity and permeability to provide a source of groundwater. However, the hot water issuing at Radium Hot Springs and Medical Springs comes from fractures in the basement. Therefore the basement complex must have some potential reservoir capacity, especially the fractured metamorphic units, and should not be eliminated from consideration as a thermal aquifer. It is suggested that areas of relatively shallow basement (3,000 to perhaps 5,000 feet) be evaluated as targets for geothermal exploration.

Continental Sedimentary Rocks:
Tuff (Tst), Sandstone (Tss), and Conglomerate (Tsc).

There are almost no exposures of the continental sedimentary unit within the project area, although a few road cuts and gravel pits do offer limited access to the unit. Distribution of these sediments is limited to discontinuous patches, predominantly in the southern part of the project area.

The continental materials are composed of tuff (Tst), sandstone (Tss), and pebble conglomerate (Tsc). The tuff is white to buff, very fine grained (silty in part), vaguely bedded, poorly indurated, and non-resistant. The sandstone members are yellow to tan, fine to very coarse grained (tuffaceous in part), well bedded, unconsolidated to well indurated, usually friable, and non-resistant. The sandstone composition is tuffaceous to arkosic. The conglomerates generally are tan to orange in color, and are composed of one-half-inch to two-inch diameter pebbles of metavolcanic and plutonic igneous rock, set in a matrix of arkosic sand.

The thickness of the unit has not been established, but a maximum of 200 feet seems a reasonable estimate. No fossils were found within the project area. The age(s) of the sediments is conjectural.

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Stratigraphic position of several of these deposits has not been established with certainty. In general, the tuff and conglomerate members are nearly flat-lying, and are only gently warped into broad, open folds. However, at two localities, the sandstone has moderate (28°) to steep (55°) dips and is overlain by flat-lying volcanic rocks. Therefore, portions of this sedimentary sequence probably pre-date an early Tertiary period of deformation and erosion, but most of the unit was deposited at a later time. Structural relationships demonstrate that most of the sediments in the North Powder and Clover Creek Valleys are younger than the platy andesite (Ta).

Exposures of the sedimentary unit are poor, at best, and contacts with other units are not exposed. However, one minute exposure in a very small road cut east of Ladd Canyon (NE-1/4, NW-1/4, sec. 24, T. 4 S., R. 38 E., Glass Hill quadrangle) discloses sandstone within the andesite section above the Columbia River Basalt. Outcrops in Antelope Valley and east reveal sedimentary rocks underlying the base of the Tertiary andesite as well as the base of the olivine basalt. There are no exposures of the older sediments in contact with the Columbia River Basalt. It is probable that deposition of the sediments occurred sporatically from the Eocene epoch (Walker, 1974, oral communication) to early Pliocene time.

The poorly consolidated sandstones and conglomerates in this unit are quite porous and permeable. The unit yields moderate to large quantities of water to wells.

Columbia River Basalt (Tcr).

Within the project area, the Columbia River Basalt is exposed only on the eastern and western upland margins and along the northeast-facing scarps of Craig Mountain. For many miles east and west of the Grande Ronde Valley the rolling and semi-dissected uplands are underlain by this basalt. A section of basalt several thousand feet thick probably exists under the floor of the Grande Ronde Valley. However, the Columbia River Basalt abruptly thins southward against the pre-Tertiary basement and probably pinches out in the vicinity of Pyles Canyon. The primary source areas for the flows that occur in the project area are the Grande Ronde dike swarm, near the junction of the Grande Ronde and Snake Rivers, and the Cornucopia dike swarm, on the east side of the Wallowa Mountains (Waters, 1961, p. 584).

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Individual basalt flows range in thickness from 15 to 60 feet and are separated, in flow-on-flow fashion, by red to orange oxidized zones 1 to 4 feet thick. These zones often have rubbly or cindery material associated with them. The tops of flows (and often the bottoms, too) are usually vesicular. The interiors of flows are jointed in a blocky, rather than columnar, manner. These angular blocks measure about 2 to 3 inches, by 3 to 4 inches, by 5 to 8 inches, and usually are weathered brown on all sides. The interiors of the blocks are dense, fine grained, dark green to black, and unweathered. Small phenocrysts of plagioclase are often discernable with the hand lens. No flow structures or textures were observed.

Chemical analyses of various units within the Columbia River Basalt have been reported previously (Walker, 1973 b, Waters, 1961, and Uppuluri, 1974). Walker (1973 b) briefly described the petrography of flows within the formation. One thin-section was examined rapidly during the present project; it showed microphenocrysts (1 - 2%) of plagioclase and pyroxene set in an intergranular(?) groundmass of plagioclase (70+%), clinopyroxene (5 - 15%), and "magnetite" (5 - 10%). Also present are phenocrysts of olivine(?) totally altered to magnetite, serpentine(?), and iddingsite.

The base of the Columbia River Basalt is not exposed within the project area; therefore, the thickness of the unit has not been determined. About 800 to 1,000 feet of section in the basalt is exposed on both the east and west flanks of the Grande Ronde Valley. The maximum thickness is probably on the order of 6,000 feet at the valley rim. Beneath the valley floor, the formation may be thicker if development of the graben proceeded during deposition of the basalt. However, the unit pinches out rapidly southward and does not extend far beyond the southern border of the valley.

No zones of hydrothermal alteration of the basalt were observed in the project area. However, the unit is fractured strongly adjacent to the major graben-bounding faults, and may be altered at depth.

Springs and seeps commonly issue from this unit. Hampton and Brown (1964, p. 39) indicated that "eleven wells (10 are artesian) in the Indian and Grande Ronde Valleys are believed to obtain water from the Columbia River Basalt." Yields average about 700 gallons per minute. Apparently, each

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of these eleven wells intersects one or more permeable, interflow, rubbly-cindery zones. Hampton and Brown (1964, p. 38) felt that little water is held by or transmitted through the dense central portions of the basalt flows. However, zones of pervasive blocky jointing might provide pathways, however circuitous, for hydrologic recharge to considerable depth.

Therefore, the Columbia River Basalt may behave in part as a reservoir rock for geothermal fluids. In areas having very highly telescoped isotherms, geothermally significant temperatures and reservoir recharge potential adequate for continuous generation of electricity probably occur at depths greater than 3,000 feet. However, the irregular hydrologic character of the formation probably has resulted in a series of discontinuous to semi-continuous reservoirs rather than a single, simple, homogeneous body. Fluid stored in each separate permeable body may have different thermodynamic qualities.

The age of the Columbia River Basalt in this area is middle to late Miocene.

Olivine-Rich Basalt (Tob).

An olivine-basalt unit has been exposed by faulting and erosion of overlying platy andesite at several widely spaced localities. The best exposures occur near Thief Valley Reservoir, on the southern flanks of Frazier Mountain, and at Glass Hill. The unit also outcrops on the north side of Frazier, in Ladd Canyon, at Craig Mountain, and in a small valley 1 mile east of the Catherine Creek Valley. The unit interfingers with the lowermost portion of the overlying platy andesite, and it lies above (or possibly interfingers with) the Columbia River Basalt. The maximum observed thickness of between 350 to 500 feet occurs one mile east of Thief Valley Reservoir. The thinnest observed section occurs in the major northeast-facing scarp on Craig Mountain, where the unit is 50 to 75 feet thick. The unit probably averages 250 to 300 feet in thickness.

All of McIntyre's (unpublished) basalt (Tb) tentatively is correlated with this olivine basalt unit because the detailed work necessary to delineate non-olivine-rich members was not undertaken in the southern tier of quadrangles.

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The olivine basalt generally forms gentle to moderate slopes with few or no outcrops. Where they occur, outcrops usually consist largely of masses of boulder-sized rubble; however, an occasional resistant ledge protrudes through the slope wash to expose the poor to fair columnar joints of in-place rock. Interflow weathered zones do not outcrop. However, much of the exposed material is vesicular, with 10 to 40 percent of the rock occurring as 0.1- to 1.0 centimeter-diameter vesicles. Druses of quartz and zeolite minerals occur in some of the vesicles.

This pale to dark gray or black basalt is characterized by the presence of 5 to 20 percent olivine phenocrysts (some altered to iddingsite and some fresh) set in a fine-grained ophitic to subophitic groundmass of subhedral plagioclase laths (50%), partially enclosed by grains and clumps of olivine (10-20%) and clinopyroxene (10-20%). The opaque mineral (3-4%) is elongate and spindly, and it may be titaniferous magnetite.

The top of Glass Hill is covered with rubble of a black, glassy, hard, porphyritic (2-20% olivine), non-vesicular rock (Tobg) that breaks with a splintery to subconchoidal fracture pattern. Immediately below this rubble field occurs a light gray variety of the typical holocrystalline olivine basalt. The black glassy rocks also occur as float in several swales in terrain where the outcrops are platy andesite exclusively (Craig Mountain) and in positions near the contact between andesite and olivine basalt (southern flank of Frazier Mountain). The glassy rocks probably mark in part the contact between andesite and olivine basalt; therefore, accumulations of glass in swales indicate the lowest elevation for the uppermost interfingering contact between the two units.

The presence of glass at the top of the olivine basalt at Glass Hill suggests that this unit may be an intrusive sill, younger than either the platy andesite or the Columbia River Basalt. Therefore, the age of the olivine basalt is not clear, but it probably is Miocene, comparable to the platy andesites and Columbia River Basalt.

Much of the olivine basalt unit is moderately to highly porous. Its permeability has not been determined; however, any weathered zones within the section have a high potential for significant permeability. The blocky, rubbly and, in places, columnar-jointed outcrop characteristics of this unit also suggest

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that it has a relatively high permeability in both the vertical and horizontal modes. This unit should perform as a moderately good aquifer. However, it is likely to overlie the principal geothermal system. Only if there are additional intrusive members of this unit at depth within either basement or Columbia River rocks is the olivine basalt likely to participate in the geothermal regime, except as avenues for downward percolation of recharge.

Basaltic Andesite (Tba).

Basaltic andesite crops out in a four square-mile area north of Thief Valley Reservoir and east of the Powder River, where it forms cliffs 10 to 25 feet high overlooking the river. It overlies continental sediments (Ts) and probably overlies olivine basalt (Tob). The age and origin of this unit are not known, but the unit is correlated tentatively with the platy andesite (Ta) because of the areal and stratigraphic relationships. Maximum thickness may be as great as 350 feet.

The andesite is a brown-weathering, flat-lying, porphyritic, vesicular, black, glassy rock. Feldspar and pyroxene phenocrysts (about 10%) are set in a hyaloophitic to intersertal groundmass composed of 0.25 mm plagioclase laths (70%), minute pyroxene(?) grains (2-3%), magnetite dust (1-2%), brown glass (5-10%), and vesicles (10%).

The limited areal extent of this unit and its relatively high position in the stratigraphic sequence indicates it to be of little consequence for the present exploration.

Platy Andesite (Ta).

A platy andesite unit crops out extensively throughout the project area, except in the southwest corner. Its principal recognized eruptive centers, which remain as local topographic highs, include Sawtooth Ridge, Frazier Mountain, and Bald Hill. A few lesser vents and dikes have been mapped as well.

The flows associated with Sawtooth Ridge, the best defined of the volcanic centers, are distributed over a crudely circular area, six miles in diameter. Dissection by faulting and erosion has obscured the original forms of the other volcanoes.

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The platy andesite, a resistant unit, varies in its topographic expression. Thick dikes and faulted flows may form cliffs 40 to 60 feet high. Relatively flat-lying, undisturbed flows commonly crop out as ledges and small cliffs. The rugged character of these outcrops originates in well-developed, vertical, joint sets which weather to 2- to 3-inch wide gashes, each separated by 2 to 15 feet of solid rock. Between outcrops, the slopes are gentle to steep and usually are littered with andesite float. Separate flows are indistinguishable even where extremely well exposed, and individual flow thicknesses were not determined. However, Patterson (1969, p. 175) indicated flow thicknesses of 20 to 50 feet, and Hampton and Brown (1964, p. 21) indicated a single 300-foot-thick flow in the Mount Fanny escarpment.

The central dikes at Sawtooth Ridge, Frazier Mountain and Bald Hill, and many of the associated flows, are composed of pale to medium bluish-gray, fresh, non-vesicular, aphanitic rocks, which contain occasional phenocrysts of hypersthene or olivine, and which weather to a dull rust color and a medium gray color. Generally, these rocks display rhythmic lamination, or platiness, with individual laminae ranging in thickness from 1/16-inch to 2-inches. The fresh rock color varies from pale gray to medium greenish-gray, to several shades of brown, reddish-brown, orange, and black. At many locations a pale yellowish or pink mineral streaking has developed, probably as the result of internal shearing during flow. However, in some andesite having wide (1-2 inch) plate spacing a spotted texture is developed, in which aphanitic green-gray areas (2-3 mm diameter) are enclosed by aphantic, yellowish-green-gray areas. This variant is largely non-porphyritic.

Significant amounts of andesite float (but few outcrops) have small, irregularly shaped, open spaces, ranging in size down to almost microscopic, spherical vesicles. Some of the irregular open spaces appear to have resulted from incipient brecciation during very late-stage movement within a nearly solid lava mass. Other irregular open-spaces and the tiny circular holes probably were the result of gas bubble formation and are, therefore, true vesicles. Some of these rocks, especially the "brecciated" ones, have a slightly rubbly character.

Chemical analyses, reported by Walker (1973 b, p. 427), of similar rocks outcropping about 7.5 miles north-northeast

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of Elgin, indicate that the platy andesites are significantly higher in silica, alumina, and sodium, but lower in total iron, magnesium, calcium, and titanium, than typical Columbia River Basalt. CIPW norms for the platy andesite suggest about 70% total feldspar, 15% quartz, 6% enstatite, and 5-7% opaque minerals. Thin-section work, during the present study, shows microphenocrysts (1-4%) of olivine and orthopyroxene (up to 1.0 mm diameter) set in a holocystalline, pilotaxitic groundmass composed of feldspar laths (75-85% of rock), pyroxene grains (10-15%) and opaque mineral grains (2-4%) all in the size range of 0.1 to 0.2 millimeters. Little or no quartz was observed. Walker (1973 b, p. 428) indicated that the plagioclase laths are calcic andesine (An_{45-50}).

A local variant of the platy andesite was recognized, containing up to 10 percent phenocrysts of plagioclase. Exposures of this porphyritic member, designated (Tap) on the map, are limited to two localities, one at the south end of Pyles Canyon, the other one mile east of Catherine Creek near Little Creek. At both localities the porphyritic member lies between typical platy andesite and olivine basalt.

Small vugs in some of the andesites contain partial or complete fillings of quartz, amorphous(?) silica, or an unidentified, white, tabular mineral. At one locality in the hills immediately west of Pyles Canyon, microveinlets (1/2 mm by 5 to 10 mm) of quartz occur in subparallel alignment with the direction of platiness.

The thickness of this unit is extremely variable due to: (1) physiography of original depositional surface, (2) distribution of the eruptive centers and volume erupted from each, and (3) faulting and erosion. Maximum thickness at the major eruptive centers (Sawtooth Ridge, Frazier Mountain, and Bald Hill) are on the order of 1,000 to 1,200 feet. These eruptive centers have been classified as shields by previous workers (Patterson, 1969 and Prostka, 1962). At Craig Mountain the maximum thickness is at least 800 feet and probably is closer to 1,000 feet. Adjacent to Ladd Canyon the thickness becomes as little as 300 feet. In the southwestern part of the area (North Powder Quadrangle) the andesite is areally restricted and has a maximum thickness of about 500 feet. No unit caps the andesite; therefore, the amount removed by erosion is indeterminant.

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Attitudes of the platy foliation in the andesite vary rapidly over short distances. The attitudes range from flat-lying to vertical, with virtually every intermediate dip represented somewhere in the area. Rapid variations in dip in these rocks can be developed in four different ways.

Each of the major vent areas (Sawtooth Ridge, Frazier Mountain, and Bald Hill) has a steeply dipping central dike which is surrounded by flows having gentler dips. Tectonic processes of faulting and folding may induce post-depositional fracture, and create joint sets of shallow to steep dip, which partially or completely mask the original foliation. Tilting of fault blocks may also cause rapid variations in attitude. Also, the platiness developed in these andesites should reflect the topography over which the lava flowed. The steep dips of gully walls are preserved in the platy foliation. This latter mechanism is probably responsible for many of the irregularities in the attitude of this unit.

The lowermost platy andesite (Ta) interfingers with the olivine basalt (Tob); therefore, the two units are partly coeval. However, contacts between andesite and all units older than the olivine basalt are unconformable. The andesite is intruded, partially incorporated, and partially covered by the basaltic pyroclastic deposits (Tp).

A small area of mild to moderate argillic alteration was noted in the eastern quarter of section 3 (T. 4 S., R. 40 E., Union Quadrangle). This alteration indicates the probable leakage of hydrothermal fluids from depth at some time since deposition of the andesite, but it is not significant to the present geothermal potential.

The platy andesite is an impermeable, fine-grained rock in small specimens. However, the persistence of numerous vertical joint sets in conjunction with fracturing along the major fault zones may provide pathways for movement of ground water. Several small springs and seeps issue from this unit although many of these dry up by summer's end. The water issuing at Hot Lake may travel through several tens of feet of andesite along the fault zone intersection that controls the spring. It is improbable, however, that the platy andesite has sufficient water-storage capacity to act as a geothermal reservoir rock, although the vertical jointing and fracturing may provide recharge conduits. Only along the near-vertical boundaries of the eruptive centers

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is it likely that this unit comes into contact with the geothermal regime at depth. Elsewhere it is likely to be too shallow for consideration. However, these eruptive centers may require further study as possible conduits into the geothermal system.

Age-dating of specimens from this unit was carried out by Teledyne Isotopes (Table 2). A sample from the central dike of Sawtooth Ridge (SR-1) was dated at 16.6 ± 0.8 m.y.; one from a "young" flow at Sawtooth Ridge (SR-2) 12.5 ± 0.9 m.y., one from the central spine of Frazier Mountain (FR-LO-4) 14.5 ± 1.5 million years, and one from a flow near High Valley (HV-1) 16.9 ± 4.5 million years. These ages are Miocene, and roughly congruent with ages of the Columbia River Basalt derived elsewhere. This may suggest that the extensive episode of volcanism occurred in a relatively short period of time.

Small Basaltic Pyroclastic Cones (Tp).

The three known cinder cones in the mapped area occur a few miles south of Union, and are aligned along a bearing of N 35° W, approximately the trend of major faulting in the area. These cones shall be referred to as the northwest, middle, and southeast cones according to location.

The northwest and southeast cones form small (100 to 140 feet high, 600 to 700 feet in diameter), roughly circular, steep-sided hills, but the middle cone has a much larger (1/2-mile diameter) outline and has gentle to moderate slopes. The southeast cone has retained a relatively youthful, non-dissected appearance, whereas the others have been more completely degraded by erosion. The deep dissection of the northwest side of the middle cone possibly reflects the original location of thick accumulations of cinders. The cinder deposits at the northwest and middle cones have been quarried at times, probably for use in the maintenance of nearby roads.

These composite cones have cinder, dike, and flow components. The cinders, which are brick red, scoriaceous, aphanitic to glassy, spherical to ovoid to angular chunks of basaltic ejecta, are poorly bedded and unsorted. They range in size from about 1/4-inch to 6 or 8 inches in diameter. Dikes and flows are composed of a denser, less-vesicular variety of the

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Table 2. RADIOMETRIC AGE-DATES, LA GRANDE - BAKER AREA

Sample #	Isotopic Age (m.y.)	scc Ar^{40} Rad/gm x 10^{-5}	% Ar^{40}Rad	%K
SR-1	16.6 ± 0.8	.079	10.0	1.15
		.077	20.0	1.18
SR-2	12.5 ± 0.9	.069	5.5	1.42
		.075	12.7	1.43
SR-3		NA		1.15
				1.19
HV-1	16.9 ± 4.5	.076	26.0	1.35
		.11	17.5	1.38
RB-1	20.4 ± 4	.11	3.6	1.14
		.076	5.4	1.12
RS-1	*	NA		1.20
				1.21
FR-LO-4	14.5 ± 1.5	.083	32.1	1.41
		.085	22.6	1.47

The constants used for the age calculations are: $\lambda_\beta = 4.72 \times 10^{-10}$ yr^{-1} $\lambda_e = 0.585 \times 10^{-10}$ yr^{-1} and $K^{40} = 1.19 \times 10^{-4}$ atom percent of natural potassium.

The error indicated for the reported ages consists of a summation of all analytical errors. All samples are done in duplicate. As the volume of radiogenic argon or the potassium content decreases, the size of the analytical error naturally increases. The error reported is that derived from the replicate Ar runs each of which consisted of three separate argon isotope dilution determinations.

All age determinations were done by Teledyne Isotopes, Westwood Laboratories, 50 Van Buren Avenue, Westwood, New Jersey 07675.

*Qualitative age estimate 20 ± 5 m.y. quoted by Donald Schutz (1974, personal communication).

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same material. These rocks have inclusions of dark gray to black, aphanitic rock chips, which were probably derived from the andesitic(?) wall rock.

Originally, these cones were thought to have been erupted during late Pliocene or early Pleistocene time. This was suggested by the relatively youthful topographic expression of the cones.

Two specimens from the northwest cone were age dated by Teledyne Isotopes (Table 2) using K-Ar radiometric methods. These yielded surprisingly old (20.4 ± 4.0 m.y. and 20 ± 5 m.y.) ages. Several factors interact to make these particular whole-rock age dates potentially less reliable than those reported for the platy andesites. These factors are: (1) these rocks are fairly low (1.13 and 1.17%) in K_2O; (2) such glassy, vesicular, materials are not preferred for potassium-argon age-dating; (3) there is foreign rock matter present as small inclusions. Of these factors, the latter appears to be the most significant source of serious contamination for these particular samples.

It is now thought that the cones were erupted about the same time as, or just after, the latest andesites, despite the lower Miocene age-dates. This is suggested by the andesite(?) inclusions within basalt, and the interbedding of andesite with some small basaltic flows associated with the northwest cone.

A fourth cone that once stood at the north end of Clover Creek Valley has been removed for use in road construction. It is assumed that this cone was generated during the magmatic event that produced the other three.

Gravel Deposits (Tg) and (QTg).

McIntyre (unpublished) indicated that terrace gravel deposits in the project area are of at least two ages. The older, pre-Pleistocene, terraces (Tg) occur in the extreme southeastern portion of the project area along the margin of the Lower Powder Valley. The age relationship between these older gravels and the tuffaceous unit (Tst) that surrounds them is uncertain. However, the gravels may correlate with the conglomerate unit (Tsc) in other parts of the project area. The younger, Pleistocene(?), gravels occur west of Haines and south of North Powder.

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Lacustrine Deposits (Qs).

The central part of the Grande Ronde Valley is underlain by lake-bed deposits composed of mixtures of clay, silt, and fine- to medium-grained sand, interbedded with lenses of clean sand or clay. Gravels occur along buried stream courses, and where the lake beds interfinger with fan deposits. Grouped with the lacustrine deposits are the more recent flood-plain deposits associated with the major creeks and the Grande Ronde River.

The lake-bed deposits thicken toward the center of the valley. A well located 4-1/2 miles east of Island City was drilled to a depth of 2,020 feet and bottomed in alluvium. Hampton and Brown (1964, Table 2) reported six wells begun in alluvium and bottomed in basalt. Data from these wells indicate that the lacustrine deposits thin northward and southward from the valley center. However, there are thick fan and possible lacustrine deposits along the east and west margins of the valley, formed by erosion of the steep fronts of adjacent mountains.

Lacustrine deposits probably overlie Tertiary volcanic rocks (Columbia River Basalt, olivine basalt unit, and platy andesite) within the Grande Ronde Valley. Permeability will vary extremely with grain size and degree of sorting of sediment. However, the lacustrine deposits are not likely to serve as a significant portion of the geothermal system.

Fan Deposits (Qf).

Four alluvial fans are mapped in the southern half of the Grande Ronde Valley. Large fans occur (Hampton and Brown, 1964, p. 25) at La Grande (22 square miles) at the mouth of the Grande Ronde River canyon, and at Union (13 square miles) where the debris from Catherine, Little, and Pyles Creeks accumulates. A much smaller fan (3 square miles) occurs at Cove, where Mill and Warm Creeks empty into the valley. A relatively small fan (2 square miles) lies at the mouth of Ladd Canyon.

These fans are composed primarily of basaltic and andesitic debris derived from the mountainous areas adjacent to the valley and transported by flood-stage streams. The

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Union fan may have significant amounts of pre-Tertiary rock incorporated with the other debris.

The size of the materials varies from clay to boulders, and is determined by the volume, discharge velocity and sediment load of the stream carrying it. Therefore, seasonal and longer-term climatic cycles are recorded by the alternation of gravel, sand and clay layers within the fan.

The upper portions of the alluvial fans were deposited after the youngest lake-bed deposits in the Grande Ronde Valley. However, the older portions of the fan deposits undoubtedly interfinger with the lacustrine materials. The thickness of these wedge-shaped fans varies rapidly with location, but the larger fans probably attain maximum thicknesses of 300 to 400 feet (Hampton and Brown, 1964, p. 76-92).

The gravelly and sandy members of this unit provide good aquifers when charged with water, but interbedded clay-rich layers are impermeable barriers that confine the water of underlying aquifers. Confining clay layers are common features in these alluvial fans (Hampton and Brown, 1964, p. 37-38). The fans probably provide hydrologic recharge routes to underlying sediments and volcanic rocks along the margins of the Grande Ronde Valley, but these deposits do not occupy positions within the proposed geothermal reservoir.

Quaternary Alluvium (Qal).

Unconsolidated gravel, sand, and silt, deposited in late Pleistocene and Holocene stream channels and flood plains, are present in the Baker, North Powder, Lower Powder and Clover Creek Valleys and along the primary tributaries to the Grande Ronde and Powder Rivers. The deposits are relatively thin, but along Catherine and Pyles Creeks and in the North Powder Valley, thicknesses of a few hundred feet are probable.

The alluvium along Catherine and Pyles Creeks remains water saturated at relatively shallow depths all year. In the various valleys the deeper alluvium probably remains saturated throughout the year, also. Water probably works downward from these sediments into permeable zones in the underlying volcanic rocks. Therefore, the alluvium serves as groundwater recharge channels, but in some locations clay-rich layers may limit groundwater circulation. However, this unit does not attain sufficient thickness to be in direct communication with the proposed heat source nor sufficient volume to be a geothermal reservoir material.

Walker (1974, oral communication) described the unconsolidated stream-channel material on the floor of Grande Ronde Valley as reworked lacustrine sediment (Qs), and it is discussed herein under that heading.

Landslide Deposits (Qls).

One major composite landslide occupies an area of approximately 2 square miles adjacent to Catherine Creek, below the north scarps of Clark Mountain. This large deposit is easily recognized on aerial photographs; however, on the ground it is less obvious because it is heavily forested and its form has been modified somewhat by erosion. The debris is largely platy andesite. The thickness of this deposit has not been investigated.

Two smaller landslide areas (1-1/4 and one-quarter square miles) occur adjacent to the Powder River a few miles south of Thief Valley Reservoir. The larger slide is developed in basalt, and the smaller is in pre-Tertiary rocks. Apparently, these slides have developed in response to faulting and undercutting by the river.

Talus and Colluvium (Qfc).

Deposits of talus and colluvium have been mapped along the east and north sides of Craig Mountain and adjacent to the major fault scarps on the east and west sides of Grande Ronde Valley. The thin deposit on the north side of Craig Mountain is composed of platy andesite (Ta) debris. The other deposits are dominantly debris from the Columbia River Basalt (Tcr) with lesser amounts of platy andesite. Only the deposits on the east side of Craig Mountain contain significant amounts of olivine basalt (Tob) in addition to the andesite and Columbia River Basalt. The thicknesses of these deposits range from a few feet or tens of feet near Hot Lake to several hundred feet adjacent to the east scarp and west scarp faults.

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These deposits may serve as pathways for infiltration of rainfall and snow melt into underlying volcanic and sedimentary rocks. Otherwise they do not participate in the geothermal system.

Volcanic Ash (Qt).

A thin, discontinuous layer of loose, unconsolidated, white to pale-gray volcanic ash occurs along the upper reaches of Ladd Canyon and one of its tributaries (along Shaw Mountain road). The contacts of the ash with the Columbia River Basalt, as shown on the geologic map, are generalized, and approximate.

Hampton and Brown (1964, p. 26) recorded the following:

> "Deposits of light-gray volcanic ash of Recent age are exposed in White Horse and upper Ladd Canyons. Similar deposits occur over much of eastern Oregon and Washington. In the canyons cited the ash overlies the alluvium and attains a thickness of about 10 feet. The ash probably was windborne and deposited as a thin layer over most of the area. It was washed off the higher areas and has accumulated locally in the valleys and other depressions."

STRUCTURE

Faults.

The Grande Ronde Valley, measuring about 12 miles east-west by 32 miles north-south, occupies the southeast quarter of a structural zone dominated by strong, northwest-trending, en echelon, normal faulting. The distance between faults within the zone varies from a maximum of 3 to 4 miles in the northwest part of the valley, to one-quarter to 1 mile southward, in the project area. Fault displacements primarily are dip-slip; however, Hampton and Brown (1964, p. 29) postulated a strike-slip component to account for anomalously thick gouge zones associated with some faults having demonstrably small vertical throws. Limited exposure makes it impossible to compare gouge zones within the project area.

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The Grande Ronde Valley is a northwest-trending, complexly faulted graben, in which the top of the Columbia River Basalt has been displaced vertically a total of 5,000 to 6,000 feet from rim rock to graben center. This offset results both from major displacements across a few faults and lesser displacements across a large number of parallel and en echelon faults distributed throughout the graben. In general, the fault blocks are down-dropped on the side closest to the graben axis; however, numerous exceptions result in the multiple horsts and grabens apparent on the geologic map and cross-sections. Across many faults, the displacement increases northwestward. This causes the graben to deepen towards La Grande as well as towards the graben axis. This relationship also is suggested by the northwest plunge of the several ridges that bound the valley on the south.

The scarps of several faults are young-looking, and some faults cut the Pliocene-to-Pleistocene(?)-age Blue Mountains anticline; therefore, Hampton and Brown (1964, p. 32) proposed a late Pleistocene age for all of the graben-forming faulting in the Grande Ronde Valley. However, none of the surficial Quaternary deposits are known to be offset by any fault in the area. On the other hand, all of the units of Miocene to early Pliocene age have been strongly faulted. Graben formation could have begun as early as middle Miocene epoch, coincident with eruption of great volumes of Columbia River Basalt. Faulting probably reached its climax of intensity during Pliocene time, and has diminished in activity through the Quaternary period.

An indication that the principal episode of tectonism occurred prior to late Pleistocene time is given by the shape of the Grande Ronde River. Within the valley, the river meanders at grade, whereas there are steep canyons both upstream and downstream from the valley. If there was active uplift or downdrop, the river would either incise its course in the valley or would build an extensive flood plain. Being at grade suggests relative stability, perhaps accompanied by slow downdrop, to forestall headward cutting by the downstream canyon.

Five geologic cross-sections have been prepared (Plate II), to demonstrate several important features of the Grande Ronde graben. The graben is a complexly faulted structure,

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which deepens northward to about the north edge of the project area. In the south, the Tertiary units form a thin, discontinuous cover over the basement complex. The Tertiary rock section thickens dramatically from approximately 2,000 feet in cross-section C-C' to 7,000 feet in cross-section A-A'. The magnitude and intensity of faulting decreases rapidly southward, and late Tertiary or Quaternary structures are absent in the southern areas. The offset across many faults increases northward. Several of the fault blocks in the Phys Point-Catherine Creek area have been rotated slightly down to the west during faulting. The amount of rotation is not well known and the geologic cross-sections are diagrammatical with respect to portrayal of dip.

Several faults are named informally on the geologic map to clarify the following discussion. On the east side of the valley, the Mill Creek, East Scarp, and Mount Fanny faults account for about 5,200 feet of the 6,000 foot cumulative offset from Mount Fanny to the graben axis (cross-section A-A'). On the west side of the valley, the total offset is about 5,000 feet. In cross-section A-A' this offset occurs over a relatively wide zone. A cross-section constructed 3 or 4 miles north of A-A' would show that most of the offset is taken up by the West Scarp fault and a few associated faults.

An important cross-fault structure is developed at Craig Mountain. A series of faults, having trends from N 45° E to N 90° E and N 80° W,have downdropped the north end of the mountain. The total offset across these faults is about 1,400 feet. This creates the complicated structural feature depicted in the western third of cross-section A-A'. Apparently it is the intersection of the Hot Lake and Craig Mountain faults that provides the conduit for the hot water issuing at Hot Lake.

Folds.

Folding of Tertiary units is not apparent within the project area; however, three broad folds of regional extent influence somewhat the rock distributions within the Grande Ronde graben area. These folds are the Blue Mountains anticline, the Grande Ronde syncline, and the Indian Creek syncline.

The Blue Mountain anticline is a broad arch that trends east-west to northeast-southwest and extends for 240 miles across northern Oregon and southern Washington. This structure is responsible in part for the development of the broad, rolling, upland that bounds the Grande Ronde Valley on the north and west sides. Basaltic strata dip 5° to 8° south and southeast on the southern flank of this feature (Hampton and Brown, 1964, p. 27).

The axis of the Blue Mountains anticline passes through a point 14 to 15 miles northwest of La Grande. It is cut repeatedly by the Grande Ronde fault swarm, and is bent into a distorted "S" shape (map view). To the southwest the axis trends N 70° E. Across the fault swarm the trend changes to N 15-20° E. Finally, near the latitude of Walla Walla, the axis follows an approximate east-west alignment.

These bends are similar to those which would result from a northwest-trending left-lateral, distributed couple. This coincidence of bends with the Grande Ronde fault swarm suggests that a component of left-lateral movement has accompanied the well-known dip-slip movement along many of these faults. The shape of the Grande Ronde Valley also could have been formed by a northwest-trending left-lateral couple.

The Grande Ronde syncline trends northeast into the Grande Ronde Valley at La Grande. On the geologic map the axial trace is shown to extend a short distance into the valley, where apparently it dies out. The syncline is a broad, open feature with maximum dips of 8 degrees (Hampton and Brown, 1964, p. 28).

The Indian Creek syncline trends north-northwest and its axis lies 2 to 3 miles east of the East Scarp Fault. Hampton and Brown (1964, p. 29) reported:

> "The strata dip toward its axis at very low angles. Within this northward plunging syncline the streams flow parallel to its axis and empty into the Grande Ronde River near Elgin."

Hampton and Brown (1964, p. 32) indicated that the folding probably progressed in two stages: one stage during the Pliocene epoch and another, more intense, one during the Pleistocene. The forces generating these stresses may have had their origin in the movement of major blocks within the North American crustal plate. That is, the Grande Ronde Valley,

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the great hole in the Miocene, may have formed in response to stresses generated at a distance by the extension and rotation of other blocks.

GEOTHERMAL REGIME

Geothermal Manifestations.

There are several surface manifestations of geothermal activity in the area. These include important hot springs at Hot Lake, within the Grande Ronde Valley, as well as farther south at Medical Springs, North Powder and Radium Hot Springs. Other features include warm springs and wells at Cove and Union, in the town of La Grande, and in the vicinity of Elgin, all within Grande Ronde Valley. Table 3 summarizes the thermal features.

A small zone of altered platy andesite at the north end of High Valley suggests the influence of hydrothermal fluids at some time since deposition of the andesite, 12 to 14 million years ago.

Temperatures of thermal waters range from mildly warm, at several points within the Grande Ronde Valley, to 180°F at Hot Lake. Thermal features include both water wells and springs. Thermal wells are abundant within Grande Ronde Valley, whereas thermal springs are found only in the southern part of the valley and farther south, towards Haines and at Medical Springs. The springs uniformly are at higher temperatures than the wells, although the latter penetrate to as much as 1,500 feet in depth. Gradients within wells commonly are 2° to 3°F per 100 feet; such gradients are not highly encouraging. However, it must be noted that most of these wells intercept aquifers recharged by meteoric water, and therefore may be cooled by dilution.

Along this line, concentrations of silica are as high, or even slightly higher, in wells of 80° and 84°F as in the highest temperature springs of the area, at up to 88 ppm SiO_2 (see Table 3a). There are no apparent sources of chalcedony or opal within the alluvial and mafic volcanic terrain; therefore, a quartz equilibrium may be present at depth. This suggests that, indeed, thermal waters ascend into aquifers at depths to 1,500 feet, and are cooled and/or diluted therein. The depth and composition of the thermal source are unknown.

Table 3a. THERMAL WATERS OF THE LA GRANDE - BAKER AREA

Map Identification No.	1	3	4	6	8	9	9	10	11	12	13
Location of well or spring	1/38-24R1	3/38-5M1	3/38-5M2	3/38-6H2	3/40-22D1	4/39-5K1	4/39-5K1	4/39-11H1	6/39-25A	6/41-25	7/39-$28G1_s$
Date of Collection	8/9/50	1/21/55	1/21/55	5/10/57	6/2/57	5/10/57	3/74	8/22/57		3/74	5/1/55
Type	Well	Well	Well	Well	Spring	Spring-1	Spring-2	Well	Spring	Spring	Spring
Depth (feet)	1,150	1,435	1,536	1,391	Cove	Hot Lake	Hot Lake	337	Mr.Crop	Medical	Radium
Source of Data	A	A	A	A	A	A	C	A		C	B
Temperature (°F)	84	77	80	81	85	180	180	58	106	140	135
Silica (SiO_2)	88	72	84	71	29	81	48	34		80	80
Calcium (Ca)	3.6	4.8	5	10	1.6	3.6	4.9	11		72	1.6
Magnesium (Mg)	0.8	1.3	0.3	0.2	0.0	0.3	0.1	4.3		0.2	0.0
Sodium (Na)	28	30	27	19	30	128	130	25		190	63
Potassium (K)	4.0	5	5	5	0.5	2.7	2.7	4.2		7.0	2.0
Bicarbonate (HCO_3)	62	63	(?)	84	5	0	75	104		26	101
Carbonate (CO_3)	4.9	--	0	0	32	31	12	0		tr	47
Sulfate (SO_4)	8.3	4.8	3.3	4.5	8.8	56	56	7.4		400	31
Chloride (Cl)	3.1	2.1	3.2	1.0	5.0	129	140	8.8		77	17
Fluoride (F)	2.0	0.5	0.5	0.5	0.3	1.6	1.7	0.3		1.2	1.0
Boron (B)	0.1	--	--	--	0.08	--	2.9	--		2.2	--
Dissolved Solids											
Calculated	174	166	163	--	109	--	--	146		--	246
Residue at 180°C	--	--	--	146	112	461	--	152		--	--
Specific conductance (micromhos at 25°C)	148	--	--	146	150	676	688	207		1173	290
pH	8.0	7.9	7.9	--	9.8	9.5	9.2	8.0		8.2	9.7

A = Hampton and Brown, 1964
B = Ducret and Anderson, 1965
C = Mariner, and others, 1974.

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Table 3b.

TEMPERATURE DATA FROM WATER WELLS IN THE LA GRANDE - HOT LAKE AREA

(from well files in the office of the Oregon State Engineer and from Hampton and Brown, 1964.)

Map No.	Well No.	Owner	Drilled Depth, ft.	Temperature, °F
2	1/39-20	"Clayton Fox Well"	1,468	81
5	3/38-6H1	Union Pacific R.R.	?	77
7	3/39-6H	Weisbaar	134	60

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Cooler waters of the region typically are calcium-magnesium bicarbonate. This is characteristic of cool, meteoric water of short residence in an aquifer. Total dissolved solids (T.D.S.) may be less than 100 ppm. A few of the cooler waters (Hampton and Brown, 1964) show slightly elevated concentrations of sodium and sulfate ions. These waters, although cool, may reflect mixing of diluted thermal water with cold, meteoric water.

With increasing temperature, composition changes. For example, chloride and sulfate, amongst anions, and sodium of the cations increase in amount, whereas calcium, magnesium and bicarbonate species either remain constant or decrease.

At Medical Springs (140°F), sulfate exceeds chloride, which exceeds bicarbonate in abundance; and sodium is more plentiful than calcium, which exceeds potassium, which in turn is more plentiful than magnesium ($SO_4 > Cl > HCO_3$; $Na > Ca > K > Mg$).

At Hot Lake, chloride is the most abundant anion, and calcium has been reduced to barely above the level of concentration of potassium ($Cl > SO_4 > HCO_3$; $Na > Ca \sim K > Mg$).

Except at Medical Springs, T.D.S. is low, usually only a few hundred ppm.

It appears that a relatively good quality hot water (perhaps less than a 1% solution) exists at depth. The fragmentary data do not suggest a steam phase. The increasing concentration of chloride with temperature suggests a sodium chloride composition within the thermal reservoir at depth. These tentative conclusions should be reviewed carefully in light of data from the 1974 field hydrochemistry program.

Heat Source.

The precise nature of the source of heat for these thermal manifestations remains undetermined. Geologic mapping and age-dating indicate that the heat source is not represented at the surface. The platy andesite and basaltic cinder cones represent magmatic events much too old to significantly increase the local geothermal gradient, unless the age-dating suffers from gross and systemmatic errors. If volcanism and igneous intrusion do post-date Mio-Pliocene time, the events remain unrecognized.

The nature of the heat source remains speculative. However, there are several indirect evidences of its nature. First, three of the thermal springs either issue from basement or from Quaternary alluvium shallowly atop basement. This supports the idea of a heat source not associated with surface volcanism, but rather coming from greater depth. Second, the springs are widespread areally, and are of widely differing chemical composition. This suggests that there may not be a single source of heat for these features. The waters issuing from these springs appear to have interacted with rocks of varying composition, to have reached different conditions of equilibrium, and to have travelled, been mixed with other waters and been stored under different conditions. Third, there is the analogy of the Snake River depression, one hundred miles to the southeast. In the Snake River structure, basaltic volcanism has occurred into Pleistocene time, locally accompanied by both (or either) development of constructional cones and maars and intrusion of basalt, diabase and gabbro dikes, sills, stocks, and perhaps larger plutons. These intrusions have been intersected in drill holes and unroofed along anticlinal and domal axes. For example, a mafic intrusion of probable Plio-Pleistocene age is exposed along an anticlinal axis a few miles southwest of Vale. The Snake River structure appears to have undergone extension and down-drop, similar to the Grande Ronde Valley, from Miocene through Pleistocene time. By analogy, therefore, mafic intrusions may underlie the Grande Ronde region at depth, ascending along fold axes and fault planes.

A cooling intrusive body or bodies of unknown size, shape, depth, and location is proposed as the source of the heat required by the warm and hot waters that issue from the various springs and wells in the area. The composition is conjectural, but the absence of felsic volcanic rocks and the abundance of intermediate and mafic volcanic rocks lend support to the speculation that the intrusive body is andesitic to basaltic.

An alternative heat source is suggested for the Grande Ronde Valley graben. This feature may represent a northwestward extension of the Snake River depression. The Snake River structure is characterized by crustal weakness and extension,

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and possibly by crustal rifting and thinning. The mantle is brought closer to the earth's surface by the crustal thinning process, and the deeper crustal isotherms likewise are brought closer to the surface. An economic geothermal source occurs where the uplifted isotherms are telescoped sufficiently, in the presence of large quantities of fluids, at drillable depths.

Thinned crust, perhaps accompanied by convecting mass and bowed-up isotherms, may extend from the Vale, Oregon-Weiser, Idaho region in a discontinuous manner to, and possibly beyond, Grande Ronde Valley. In such a case, the presence of a discrete plutonic intrusion or a young eruptive center may offer an obvious target for exploration, but is not the cause of the thermal anomaly. The relative shallowness to mantle is the source of heat.

It must be recognized, of course, that neither hypothesis may provide a sufficiently intense, shallow and large-scale source of heat to power a geothermal system of commercial significance. Data available to date are not conclusive. However, this prospect does not exhibit either the intensity or youthfulness of thermal phenomena farther to the southeast on the Snake River structure.

Reservoir.

Several lithologic units suggest themselves as potential geothermal reservoir rocks. Working downward through the stratigraphic column, the units are presented in the order they would be encountered by the drill bit.

The platy andesite (Ta) is a compact, non-porous, impermeable rock that has been faulted and fractured. Although a few of the faults and several of the vertical joint systems may permit limited ground-water movement through the unit, the platy andesite probably acts as a major cap rock unit.

The olivine basalt (Tob) is vesicular to compact, highly porous to non-porous, blocky to rubbly, but occasionally columnar jointed, and is probably highly permeable along thin horizons. This rock is a discontinuous aquifer, however, and this and the thinness of the unit may limit its potential as a geothermal reservoir.

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The hydrologic characteristics of the Columbia River Basalt (Tcr) are reasonably well known. Wells that penetrate saturated, rubbly, interflow zones produce moderate to large quantities of water. The blocky jointing of this unit provides routes for limited ground-water circulation between the interflow zones. However, the massive central portions of many flows act as "hydrologic separations" (Hampton and Brown, 1964, p. 38). Faulting and the original discontinuity of the rubbly interflow zones indicate that the potentials for geothermal zones within this basalt are multiple and discontinuous. Therefore, the siting of each well must be preceded by careful, detailed analysis of all available geological, geophysical, and geochemical data.

Clean sand and conglomerate members of the continental sedimentary unit (Ts) may provide aquifers of potential significance. The position of portions of this unit beneath the Columbia River Basalt may enhance the thermal character of its waters. However, the lack of lateral continuity, and compaction and possible cementation of the older portions of the unit, may limit its effective hydrologic coupling with the heat source, as well as limit its reservoir volume and recharge rate.

Comparatively little is known about the hydrologic character of the various rocks of the basement complex. However, the issuance of hot water from the pre-Tertiary basement complex (Radium Hot Springs, Medical Springs, and at Mr. Crop's farm one-and-one-half miles east of North Powder) indicates that these rocks can provide significant pathways for migrating fluids and an adequate volume of reservoir for fluid storage and heating. The primary targets for a basement reservoir are the zones of porosity and permeability associated with faulting and pervasive fracturing. The volume of this potential reservoir is unknown; it may involve a thickness of several thousand feet.

Therefore, the most favorable reservoir rocks are the Columbia River Basalt, and fractured or faulted zones in the basement complex. A secondary target might comprise the continental sedimentary rocks underlying the Columbia River Basalt. In the central Grande Ronde Valley, the basalt may be 5,000 to 6,000 feet thick, beneath more than 2,000 feet of Quaternary debris, and the depth to productive geothermal zones may prohibit economic exploitation. In the south, caprock units are absent; however, thermal waters reaching the surface via pre-Tertiary

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rocks are not excessively hot, and the thermal springs are widely spaced. Therefore, either the thermal waters have migrated relatively far from the heat source before being discharged from basement, or there is excessive dilution by shallow, cool waters. Structural control of the springs is dictated by their random, wide-spaced distribution.

The recommended target zone lies between the deep Grande Ronde Valley and the uncovered basement. The most favorable locations occur where 3,000 to 5,000 feet of basalt and andesite overlie prospectively permeable zones in the basement rocks. These requirements are met in a northeast-trending zone about 20 miles long and 6 miles wide that is bisected roughly by cross-section line B-B' (see Plate I, geologic map, and Plate II, cross-sections).

Specific targets within this zone are difficult to define for a number of reasons. The hot springs of the area are structurally controlled, and their locations do not necessarily reflect the location of specific heat sources. The deeper structural configuration in the area covered by Quaternary deposits is not well known; therefore, the depth to a geothermal target in this area is more speculative than in adjacent areas. The structural and hydrologic properties of basement, where covered, is unknown. Potentially productive zones in basement may be relatively narrow and difficult to locate by drilling. The interflow aquifers of the Columbia River Basalt are discontinuous and unpredictable. There are few deep wells in the area.

Although Hampton and Brown (1964, p. 38-39) referred to water wells, the following statement applies equally well to geothermal wells drilled to targets in the Columbia River Basalt:

> Because of these discontinuities. . . wells drilled to the same depth and relatively close together may obtain water from different interflow zones. Also, they may have different static water levels and, in general, different hydrologic characteristics.

The recent exploratory drill-hole at Hot Lake (Magma Power Company) offers little additional insight. Total depth was about 2,700 feet, which is patently inadequate for a

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geothermal target in this region. Beneath a section of Quaternary sediment approximately 1,700 feet in thickness, rocks correlative with Columbia River Basalt were encountered. Temperatures apparently were not high enough to encourage further drilling.

Recharge.

If a geothermal aquifer is sought in the Columbia River Basalt, storage capacity is likely to be great, and reserves of fluid are not likely to become a problem. Recharge into the system probably occurs through coarser-grained fan deposits, river channel deposits, talus and colluvium, and along principal fault zones.

Should the pre-Tertiary basement become the target for a geothermal reservoir, storage-capacity will become a major question. Recharge into basement may occur through overlying Tertiary volcanic and sedimentary rocks, through coarser-grained Quaternary sediments, or as direct infiltration into surface outcrops. In any case, faults and other fractures are likely to serve as recharge channels. These same features may constitute the principal reservoir, or at least serve as communication channels between more-heavily and less-heavily fractured lithologies in the basement.

EXPLORATION PROGRAM

As outlined above, the focus for further exploration will be a northeast-trending zone up to 6 miles in width at the south end of Grande Ronde Valley, where depth to basement is believed to be 3,000 to 5,000 feet. Exploration will have as principal goals the interpretation of structure, determination of depth to basement and location of aquifers in this target area.

It is necessary to integrate the results of the 1974 field exploration program into a coherent picture. This will require the reduction of gravity data to complete Bouguer anomalies, and the interrogation of gravity and magnetic data to provide information on:

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1. structural patterns, including faults, especially beneath the cover of Quaternary sediment;

2. depths to and shape of basement;

3. possible presence of youthful intrusions within basement or overlying section of Tertiary and Quaternary materials.

The hydrochemical data should be studied closely, and mixing models considered, such that the chemical nature and thermodynamic character of the reservoir fluid can be approximately known.

Data from earlier passive seismic surveys should be reviewed, and compared with geologic maps and cross-sections and structural inferences obtained from magnetic and gravity data. After this had been done, it may be necessary to carry out additional gravity and/or magnetic surveys across the southern end of the project area, especially the southern part of Grande Ronde Valley and immediately to the south.

It is expected that deep resistivity surveys, utilizing dipole mapping and deep sounding techniques, will become advisable. Electromagnetic soundings may replace or supplement large Schlumberger-equatorial expansions. These surveys may provide data on depth to and shape of basement, probable permeable zones and potential thermal aquifers. However, it may be worthwhile to perform an active seismic profiling survey. The extent and thickness of basalt flows and related mafic rocks may preclude such a survey, however.

If geological and geophysical targets are recognized, the drilling of slim holes will be in order. These should be drilled deep enough to penetrate the principal regional aquifers, in order to avoid calculation of unrealistic temperature gradients. Individual holes may be reamed to greater width, and deepened, if data are encouraging.

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