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GEOLOGIC MODEL OF THE BACA GEOTHERMAL RESERVOIR, VALLES CALDERA, NEW MEXICO

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ABSTRACT

Logging of drill cuttings from Union Oil Company's Baca geothermal project has resulted in a detailed geologic picture of the Baca geothermal reservoir. The reservoir is located in a complex geologic environment with both fracture and stratigraphic permeability, which have been modified (largely reduced) by hydrothermal alteration. The geothermal system is principally hosted by ash-flow tuffs and volcaniclastic rocks associated with the development of the Valles and Toledo calderas and preceding explosive rhyolitic eruptions. The cooling history of these rocks has produced non-welded tuffs, with considerable intergranular permeability and extensive hydrothermal alteration, through densely welded ash-flow tuffs with little intrinsic permeability. Lithologic units beneath the ash-flow tuff sequence are commonly altered and metamorphosed but contain few hot-water entries, although some, such as the Madera Limestone, are regional groundwater aquifers outside the caldera.

Previous workers have reported that the Baca field has a permeability-thickness product of about 6,000 md-ft, which is low compared with other producing geothermal areas. A model for the development of the Redondo Creek resurgent dome, within which the Baca field is located, explains these low permeabilities by emphasizing the nature of strain and resulting fracture permeability in the host lithologies. The model also helps emphasize the importance of inherited structures in the formation of the dome and suggests that these faults may be the principal conduits for geothermal fluids from depth in the system. Another implication of modeling dome development is that the magmatic heat source for the geothermal system lies beneath present drilling depths.

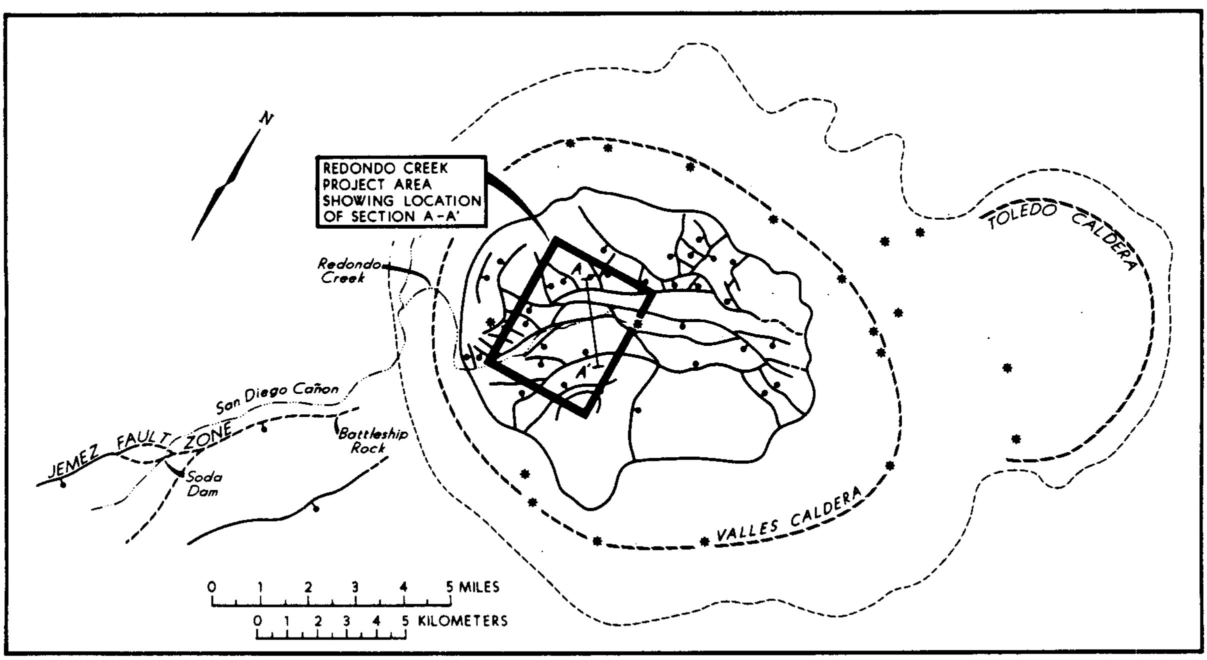

Figure 1. Index map showing location of the Valles-Toledo caldera complex.

The stratigraphic and structural hydrothermal fluid paths at Baca can be characterized as follows: 1) those sealed by alteration, 2) those which do not produce fluids but do accept fluids, and 3) those which produce geothermal fluids.

INTRODUCTION

The caldera environment represents a complex interaction of volcanic, structural, and often, hydrothermal processes. As a result calderas are often targets for geothermal exploration and development. From the standpoint of the reservoir engineer, such geothermal systems would be hosted by rocks that display a complex interplay of stratigraphic permeability, structural permeability (both faults, fractures and joints), and changing permeability which results from the process of hydrothermal alteration and new fracture generation. The purpose of this paper is to present a geologic model of the Baca geothermal reservoir which is situated within a small portion of the Valles caldera in New Mexico (Fig. 1.). The geologic history of the Valles caldera is presented in Smith and Bailey (1968). The data we present is largely based on our studies of subsurface samples from Union Oil Company's Baca project area. Additional results of our work have been published previously (Hulen and Nielson, 1982, 1983; Nielson and Hulen, in press).

STRATIGRAPHY

The Precambrian to Quaternary stratigraphic sequence penetrated by deep Union wells in the Redondo Creek area of the Valles caldera has been characterized in the reports cited immediately above and to which the reader is guided for more detailed description of individual lithologies. This paper will restrict discussion of these rocks mostly to features related to structural or stratigraphic permeability.

The Baca geothermal reservoir is hosted principally by a sequence of Pleistocene felsic ash-flow tuffs and associated volcaniclastic sediments locally exceeding 1800 m in thickness within the Valles caldera. The two members of the Bandelier Tuff, the Otowi and overlying Tshirege, form the middle portion of this sequence (Fig. 2). The Tshirege is overlain by the "Upper Tuffs" (Nielson and Hulen, in press), dominantly non-welded to poorly welded felsic ash-flow tuffs; the Otowi rests unconformably on complexly interstratified, variably welded felsic ash-flow tuffs and sediments of limited local extent grouped by Nielson and Hulen (in press) as the "Lower Tuffs".

Permeability (and former permeability) in the felsic tuff sequence at Redondo Creek is both structural and stratigraphic. Stratigraphic permeability is controlled by thin, intra-tuff sandstones, discrete, non-welded tuff horizons and perhaps air-fall pumice beds (Hulen and Nielson, 1982). Structural permeability is developed along high-angle normal faults disrupting the felsic tuff sequence as well as underlying units. We believe these faults to be the principal paths along which thermal fluids ascend. Once within the felsic tuff sequence, however, the fluids appear to be diverted in part into intra-tuff stratigraphic aquifers (Fig. 2), creating an intricate circulation system requiring much more caution in targeting from the surface than a fault-controlled system alone.

The Otowi and Tshirege Members of the Bandelier Tuff (Fig. 2), initially deposited as thick, hot (600-700°C) ash flows, have undergone profound compaction, welding, devitrification (a process by which silica minerals and feldspar nucleate from the glass initially present) and widespread granophyric crystallization. As a result, both members, generally exceeding 300 m in thickness in the Redondo Creek wells, are typically dense and impermable except where faulted or fractured or where they include thin permeable strata. The Otowi and Tshirege, in fact, may serve as local caprocks above geothermal fluids circulating in the Lower Tuffs and underlying rocks.

Several productive thermal fluid entries have been encountered in the Paliza Canyon Formation, a sequence of Pliocene intermediate-composition flows, tuffs, subvolcanic intrusives (?) and volaniclastic rocks beneath the "Lower Tuffs". The Paliza Canyon has not been sufficiently investigated to state with certainty that the entries are stratigraphically or structurally controlled. Furthermore, one of the most productive Paliza Canyon entries occurs at the bottom of well B-24, where the nature of permeability control cannot be ascertained.

Stratigraphic geothermal targets in sub-Paliza Canyon rocks included friable arkose of the Tertiary Santa Fe Sandstone/Abiquiu Tuff (Fig. 2), red-bed arkose of the Permian Abo Formation, solution voids/karstic terrain in limestone of the Pennsylvanian Madera Formation and gruss developed on deep Precambrian granitic rocks. No thermal fluid entries were penetrated beneath the Paliza Canyon Formation. Lost-circulation zones, however, were very common (Molloy and Laughlin, 1982). This implies locally adequate permeability in these rocks, but either no connection with major thermal fluid conduits or perhaps pervasive underpressuring of the reservoir at depth.

STRUCTURE

Nielson and Hulen (in press) have modeled the development of the Redondo dome following the philosophy developed by Johnson (1970) for the emplacement of the Henry Mountains

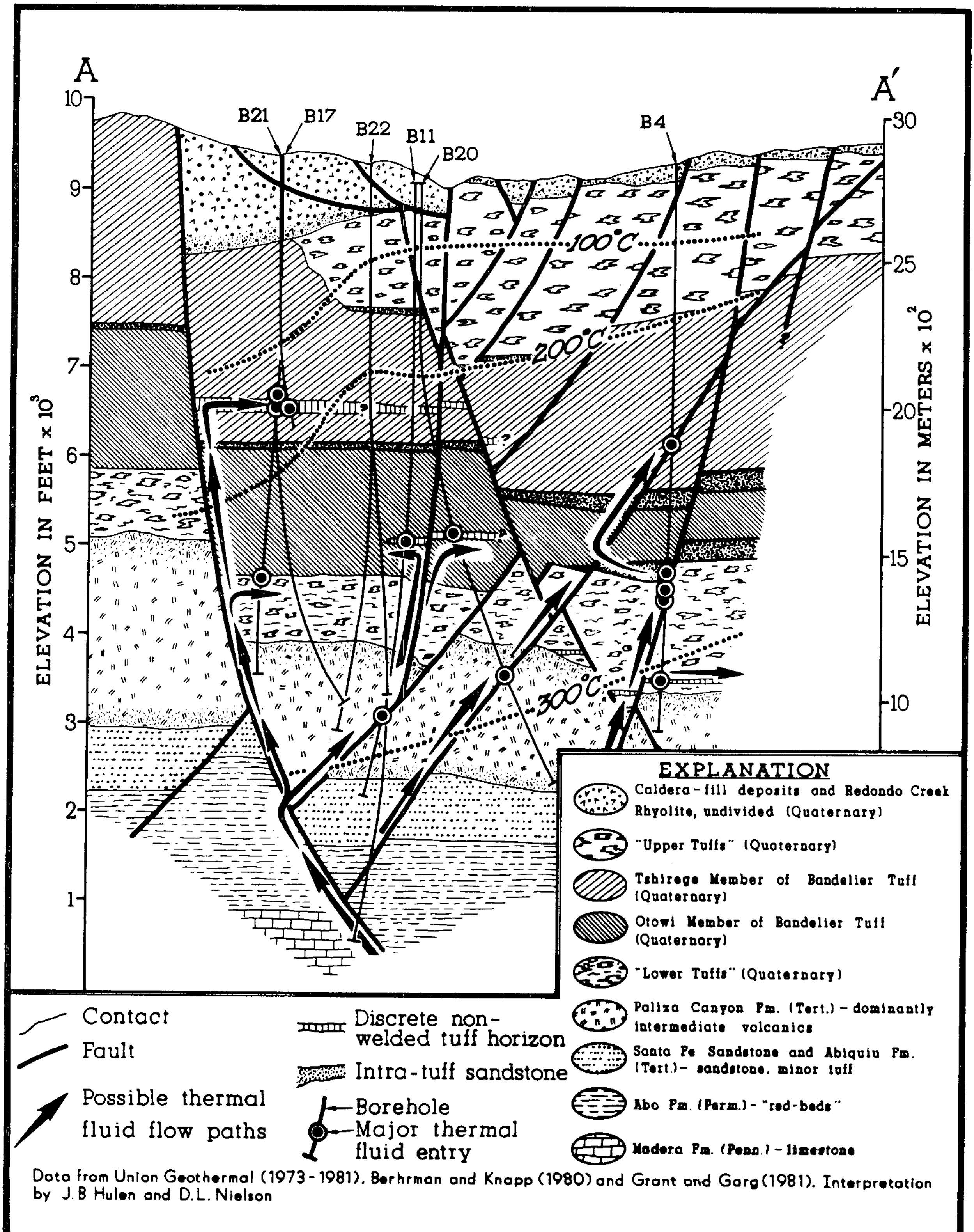

Figure 2. Geologic cross-section through the Redondo Creek project area, showing possible thermal fluid migration channels.

laccolith in Utah. We did not intend to model rigorously the formation of the Redondo Dome, but rather to use theoretical concepts of dome formation to help explain the permeabilities found in the Baca project area.

Most workers agree that resurgent domes are formed after caldera collapse by upward pressure of still molten magma. This upward pressure results in the formation of a structural dome, generally in the center of the caldera. As a result of the doming process, the affected strata are subjected to differential stresses. In the upper portions of the dome, the rocks are under tension. This results in the development of faulting along the crest of the dome that forms most of the fracturing that is often identified as an apical graben of the dome. Approximately half way down through the dome, a surface called the neutral plane separates the upper tensional environment from a lower region characterized by compression. In contrast to the normal faults above the neutral plane, the region below the neutral plane will be characterized by the development of conjugate shears.

On the basis of consideration of the dome development process, Nielson and Hulen (in press) concluded that the idealized model of dome development was modified by the reactivation of older structures associated with the Jemez fault (Fig. 1). These structures were steep, throughgoing fault zones prior to the formation of the Redondo dome, and they have continued to maintain that character during and after the formation of the dome. These faults may extend to depths where they intersect crystallized magma which is the cause of the structural doming. It is our opinion that these reactivated faults are the principal conduits of upwelling hydrothermal fluids, and that successful wells in the field intersect these fractures, or fractures or stratigraphic horizons which communicate with these principal fluid conduits.

In conjunction with injection studies at Baca, Riney and Garg (1982) have commented on the ability of some permeable zones to serve as fluid producers while other zones in the same well serve as fluid acceptors. It is clearly possible that the zones which serve as fluid acceptors were fractures formed solely as a result of dome formation while those that act as fluid producers are part of, or connect with, the reactivated structures which we feel are transporting the geothermal fluids from depth.

The conceptualization of the stress fields and related faulting and fracturing is also important in the planning and implementation of stimulation experiments. The fracturing of the region around the well bore will not necessarily result in sustained increased production unless that artificial fracturing is able to intersect the principal fracture zones which carry the geothermal fluids. In addition, in the stress field above the neutral plane, it is probable that stimulation will open fractures which are associated with extension along the top of the domed structure rather than the reactivated structures which we feel may be the more important geothermal conduits.

One conclusion from our structural work at the Baca project area has been that resurgent domes are inherently impermeable due to their mode of structural development. Observations of other resurgent dome features tend to support this conclusion. In most hydrothermally active caldera systems (such as Yellowstone), hot spring and fumarolic activity are spatially associated with the margins of resurgent domes, where these dome structures are thought to intersect the ring fracture system of the caldera. Very little hot spring or fumarolic activity is present on the dome itself. This conclusion seems also to be borne out in older calderas which have been dissected by erosion, such as the Creede caldera. In these instances, hydrothermal mineralization is marginal to the resurgent dome or even outside the caldera structure.

Another interesting result is that the structural model can be used to predict the depth to the magma body which produced the resurgent doming (Johnson, 1970). If the Redondo dome is approximated by a circular feature with a diameter of 10,900 m, the depth to the top of the intrusive is approximately 4,700 m. The deepest hole in the field is Baca-12 which is 3,242 m deep and bottoms in Precambrian granite. Neither Baca-12 nor any of the other holes in the field intersect significant amounts of intrusive rock which can be related to the resurgent doming process.

HYDROTHERMAL ALTERATION AND ITS INFLUENCE ON PERMEABILITY

Beneath a zone of high-level clay alteration, the thick felsic tuff sequence which includes the Bandelier Tuff within the project area is largely unaltered. However, restricted fracture zones, faults, and some stratigraphic horizons are pervasively altered. In particular, non-welded ash-flow tuffs and volcaniclastic sediments are commonly highly altered, indicating the passage of hydrothermal solutions. Many of these zones are not fluid producers at the present time, the most obvious reason being that the alteration has reduced permeability and choked off the hydrothermal channels. Alteration assemblages within the Bandelier tuff are dominated by illite, suggesting the fixation of potassium and the release of sodium during the alteration process.

Studies by Hulen and Nielson (1983) in the high-level clay alteration zone in the upper portion of well Baca-20 have demonstrated the presence of smectite and allevardite-ordered illite-smectite (I/S) mixed-layer clay in the formerly permeable "Upper Tuffs". Present temperatures of about 30°C in this upper zone contrast with temperatures of formation of allevardite-ordered I/S of between 100° and 175°C. Thus, this pervasive clay-rich alteration was probably developed at an earlier stage in the evolution of the hydrothermal system, when temperatures were higher than they are at the present time. It was also the suggestion of Hulen and Nielson (1983) that this upper level alteration may be the "cap rock" postulated by Hartz (1976) and Grant and Garg (1981). It also represents a zone, which is over 300 meters thick in Baca-20, that should demonstrate relatively low electrical resistivity. This overlies the reservoir zone itself which should be of higher electrical resistivity due to the narrow production zones within largely unaltered thick sequences of Bandelier Tuff. The electrical resistivity structure has important implications for the use of resistivity methods for both resource exploration and development of the field.

Productive thermal fluid entries, both stratigraphically and structurally controlled, are invariably associated with moderate to intense hydrothermal alteration. The alteration assemblages, as yet incompletely characterized, are apparently dependent in part on host rock composition. Fluid entries in the felsic Bandelier Tuff and "Lower Tuffs", for example, are associated with the assemblage illite-calcite-pyrite with calcite subordinate. Altered rock from an unusual entry of this type at a depth of 811 m in well B-17 contains, as indicated by semi-quantitative XRD, 56% pyrite, 32% illite and 9% calcite with only a few percent (presumably) original rock-forming quartz and feldspar. A clay separate prepared from this sample contains, in addition, traces of smectite and chlorite. Entries in the intermediate-composition Paliza Canyon Formation contain abundant chlorite (and chlorite-rich mixed-layer chlorite-smectite) in addition to calcite, illite, pyrite and minor epidote, plagioclase and potassium feldspar, but some or all of these phases could predate the present geothermal system. Alteration zones mineralogically and texturally similar to those described above, but not associated with active fluid entries, are relatively common in the Baca wells. It seems very likely that these zones represent former fluid flow channels now completely sealed by alteration.

Other zones which resulted in extreme lost circulation problems during drilling operations demonstrate little or no alteration suggesting lack of communication with the hydrothermal system.

In summary, the fluid conduits at Baca can be categorized in the following manner.

1. Former fluid channels sealed by alteration. These include both stratigraphic and structurally controlled fluid entries.

2. Open conduits which do not produce geothermal fluids. Again, these are both stratigraphic and structural intervals and are characterized as lost circulation zones. These constitute the stratigraphic and structural intervals which do not communicate with the reactivated fault zones which are thought to be the principal fluid conduits in the system.

3. Geothermal production zones. All commercial production zones apparently are structurally controlled while subcommercial zones are controlled by both structures and stratigraphic intervals.

Fluid entries have been documented only within the Bandelier Tuff and Paliza Canyon Formations, although this may be a function of drilling depths within the system.

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