An Overview and Conceptual Model of the Crump Geyser Geothermal Area

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ABSTRACT

Geological and structural mapping, extensive geophysical studies and fluid geochemical analysis at the Crump Geyser geothermal area in the Warner Valley, Oregon provide the foundation for an initial conceptual hydrothermal model. This simplified model illustrates a broad region of high permeability and significant fluid flow within underlying volcanic formations and along intersecting N-NE and NW trending faults and fractures.

Introduction

The Crump Geyser geothermal area is located within Warner Valley, in Lake County, south central Oregon (Figure 1).

Located just north of the rural community of Adel, the Crump Geyser came into being via the regional drilling program and search for super-heated water in 1959 by the Nevada Thermal Power Company (NTPC). NTPC drilled the well on land belonging to Charles Crump, and after failing to encounter the super heated temperatures they were hoping for, they walked away from the well, leaving it unsecured. Two days later, the well heated sufficiently and blew out, beginning its new life as a geyser. Witness accounts of the geyser recorded temperatures of 99°C at the edge of the casing, and geyser heights reaching nearly 60 meters in the air (Peterson, 1959). Over time, the geyser activity subsided, became intermittent, and was eventually "vandalized" with debris and rubble (and possibly cement) thrown into the wellbore.

Over the last six decades numerous geological and geophysical studies have been completed within the Warner Valley to provide insight on the nature of the hydrothermal resource, its source and the geologic structures controlling its activity. Ongoing investigations by Nevada Geothermal Power in conjunction with the USGS and the US Department of Energy (DOE) will further characterize this resource and lead into the development of commercial power generation within several years. This paper summarizes the existing data and sets forth an initial conceptual model to guide current and planned work for the Crump Geyser geothermal area.

Geologic Setting

The Warner Valley (Figure 2) is a large graben structure developed within Tertiary age volcanic formations. Presently, the valley floor and toes of the escarpments are dominated by Quaternary alluvial and lacustrine sediments and landslide debris.

One recent geologic mapping project has been completed by Michelle Dooley (2010), providing a comprehensive review and detailed account of the lithologic characteristics, and generalized structural setting in the southern Warner Valley. The Crump Geyser area shares many of the gross morphological and structural characteristics as the entire valley, though a unique combination of geology and structure combine to define the characteristics of the underlying hydrothermal resources.

Figure 1. Regional location map.

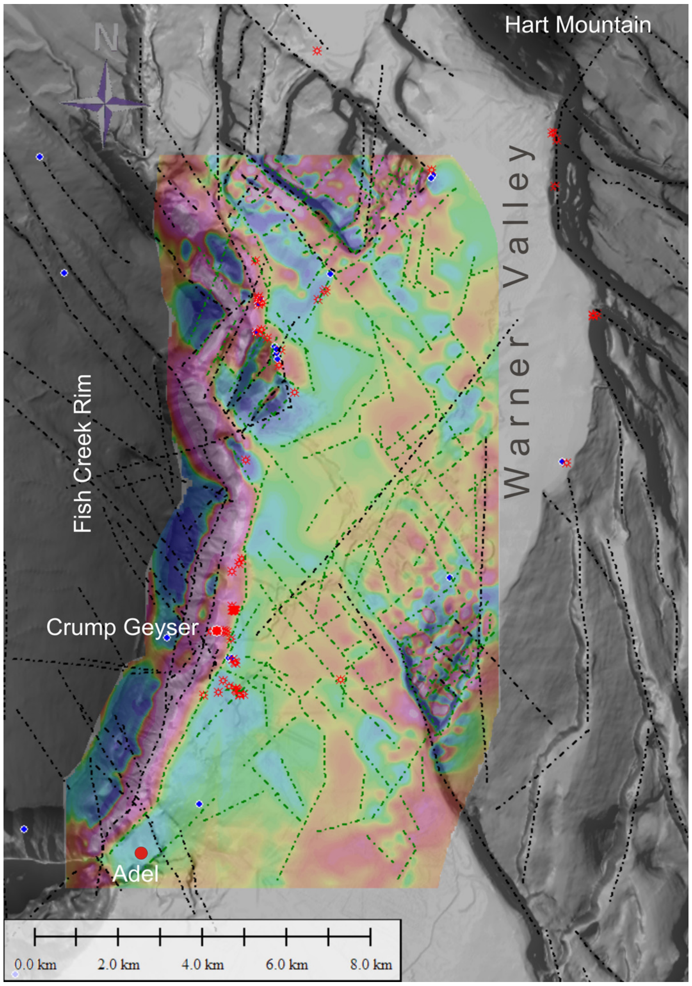

Figure 2. Shaded relief map showing topographic and magnetic lineaments over shaded relief. Red stars are hot springs, and blue dots are cold springs.

Structural Setting

Surface Evidence

The Warner Valley is an elongate, N-NE trending graben (Figure 2). It is fault bounded along its west and east margins by E-NE and W-NW dipping fault zones respectively. These fault zones have created prominent escarpments with the maximum vertical relief estimated at a minimum of ~725 meters from valley floor to the Fish Creek Rim near Crump Geyser, and as much as ~980 meters at Hart Mountain to the north. The amount of the true vertical offset will be greater, depending on the depth to the underlying top of offset lavas. The sense of motion on the southwestern section of this fault zone (near Adel) is known from an exposure of slickenlines to be pure normal, dipping ~70° SE. More northern sections of the range front escarpments are believed to be dominantly normal, though possibly slightly oblique.

The valley is also crosscut by NW striking faults, prominently visible to the north and to the west of Crump Lake. One fault exposure to the north of Crump Lake at the western base of Hart Mountain shows a strike of N40W, dipping 75°S, with slickenlines indicating a significant portion of oblique dextral motion. NW trending faults to the east of Crump Lake become oriented progressively more N-NW to N trending progressing southward. Multiple sub parallel fault segments in this region combine to result in a stair-stepped, arcuate (concave to the west) escarpment along the eastern margin of the valley, reminiscent of a slump block headwall. Previous regional studies have shown that N-NE trending normal faults overprint the NW trending faults, that is, the NE faulting initiated subsequent to prior development of the NW trending faults (Scarberry et al., 2009).

Subsurface Evidence

Gravity

The earliest known gravity study (Plouff and Conradi, 1975) does not provide great detail on subsurface features immediately around the Crump Geyser area. There is however, a clearly delineated, steep gravity gradient just south of the geyser well that coincides with and is interpreted as the ESE dipping range front fault. NW trending lineaments present in this gravity data do little more than suggest that the prominent NW trending features identified on the surface (presumed faults), do carry through across the valley.

To provide greater detail on the subsurface structure, the USGS is conducting a precision gravity survey at, east of, and southeast of the Crump Geyser area. Preliminary review and interpretation illustrates that this new gravity survey is successfully imaging subsurface features that were previously unmapped. Completion of this work is expected in the summer of 2010 and will coincide with collection of ground based magnetic studies, discussed below.

Magnetics

Two magnetic studies performed in 1975 (Plouff and Conradi), including truckborne magnetometer, and aeromagnetic studies provide limited insight on the area specifically around the Crump Geyser. The truckborne survey provides an interesting cross section through the range front fault along highway 140 through Adel that suggests the possibility of two range front faults west of Adel. The westernmost interpreted fault aligns approximately with the prominent NE trending western boundary fault, but the interpreted fault located east of the first, does not. This second feature could be interpreted as identifying an unknown buried trace of the range front fault zone, or results from a known NW-trending fault through that area.

The aeromagnetic survey provides only a very broad view of magnetic trends across the valley, and does not provide great detail on the primary region of interest targeted for geothermal development. The data do show both NW-SE and NE-SW trending features and gross basin morphology, but they are not well defined, and do not provide much more detail than is already assumed from topographical features, i.e. that NW and NE trending structural grain is also present in bedrock beneath valley fill.

The 2005 ground and 2010 aeromagnetic (Figure 2) surveys together provide the highest resolution, and most dense coverage of all the magnetic surveys to date providing a much greater level of detail on intra-basin structure, primarily identifying distinct fault blocks, and through-going NW and NE trending faults offsetting underlying basalt lavas. The data has clearly imaged locally significant faults and key structural relationships that are influencing permeability in the primary geothermal development target area near a prominent sinter ridge and the Crump geyser wells. Ongoing USGS magnetic surveys to be completed in 2010 will provide one the densest geophysical datasets across a geothermal system.

Resistivity

An Audio Magnetotelluric (AMT) survey (Gregory and Martinez, 1975), and a subsequent 3-point schlumberger survey in 2006 combine to provide a broad overview of valley-wide and locally detailed resistivity trends. The data show strong broad NW-SE trending conductive anomalies that broadly coincides with the Crump geyser well, the sinter ridge, and the hot spring thermal anomaly at mid-range depths, as well as identifying a highly conductive anomaly immediately surrounding, and east of the Crump geyser area. A mid-level conductive feature is also identified extending E, SE and S into the valley. While the data does not provide sufficient detail for precise well targeting, the high conductive anomaly encompasses approximately 2 square miles and highlights a region of significant fluid flow, which has the highest developmental potential.

Earthquakes

The Warner Valley experienced a swarm of earthquakes in 1968, which was measured and recorded by the USGS and UNR (Wong and Jacqueline, 1995). Analysis of the data defined a 15-km-long, and 6-km-wide, north trending zone between the depths of 3 and 12.5 km to the northwest of Adel (Schaff, 1976). A separate analysis of the events suggested they were the result of normal faulting on an approximately north striking plane. This plane is interpreted here to be along the N-NE trending western boundary fault zone. A closer review of the event locations will be tied into more recent mapping results to provide additional detail on specific fault structures. Certainly, active, and especially seismically active faults in this region are favorable for maintaining a highly permeable fault and fracture network to sustain and promote high rates of fluid flow within the hydrothermal system.

Springs

Springs are common throughout the Warner Valley (Figure 2) and their distribution offers insight to the structures controlling valley morphology. Cooler and cold springs typically occur on the escarpments, either near the toe or mid scarp, typically at formation contacts or associated with landslide debris, though they do also occur in similar environments as, and among the hot springs. Spring temperatures and geochemical characteristics vary along the range front from north to south, and can be grouped more or less into two spatially distinct groups; the northern and southern zones.

The northern zone of hot springs exhibit a range of temperatures between 24°C and 30°C, and generally have higher flow rates than those to the south. The springs occur along the complicated, segmented escarpment, where strong NW faults intersect the dominant NE valley trend which coincides with the relative bedrock high point between Crump and Hart lakes.

The southern zone of hot springs exhibit a range of temperatures between 38°C and 56°C, and generally have lower flow rates than those to the north. Unlike the hot springs to the north, the southerly springs are often associated with abundant siliceous and calcareous sinter mounds. On a small scale the springs occur along trend with predominate NW lineaments (presumed faults) in one sense, and also align somewhat along the NE trending western valley escarpment. At a larger scale view the individual springs do not align exactly with the dominant NW trend, but tend to assume a more W-NW (or E-SE) alignment. This suggests that primary permeability is hosted along the primary NE trending fault and secondarily along NW trending faults which are the dominant regional trends. There may be additional structural influences which have not yet been recognized that could influence spring alignment, but these elements would be quite variable and subject to local conditions within the valley.

Wells and Thermal Gradient Holes

The two wells, for which the Crump Geyser area was named are located between and west of Crump and Pelican lakes along the range front (Figure 2). The southern and larger well was originally drilled to 1684' depth before being abandoned and subsequently erupting – becoming the "Crump Geyser". Temperature measurements made while drilling indicated a maximum temperature of ~122°C at ~200 meters depth, with a temperature reversal below that. Because these are temperatures recorded while drilling they are not representative of true formation temperatures. However it is clear that they intersected a hot geothermal fluid zone. It is likely the drill hole intersected the predominant range front fault zone, or a segment thereof. The northern well (~30m north) confirms these temperatures with a maximum of 122°C at a depth of only 12 meters, and is nearly isothermal to the maximum reachable depth (TD or blockage) of 21 meters.

The USGS performed a regional heat-flow study in the Warner Valley from 13 shallow wells between 1970 and 1990 (Saas et al., 2005). The wells were all less than 100 meters in depth and show temperature gradients between approximately 20°C/Km and 245°C/Km. None of the well locations are close to the Crump geyser area, and thus provide little information on the thermal characteristics of the principal geothermal anomaly.

Geochemistry

Geochemical analysis of fluids from the Crump Geyser area give a likely reservoir temperature of 150°C +/- 10°C, based primarily on the Chalcedony and other geothermometry indications (Molling, 2006). The source of fluids remains somewhat debatable with two end member theories. The first probable source for fluids is from a saline lake, the second being a magmatic source. While the presence of a deep magmatic source is in no way confirmed, there remains a potential that at least some component of the fluids is derived from an intrusive source. The presence of local extensive volcanism combined with geochemical indicators leaves this as a plausible scenario. The saline lake source is a much higher probability scenario and fits best with our current observations and geochemical analysis, where there are several key geochemical similarities between the surface waters and the sampled geothermal fluids. Pristine fluid samples from future drilling programs will hopefully provide more conclusive insight to the fluid source and history.

Conceptual Model

A conceptual model of the Crump Geyser geothermal system has been developed from the existing geological, geophysical and geochemical datasets (Figure 3). The hydrothermal system is hosted primarily within a complex fault and fracture network which has developed as a consequence of complicated regional structural dynamics, which are not discussed herein.

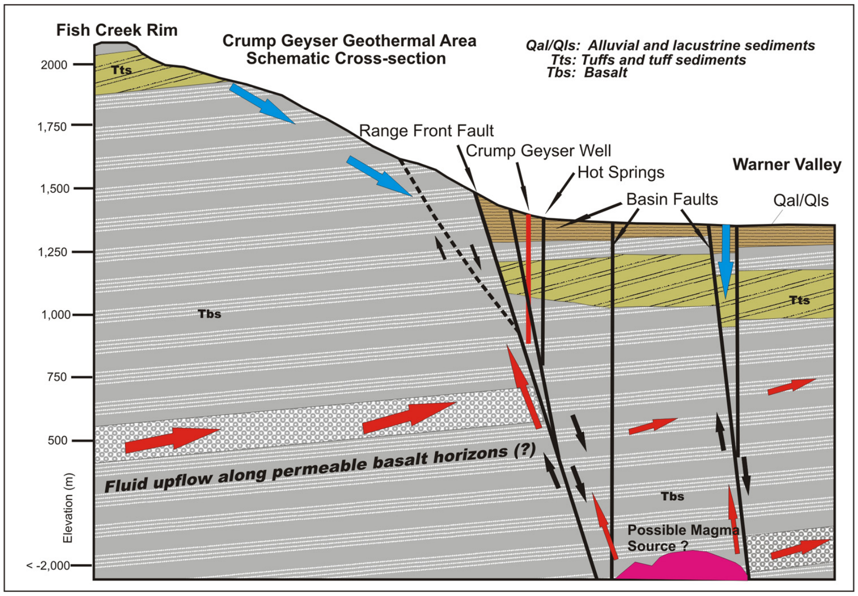

Figure 3. Schematic cross section from Fish Creek Rim through Crump Geyser. Schematic shows probable faults and possible fluid flow dynamics.

The dominant structural feature for this model is the N-NE trending, east dipping normal fault which is the western boundary to Warner Valley. This fault zone provides the primary conduit for deep circulation of fluids. Intersecting NW-trending faults and fractures provide a set of secondary fluid circulation pathways that feed from the principal fault at various depths. This 'secondary' circulation gives greatly increased volume to the system and disperses heat over a broad area.

While the body of evidence indicates that the system is largely controlled by faults and fractures, there are reasons to believe that some or even a significant portion of the overall system permeability is contained within underlying geologic formations. Resistivity data has clearly identified a mid-level conductive zone, which is likely resultant from one or more of the local volcanic formations (i.e. vesicular lavas or volcanic tuff) with an inherent porosity or permeability. These underlying formations are widespread, and may be nearly continuous across the valley.

The parent source of fluids is debatable, but the preferred model employs overlying saline lake waters migrating and infiltrating downward through basin sediments and eventually establishing circulation along faults and fractures developed in the bedrock. High pressures in the system force the fluids to emanate as springs at the ground surface where their distinct alignments reflect the distribution of the inherent underlying permeable fracture network. In this model that network is comprised of the dominant N-NE trending range front fault and intersecting NW striking faults.

An alternative model suggests the presence of a magmatic geothermal system. In this case ground water still migrates downward, subsequently mixing with magmatically derived and heated fluids, which then rise upwards along the dominant fault system. While this model is more difficult to explain geochemically, and there is a relative lack of evidence for an underlying magmatic body, it might suggest a high potential for increased recharge rates, sustained system pressures, and a more sustainable heat supply entering the system.

A second alternative model postulates that system recharge may be occurring from the west as upflow along gently west dipping, permeable volcanic formations. Some portion of the fluids would be derived from beneath the Warner Range, migrate up dip to reach the Warner Valley, and subsequently migrate up the western boundary fault. This model does not preclude a magmatic source which could theoretically reside immediately beneath the Warner Valley at the base of the fault zone, or beneath the Warner Range as the fluid source for this alternative recharge model. This model provides and attractive recharge source with implications for sustaining thermal longevity and continued pressure support during exploitation. In all cases, local natural groundwater recharge is an integral element to the geothermal model.

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