VALLES CALDERA GEOTHERMAL SYSTEMS, NEW MEXICO, U.S.A.

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ABSTRACT


Valles Caldera is part of a Quaternary silicic volcano in northern New Mexico that possesses enormous geothermal potential. The caldera has formed at the intersection of the volcanically active Jemez lineament and the tectonically active Rio Grande rift. Volcanic rocks of the Jemez Mountains overlie Paleozoic—Mesozoic sediments, and Precambrian granitic basement. Although the regional heat flow along the Rio Grande rift is ~2.7 HFU*, convective heat flow within the caldera exceeds 10 HFU. A moderately saline hot-water geothermal system (T > 260°C, Cl = 3000 mg/l) has been tapped in fractured caldera-fill ignimbrites at depths of 1800 m. Surface geothermal phenomena include central fumaroles and acid-sulfate springs surrounded by dilute thermal meteoric hot springs. Derivative hot springs from the deep geothermal reservoir issue along the Jemez fault zone, 10 km southwest of the caldera. Present geothermal projects are: (1) proposed construction of an initial 50-MW_{el} power plant utilizing the known geothermal reservoir; (2) research and development of the prototype hot dry rock (HDR) geothermal system that circulates surface water through deep Precambrian basement (~5 MW_{th}); (3) exploration for deep hot fluids in adjacent basin-fill sediments of the Rio Grande rift; and (4) shallow exploration drilling for hot fluids along the Jemez fault zone.

INTRODUCTION

Large Quaternary magma-hydrothermal systems and continental rifts have vast potential for the production of geothermal energy in the western U.S.A. (Muffler, 1979; Goff and Waters, 1980). Valles Caldera in northern New Mexico is a large Quaternary silicic volcanic complex adjacent to the Rio Grande rift that presents a well-defined geothermal target with several opportunities for exploration and development. Among these ventures are the prototype hot dry rock (HDR) geothermal system on the west flank of the caldera and a moderate-sized conventional hydrothermal system within it. The caldera also contains a relatively simple suite of natural thermal fluids that can be used to evaluate hydrothermal resources. The object of this paper is to review the geology and tectonics of the Valles region, differentiate the thermal waters, and describe four geothermal prospects.

*1 HFU (heat flow unit) = 1 μcal. s⁻¹ cm⁻² = 41.87 mW m⁻².
GEOLOGICAL OVERVIEW

Geologic and tectonic setting

Valles Caldera formed from catastrophic ignimbrite eruptions of Bandelier Tuff ~1.1 Myr. ago (R.L. Smith and Bailey, 1966) and represents the culminating phase of volcanism within the Jemez Mountains volcanic field (R.L. Smith et al., 1970). The Jemez Mountains (Fig. 1) lie at the intersection of the Jemez volcanic lineament and the Rio Grande rift tectonic province (Mayo, 1958; Chapin, 1979; Laughlin, 1981). Several volcanic fields have erupted along the lineament. They consist of Miocene–Quaternary age basalts and lesser quantities of more silicic lavas and tuffs. No systematic age or compositional variations can be correlated with direction along the lineament (Laughlin et al., 1976). By far the largest volume of intermediate- and silicic volcanics are found in the Jemez Mountains.

The Rio Grande rift is a continental rift, stretching from northern Colorado into Mexico, that began development ~30 Myr. ago (Chapin, 1979). The rift is composed of three major segments that become progressively older to the south. Three en echelon basins compose the middle segment (east of the Jemez Mountains), and each basin is filled with thick middle–late Tertiary sedimentary sequences (Fig. 1). Ignimbrite eruptions from Valles Caldera poured over the western edge of the central basin to form the Pajarito Plateau (Figs. 2 and 3).

Basins of the rift are bounded on the west by extensive normal faults

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Fig. 1. Location map of northern New Mexico showing relationship of Jemez lineament and Rio Grande rift to the Jemez Mountains volcanic field.
of Bandelier presents the culmi­
canic field (R.L. 
the intersection of 
tectonic province 
volcanic fields have 
—Quaternary age 
f. No systematic 
direction along the 
t of intermediate 
m northern Colo­
o (Chapin, 1979). 
ome progressively 
e middle segment 
th thick middle-
e eruptions from 
 basin to form the 
ive normal faults

which cut volcanics of the Jemez Mountains. Two of the more important 
 faults are the Pajarito and Jemez fault zones (Figs. 2 and 3). Ignimbrite 
sheets of Bandelier Tuff are offset roughly 200 m and 50 m, respectively, by 
these fault zones. The Jemez fault zone, which trends northeastward toward 
the center of Valles Caldera, is locally a surface tectonic expression of the 
Jemez lineament (Goff et al., 1981).

Heat flow along the west margin of the Rio Grande rift averages 2.7 HFU 
whereas heat flow within Valles Caldera locally exceeds 10 HFU because of 
convection (Reiter et al., 1975, 1976).

**Geologic section**

The following discussion describes selected aspects of geology and struc­
ture which elucidate the setting of natural thermal waters and the various 
geothermal targets within the Jemez Mountains. The reader should refer to 
the superb geologic map of R.L. Smith et al. (1970) and the review paper by 
Laughlin (1981) for more details. The cross-section of Fig. 3 is an over-
simplification but includes recent data from many deep wells that were not 
available to earlier workers. A more conventional interpretation is presented 
by the cross-section of Eichelberger and Westrich (1980).

The Jemez Mountains volcanic rocks overlie Precambrian granite, gneiss
Fig. 2. Simplified cross-section through the Jemez Mountains showing major structures and stratigraphic units. Geologic settings of natural thermal waters and geothermal targets are discussed in text. The white area beneath the eastern portion of Valles Caldera indicates where structure and stratigraphy are not well defined by geophysics or drill holes.
and schist, and also the relatively undeformed Paleozoic–Mesozoic marine carbonates, sandstones, shales and evaporites of the Colorado Plateau. As shown in Fig. 3, these basement rocks are progressively down-faulted eastward into the Rio Grande rift. Unconsolidated to weakly indurated Tertiary sediments overlie the fault blocks and thicken to the east into the rift. Older Miocene–Pliocene volcanic sequences of the Jemez Mountains (i.e. Paliza Canyon and Tschicoma Formations) overlie and interfinger with the Tertiary sediments.

Rift structures formed during the late Tertiary have been overprinted by caldera structures formed in Quaternary time during eruption of Bandelier Tuff and subsequent caldera events. Eruption of \( \sim 500 \text{ km}^3 \) or more of ignimbrite suggests existence of a relatively shallow silicic magma body beneath Valles Caldera of almost batholithic size (R.L. Smith and Bailey, 1968). The "floor" of the caldera collapsed several thousand meters during and after these eruptions producing a series of ring fracture faults. After collapse, the central floor presumably was uplifted by resurgent (structural) doming according to mechanisms outlined by R.L. Smith and Bailey (1968). Finally, the moat area between the resurgent dome and caldera walls was partially filled by rhyolite domes, flows and small-volume tuffs which are \( \sim 1.0–0.1 \text{ Myr} \) old (Doell et al., 1968).

Fig. 3 shows a large area beneath the eastern caldera where stratigraphy and fault displacements are unknown. Several structural configurations could be drawn in this space (and have been) but no deep drill hole and little geophysical data exist to confirm them. For example, a detailed gravity survey of the caldera presented by Dondanville (1971) shows a gravity low of \( >25 \text{ mGal} \), centered over the eastern side. This could be a reflection of thicker ignimbrite fill on a more deeply down-faulted block of pre-caldera (rift) origin. On the other hand, the gravity low could suggest extensive vents for ignimbrite eruptions concentrated on the east side of the caldera. Other interpretations that consider variable densities of caldera-fill materials caused by hydrothermal alteration are also possible.

Drilling of 24 deep drill holes through the resurgent dome into Bandelier Tuff and pre-caldera rocks does not verify structural uplift of the dome, as conceived by R.L. Smith and R.A. Bailey. Drill-hole information shows general down-faulting of Precambrian basement to the east towards the rift. Tertiary rift sediments increase in thickness to the east, as well (Slodowski, 1976; R. Denton, Union Oil Co., person. commun., 1980). Examination of cuttings by Union Oil Co. has not revealed any evidence for injection of shallow silicic plugs, dikes, sills or laccoliths into the resurgent dome from the underlying batholith.

Although the resurgent dome is cut by a multitude of normal faults (not shown in Fig. 3) to form a "keystone" graben, these faults are on trend with the Jemez fault zone, southwest of the caldera. This suggests that structures within the resurgent dome are controlled by pre-existing rift faults.

Several important questions could possibly be answered by a deep bore-
Fig. 4. Plots of: (A) δD vs. δ¹⁸O and Cl vs. δ¹⁸O; and (B) Na vs. Cl and B vs. Cl for thermal, non-thermal, and hot dry rock fluids in the Valles Caldera region; symbols listed in Table I.
A hole (~5–8 km deep) on the east side of the caldera: (1) the depth to pre-volcanic rocks would tell us if the caldera floor is indeed asymmetric due to rift tectonics; (2) the resulting stratigraphic information would control parameters used in geophysical models; (3) the eastern limit of the hydrothermal system (see p. 129) could be better ascertained; and (4) stratigraphic and structural boundaries between Valles Caldera and the earlier Toledo Caldera (Fig. 2) could possibly be resolved.

**NATURAL THERMAL WATERS**

*Setting, simplified hydrology and geochemistry*

Three types of natural thermal water are found in Valles Caldera. Each possesses distinct geologic and structural controls, and displays unique chemical and isotopic characteristics. These waters are herein named: (1) acid-sulfate; (2) thermal meteoric; and (3) deep geothermal and derivative types. Several of the ideas that follow were first suggested by Trainer (1975) and by Dondanville (1978).

**Acid-sulfate waters**

Waters of this type are restricted to the interior of Valles Caldera where they discharge from faults and fractures within the resurgent dome. The largest zone of activity is at Sulphur Springs (Fig. 3) where several faults and fractures intersect (Summers, 1976; Goff and Gardner, 1980). Sulphur Springs is a hydrothermally altered area of small-volume acid springs, mud pots, gaseous cold springs and fumaroles. Flow rates and temperatures are seasonal with the lowest flow rate and highest temperature occurring during the late summer and early fall.

Chemical data for two samples from Sulphur Springs reveal them to have extremely high $\text{SO}_4$, low pH, and more K than Na (Table I). Isotopic data (Fig. 4A) show that the flowing acid spring is isotopically meteoric whereas the bubbling mud pot is shifted towards enriched values of $^{18}\text{O}$. Although $\text{H}_2\text{S}$ and sublimed sulphur occur here, $\text{CO}_2$ is by far the dominant insoluble gas (Table II). Related gaseous springs, which discharge what we have named carbonated meteoric waters, discharge around the periphery of Sulphur Springs. Although these waters bubble $\text{CO}_2$ freely, their relative acidity does not allow much $\text{HCO}_3$ to remain in solution. Chemically they are dilute (Table I) and isotopically they are meteoric (Fig. 4A).

Spring systems such as Sulphur Springs display all the characteristics of vapor-dominated geothermal systems (White et al., 1971). Water vapor, $\text{H}_2\text{S}$ and $\text{CO}_2$ are distilled from an underlying boiling-water table. When these gases reach the surface, $\text{H}_2\text{S}$ is oxidized to form sulfuric acid. This condensed acid water effectively leaches and attacks surface rocks. If enough
TABLE I

Field data, chemical analyses and isotopic data from thermal, mineral and non-thermal natural waters of the Valles Caldera region and selected analyses of fluids from the Los Alamos hot dry rock (HDR) geothermal demonstration project (chemical analyses reported in mg/l; isotope analyses reported in per mille relative to SMOW)

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Temperature (°C)</th>
<th>Field pH</th>
<th>Flow (l/min.)</th>
<th>Rock*1</th>
<th>SiO₂</th>
<th>Fe</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
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<td><strong>Surface meteoric water:</strong></td>
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<td></td>
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<tr>
<td>Agua Durme Springs*2</td>
<td>m</td>
<td>16</td>
<td>7.8</td>
<td>400</td>
<td>V</td>
<td>64</td>
<td>-</td>
<td>-</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>Fish hatchery spring*2</td>
<td>m</td>
<td>11.5</td>
<td>-</td>
<td>-</td>
<td>V</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>11</td>
<td>1</td>
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<tr>
<td><strong>Carbonated meteoric water:</strong></td>
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</tr>
<tr>
<td>Bubbling pool</td>
<td>cm</td>
<td>0</td>
<td>4.5</td>
<td>5</td>
<td>V</td>
<td>44</td>
<td>1.35</td>
<td>14.3</td>
<td>2.7</td>
<td>5.8</td>
</tr>
<tr>
<td>Bubbling seep</td>
<td>cm</td>
<td>6.7</td>
<td>5.2</td>
<td>1</td>
<td>V</td>
<td>51</td>
<td>0.28</td>
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<tr>
<td>Spence Springs</td>
<td>tm</td>
<td>45</td>
<td>6.7</td>
<td>60</td>
<td>V (P)</td>
<td>66</td>
<td>0.04</td>
<td>-</td>
<td>1.9</td>
<td>50</td>
</tr>
<tr>
<td>San Antonio Springs</td>
<td>tm</td>
<td>45</td>
<td>6.8</td>
<td>160</td>
<td>V</td>
<td>79</td>
<td>0.04</td>
<td>-</td>
<td>2.3</td>
<td>0.3</td>
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<td><strong>Acid-sulphate water:</strong></td>
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<tr>
<td>Sulphur Springs, mud pot</td>
<td>a</td>
<td>78</td>
<td>2.5</td>
<td>0</td>
<td>V</td>
<td>103</td>
<td>4.55</td>
<td>21</td>
<td>1.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Sulphur Springs, acid spring</td>
<td>a</td>
<td>62.8</td>
<td>2.4</td>
<td>2</td>
<td>V</td>
<td>229</td>
<td>26.0</td>
<td>90.8</td>
<td>16.2</td>
<td>11.6</td>
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<tr>
<td><strong>Deep geothermal fluid and derivatives:</strong></td>
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<tr>
<td>Valles Caldera (Baca 4)**</td>
<td>d</td>
<td>-</td>
<td>9.0 (lab.)</td>
<td>-</td>
<td>V</td>
<td>820</td>
<td>-</td>
<td>0.0</td>
<td>0.0</td>
<td>2.1</td>
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<td><strong>Hot dry rock (HDR) fluids:</strong></td>
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<tr>
<td>Make-up well</td>
<td>hm</td>
<td>20</td>
<td>7.9</td>
<td>38</td>
<td>V</td>
<td>68</td>
<td>0.01</td>
<td>39.3</td>
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<tr>
<td>Initial sample</td>
<td>hi</td>
<td>155</td>
<td>6.6</td>
<td>750</td>
<td>G</td>
<td>245</td>
<td>1.4</td>
<td>51</td>
<td>1.3</td>
<td>1.04</td>
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<tr>
<td>&quot;Steady state&quot;</td>
<td>ha</td>
<td>155</td>
<td>6.3</td>
<td>380</td>
<td>G</td>
<td>236</td>
<td>1.0</td>
<td>48</td>
<td>0.9</td>
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<tr>
<td>GT-2a Madera Formation*3</td>
<td>d</td>
<td>76</td>
<td>8.8</td>
<td>-</td>
<td>P</td>
<td>-</td>
<td>1.2</td>
<td>2</td>
<td>2</td>
<td>6,300*4</td>
</tr>
<tr>
<td>GT-2b Madera Formation*7</td>
<td>d</td>
<td>56</td>
<td>7.4</td>
<td>-</td>
<td>P</td>
<td>115</td>
<td>4.2</td>
<td>78</td>
<td>42</td>
<td>550</td>
</tr>
</tbody>
</table>

**TABLE I (continued)**

<table>
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<tr>
<th>Name</th>
<th>K</th>
<th>Li</th>
<th>HCO₃</th>
<th>SO₄</th>
<th>Cl</th>
<th>F</th>
<th>B</th>
<th>δD</th>
<th>δ¹⁸O</th>
</tr>
</thead>
</table>

*Rock type: V=Volcanic, P=Porphyry, M=Marble, W=Wallrock
**δD and δ¹⁸O values are given relative to SMOW.**
TABLE I (continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>K</th>
<th>Li</th>
<th>HCO₃⁻</th>
<th>SO₄²⁻</th>
<th>Cl</th>
<th>F</th>
<th>B</th>
<th>δD</th>
<th>δ¹⁸O</th>
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<tr>
<td>Agua Durme Springs*²</td>
<td>&lt;76</td>
<td>8.8</td>
<td>-</td>
<td>F</td>
<td>1.2</td>
<td>2</td>
<td>2</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>Fish hatchery spring*³</td>
<td>96</td>
<td>7.4</td>
<td>-</td>
<td>F</td>
<td>115</td>
<td>-</td>
<td>78</td>
<td>42</td>
<td>550</td>
</tr>
<tr>
<td><strong>Carbonated meteoric water:</strong></td>
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<td>9</td>
<td>109</td>
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<td>Bubbling seep</td>
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<td>0.08</td>
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<td>254</td>
<td>7.2</td>
<td>0.23</td>
<td>&lt;0.1</td>
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<tr>
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<td>1.3</td>
<td>0.66</td>
<td>144</td>
<td>16</td>
<td>8</td>
<td>0.55</td>
<td>0.15</td>
<td>-86.4</td>
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<tr>
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<td>1.7</td>
<td>&lt;0.02</td>
<td>56</td>
<td>7</td>
<td>2</td>
<td>0.08</td>
<td>&lt;0.05</td>
<td>-92.0</td>
<td>-12.65</td>
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<td><strong>Acid-sulfate water:</strong></td>
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</tr>
<tr>
<td>Sulphur Springs, mud pot</td>
<td>8.2</td>
<td>0.02</td>
<td>0</td>
<td>786</td>
<td>2.48</td>
<td>6.35</td>
<td>&lt;0.1</td>
<td>-50.2</td>
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<td>2,110</td>
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<tr>
<td>Valles Caldera (Baca 4)*⁴</td>
<td>777</td>
<td>-</td>
<td>323</td>
<td>66</td>
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<td>15</td>
<td>38</td>
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<td>-</td>
<td>127</td>
<td>84</td>
<td>3.067</td>
<td>-</td>
<td>-23</td>
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<td>38</td>
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<td>13.82</td>
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<td>Main Jemez Springs</td>
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<td>10.1</td>
<td>711</td>
<td>41</td>
<td>904</td>
<td>5.19</td>
<td>7.86</td>
<td>-83.2</td>
<td>-10.6</td>
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<td>Travertine mound spring*⁶</td>
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<td>8.2</td>
<td>723</td>
<td>36</td>
<td>829</td>
<td>5.21</td>
<td>7.83</td>
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<td>-10.52</td>
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<td><strong>Hot dry rock (HDR) fluids:</strong></td>
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<td></td>
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<tr>
<td>Make-up well</td>
<td>4.1</td>
<td>&lt;0.02</td>
<td>118</td>
<td>12.3</td>
<td>19.0</td>
<td>0.07</td>
<td>0.02</td>
<td>-90.0</td>
<td>-12.75</td>
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<tr>
<td>Initial sample</td>
<td>85</td>
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<td>373</td>
<td>520</td>
<td>1,502</td>
<td>8.57</td>
<td>41.6</td>
<td>-77.8</td>
<td>-8.55</td>
</tr>
<tr>
<td>&quot;Steady state&quot;</td>
<td>59</td>
<td>11</td>
<td>415</td>
<td>820</td>
<td>623</td>
<td>10.0</td>
<td>16.2</td>
<td>-81.0</td>
<td>-9.60</td>
</tr>
<tr>
<td>GT-2a Madera Formation*³</td>
<td>350</td>
<td>25</td>
<td>6,620*²</td>
<td>4,110</td>
<td>3,300</td>
<td>0</td>
<td>25.0</td>
<td>-78.9</td>
<td>-8.12</td>
</tr>
<tr>
<td>GT-2b Madera Formation*⁷</td>
<td>-</td>
<td>-</td>
<td>1,250</td>
<td>200</td>
<td>400</td>
<td>3.1</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

tr. = trace.
* Rock type: V = Plio-Pleistocene volcanics; Al = Alluvium; P = Paleozoic rocks; G = Precambrian granodiorite; ( ) = rock type at depth.
*² Sample probably contaminated with Na₂CO₃ from drilling mud.
*³ Trainer (1978).
*⁴ Dondanville (oral commun., 1978) (average of 5 analyses).
*⁵ Purtyman et al. (1974).
TABLE II
Gas compositions associated with fluid analyses from Table I (gas compositions expressed as percent of total gas)

<table>
<thead>
<tr>
<th>Gas</th>
<th>Sulphur Springs area</th>
<th>Jemez fault zone*1</th>
<th>Hot dry rock</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>carbonated acid sulfate</td>
<td>Soda Dam</td>
<td>M. Jemez Springs</td>
</tr>
<tr>
<td>CO₂</td>
<td>94.5</td>
<td>90.2</td>
<td>89.7</td>
</tr>
<tr>
<td>N₂</td>
<td>71.9</td>
<td>1.7</td>
<td>1.5</td>
</tr>
<tr>
<td>O₂</td>
<td>4.2*2</td>
<td>4.6*2</td>
<td>0.8*3</td>
</tr>
<tr>
<td>H₂S</td>
<td>0.53</td>
<td>tr.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

tr. = trace; n.d. = not determined.
*1 Samples GT235 frs 72 and GT237 frs 72, U.S. Geological Survey files.
*2 Probably atmospheric contamination.
*3 Including argon.

Surface groundwater is mixed with the acid condensate, flowing springs result. Because the condensed water from the bubbling mud pot has a pronounced 18O shift, considerable rock-water isotopic exchange has occurred at depth, suggesting that the boiling-water table may be hotter than the boiling point at the surface (93°C at 2800 m). Two exploratory wells, Baca Nos. 1 and 3, failed to intersect the boiling-water table at depths of ~650 m beneath Sulphur Springs but achieved temperatures in excess of 100°C.

**Thermal meteoric waters**

This type of water is found in the moat region of the caldera, where it discharges from fractures and from the contacts of rhyolite and underlying volcanic and Paleozoic units (Fig. 3). Some water wells have encountered this type of water at shallow depths in Quaternary alluvium and lacustrine units, filling the southwest section of the moat.

Thermal meteoric water is nothing more than heated near-surface groundwater. It is chemically dilute and of near-neutral pH (Table I). Trace elements such as Li and B are barely enriched above background levels. Isotopically, the water is meteoric (Fig. 4). However, low concentrations of 3H (Dondanville, 1971) indicate that this water has a relatively longer residence time underground than most near-surface waters of the region.

**Deep geothermal and derivative waters**

Water of this type was first discovered by deep exploration drilling into the resurgent dome east of Sulphur Springs (i.e. Baca 4, see Fig. 3). Deep geothermal fluids are localized along faults and fractures of the keystone graben in silicic and underlying volcanic rocks. Exploited in the eastern limit of the graben at a depth is ~1500 m. Chemical, isotopic, and geophysical studies demonstrate that these fluids are derived from upper crustal sources. Geologically, they are chemically dilute, heat dilute, and of near-neutral pH (Table I) and are distinct from other geothermal fluids in the region.

Chemically, the fluids are near neutral. Geochemically, they are chemically similar to the meteoric water in Table I. Isotopically, the fluids have a high 18O content, consistent with a meteoric origin. The fluids are also enriched in 3H, consistent with a geothermal origin.

**Baca project**

To date, the Baca project has demonstrated the feasibility of producing geothermal energy from the central and resurgent parts of the caldera. Deep geothermal wells have been drilled into the resurgent dome and into the central caldera. A 50-MW geothermal power plant has been constructed on the site. The plant is expected to be operational by 1983.
graben in silicified ignimbrite (Dondanville, 1978). Producing zones in underlying volcanics, Tertiary sediments and Paleozoic formations may be exploited in the future (R. Denton, pers. commun., 1980). Average producing depth is \(~1500\) m at temperatures of \(260^\circ-300^\circ\)C. Fig. 3 shows that the eastern limit of the deep geothermal system is not clearly known. However, shallow-hole geothermal gradient data acquired by Union Oil Co. indicate that the thermal anomaly does not extend to the eastern caldera wall.

Chemically, the deep fluid is distinct, having \(~7000\) mg/l total dissolved solids (TDS) and significant concentrations of Na, Cl and B (Table I). Isotopically, this water is enriched in $^{18}\text{O}$ resulting from high-temperature rock-water isotopic exchange (Fig. 4A). However, distinct enrichment in $^2\text{H}$ suggests these waters may contain some connate fluids derived possibly from underlying Paleozoic rocks (White et al., 1973).

Derivative geothermal fluids containing surface meteoric water discharge along the Jemez fault zone at Soda Dam and Jemez Springs (Figs. 2 and 3). Isotopically, the derivative waters fall between meteoric waters and the deep geothermal fluid, Baca 4 on the Craig meteoric line (Fig. 4A). Chloride variation diagrams (Fig. 4B) show that the derivative waters have identical ratios of Na, and B to Cl as the deep fluid. Apparently the deep fluid leaks laterally out of the caldera along the Jemez fault zone and mixes with surface water before it discharges (Trainer, 1975; Goff et al., 1981). The deep fluids dissolve considerable Paleozoic limestone during flow to Jemez Springs (Fig. 3; Table I) and form copious travertine deposits where they issue.

To date, nothing is known about the age and chemical evolution of the hydrothermal system, or the variation in temperature and rate of leakage of deep fluids out of the caldera.

**GEOTHERMAL TARGETS**

*Baca project*

To date Union Oil Co. of New Mexico has drilled 24 deep wells into the central and west portions of the resurgent dome at Valles Caldera to tap the deep geothermal reservoir. Although Union Oil initially thought that a separate vapor-dominated zone existed at depth in the geothermal field, Grant (1979) has indicated that only a liquid-dominated reservoir exists (Fig. 3).

A 50-MW$_{el}$ power plant is now planned, and Union Oil Co. originally felt that another 350 MW$_{el}$ could be extracted. Bodvarsson et al. (1980) have modeled the longevity of the Baca reservoir, using recharge, volume and discharge calculations, and think that the real capacity may be less. However, producing zones in rocks underlying fractured ignimbrite have not been exploited and the zone underneath Sulphur Springs on the west flank of the resurgent dome is not well explored.
Jemez fault zone

The community of Jemez Springs (Fig. 3) drilled a 255 m deep exploration well in 1979 to try and tap a hot reservoir to use for space heating. This venture encountered the hottest fluid (72°C) at 30 m in Paleozoic limestone and finally bottomed in Precambrian granite (Goff and Kron, 1980). Available data indicate that the thermal fluids originate from the deep geothermal system in Valles Caldera (Goff et al., 1981). Maximum volume is expected to be $\geq 600$ l/min. along the Jemez fault zone (Summers, 1976), and hotter reservoirs may be found in the direction of the caldera. Recent resistivity surveys in the area (Pearson and Goff, 1981) verify that these small reservoirs exist at depths of 50 m or less, thus modest ventures to develop space heat appear to have good potential.

Prototype hot dry rock (HDR) system

Robinson et al. (1971) and Smith et al. (1976) proposed that heat could be extracted from HDR by drilling into low-permeability rock to a depth where the temperature is high enough to be useful, creating a reservoir by hydraulic fracturing, and then drilling a second hole to intersect the hydraulically fractured region (Fig. 5). Thermal energy would be extracted from this system by injecting cold water down the first hole, forcing the water through the hot fractured system, and then returning the hot water to the surface where the thermal energy would be converted to electrical energy or used for other purposes. System pressures would be maintained so only one phase, (liquid) water, would be present in the reservoir and the drilled holes.

This concept is being investigated at Fenton Hill, New Mexico, (Fig. 2) by the Los Alamos National Laboratory. The location of these experiments on the west lip of Valles Caldera is a favorable one because the thermal gradient in Precambrian granodiorite and granitic gneiss is high (55°C/km) but intense Quaternary faulting and fracturing due to caldera collapse is non-existent. A vast area exists on the west flank of the caldera where this method could be utilized. The first deep borehole, Geothermal Test-2 (GT-2), bottomed in granitic rock at a depth of 2,929 km where the temperature was 197°C. A second borehole, Energy Extraction-1 (EE-1) was drilled towards a hydraulic fracture made by pressurizing the GT-2 well bore in order to complete a circulating heat-extraction system (Fig. 5).

Reservoir performance was evaluated by two flow tests in which hot water from the production well, GT-2, was directed to the water-to-air heat exchanger. Then the water was cooled to $\sim 25^\circ$C before reinjection. The cooled water, in addition to the make-up water that was required to replace down-hole losses to the rock surrounding the fractured region, was then pumped down the injection well, EE-1, and through the fracture system. Heat was transferred to the water by means of conduction within the nearly impermeable rock of the fracture, and the heated water was withdrawn by means
Fig. 5. Schematic of Hot Dry Rock Geothermal Energy Reservoir concept showing injection and production wells connected by a vertical hydraulic fracture. Also shown is a proposed binary cycle electric generation scheme for producing electricity from low-grade heat.

of the production well. The circulating volume of the reservoir is \( \sim 2.8 \cdot 10^5 \) l and circulation rate is \( \sim 380 \) l/min. (Tester and Albright, 1979; Murphy, 1980). A 60-KW\textsubscript{el} binary electric generator is presently connected to this pilot HDR system.

Samples of the produced, injected and make-up fluids were collected and analyzed during both tests. Examples of these analyses are presented in Table I. Graphs of SiO\textsubscript{2} vs. time and Cl vs. time are shown in Fig. 6A and B for the two tests. Modeling of the chemical behavior of the system indicates that most of the chemical effects are due to addition of small amounts of pre-existing (NaCl) pore water to the fluid as it circulates through the fracture system. The circulating fluid chemistry is essentially benign — the pH is in the range of 6.5–7.5 and TDS are less than 2500 ppm — and no scaling or corrosion has been observed in the surface piping system.

Comparisons of the natural thermal fluids from the Valles Caldera region and the recirculating fluid at Fenton Hill are shown in Fig. 4A and B. At first glance, the Fenton Hill fluids appear to be related to the deep geothermal fluid; however, the B concentrations in the Fenton Hill fluids cannot be derived by mixing the deep geothermal fluid from the Valles with surface
Fig. 6. Comparison of: (A) measured monomeric SiO₂; and (B) measured Cl concentrations as a function of time for the first reservoir (75-day experiment) and for the larger second reservoir (24-day experiment).

meteoric water (Fig. 4B). On the other hand, it is clear from Na/Cl and B/Cl ratios that the overlying, natural fluid GT-2a and GT-2b circulating through Paleozoic limestone (Madera Formation) at Fenton Hill is derived from the deep geothermal fluid. Work in progress at Los Alamos will provide further insight into the origin of the chemical variations observed in the Fenton Hill fluids.

For the two experimental tests briefly described here, an average of 3–5 MWₑₜₜ were extracted. Fluid losses were low and there was only minor induced seismic activity (Richter magnitude < −1). For further details of the system geometry, operation and results during these tests, consult Tester and Albright (1979) and Murphy (1980). A more detailed presentation of the fluid chemistry underway at Fenton Hill >4 km and/or shallower is planned for a future Los Alamos report.

Pajarito Plateau

The RIRC performed a series of geothermal reservoir investigations at wells 2 and 3, and 4. The overlying natural fluids feeding the water bodies on the Pajarito Plateau (Fig. 1) are a mixture of basaltic and/or saline meteoric water and/or saline meteoric water.

No thermal fluids from the Pajarito caldera are presently known to provide some insight into the origin of the wetting fluids for the hydrothermal Fenton Hill reservoir. A more detailed presentation of the fluid chemistry is planned for a future Los Alamos report.
fluid chemistry will be found in Grigsby et al. (in prep.). Drilling is currently underway at Fenton Hill to construct a 20-MWe HDR system at depths of >4 km and temperatures >300°C which will be used to demonstrate the commercial viability of HDR geothermal systems.

**Pajarito Plateau**

The Rio Grande rift contains deep sediment-filled basins that may have geothermal fluids at depth. In order to investigate this possibility, Los Alamos National Laboratory conducted geophysical and geochemical investigations to evaluate geothermal prospects beneath the Pajarito Plateau (Figs. 2 and 3). Los Alamos National Laboratory is interested in using geothermal fluids for space heating of laboratory facilities.

Data acquired from gravity surveys (Budding, 1978; Cordell, 1978) and seismic lines (Los Alamos National Laboratory, unpub. data, 1979) were used to model the sub-surface structure and stratigraphy beneath the Pajarito Plateau (Fig. 3). A time-domain electric survey (Williston, McNeal & Associates, 1979) found a 3–7 Ω-m resistivity low east of the Pajarito fault at a depth >2000 m. The obvious conclusion was that this low is caused by warm and/or saline fluids within probable Paleozoic limestones at depth.

No thermal springs of any kind are found east of Valles Caldera on the Pajarito Plateau. If a deep thermal aquifer does exist at depth beneath the Pajarito Plateau, it is probably independent of geothermal fluids within the caldera by virtue of groundwater barriers such as ring fracture faults and the Pajarito fault (Fig. 3). Hydrologic investigations by Purdyman and Johansen (1974) show that an extensive potable aquifer underlies the Pajarito Plateau at depths of 600 m and that it slopes gently eastward. This aquifer has a temperature of 30–35°C and contains barely any geochemical indicators of a deep geothermal component (Goff and Sayer, 1980).

Although the conductive heat flow along the west margin of the rift is 2.7 HFU, convective effects due to flushing of cool water through overlying potable aquifers is expected to lower the normal temperature gradient beneath the Pajarito Plateau. A conservative estimate suggests that moderately saline waters exist at a temperature ≥90°C at a depth of 3–3.5 km in limestone. The possibility of drilling through the high-conductivity zone into Precambrian basement to try HDR methods also has been entertained.

Los Alamos National Laboratory's first attempt to reach this geothermal target by means of an alternate energy well (Fig. 3) was a failure. Drilling was severely hampered by lost circulation zones in fractured and jointed Bandelier Tuff and by caving in unconsolidated Tertiary sediments of the rift. High costs for drilling mud and cement made necessary by these problems caused drilling to stop at a total depth of only 600 m. A second attempt has not been planned.
TABLE III
Summary of data for geothermal targets in the Valles Caldera region, New Mexico

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (km)</th>
<th>Temperature (°C)</th>
<th>Reservoir rock</th>
<th>Use</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baca project</td>
<td>Valles Caldera 1-3</td>
<td>260-300</td>
<td>ignimbrite*1</td>
<td>electricity generation</td>
<td>50 MW_e planned</td>
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<tr>
<td>Jemez fault zone</td>
<td>Jemez Springs 0.25</td>
<td>72</td>
<td>limestone</td>
<td>space</td>
<td>no plans</td>
</tr>
<tr>
<td>Hot dry rock system</td>
<td>Fenton Hill 3-5</td>
<td>200-300</td>
<td>granodiorite</td>
<td>electricity generation</td>
<td>10-20 MW_e planned for 2nd loop</td>
</tr>
<tr>
<td>Pajarito Plateau</td>
<td>Los Alamos 3-4</td>
<td>&gt;90</td>
<td>limestone*1</td>
<td>space</td>
<td>no plans</td>
</tr>
</tbody>
</table>

*1 Reservoirs in underlying formations not evaluated.
*2 Possible hot dry rock reservoir in underlying Precambrian rock.

CONCLUSIONS

Valles Caldera and surrounding areas possess enormous geothermal potential due to: (1) a large Quaternary magma-hydrothermal system; and (2) an active continental rift. Natural thermal waters in the Jemez Mountains display distinct chemical and isotopic characteristics, and geologic settings that can be used as exploration tools for geothermal reservoirs. Four geothermal targets exist in the Valles region (Table III). The Baca project is a conventional magma-hydrothermal prospect that may eventually produce 400 MW_e, whereas the Jemez fault zone is a low-temperature hydrothermal prospect of limited volume. Prospects beneath the Pajarito Plateau are still hypothetical. In contrast, the prototype HDR system has the greatest geothermal potential (if the method becomes economical), because the Valles Caldera region contains vastly more heat in near-surface impermeable crystalline rock than in all the hot fluids combined.

ACKNOWLEDGMENTS

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