CONCEPTUAL MODEL OF THE KLAMATH FALLS, OREGON GEOTHERMAL AREA

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ABSTRACT

Over the last 50 years significant amounts of data have been obtained from the Klamath Falls geothermal resource. To date, the complexity of the system has stymied researchers, leading to the development of only very generalized hydrogeologic and geothermal models of the area. Recently, the large quantity of available temperature data have been re-evaluated, revealing new information on subsurface heat flow and locations of faults in the system. These inferences are supported by borehole, geochemical, geophysical, and hydrologic data. Based on re-evaluation of all available data, a detailed conceptual model for the Klamath Falls geothermal resource is proposed.

INTRODUCTION

The Klamath Falls KGRA (Known Geothermal Resource Area), located in south-central Oregon, is a low- to moderate-temperature resource (Figure 1). The approximately 2 square mile shallow thermal anomaly is associated with an adjacent large normal fault, shown in Figure 2 (Sammel, 1984). Over 500 wells have been drilled in the area, ranging in depth from 90 to 1900 ft. Most temperatures encountered in these wells range from 70 to 120 °C. Temperatures in one well have been measured as high as 140 °C, but this data is somewhat suspect (Gene Culver, personal communication). The geothermal resource has been used for space heating for some 70 years; special uses

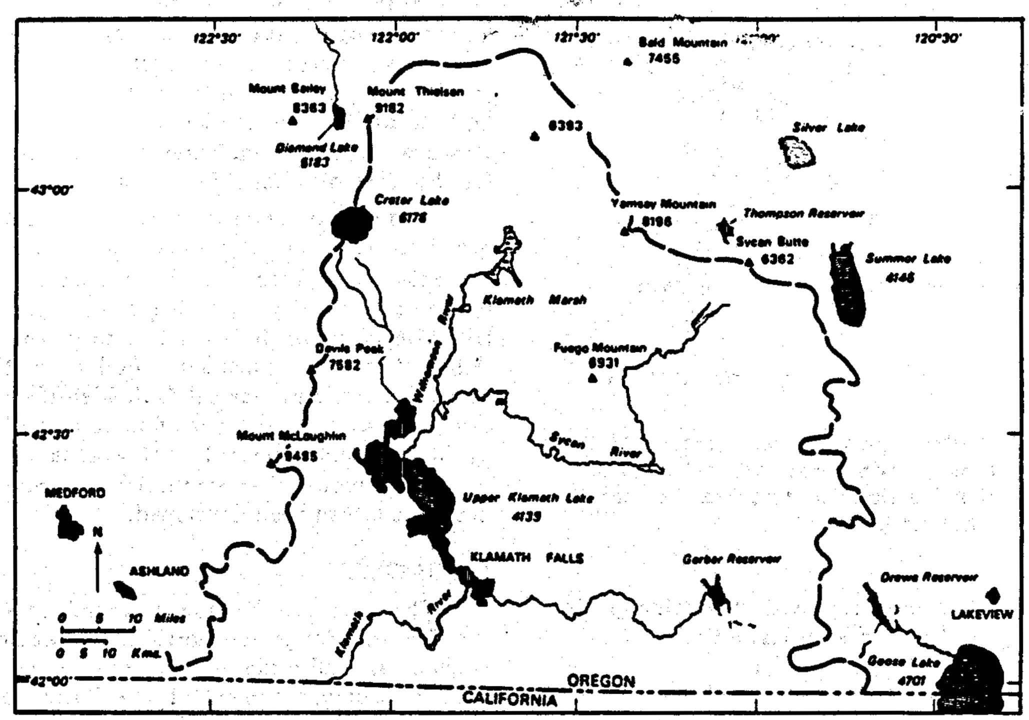

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Figure 1. Location map of Klamath Falls, Oregon.

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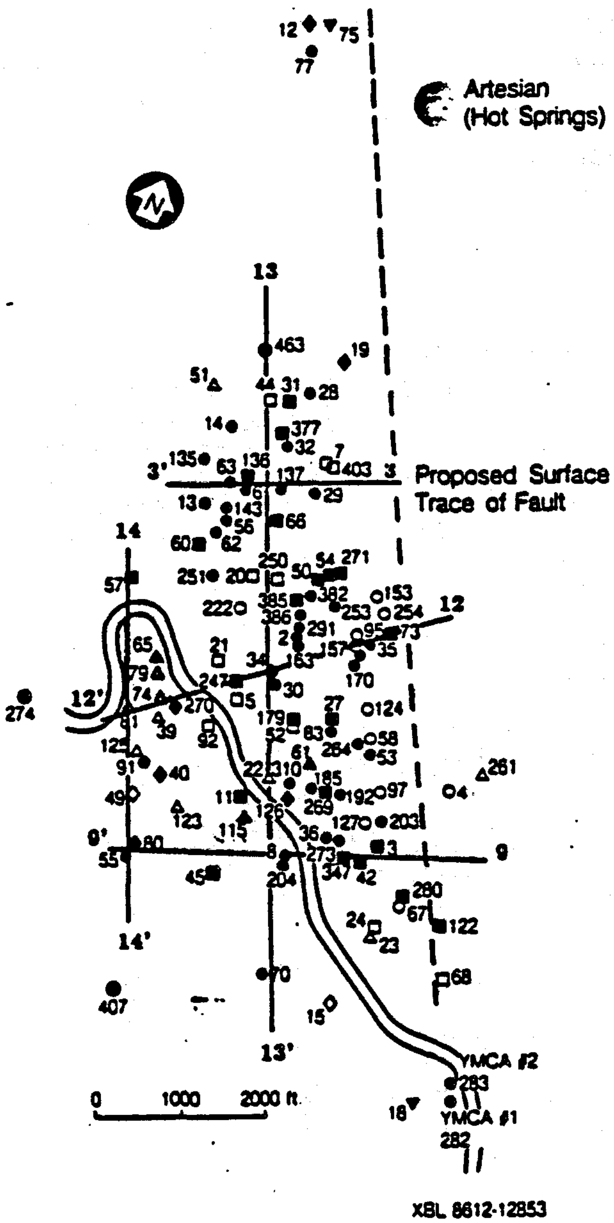

Figure 2. Wells supplying temperature data. Lines drawn across the wells indicate the location of temperature profile cross-sections.

include heating greenhouses and swimming pools, snow melting, and milk pasteurization.

Various investigators have obtained and evaluated data from the Klamath Falls geothermal area. Moore (1937) was the first to describe the rocks of the greater Klamath region. Meyers and Newcomb (1952) and Newcomb (1958) were the first to describe the geology in detail and evaluate the groundwater resources of the region. Peterson and McIntyre (1970) investigated the economic potential of eastern Klamath and western Lake Counties by reconnaissance geology methods, and proposed a conceptual model for the system. These authors postulate that the heat source is a shallow, igneous dike or sill-like body of Pliocene-Peistocene age, intercalated in lacustrine deposits which transform cold flowing groundwater into steam that rises along fault zones and heats the surrounding reservoir rock.

Sammel (1980) presents an alternate conceptual model for the Klamath Falls geothermal system. He proposes that water is circulated to great depths along faults, where it is heated to rock temperatures corresponding to a 30 °C/km gradient. The hot water then rises to shallow depths through conduits closely associated with major faults, until it begins to flow laterally towards the southwest through horizontal permable strata. Stark et al. (1980) studied the geophysical characteristics of the Klamath Basin; in particular they studied the Swan Lake, Klamath Hills and Klamath Falls areas. They found no direct evidence to either support or refute the possible existence of an igneous heat source, or the concept of deep circulation along fault zones penetrating a hotter-than-average crust.

In 1983, Lawrence Berkeley Laboratory, Stanford University, Oregon Institute of Technology (OIT), and the U.S. Geological Survey collaborated in pumping and injection tests at Klamath Falls. The hydrologic data confirm the highly-fractured and faulted nature of the system as indicated by the high degree of connectivity between wells and high transmissivity of the aquifer. A recent well test near OIT also indicates a high transmissivity for the reservoir (Nork, Inc., 1986).

This paper reviews conceptual models proposed to date, and considers a new model for the Klamath Falls geothermal system based on recent interpretations. By analyzing the temperature distribution in detail, it is possible to detect the locations of several subsidiary faults to the large northwest-trending normal fault identified in previous reports. The existence of these faults is verified by high-altitude infrared photographs of the area. A detailed model that emphasizes the role of subsidiary faults has been developed.

GEOLOGY

The Klamath Falls geothermal area, east of the Cascade Range and north of the Medicine Lake Highlands, California, is situated in a horst and graben structure typical of the Basin and Range province. The Klamath graben complex extends some 80 km, from Lower Klamath Lake, to as far north as Crater Lake, trending approximately N40W. Faulting in the area is believed to have commenced during the late Pliocene and continued well into the Pleistocene. Large, steeply dipping normal faults with vertical throws up to 1600 ft flank either side of the graben complex and trend

N25-35W. On the western shore of Upper Klamath Lake the large fault blocks dip towards the southwest, while on the eastern shore they dip to the northeast, suggesting that the axis of the graben complex passes through the lake.

The two types of faulting occurring in the immediate region are NW-trending normal faults and NE-trending, strike-slip cross-faults. Donath (1962) describes these two sets of faults as being contemporaneous, originally developing as conjugate strike-slip shears in a stress system with a north-south maximum principal stress and an east-west minimum principal stress. The system forms what Donath refers to as a rhombic fracture pattern. Lawrence (1976) interprets the Basin and Range faulting in Oregon as being separated by four strike-slip zones trending WNW. The fault blocks between these strike slip fault zones exhibit the rhombic fracture pattern suggested by Donath (1962). Lawrence (1976) suggests that the rhombic pattern of normal faulting in the region is a result of the interaction of extensional faulting between the fault zones and right-lateral strike-slip motion at the edges of the blocks.

The geology of the area has been mapped and described by Peterson and McIntyre (1970). Four dominant rock units occur in the immediate Klamath Falls area, identified by outcrops and borehole data Newcomb (1958). These rock units are, from earliest to most recent, a Pliocene basement basalt, the thick Pliocene Yonna Formation, a Pleistocene andesitic-basaltic flow sequence, and Quaternary alluvium.

The Pliocene basaltic rock of undetermined thickness is defined by Newcomb (1958) as the basement rock. Although this basalt does not outcrop in the immediate vicinity of the resource, it has been penetrated by wells at the OIT campus, 2 miles north of Klamath Falls city, and by the two YMCA wells in the southern part of the resource.

The Pliocene Yonna Formation, comprised of a sequence of lacustrine and fluvial tuffaceous siltstone, sandstone, ashy diatomite, basaltic tuff and breccia, and a few thin basalt flows, uncomformably overlies the basement rock (Newcomb, 1958). This formation is primarily subaqueous, as evidenced by the brecciated and altered basalt flows, deposited during a period when swamps and lakes covered the region. Explosive and quiescent volcanisms were nearly contemporaneous with the deposition of the Yonna Formation, as is suggested by the maars, tuff rings, and welded tuffs. The Yonna Formation is estimated by Newcomb (1958) to be approximately 1000 ft thick. Sammel (1980) estimates the thickness to be at least 850 ft. This formation represents the oldest rock unit that outcrops in the immediate Klamath Falls geothermal area.

The Yonna Formation is a large sequence of interbedded strata with high vertical and horizontal variability. Extensive erosion of this unit is indicated by the varying thickness encountered in outcrops and in driller's logs, as well as unconformable rock contacts.

Outcrops of an andesitic-basaltic flow sequence(s) with volcaniclastic interbeds of late Pliocene-early Pleistocene age, lying above the Yonna Formation, range in thickness from 0-180 ft. Just north of the immediate Klamath Falls geothermal area, on the southeast shore of Upper Klamath Lake, Peterson and McIntyre (1970) mapped several basalt eruptive centers. Newcomb (1958) describes several dikes which cut through or into sedimentary Tertiary rocks in the area surrounding the geothermal anomaly. These igneous features are considered to be contemporaneous with the Pliocene-early Pleistocene basalt flow sequence.

Much of the lower valleys in the Klamath Basin are covered by Quaternary alluvium. To the immediate south of the geothermal area, however, Quaternary fluvial terraces and lacustrine deposits are found.

Nearby volcanic activity has been dated by both paleontological data and potassium/argon (K/Ar) methods. K/Ar methods have indicated volcanic activity as recent as 1.9 m.y.b.p. and up to 4 to 5 m.y.b.p., for rocks on the KGRA periphery (M. O'Brian, personal communication). Diatom species obtained from well cuttings were used to correlate and date strata. It was concluded that surface outcrops are late Pliocene while subsurface samples range from mid to late Pliocene. Correlation of lithologic strata was difficult, due to the hydrothermal alteration of diatomaceous sediments (M. O'Brien, personal communication).

WELL TESTING

Numerous interference tests have been conducted within the Klamath Falls KGRA. From these tests, the hydrological parameters of the reservoir (kH/μ and $\phi c_t H$) have been determined and the nature of the thermal aquifer has been investigated. Results of these tests, summarized in Table 1, show the aquifer to be highly permeable. In general, the pressure transients are indicative of a naturally fractured system, with high permeability fractures and relatively low permeability matrix blocks (Sammel et al, 1984). Several localized heterogeneities have also been detected in the reservoir, including a high-permeability region centered in the Old Fort Road area and a semi-permeable fault near OIT (Benson and Lai, 1986; Nork, Inc., 1986).

Unexpectedly, the faults and fractures in the KGRA behaved neither as constant potential boundaries, nor as no-flow boundaries. Several

Table 1. Reservoir Parameters

Well Location	Transmissivity (kH/μ) x $10^{-6} m^3/Pa \cdot s$	Storativity ($\phi c_t H$) x $10^{-6} m/Pa$	Source
south central area	2.192	0.102-1.02	Lund, 1978
south central area	1.096	0.102-1.02	Sammel, 1980
south central area	4.21-4.51	0.106-.345	Benson, 1980
south central area	3.0-9.03	0.039-0.088	Benson, 1982a.
south central area	6.017	——	Benson, 1982b.
south central area	1.955	0.0301	Benson, 1983
OIT area	.498-7.48	0.0408-1.02	Nork Inc., 1986
south central area	2.11	0.0221	Sammel et al., 1984

hypotheses were suggested to explain this observation, including: (1) the hot water upwells over a broad zone instead of a single fault zone, (2) the permeability of the fault zone is similiar to that of the near surface strata permeability, or (3) a single fault is responsible for the deep fluid upwelling, but the fault's effective width increases towards the surface, creating a diffuse permeable zone (Sammel et al, 1984).

GEOPHYSICS

Peterson and McIntyre (1976) prepared a Bouger gravity map for the Klamath Basin. He estimated the thickness of the valley fill in the graben structure to be on the order of 3000 ft southeast of Klamath Falls. and 6000 ft southwest of Klamath Hills. Stark et al. (1980) employed various geophysical methods to investigate the geothermal system in the Klamath Basin. Based on the results of remote sensing, gravity, geology, aeromagnetic and resistivity survey data, they conclude that the shallow hydrothermal circulation is related to the intersection of northeast-trending cross-faults and northwest-trending normal faults. These surveys did not reveal any new information on the heat source; however, they did suggest that either the conceptual model proposed by Peterson and McIntyre (1970) or Sammel et al (1984) could be correct.

THE GEOTHERMAL AQUIFER

Based on logs from a well drilled at the OIT campus, Sammel (1980) concluded that the rocks comprising the geothermal aquifer are believed to extend to at least 2000 ft. In the aquifer, water flows preferentially through strata consisting of volcanic breccia (cinders, broken lava, porous lava, etc.), jointed and fractured vesicular basalt flows, and fractured, indurated lacustrine sediments. These strata range in thickness from one to a few feet and have high vertical and areal variability. The permeable strata are interspersed with layers of lacustrine and tuffaceous sediments and diatomite, from 30 to 150 ft thick.

Fluid flows from the fault zone toward the southwest, following the general surface topography, as indicated by static water level maps drawn by Lund (1978) and Sammel et al. (1984).

GEOCHEMISTRY

Geochemical data contributes valuable information regarding maximum reservoir temperatures, mixing of thermal waters, fluid residence times and possible sources of recharge. Janik et al. (1985) used tritium data to determine the cold water residence time in the aquifer to be at least 30 years, and that of the thermal waters to be at least 60 years. From tritium and deuterium data they were also able to conclude that the cold water recharge probably does not originate from the modern Klamath Lake (Sammel, 1980). The tritium data also leads Janik et al. (1985) to suspect two cold water sources—a very shallow one containing tritium and a deeper one that is tritium-free. Geothermometry and mixing models indicate a maximum source-water temperature of 190 °C.

Janik et al. (1985) developed a conceptual model consisting of a shallow 70-100 °C thermal aquifer, caused by the mixing of 100-120 °C and 20 °C waters. The hot water may be derived from a deeper source where mixing of older tritium-free hot and cold water occurs. Although the maximum source-water temperature has not been encountered yet, geothermometry indicates temperatures of 150 to 190 °C somewhere in the system.

TEMPERATURE DATA

Temperature data are very important to the understanding of a hydrothermal system. The temperature data used in this study were obtained primarily from drillers' logs. Temperatures in most cases were measured using a maximum reading thermometer or a simple thermistor apparatus. A few reports (Lund, 1978; Sammel and Peterson, 1976; and Sammel, 1980; Sass and Sammel, 1976) also recorded independent temperature data for the Klamath Falls geothermal area. According to Sass and Sammel (1976), temperature profiles in the Basin and Range province are classified into four distinct types:

1. near-isothermal temperature profiles, indicating hydrologic recharge;
2. quasi-conductive temperature profiles;
3. convex-upward profiles with elevated temperatures, indicating areas of discharge;
4. temperature profiles exhibiting varied types of curvature, implying a combination of upward and downward flow.

As shown in Figure 3, profiles from Klamath Falls exhibit all four types of data; however, most temperature profiles show a combination of conductive and convective heat flow.

METHODOLOGY

In this section we discuss the methodology used to infer the location of faults from the large amounts of temperature data available from the Klamath Falls geothermal area. The data are depicted both in cross-sections and as contour plots. Both offer a good deal of information regarding the location and relative size of faults, size of the system and influence of surface phenomena.

Cross-sections were constructed approximately parallel and perpendicular to the proposed surface trace of the main normal fault associated with the geothermal system. Twenty such cross-sections

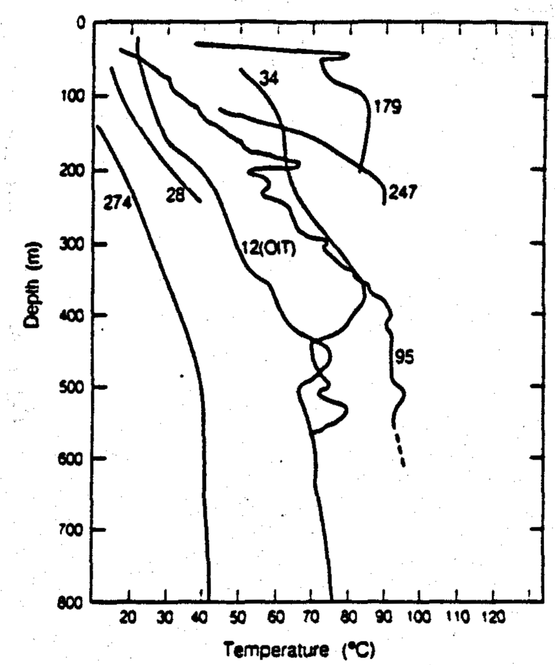

Figure 3. Various temperature profiles from the Klamath Falls geothermal resource.

were constructed for the geothermal area; five are shown in Figures 4 and 5 and their locations are shown in Figure 2. Since relatively little temperature data exist east of the normal fault, no cross-sections or horizontal contour maps were constructed for that area.

Figure 4 shows two cross-sections parallel to the main normal fault, while Figure 5 shows three cross-sections perpendicular, or oblique, to the fault. Both sets of cross-sections show thermal features which can only be explained by complex convection heat transfer mechanisms. Cross-section 13, which is parallel to the fault, shows temperatures at both ends of the anomaly decreasing rapidly. We propose that northeast-trending cross-faults limit the northern and southern extension of the resource, and that the region between wells 31 and 9 is the primary zone of hot water recharge.

In cross-sections 3, 12, and 9, perpendicular to the normal fault, a higher thermal gradient zone is seen on the right (NE) side, most likely indicating the location of the main normal fault. This helps to confirm the existence and define the location of this normal fault, as suggested in previous reports. In Figure 2, perpendicular cross-sections not shown in this report, indicate similiar trends in temperature distribution.

Both sets of cross-sections show the locations of very high, near-surface thermal gradients (see wells 31, 386, 179, 137, 74, 247, 45). When the cross-sections are aligned these thermal anomalies fall along lineaments, interpreted in this report as faults (see Figure 6). Several 3-dimensional models were constructed revealing these fault lineaments in more detail. Cross-sections 3, 12 and 9 in Figure 5 suggest the existence of a subsidiary normal fault (Fault 1b) parallel to the main normal fault (Fault 1a) intersecting wells 45, 247, and 137. The northern and southern extent of the subsidiary normal fault cannot be determined from the available data.

The locations of several right lateral strike-slip cross-faults, roughly perpendicular to the main normal fault are also inferred from cross-sections 13 and 14 (Figure 4). These faults intersect wells, 31, 137, 386, and 179, as seen in Figure 6.

Figure 7 shows contour maps of the temperature distribution at three elevations (4100, 3900, and 3600 ft, a.s.l.). The locations of artesian springs, a canal that runs through the city, main roads, and the trace of the main normal fault are also shown. In general, at greater depths and larger distances from the center of the anomaly, fewer data are available. Consequently, only general inferences can be made for these areas. Dashed lines in both cross-sections and horizontal contour plots represent areas where data are limited.

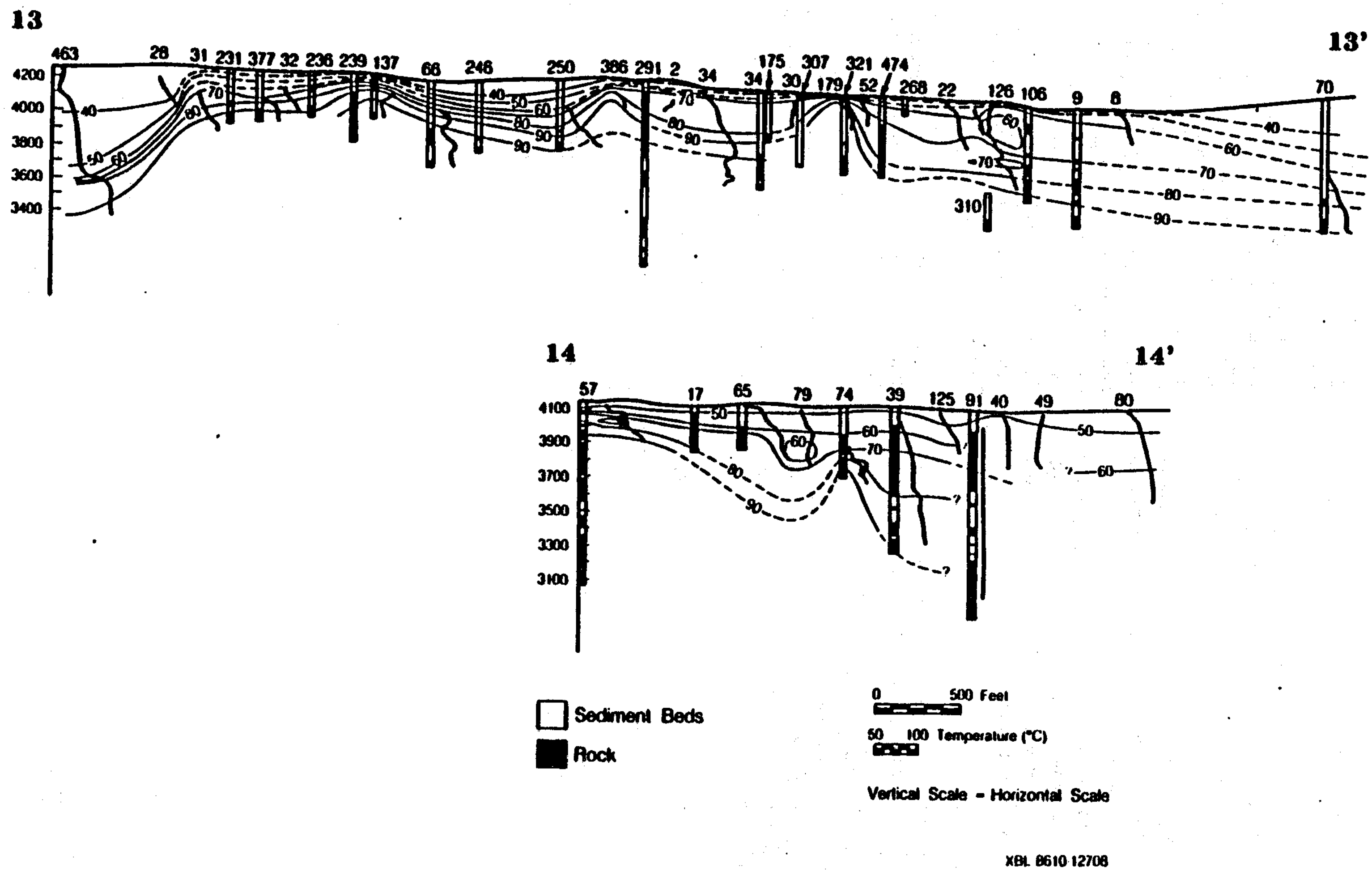

Figure 4. Cross-sectional temperature profiles drawn parallel to the main normal fault. Well numbers appear above the isotherms.

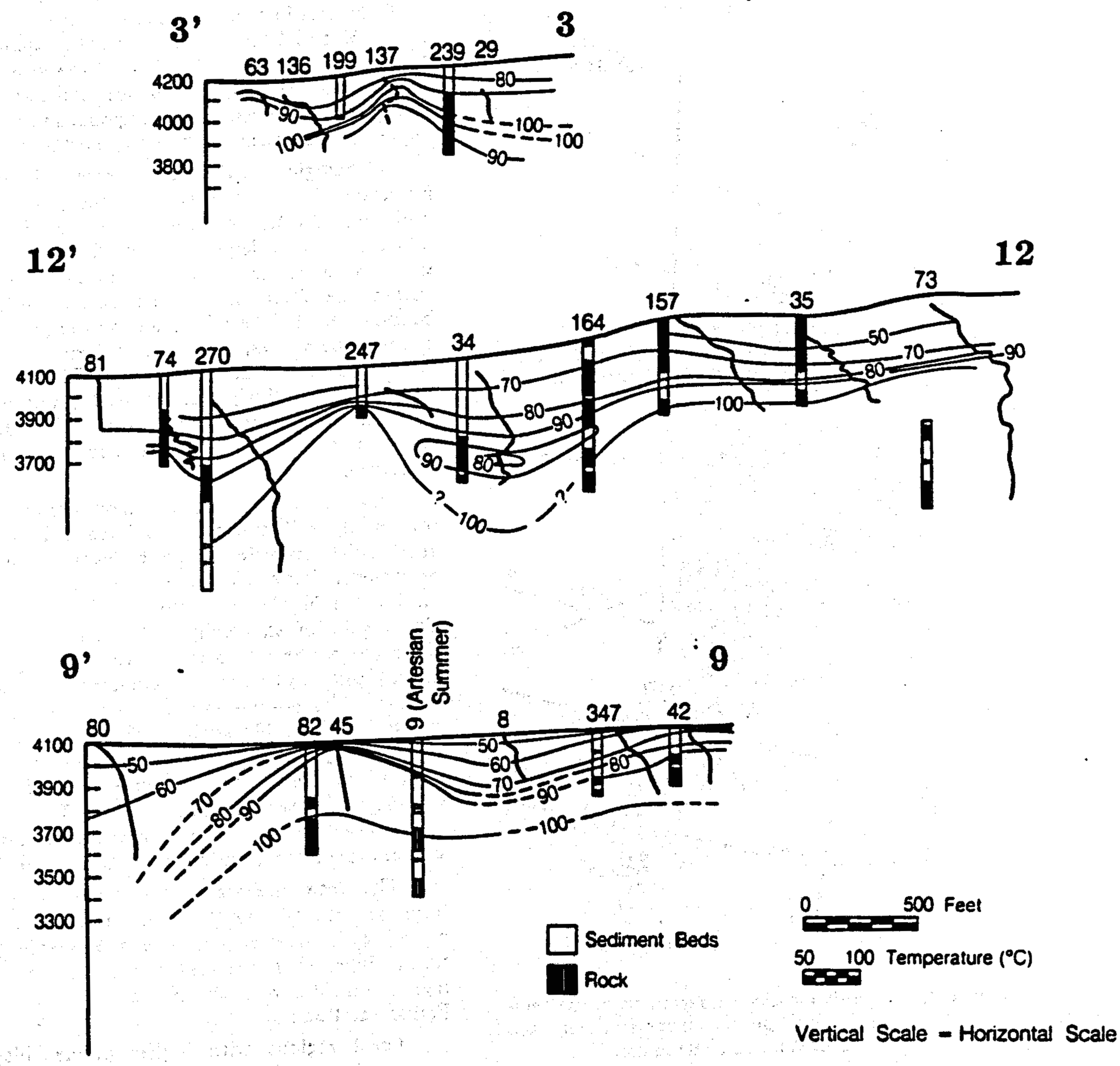

Figure 5. Cross-sectional temperature profiles drawn perpendicular to the main normal fault. Well numbers appear above the isotherms.

Although the temperatures in most wells increase quickly with depth, temperatures to the southwest of the artesian springs seem to increase much more slowly. This might be explained by a third normal fault (Fault 1c) trending northwest (see Figure 7), which impedes the flow of hot water toward the southwest. This same characteristic feature is seen in wells located southeast of Fault 2, and northwest of Fault 8, which seems to imply that the thermal anomaly is bounded on all sides by large faults.

Near surface temperatures are much more variable, as seen in Figure 7. This can be attributed to surficial effects and to a greater amount of data available at shallow depths. The temperature distribution is correlated with faults, artesian springs, regional groundwater flow, and the city canal. At all depths maximum temperatures are associated with the faults shown in Figure 6, while at shallow depths, high temperatures are also related to the artesian springs. On the other hand, cooler temperatures are associated with the canal, which leaks cold water into the surrounding formation. Temperatures decrease towards the southwest in response to the south-southwesterly regional flow of cold groundwater.

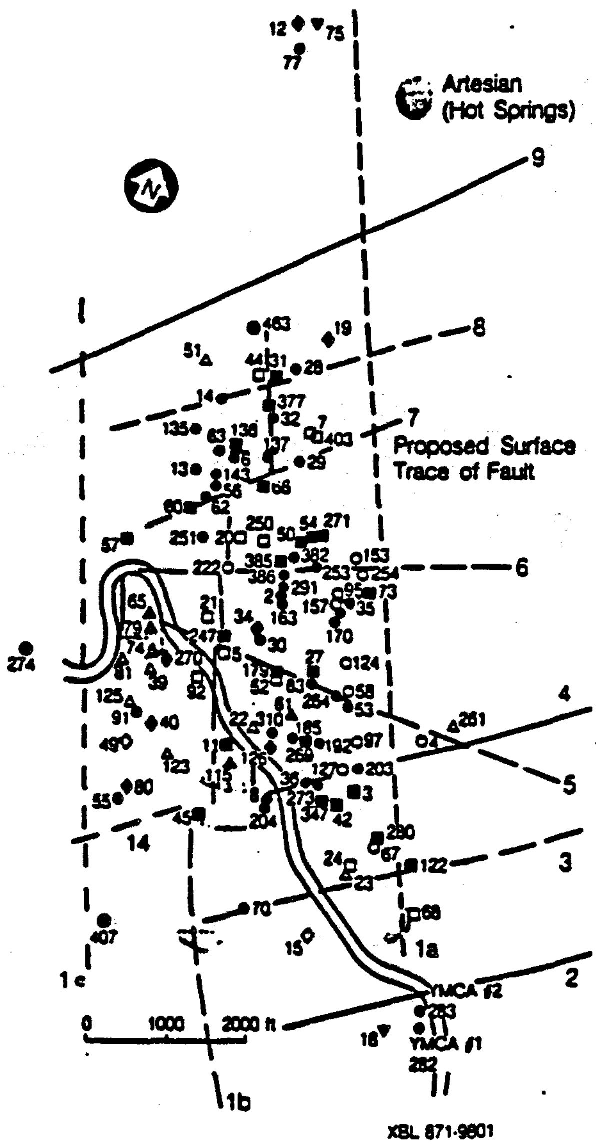

Figure 6. Fault locations inferred from the temperature profile cross-sections and temperature contour maps.

FAULT LOCATIONS

In order to confirm the existence of the faults shown in Figure 6, hydrologic, geophysical, and lithologic data as well as high altitude infrared photographs were analyzed. From high altitude photographs, Faults 1a, 2, 3, 4, 8 and 9 were easily identified because of their clearly visible surface traces. Faults 5, 6 and 7 were less pronounced because their traces tend to be localized, while fault 1b could not be detected. The exact locations of Faults 2, 3, and 9 were more easily recognized using areal photographs, as their traces were found to extend well into the region east of the main normal fault (Fault 1a).

The ease of detecting the various faults is due to differences in their size and displacement. Faults 1b, 5, 6, and 7 appear much smaller than Faults 1a, 2, 3, 4, 8, and 9, in view of the size of their relative temperature disturbance. All of the faults in Figure 6 conform to the regional fault pattern, which trends either northwest or northeast.

Lithologic data were re-examined with the intention of confirming the existence of the newly-proposed faults; however, this proved more difficult than anticipated. Poor lithologic correlations were found between nearby wells, both within the fault blocks and across fault block boundaries. This is partly due to the poor quality of the drillers' logs, and the complexity of the sedimentation and erosion processes. However, the system most likely experienced faulting concurrently with erosion and deposition of sediments, resulting in the highly complex subsurface geologic structure.

Also supportive of the new faults are the results of well testing in Klamath Falls. The geothermal reservoir appears to have a high degree of transmissivity and connectivity between wells, implying a highly fractured and faulted medium. The results of the many well tests conducted in the area can be interpreted within the framework of a fault and fracture dominated hydrologic regime. The normal faults, cross-faults and contacts between lithologic layers act as high-permeability conduits. Low permeability strata within the fault blocks provide a large storage volume for the thermal fluids. The double-porosity behavior reflected by the well test data support this interpretation (Benson and Lai, 1986).

The data interpretation for one of the well tests suggest the existence of and an approximately cylindrical region with a permeability 7.5 times higher than the rest of the reservoir. This region coincides with the proposed intersection of Faults 1a, 4 and 5.

Local regions with higher permeability are expected at each intersection of two or more faults. Although data to support this hypothesis at Klamath Falls are not yet available, the locations of once-active artesian hot springs generally coincide with the intersection of the strike-slip and normal faults (see Figure 6). This suggests that higher permeability regions are associated with the intersections of two or more faults throughout the KGRA.

Geophysical data, although very regional, suggest that the whole Klamath Basin graben has been offset along northeast-trending cross-faults. Although these cross-faults are indicated only on a regional scale, it was suggested that the shallow hydrothermal circulation is related to the intersection of northeast trending cross-faults and the northwest trending normal faults (Stark et al., 1980).

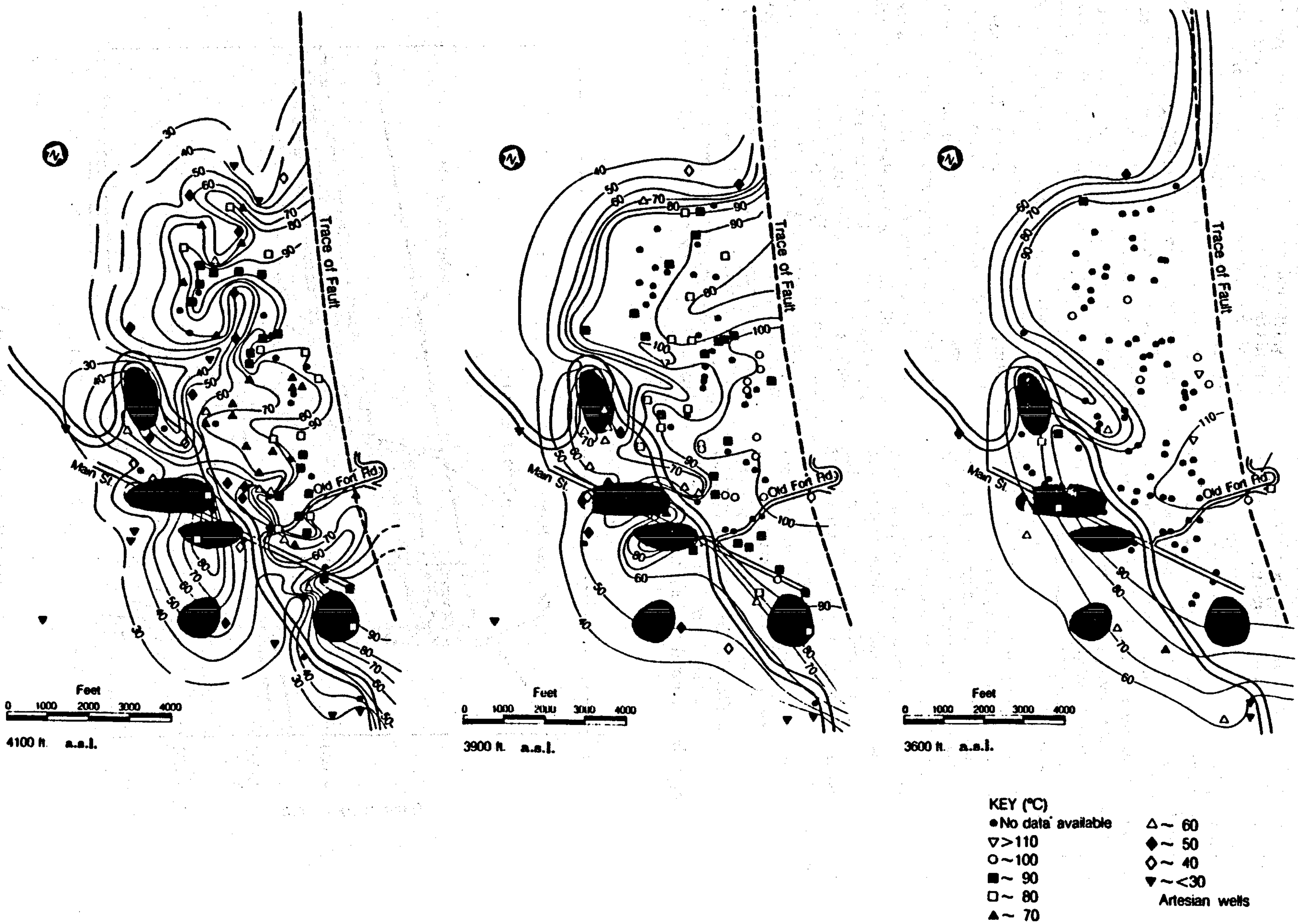

Figure 7. Temperature contour maps drawn at 4100 ft, 3900 ft and 3600 ft.

CONCEPTUAL MODEL

Figure 8 represents a conceptual model of the Klamath Falls geothermal area. The reservoir consists of a shallow and a deep aquifer. For the sake of simplicity, three permeable layers represent the shallow aquifer zone. The deep aquifer is inferred from geochemical data, although it has not been penetrated by wells. The two aquifers are connected through the main normal fault and possibly by the two subsidiary normal faults. Although upflow occurs along fault planes, we propose that the most permeable zones occur at the intersections of the normal and cross-faults as described in the previous section.

The dominant normal fault and two subsidiary normal faults indicate down-throws toward the southwest. This displacement might explain the successively lower temperatures encountered at greater distances from the main normal fault.

Hot water recharge may be derived from two possible sources. It is possible that thermal waters flow into the geothermal system from the upthrown block (mountainous region to the east of the main normal fault). Hot water could also be recharged from the west indicating a possible connection to a deep aquifer within the klamath Falls graben. At depth, it is unclear whether hot water from the deep aquifer is driven up individual faults, or whether the main normal fault recharges the two subsidiary normal faults at a shallower depth.

At shallow depths thermal waters spread laterally through permeable strata, and mixes with colder regional groundwater. Mixing also occurs along the faults. As the thermal water flows toward the southwest, temperatures are cooled to regional groundwater temperatures.

An age of 2 to 4 million years is estimated for the geothermal system. Silicified palagonitic tuff, found at elevations up to several hundred feet above the present geothermal system suggests that the system was associated with early fault displacements (Sammel, 1980). The fresh appearance of the normal fault scarps in the area indicates recent fault displacements. Paleontological dates and the age of recent volcanic activity suggest that faulting in the region began during the late Pliocene and continued well into the Holocene.

Two hypotheses have been made on the possible heat source. Peterson and McIntyre (1970) suggest the heat source is associated with a cooling dike or sill. Sammel and Peterson (1976) consider the Klamath Falls KGRA as a normal geothermal gradient system. This would require a fault zone that extends to nearly 6 km in order to reach temperatures approaching 190 °C at depth. Sammel and Peterson (1976) point out that no noticeable surficial volcanic manifestations or dike intrusions are found within the KGRA. Although this is true for the KGRA, geologic maps indicate a high degree of relatively recent volcanic activity in the surrounding area.

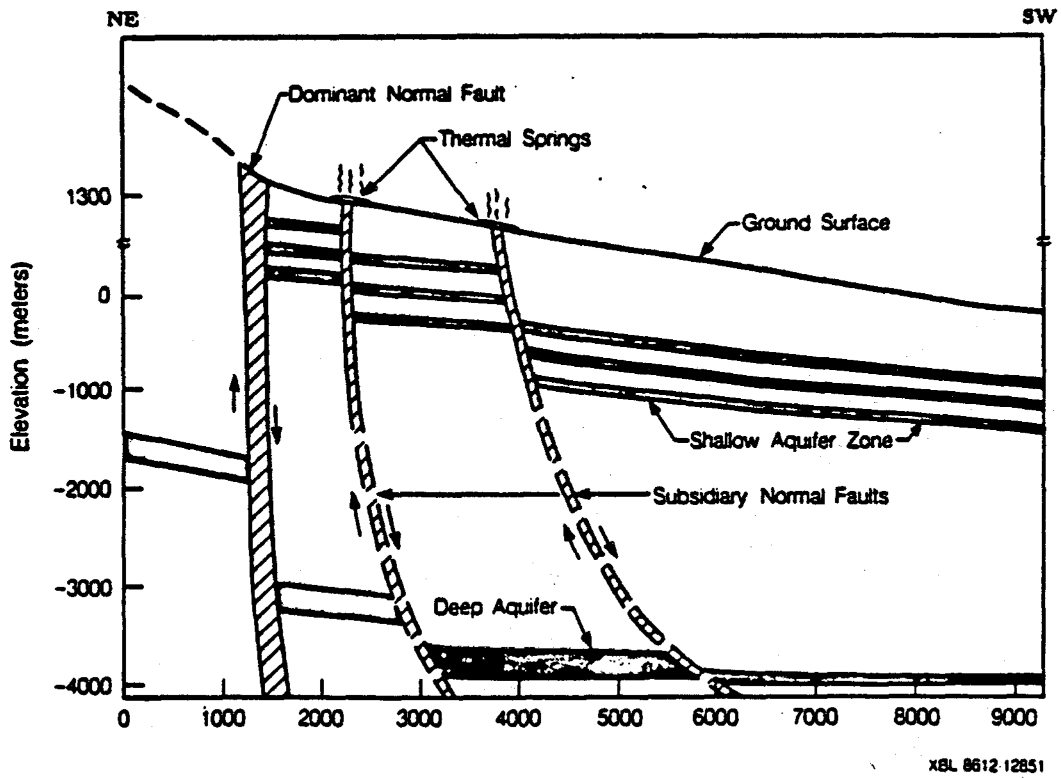

Figure 8. Conceptual model for the Klamath Falls geothermal system.

Additional deep drilling is needed to further characterize the source recharging the Klamath Falls geothermal system. Further work is still needed to identify and describe the actual fault systems in the area and determine the role of the different faults in the development and dynamics of the geothermal reservoir.

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