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RESULTS OF DEEP DRILLING IN THE VALLES CALDERA, NEW MEXICO

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Over 42,000 meters of deep drilling have been completed by Union Oil Co. during geothermal exploration of a portion of the Valles caldera in New Mexico. Data from the drilling now forms the basis of a scientific study of eruptive history, structural development of the resurgent dome of the caldera, hydrothermal alteration, ore deposit formation, and the dynamics of an active hydrothermal convection system.

Caldera formation was initiated upon a deeply incised erosional surface composed largely of Pliocene volcanic rocks of intermediate composition. The initial products of the felsic activity are a series of ash-flow tuffs and associated rocks which are poorly exposed outside the caldera. At 1.4 my the formation of the Toledo caldera resulted in the deposition of the Otowi Member of the Bandelier Tuff. After a period of erosion, the Tshirege Member of the Bandelier Tuff was emplaced during the formation of the Valles caldera (1.1. my ago). Both of these members are predominantly densely welded with distinctive interior zones of granophyric crystallization. Closely following the emplacement of the Tshirege Member, resurgent doming was initiated. At this time pre-existing fault structures were reactivated as evidenced by erosion and fluvial deposition oriented along the Jemez fault, a pre-caldera structural trend. During the resurgent doming phase, localized ash-flow tuff eruptions produced at least three additional cooling units.

We have used our subsurface observations to apply a numerical model of dome formation to the development of the resurgent Redondo Dome. This model helps explain the structural relationships observed in the dome. The model also supports present concepts of resurgent dome formation by predicting that the magma responsible for the resurgent doming should occur beneath present drilling depths.

Hydrothermal alteration is both stratigraphically and structurally controlled. It is most intense not only in and adjacent to well developed faults and fractures, but also within permeable (or initially permeable) volcaniclastic and non-welded tuff units. Beneath a high-level clay-rich zone, alteration assemblages are dominated by micaeous illite with commonly abundant pyrite. Within the clay-rich zone, calcium-rich smectite and allevardite-ordered, mixed-layer illite-smectite are the principal phases. The illite-smectite, normally stable at temperatures greater than 100°C, is found in the clay-rich zone at current temperatures as low as 30°C. This implies that the hydrothermal system in this areas was at one time hotter than it is at present.

Most of the lithologic samples from the Valles wells are drill cuttings. Although cuttings can yield valuable information if carefully investigated, they have obvious disadvantages in scientific studies, and the geologic community is well aware of the need for core from holes which are drilled for scientific purposes. In addition, we would also point out the advantages of placement of a deep scientific hole in areas which already contain a large subsurface data base.

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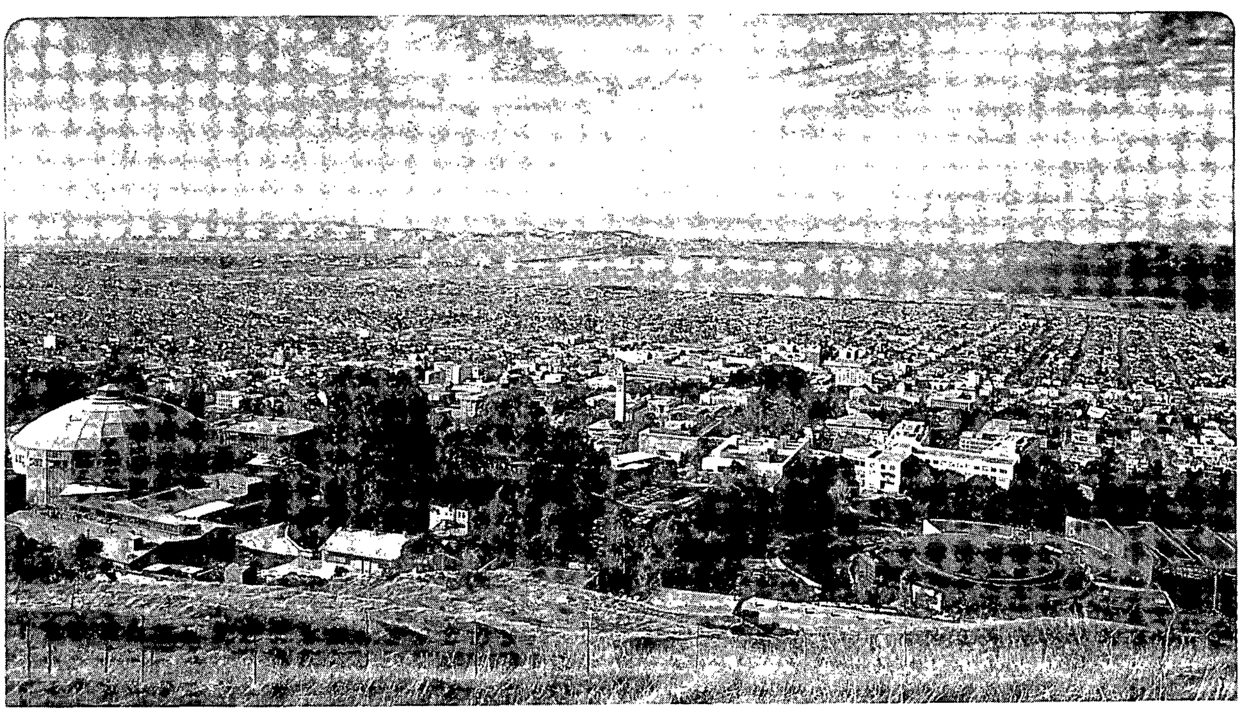
UNIVERSITY OF CALIFORNIA

EARTH SCIENCES DIVISION

FINAL REPORT OF THE DEPARTMENT OF ENERGY RESERVOIR DEFINITION REVIEW TEAM FOR THE BACA GEOTHERMAL DEMONSTRATION PROJECT

Norman E. Goldstein, William R. Holman,
and Martin W. Molloy

June 1982



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BACA GEOTHERMAL DEMONSTRATION PROJECT

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INTRODUCTION AND PURPOSE

M. W. Molloy, A. William Laughlin, and N. E. Goldstein

The geothermal potential of the Valles Caldera, New Mexico, was recognized in the early 1960's after the drilling of four exploratory wells (Bond 1 and Baca 1 to 3) in the Sulphur Creek area, and confirmed in 1970 with the drilling of the discovery well (Baca 4) in the Redondo Creek area of the caldera. Union Oil Company leased approximately 100,000 acres of the Baca Ranch in April 1971 and began an active drilling program. By the end of 1976, Union Oil Company (Union) had drilled ten more wells in Redondo Creek (Baca 5A, 6, and 9 through 16), and two more wells in nearby Sulphur Creek (Baca 7 and 8).

In 1977, the Department of Energy (DOE) issued a Program Opportunity Notice soliciting cooperative participation from industry for the development of a geothermal demonstration power plant. As a result of this initiative, Union, Public Service Company of New Mexico, and DOE signed a cooperative agreement in 1978 for the development of a 50-MW demonstration power plant at the Baca site in Redondo Creek.

Prior to the agreement, five of the 11 Union wells flowed at commercially acceptable rates and pressures. One wellbore had collapsed, but the remaining four wells provided 320,000 lb/hr of steam at line pressure, or about one-third the power plant requirements. Union estimated that approximately 10 more successful wells were needed to supply the additional 600,000 lb/hr for the proposed plant.

Subsequent drilling yielded only two successful wells of the 13 drilled (including redrills). As a consequence, steam production was increased to only 353,000 lb/hr.

On May 1, 1981, Union formally notified DOE of their inability to find sufficient steam production to support the power plant. Union suggested that a modified program of deep drilling be undertaken to test the permeability of possible sub-Bandelier reservoir rocks. Union further suggested that hydraulic fracture of two marginal wells in the Bandelier Tuff be attempted in order to increase their permeability.

DOE accepted Union's suggestions, and the DOE Baca Project Manager, Mr. Art Wilbur, formed the DOE Baca Reservoir Definition Review Team. The Team's responsibilities were to: "provide independent review of Union's reservoir program results, conclusion and plans; and provide DOE with the best possible basis for assessing whether the project can succeed technically." Review Team members were selected to cover the critical technical disciplines that are unique to the Baca project (Appendix 1). The DOE Team received technical briefings from Union's geologists and reservoir engineers. Members studied Union's data and reports in their areas of specialty and shared their evaluations with Union's technical staff.

Disappointing results were obtained from the deep drilling and hydrofrac program for a variety of reasons, and in January 1982 the three parties to the agreement decided to terminate the project. The DOE Program Manager asked the Review Team to prepare this final report. Individual sections were prepared by the specialists involved in those aspects of the work; all team members reviewed the overall document and contributed to the Summary and Conclusions.

This report is intended to serve as a constructive summary of the lessons learned during geothermal resource development at Baca. The three main objectives are to provide a concise analysis of the technical work performed in connection with reservoir development, to elucidate the problems encountered during developmental drilling, and to suggest methods or procedures that geothermal developers might follow to avoid the reservoir definition problems encountered.

REGIONAL GEOLOGY

Dennis L. Nielson

The Baca Geothermal Demonstration Power Project is located within the central portion of the Valles Caldera in north-central New Mexico (Fig. 1). On a regional basis, the caldera is located at the western margin of the Rio Grande Rift, where the rift is intersected by the northeast-southwest-trending Jemez Lineament, a zone of late Tertiary to Quaternary volcanic activity (Fig. 2).

The following description is from Doell et al. (1968) and Smith and Bailey (1968); the reader is directed to those publications for a more complete discussion. Caldera formation began about 1.4 million years ago with the eruption of the Otowi Member of the Bandelier Tuff. About 300 km^3 of material was erupted at this time to form the Toledo Caldera. About 1.1 million years ago, an eruption comparable to that of the Toledo Caldera formed the Valles Caldera with the emplacement of the Tshirege Member of the Bandelier Tuff. Subsequent rhyolitic activity has resulted in extrusion of domes in the moat area of the Valles Caldera. Rhyolite and ash flow tuff eruptions continued until 100,000 years ago.

Following the formation of the Valles Caldera, the resurgent Redondo Dome was formed by continued upward pressure from the still-molten magma chamber. As a result of this doming, a complex series of faults developed across the crest of the dome. The Baca Geothermal Demonstration Power Project is located within the center of this dome. The geothermal system is believed to be controlled by normal faulting that developed during the formation of the resurgent dome.

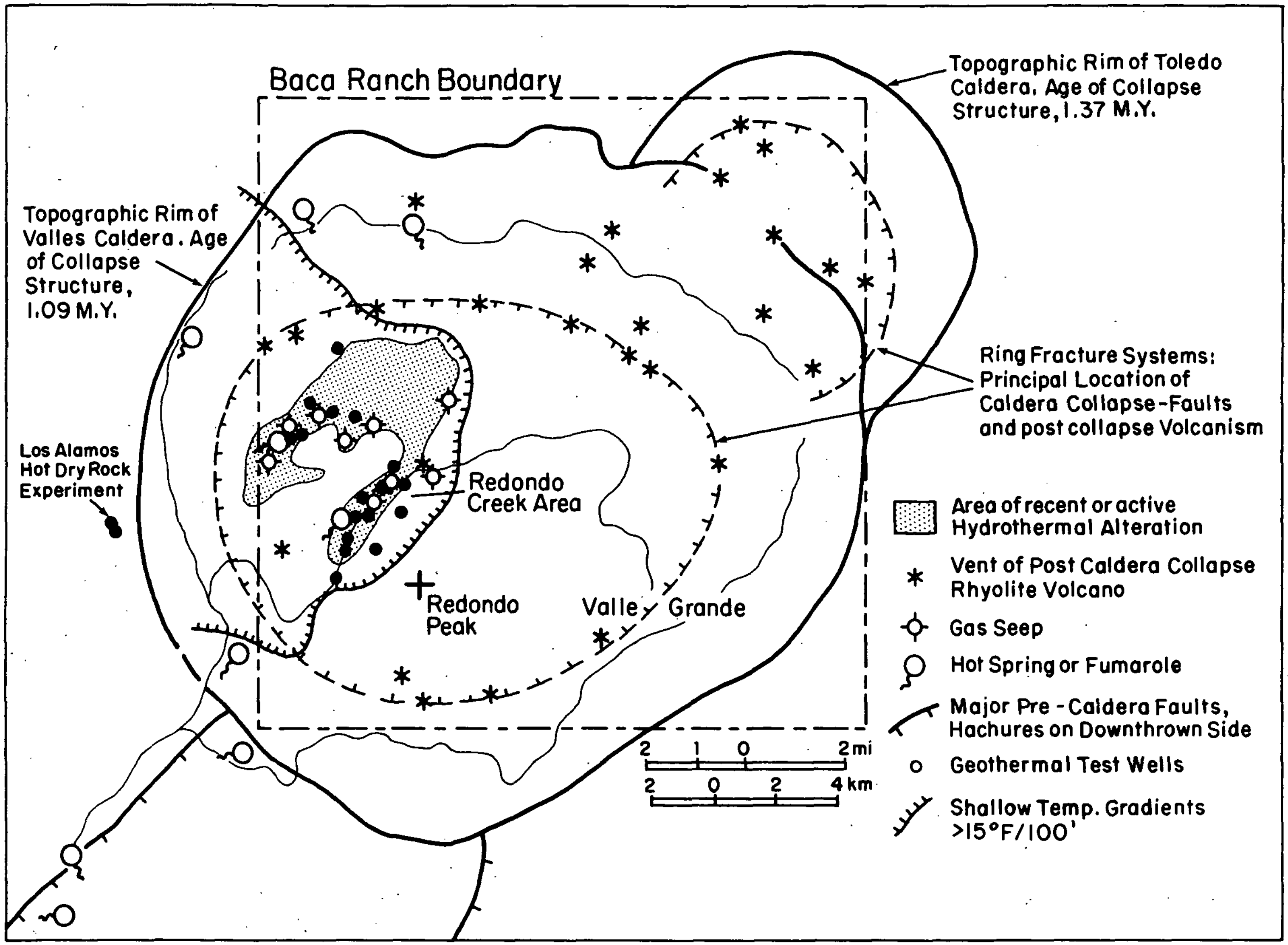

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Figure 1. Map showing the Baca location in the Valles Caldera, New Mexico.

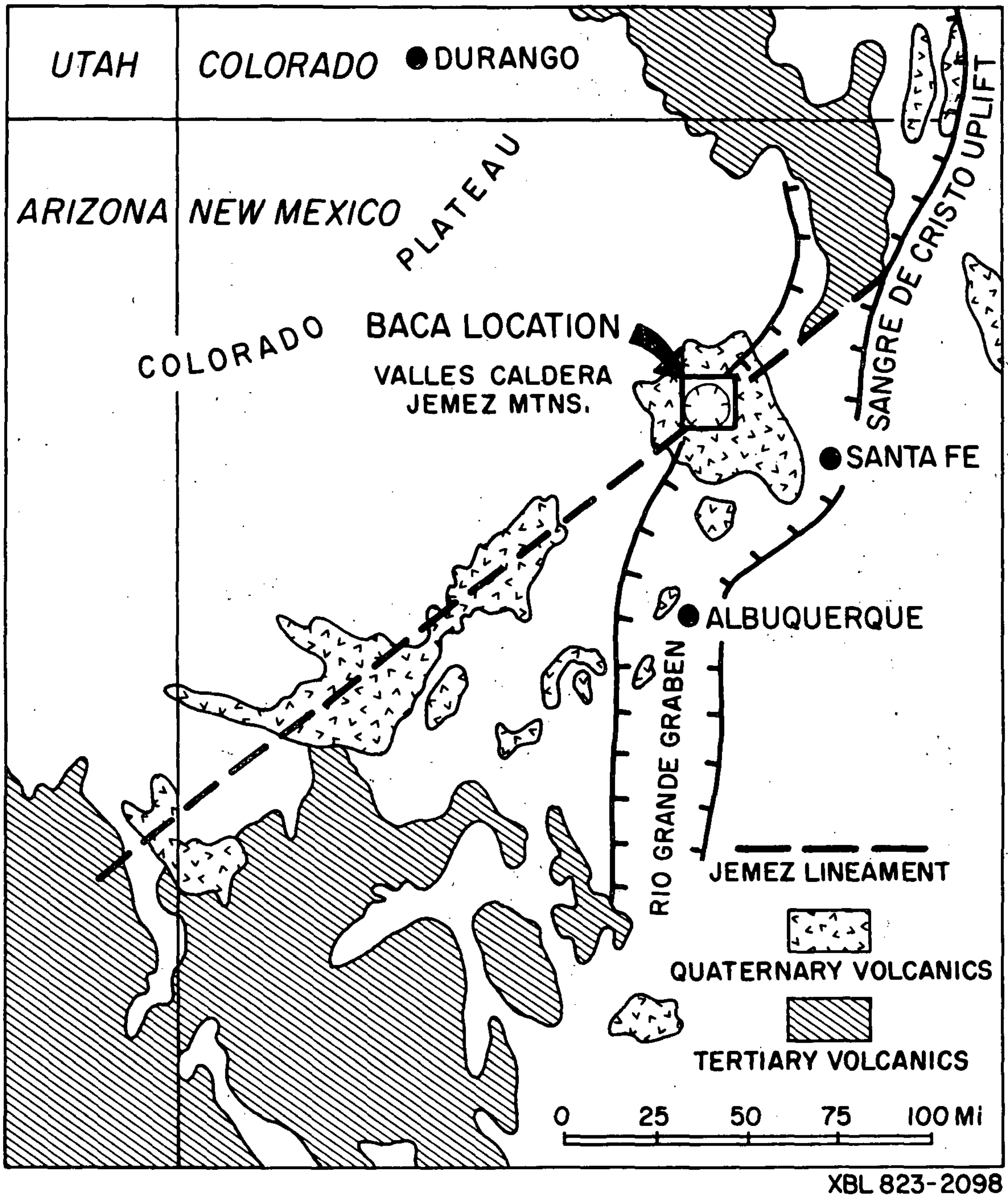

Figure 2. Generalized regional geologic map of the Valles Caldera area, New Mexico.

STRUCTURE, STRATIGRAPHY, AND PERMEABILITY IN THE REDONDO CREEK PROJECT AREA

Jeffrey B. Hulen

Thermal fluid flow in the Baca geothermal reservoir, as defined by drilling to date, is both stratigraphically and structurally controlled. Stratigraphic permeability is provided by volcaniclastic sediments and non-welded tuffs, primarily within the Quaternary Bandelier Tuff. Structural permeability is developed along faults and associated fractures that form the central downdropped block (medial graben) of the Valles Caldera.

The Redondo Creek project area is situated within the medial graben, a major northeast-southwest-trending structure developed near the structural apex of resurgent doming within the Valles Caldera (Smith and Bailey, 1968). High-angle faults forming the graben are a major control on thermal fluid flow within and near the project area. This relationship is strongly indicated at the surface by alignment of fumaroles, gas seeps, and thermal springs, as well as by zones of bleaching and alteration. These hydrothermal phenomena lie along fault traces at Redondo Creek (Fig. 3; Dondanville, 1971, 1978) and along similar structures in the Sulphur Creek area, immediately to the northwest (Goff and Gardner, 1980). Fault control of fluid flow at depth is indicated by the correlation between fracture/fault zones interpreted in Union well logs, steam or hot water entries in Union wells, and faults mapped at the surface (Figs. 3 and 4; Behrman and Knapp, 1980). Union's detailed analysis of dipmeter data from wells in Redondo Creek showed a preferred northwest-southeast orientation of fractures. It would appear, therefore, that the geothermal anomaly in Redondo Creek is conditioned by the intersection of these fractures with northeast-southwest-trending faults. Apparent displacements on these high-angle faults range from a few

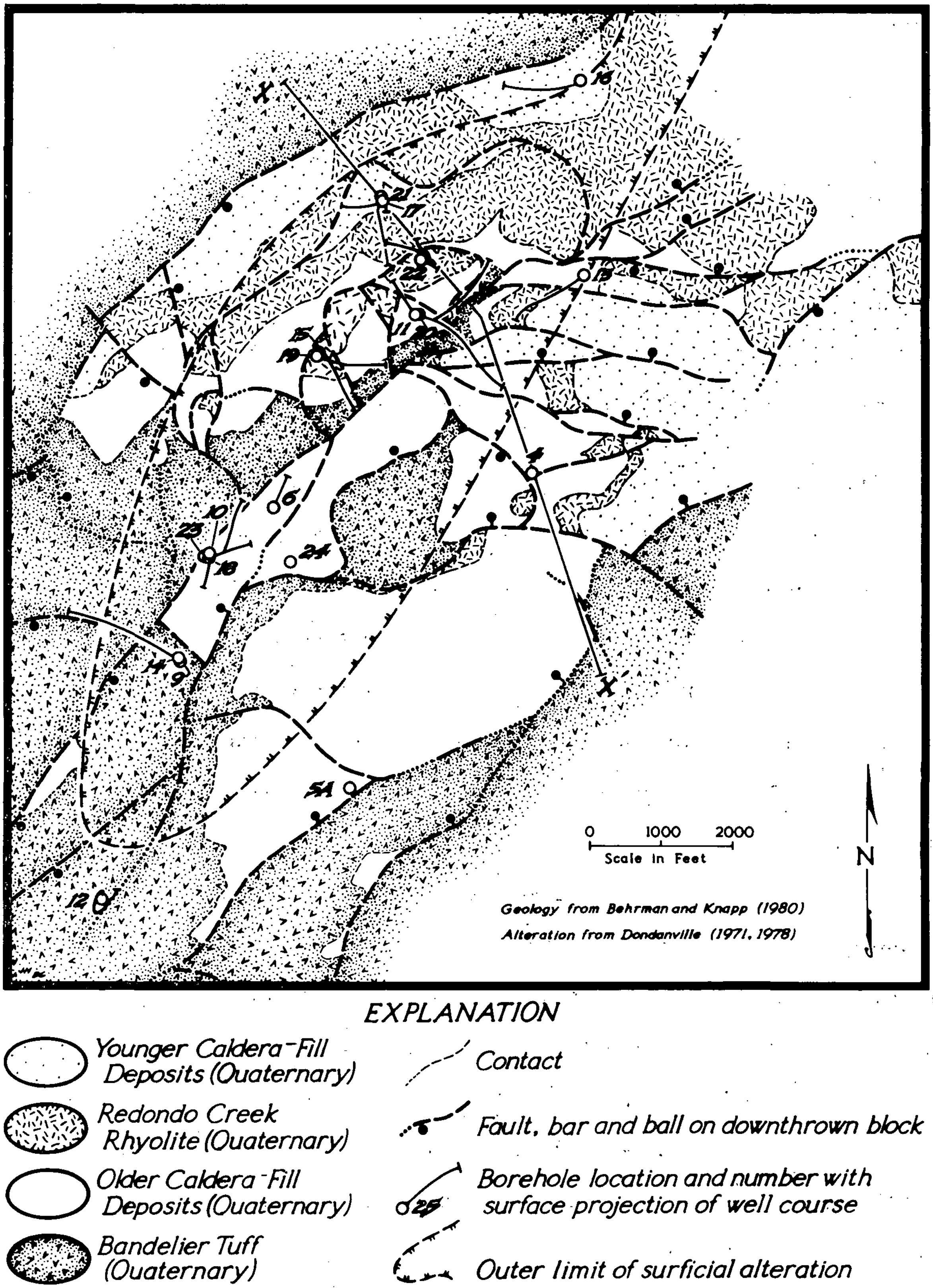

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Figure 3. Geologic map of the Redondo Creek project area, Valles Caldera, New Mexico.

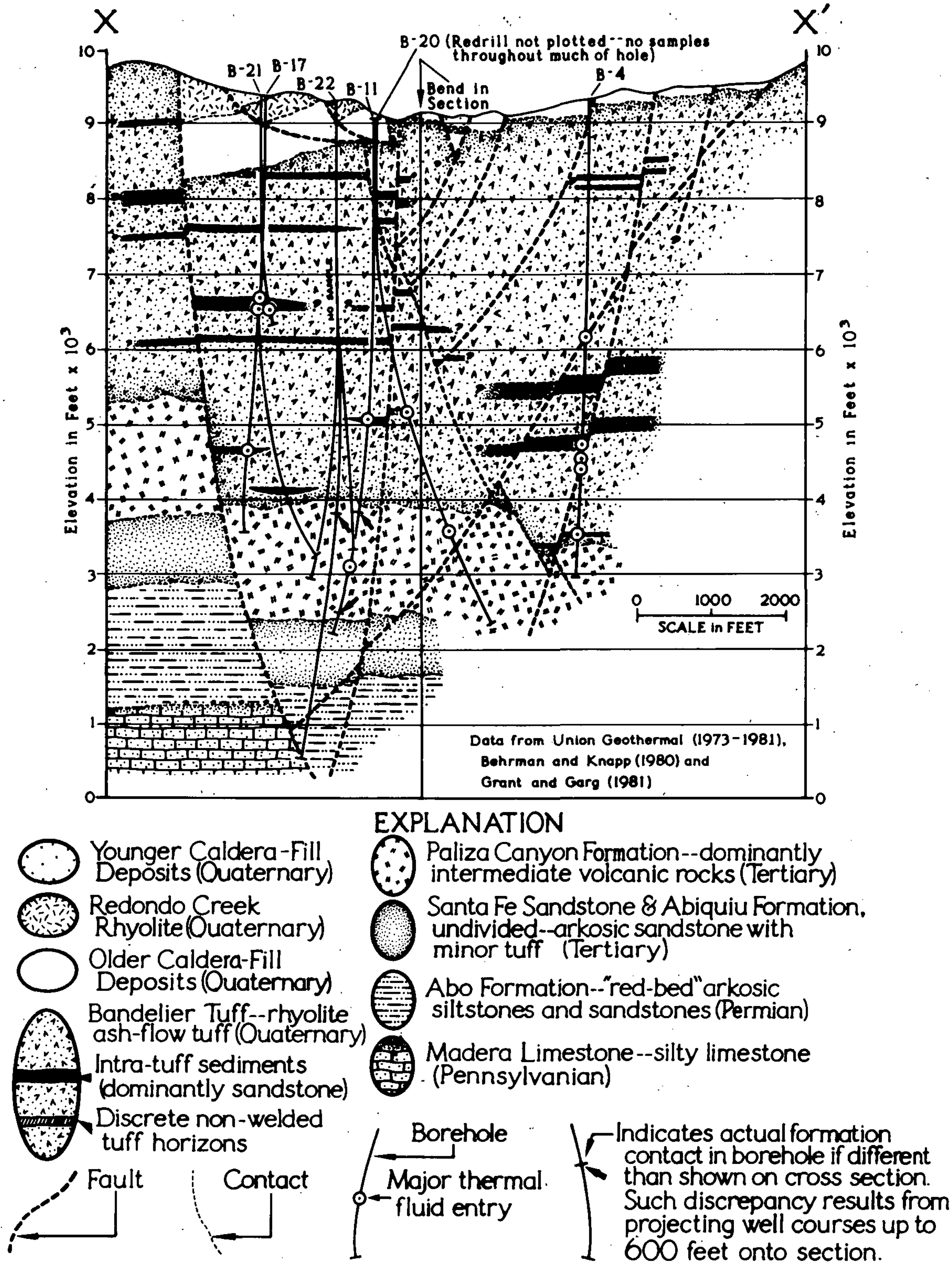

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Figure 4. Geologic section through the northeastern portion of the Redondo Creek project area, Valles Caldera, New Mexico.

hundred to at least 1400 ft. Zones of intense hydrothermal alteration in welded Bandelier Tuff were penetrated by several wells (Union Geothermal, 1973-1981). These zones probably mark former fault- and fracture-controlled flow channels, now hydrothermally sealed.

The Baca reservoir is primarily confined to the 1.4 to 1.0 million-year-old Bandelier Tuff (Doell et al., 1968). The catastrophic eruption of this tuff led, in stages, to formation of the Valles Caldera. The Bandelier is generally less than 1000 ft thick outside the caldera (Dondanville, 1978), but locally exceeds 6000 ft in thickness within the Redondo Creek project area (Figs. 3 and 4) at the caldera's southwestern margin. The tuff is described in Union's lithologic logs (1973-1981) as dominantly welded, glassy to devitrified rhyolite tuff (almost certainly of ash-flow origin), with sparse to abundant quartz and feldspar (mostly sanidine) phenocrysts, rare biotite, and variable pumice content. Restricted intervals in the Bandelier are described as breccia of unspecified origin. In several deep Union drill holes, the basal 1000 ft of the formation is relatively pumice rich (Dondanville, 1978) and moderately to strongly welded.

Immediately above the base and scattered throughout the Bandelier Tuff are non-welded tuff beds and well-sorted, tuffaceous sandstones, some of which may represent pyroclastic base surge deposits. These rocks are not continuous throughout the project area, but can be correlated between neighboring wells (Fig. 4). These units are essentially flat lying in the northeastern portion of the project area. Elsewhere within the caldera, surface mapping reveals that the Bandelier dips radially outward from the resurgent dome by as much as 23° (Smith et al., 1970).

The tuffaceous sandstones within the Bandelier range in thickness from a few feet up to 360 ft; the non-welded tuffs range from a well-defined 9 ft to vaguely defined intervals in excess of 250 ft. These permeable units, which aggregate less than 8 percent of the total formation thickness in any given well, appear to be important stratigraphic controls on thermal fluid flow at Baca -- second only to the steeply-dipping medial graben faults cited as major fluid flow channels by Dondanville (1971, 1978) and Behrman and Knapp (1980). Of 23 major steam or hot water entries identified in the Bandelier by Union Geothermal (1973-1981), Behrman and Knapp (1980), and Grant and Garg (1981) in 14 deep Baca wells, seven occur within tuffaceous sandstone units, and five within thin (less than 100 ft), discrete, non-welded tuff horizons. Non-producing Bandelier sandstones and non-welded tuffs encountered in the wells are generally much more intensely altered than enclosing welded tuffs. This relationship suggests that these permeable units were formerly thermal fluid conduits, but have become impermeable through interstitital deposition of secondary alteration minerals.

Within the project area the Bandelier tuff is eroded and locally concealed beneath Quaternary "caldera fill" deposits (Fig. 3) consisting of landslide debris as well as volcanic and lake sediments. These deposits seldom exceed 1000 ft and are separated in time from the Bandelier by the Redondo Creek Member of the Quaternary Valles Rhyolite.

The Bandelier rests unconformably on the Pliocene Paliza Canyon Formation (Bailey et al., 1969), a 700- to 1300-ft sequence of dense, propylitized flow rocks with locally interbedded tuff and volcaniclastic sandstone. Grant and Garg (1981) identify three important thermal fluid entries in the Paliza Canyon. One of these occurs in andesite porphyry and may be structurally controlled; another occurs in a poorly consolidated tuff and is probably a stratigraphic aquifer; the third is at the bottom of a well, where the nature of the controlling permeability cannot be determined.

Union's deep wells penetrating through the Paliza Canyon Formation encountered up to 540 ft of friable, poorly sorted arkosic and volcaniclastic sandstones, occasionally with interbedded tuffs. These sandstones have been logged as the Oligocene Abiquiu Formation (Goff and Kron, 1980) and as the Miocene Santa Fe Sandstone (Smith et al., 1970). They may be too unconsolidated to support commercial production in the Redondo Creek area. The Santa Fe, for example, actually flowed into well Baca 14, which then required extensive remedial cementation (Behrman and Knapp, 1980).

The Permian Abo Formation, disconformably underlying the Santa Fe/Abiquiu Sandstones, was reached in three Redondo Creek wells and drilled through in two. In Baca 12 (deepening), the formation is apparently 1650-ft thick, and in Baca 22 (Redrill 3), about 800 ft of Abo was penetrated above an apparent major fault zone (Fig. 4). The Abo "red beds" consist of interbedded arkosic siltstones and sandstones, which are locally anhydrite rich. Drilling in the Abo was hindered by severe lost-circulation problems due either to stratigraphic or structural permeability. Despite these lost circulation problems, the Abo yielded no thermal fluid production. This paradox may be interpreted in at least three ways. First, existing fractures were opened by overpressured drilling fluids and subsequently closed as reservoir production pressures decreased. Second, the Abo was deficient in formation fluid where it was penetrated by Union wells. Third, fractures were blocked by drilling fluids and detritus (formation mud damage).

Baca 12 (Deepening) and 22 (Redrill 3) were drilled to test the reservoir potential of rock units below the Abo Formation. Targets included possible solution voids in the Pennsylvanian Madera Limestone, permeability developed by weathering of the erosion surface of the underlying Precambrian granite, and fault/fracture zones in the granite basement. Baca 22 (Redrill 3) was lost just after the Madera was reached. Baca 12 (Deepening) penetrated about 950 ft of Madera before drilling about 470 ft into the granite. Although a maximum temperature of 646°F was recorded,* both units proved to be impermeable.

Other structural features recognized by Behrman and Knapp (1980) within the project area are the low-angle faults and possible cooling joints in the welded tuff. Low-angle faults with arcuate surface traces mapped within the project area (Fig. 3) apparently form the sole of shallow landslide blocks. These landslides incorporate "caldera-fill" deposits, Redondo Creek Rhyolite, and the uppermost Bandelier Tuff (Fig. 4), and are not important in controlling the Baca geothermal resource.

Behrman and Knapp (1980) suggest that cooling joints in welded Bandelier Tuff may control thermal fluid flow or cause lost circulation in several Union wells. Cooling joints are typical features of welded ash-flow tuff and are common in the Bandelier outside the Valles Caldera (Ross and Smith, 1961). Distinguishing joints from tectonically produced fractures is difficult in drill cuttings or E-logs. Whatever their origin, features identified on well logs as joints seem to be confined to specific horizons within the Bandelier and may be useful for correlation of reservoir zones within the caldera.

*For comparison, the temperature at the same depth (approximately 10,000 ft) at the Fenton Hill HDR site was 400°F.

In summary, Union wells in the Redondo Creek area show that the Baca geothermal system is apparently confined to stratigraphic and structural aquifers in the Bandelier Tuff and Paliza Canyon Formation. Significant thermal fluid production has not been encountered below these units. Lost circulation zones encountered in the Paliza Canyon and underlying Abo Formations were unproductive, and may be attributed to closed fractures, lack of formation fluids, or mud damage. The underlying Santa Fe and Abiquiu Sandstones may be too friable to permit commercial production (Behrman and Knapp, 1980).

The underlying Madera Limestone and Precambrian granite basement were impermeable in the single well (Baca 12, Deepening) tested.

The importance of faults and fractures in controlling flow and storage of thermal fluids in the Redondo Creek area has been stressed by Behrman and Knapp (1980). The occurrence of warm springs on the margin of the Caldera and the presence of stratigraphic aquifers within the Bandelier Tuff suggest that there could be good hydraulic communication between faults of the resurgent dome and caldera boundary faults.

GEOPHYSICS

M. Wilt, N. E. Goldstein, and S. Vonder Haar

Reconnaissance geophysical studies were performed over the Valles Caldera by Union Geothermal to obtain regional structural information and to identify anomalous areas with geothermal potential. Gravity and magnetic methods were used to determine regional structure and to estimate basement depth. Electrical and electromagnetic methods (dc resistivity, electromagnetics, tellurics and magnetotellurics) were used to locate regions of anomalously low resistivity that may be associated with geothermal reservoirs. These surveys were performed early in the development of the prospect; large areas were surveyed at low station density. In Redondo Creek, station density was higher, but less than adequate for detailed subsurface mapping.

Valles Caldera is characterized by a broad gravity low and a resistivity low in the western half. The depressed gravity principally results from the lower-density material that filled the caldera after its collapse. Gravity modeling indicates that the depth to Precambrian basement is greater than 3 km under Redondo Creek and as great as 5 km in the deepest parts of the caldera (Segar, 1971; Wilt and Vonder Haar, 1982). For contrast, the Precambrian is 500 m deep at Fenton Hill (Jiracek et al., 1975). Gravity modeling suggests that the caldera and the Redondo Creek graben are inclined to the southeast, toward the Rio Grande rift, so that the boundary faults on the western side of the graben have shallower dips than those on the eastern side.

Lower resistivities in the western half of the caldera seem to be caused by more intense hydrothermal alteration and high-temperature saline waters at depth. Resistivities are generally high at Redondo Creek, except at the surface over hydrothermally altered regions, and at depth in the restricted area of the well field. Magnetotelluric soundings reveal a deep low-resistivity zone (Fig. 5) that correlates well with the productive depths in Baca 11 and 13 (Wilt and Vonder Haar, 1982). Resistivity is much higher in areas where drilling encountered hot but dry conditions, indicating that the low resistivity is principally due to the presence of hot fluids. Telluric profile data, useful in locating lateral changes in resistivity, define a 10-km^2 area of anomalously low resistivity at depth. All the successful deep wells at Baca lie within this zone. Improved definition of this 10-km^2 region is therefore important for future drilling and reservoir production estimates.

Geophysical surveys helped Union Geothermal locate a low-resistivity anomaly at depth in Redondo Canyon. Union considered additional investigations, including active seismic, MT, EM, and SP surveys. At that time, however, the structural and topographic complexities of the narrow canyon and the difficulties of interpretation led Union to the conclusion that further geophysical work would not significantly contribute to the delineation of productive drilling targets. Additional magnetotelluric and telluric measurements are necessary if the cause of the anomaly is to be determined more exactly and if the low-resistivity zone is to be mapped in more detail. A geophysical technique that has proved successful in locating continuous fluid-filled fractures in other geothermal systems is the self-potential (SP) method (Corwin and Hoover, 1979; Morrison and Corwin, 1981). This cost-effective technique may prove useful for identifying fault/fracture zone drilling targets at Baca.

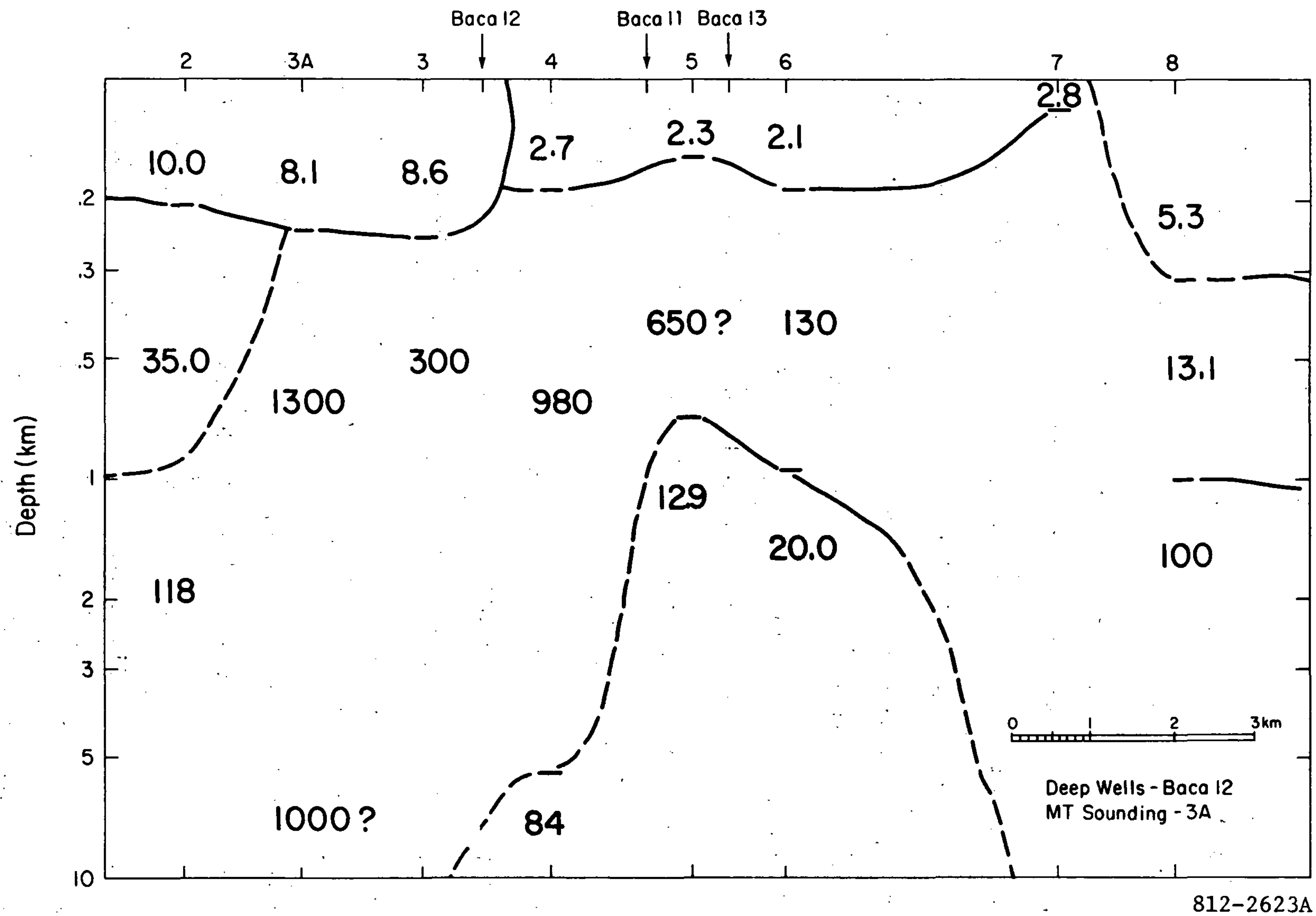

Figure 5. Composite plot of layered-model inversions for magnetotelluric soundings along a profile through Redondo Creek.

GEOCHEMICAL INDICATORS OF RESERVOIR CONDITIONS

J. M. Delany and A. H. Truesdell

Geochemical methods are useful for determining the chemical and thermodynamic state of geothermal reservoirs, as well as for monitoring production-induced chemical changes. The chemical composition of geothermal fluids collected at the wellhead can be used to estimate compositions and temperatures of deep reservoir fluids and to evaluate whether processes such as boiling, fluid flow, recharge, etc. occur within the reservoir. As geochemical analyses are rather simple and inexpensive, considerable effort is usually devoted to their employment in the exploration and development of geothermal fields. Geochemical data made available by Union from production flow tests from 1972 through 1981 consist of 35 analyses for nine Redondo Creek wells (accompanying production data are available for six of the wells).

Comparison of average concentrations of chemical constituents from Baca 4, 6, 11, 13, 15, and 20 (Hartz, 1976, 1977; Christensen and Atkinson, 1981) indicates that fluids from all wells within Redondo Creek originated from a common reservoir. Re-evaluation of the Baca geochemical data indicates original fluid inhomogenities, and that local and general boiling are characteristic of the Baca reservoir. Local boiling (associated with all wells) occurs in response to the pressure drop induced at the wellbore by production. A cooled zone around the well is indicated by silica geothermometer temperatures (Truesdell, 1976) that are about 30 to 60°C lower than the reservoir temperatures. General boiling is verified by the existence of a two-phase liquid-steam zone in the central portion of the field (Union, 1978; Grant and Garg, 1981) that probably existed before development.

Na/K/Ca geothermometer temperatures (Fournier and Truesdell, 1973) of well fluids are in agreement with measured downhole data, and can be directly associated with feed point locations identified by Grant and Garg (1981) and Riney and Garg (1982) within the Bandelier Tuff and Paliza Canyon Formation (Table 1). Na/K/Ca temperatures for wells that penetrate the two-phase zone (Baca 4, 11, 15, and possibly 20), and for wells that produce only from the liquid zone (Baca 6, 13, and probably 23 and 24), can be used to reconstruct aquifer chloride and enthalpy relationships (Fig. 6). The wide range in chloride content (2500 to 3750 ppm), shown by the solid symbols in Figure 6, along with the relatively narrow temperature interval of production, is interpreted to result from minor convective circulation within the reservoir. This feature is consistent with conductive heating from below, as shown by the high temperatures encountered by the deepening of Baca 12. Chloride concentration variations do not suggest dilution within the reservoir. Analyses for Baca 23 and 24 yield computed reservoir temperatures ($T_{Na/K/Ca}$) that are considerably lower than those for the other producing wells, supporting the interpretation that there is little convective mixing. However, interpretation of the chemistry of Baca 22, 23, and 24 is made difficult by the limited amount of data and lack of duplicate analyses.

The geochemical data for well fluids that have been collected by Union at Baca have not been fully interpreted. Preliminary evaluation has been useful in defining reservoir temperatures (and enthalpy), chemistry, zones of boiling, and the locations of production horizons. Additional sampling would allow for a detailed geochemical interpretation of processes occurring at depth within the reservoir.

Table 1. Geochemical analyses of Baca wells.

Baca well	No. of chemical analyses and year[a]	$T_{Na/K/Ca}$ this study (°C/°F)	Zones of primary permeability		
			Depth (ft ASL)	Formation	Reservoir temp (°F)
4	16 (1973)	286/547	4546	Bandelier	~500[c]
	1 (1981)		4349	Bandelier	<566[b]
6	3 (1972-1973, 1975)	273/523	5058	Bandelier	~500[b] (>524)[c]
			4033	Bandelier	>550[c]
11	6 (1974-1976)	290/554	5075	Bandelier	~536[b]
			3102	Paliza Canyon	>600[b]
13	6 (1974-1976)	285/545	4836	Bandelier	~500[b] (491)[c]
			3377	Paliza Canyon	>525[b] (>500)[c]
15	1 (1976)	286/547	6610	Bandelier	>465[b] (~500)[c]
			3755	Paliza Canyon	>540[b,c]
20	3 (1980)	261/502	5165	Bandelier	~488[a]
			4450[e]	Bandelier	490[d]
22	1 (1981)	275/527	No downhole P/T analysis available.		
23	1 (1981)	253/487	5526	Bandelier	~450[c]
24	1 (1981)	258/496	3273	Bandelier	>500[c]

a No production testing was conducted between 1976 and 1980.
b Grant and Garg (1981).
c Riney and Garg (1982).
d Christiansen and Atkinson (1981).
e Measured depth along wellbore.

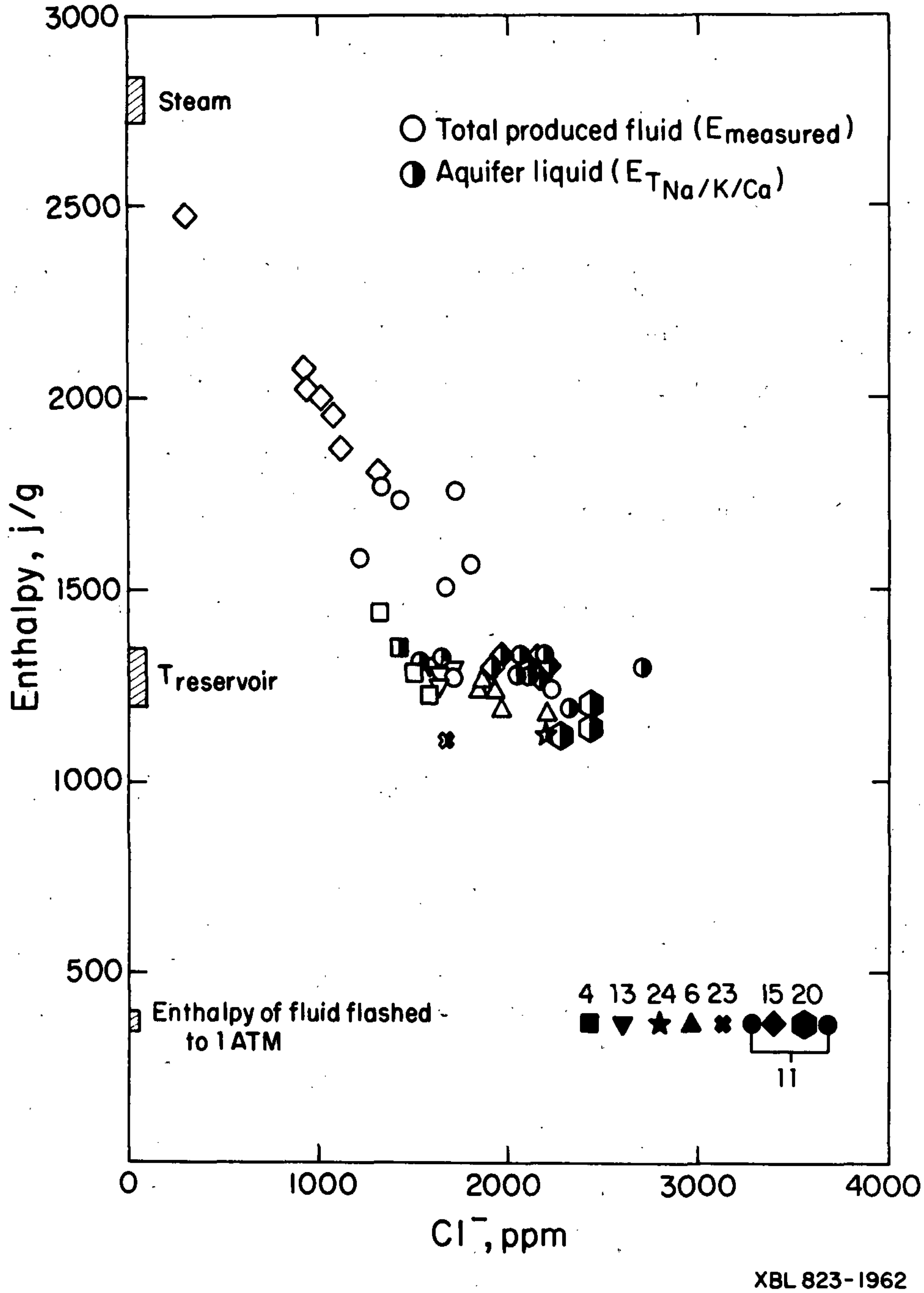

Figure 6. Enthalpy-chloride plot of steam from production wells in the Redondo Creek area. The variation in chloride content for wells 4, 6, 11, 13, 15, 20, 23, and 24 is shown by the solid symbols with an enthalpy value of ~400j/g for a fluid flashed to one atmosphere at an elevation of ~9000 feet. Aquifer chloride values (half-shaded symbols) were completed using the reservoir temperature ($T_{Na/K/Ca}$), and the total produced fluid values (open symbols) are shown plotted on a dilution trend toward pure steam.

DRILLING PROBLEMS

M. W. Molloy and A. William Laughlin

By the end of 1981, Union Geothermal had drilled 19 wells, deepened two wells, and redrilled 10 wells within the project area (Fig. 7). Union experienced serious drilling or completion problems in 23 (74%) of these 31 attempts and lost nine (29%) of the wells. Union considers only five (16%) of the wells to be commercial producers. (One new well is commercial, but one well regarded as commerical prior to the agreement was lost.)

Drilling and completion problems encountered at Baca are described in Pye (1981) and summarized in Table 2 and Appendix 2. Failed fishing operations (which generally arose from stuck pipe or twist-offs) were the major cause of lost or damaged wells. Eight wells (25%) were lost from this cause alone.

These problems stem primarily from the numerous lost circulation zones and the underpressured reservoir (pressures generally 600 to 900 psi less than hydrostatic as measured from the wellhead). To flush cuttings to the surface under these circumstances, Union used aerated water as a drilling fluid. This severely aggravated the corrosion of drill pipe and casing, increased the likelihood of stuck drill pipe, and allowed no forewarning of pressure "kicks" when drilling. By adding caustic, Unisteam, and ammonium hydroxide to control pH, Union was able to reduce corrosion to an acceptable level. The other difficulties continued to plague the project until its termination.

The two deepened wells (Baca 12 and 22) were particularly afflicted by lost circulation problems. Because the known productive formations had to be cased off in order to drill deeper, it was first necessary to seal off

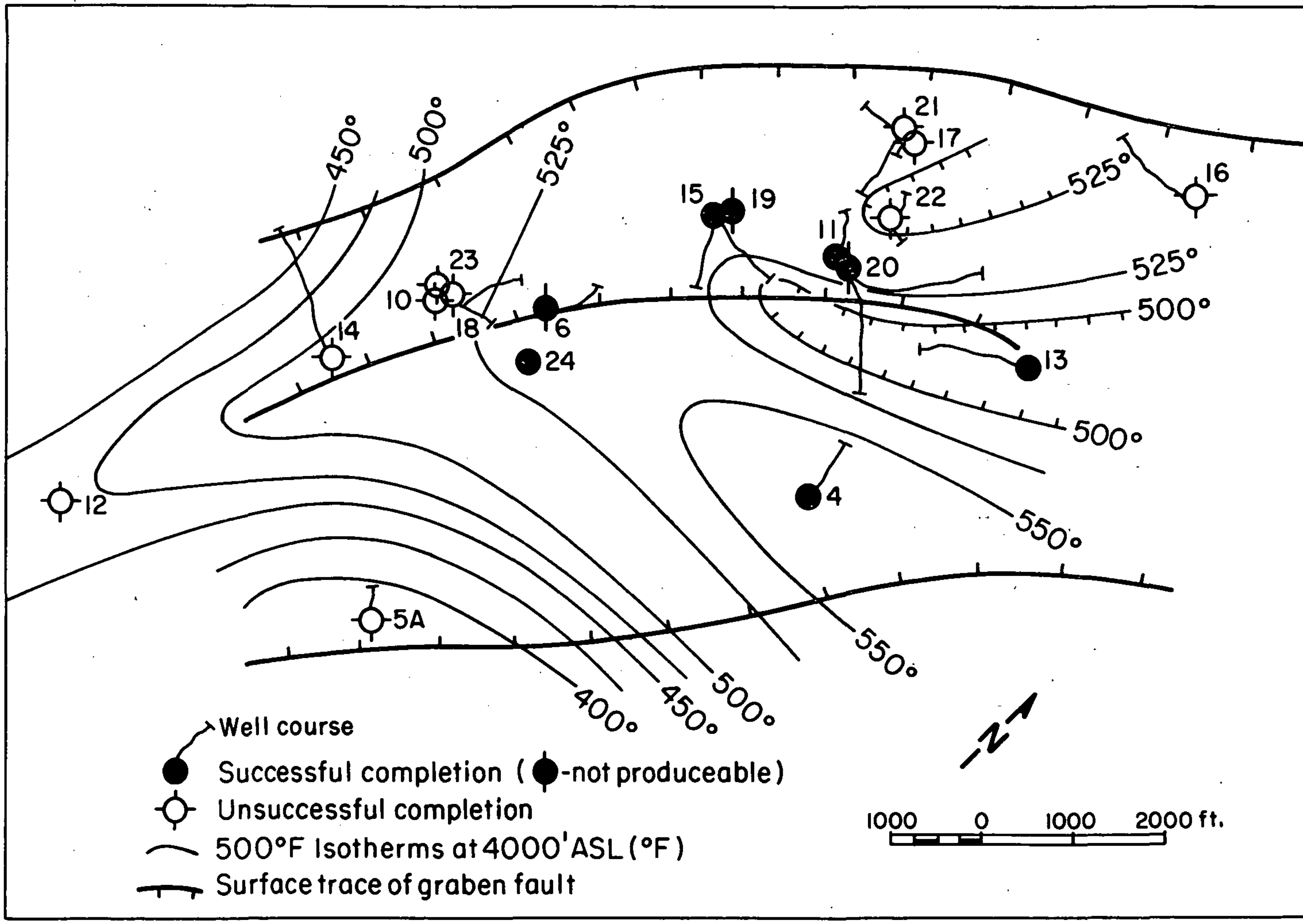

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Figure 7. Location of the Baca wells in the Redondo Creek area.

Table 2. Summary of drilling problems at Baca project.

	Lost wells	Totals	Percent
Fish in hole (lost, sidetracked)	Baca-50H-90H&RD, -180H&RD1 -200H, -220H, - 22RD3	8	26
Casing and liner (worn, collapsed)	Baca-9-RD, - 17RD	2	6
	Total - lost wells	10	
	Drilling difficulties		
Extensive fishing	Baca-50H, - 90H, -19, -200H, -220H, -23 Recompl., -24	7	23
Sidetracked fish	Baca-24	1	3
Extensive steam/ water entries	Baca-40H, -5A, -24 (also Baca 1)	3	10
Bad sloughing	Baca-50H, -90H&RD, -10 -11, -14	6	19
Casing & liner (break, collapsed, unable to run)	Baca-6 deep	1	3
Damaged production zone (from fishing)	Baca-10	1	3
Bridged wellbore	Baca-6 deep	1	3
Wellbore scaling	Baca-60H, -11, -14	3	10
	Total - drilling difficulties	23	

[a] Baca 5 OH.

all lost circulation zones. This took 42 cement plugs in Baca 12 and would have taken more than 31 plugs in Baca 22 had that well been completed to the planned depth.

The high rate of mechanical failures in Union's Baca wells resulted in a significant loss of information on geologic structure, stratigraphy, and hot water/steam entry, in addition to increased drilling costs and lost steam production capacity. In certain wells, e.g., Baca 24, the information that was lost might have improved the targeting of subsequent wells by constraining conceptual geologic models of potential production zones and features controlling permeability.

FRACTURE STIMULATION EXPERIMENTS

C. W. Morris, R. J. Hanold, and C. F. Pearson

The DOE-sponsored Geothermal Well Stimulation Program group performed hydraulic fracture treatments on two wells. The treatment in Baca 23 was a large hydraulic fracture stimulation of a 231-ft interval from 3300 to 3531 ft (details of the treatment are contained in Table 3). This zone was non-productive prior to stimulation. The frac fluid was pumped at high rates to assure a wide fracture opening and to enhance proppant placement.

From post-stimulation temperature surveys, the zone cooled by the frac fluids was estimated to be more than 300 ft in height at the wellbore. A 6-hr production test, using a modified drillstem test (DST) technique, was utilized to evaluate the stimulation job. The well was flowed at a steady rate of about 21,000 lb/hr, and pressure data obtained downhole provided an indication of the wellbore storage effects, fracture flow effects, and reservoir transmissivity. Conventional transient pressure analysis of the data yielded a reservoir permeability-thickness of 2500 md-ft. This compares closely with results from other wells in the area. Although the linear flow indicators in the pressure data were weak, the length of the fracture was calculated to be about 300 ft. The maximum recorded temperature during the test was 342°F, which indicated that the near-wellbore area had not recovered from the injection of cold fluids.

Following the modified DST, a 49-hr flow test was performed to determine the well's productive capacity. The results showed that the well could produce approximately 120,000 lb/hr total mass flow at a wellhead pressure of 45 psig, although the rate was continuing to decline. Union then performed a

Table 3. Comparison of Baca 23 and Baca 20 stimulation treatments.

	Baca 23	Baca 20
Date performed	March 22, 1981	October 5, 1981
Stimulation interval	231 ft	240 ft
Stimulation depth	3300-3531 ft	4880-5120 ft
Water pre-pad	3600 bbl	3000 bbl
Gelled water frac fluid	4000 bbl	5700 bbl
Proppants	97,200 lb of 20/40 mesh sintered bauxite; 82,800 lb of 20/40 mesh resin-coated sand	120,000 lb of 16/20 mesh sintered bauxite; 120,000 lb of 12/20 mesh sintered bauxite
Pumping rate	40-75 BPM	40-80 BPM

long-term flow test. The pressure and temperature data obtained in the well during this test indicated that two-phase flow was occurring in the formation, with the steam fraction estimated at more than 50 percent. This two-phase flow condition has been observed in other wells in the field. Of greater concern is the lower productivity observed during this long-term test. Analysis of the long-term test data by Riney and Garg (1982) indicated a permeability-thickness value of 4340 md-ft (Table 4). The mass flow rate dropped to about 70,000 lb/hr with a wellhead pressure of 37 psig. Since the well recovers productivity following each shut-in period and then exhibits the same decline again, the cause of the rate decline is probably not due to scaling in the formation. Partial closing of the fracture is possible, but the productivity loss is more likely the result of permeability reduction associated with two-phase flow effects in the formation. The relatively low formation temperature in the completion interval also contributes to the well's poor productivity. It was concluded that future stimulation treatments at Baca should be conducted in deeper and hotter portions of the formation.

The second treatment was conducted in Baca 20 and consisted of a large hydraulic fracture stimulation of a 240-ft interval from 4880 to 5120 ft. Prior to the treatment, this isolated zone was essentially nonproductive. A comparison between the Baca 23 and Baca 20 stimulation treatments is presented in Table 3. The increased treatment volume, increased proppant pack, and the exclusive use of larger diameter sintered bauxite proppants were justified in an attempt to produce very large, highly conductive fractures. Calcium carbonate was employed as the fluid-loss additive during the early stages of the treatment to maximize the fracturing fluid efficiency. The frac fluid was again pumped at high rates to enhance proppant placement throughout the created fractures.

During both treatments, acoustic emissions were monitored using a removable seismometer package in a neighboring well located within 1 km of the stimulated zone. The orientation and size of the hydraulic fractures could then be inferred from the locations of acoustic emissions generated during the hydraulic stimulation experiments (Albright and Pearson, 1982). During the Baca 23 treatment, the events were distributed along a northeast-southwest-trending vertical zone nearly 600 m long. During the Baca 20 treatment, the events did not seem to be localized along a definable fracture. Instead the events occurred within a rectangular volume about 400 m on a side and 40 m thick. Since these acoustic emissions are caused by local increases in pore pressures associated with the hydraulic fracturing process (Pearson, 1981), the size of the seismic zones is related to the reservoir volume that was pressurized during the hydraulic stimulation. Some of these acoustically active volumes may not remain in communication with the wellbore during subsequent production tests.

From post-stimulation temperature surveys, the zone cooled by the frac fluids was estimated to be less than 100 ft in height and to be located near the bottom of the open interval. A 6-hr production test was performed, again using the modified DST method, and a steady rate of about 21,000 lb/hr single-phase flow was maintained to the wellbore. Pressure and temperature data were obtained downhole, and conventional transient pressure analysis techniques were applied to the data. The analysis yielded a reservoir permeability-thickness of about 1000 md-ft. The length of the fracture was calculated from the pressure data to be about 280 ft. Numerical simulation of a high-conductivity fracture in a low-permeability formation supports this interpretation, although the solution is not unique. The maximum recorded temperature during this test was 320°F, indicating that the near-wellbore area had not recovered from the injection of cold fluids. Additional temperature surveys were run in the well following the DST, which indicated that the fluid was entering the wellbore in the lower part of the open interval.

Following the modified DST, a 14-day flow test was performed by Union to determine the well's productive capacity. The well initially produced approximately 120,000 lb/hr total mass flow, but declined rapidly to a final stabilized rate of approximately 50,000 lb/hr (wellhead pressure of 25 psig) under two-phase flow conditions in the formation. The steam fraction was estimated at more than 85 percent. Because of the poor performance of the well, an acid cleanout of the fracture was recommended to remove the calcium carbonate that was used as the fluid-loss additive during the hydraulic fracture treatment. This material was used with the expressed intent of performing an acid cleanout should the fracture conductivity show damage. The possibility of such damage with insoluble fluid-loss additives such as

100-mesh sand has been a concern in prior stimulation experiments. Although the pressure data do not indicate that the fracture conductivity has been damaged, the possibility remains that the calcium carbonate has plugged the natural fractures and flow paths in the formation that intersect the artificial fracture.

The results of the two stimulation experiments performed at the Baca project area yield the following conclusions:

1. Large hydraulic fracture treatments were successfully performed on both Baca 23 and Baca 20. Production tests indicated that high conductivity fractures were propped near the wellbore and that communication with the reservoir system was established.

2. Productivities of Baca 23 and Baca 20 have declined to 70,000 and 50,000 lb/hr, respectively, since the fracture treatments. The probable cause is permeability reduction associated with two-phase flow effects in the formation. This implies that major fluid-producing features were not intersected by the created fractures.

3. The ability of Baca 23 to produce substantial quantities of fluids at a high wellhead pressure is limited, because of the low formation temperature in the shallow treatment interval and the low permeability formation. The productivity of Baca 20 is severely restricted because of the low-permeability formation surrounding the created fractures. This reservoir is particularly sensitive to these factors because of its low initial pressure.

4. Although the stimulation treatments did not result in high productivity wells at Baca, the hydraulic fracturing techniques show promise for future stimulation operations and as a valid alternative to redrilling. If major fluid producing features could be intersected by hydraulic fractures, it is believed that stimulation could result in wells whose productivity would match the better wells in the field.

RESERVOIR DEFINITION AND CONCEPTUAL MODEL

Sabodh Garg and T. David Riney

The surface locations of the 19 wells that have been drilled in the Redondo Creek area to date are shown in Figures 3 and 7. In their attempt to increase well productivity or to overcome drilling and completion problems, Union Geothermal plugged many of the original boreholes and employed deviation drilling to obtain successive redrill holes at a given well site.

Nearly all of the production from the wells comes from fractures or thin statigraphic interbeds in the Bandelier Tuff, which is 4500 to 6500 ft thick in the Redondo Creek area. Cores of the Bandelier Tuff from Baca 13 indicate that interstitial permeability of the welded tuff is less than 1 md and porosity is 4 to 10 percent. Recent deep drilling at wells Baca 12 and 22 failed to find productive formations below the tuff. The maximum temperatures measured in the wells were generally 550 to 600°F.

Since the bulk of the reservoir permeability is in a fracture network, the performance of a well depends to a large degree on whether it intersects one or more fractures, how large each intersected fracture is, and how well it is connected to the rest of the network. The well is open to reservoir fluid at the depth(s) where it intersects such a fracture; for the balance of its depth the well penetrates rock that is hot but essentially impermeable. Analysis of the downhole data (drilling records, downhole pressure and temperature surveys, surface fluid characteristics) indicates that stratigraphic permeability primarily occurs in two zones across the portion of the reservoir penetrated by the Baca wells (Grant and Garg, 1981). The deeper zone closely corresponds to the contact between the Bandelier Tuff and the underlying

Paliza Canyon Formation. The apparently more permeable shallower zone lies within the tuff. The reservoir pressures define a straight line of slope 0.348 psi/ft when plotted against elevations above sea level. This corresponds to a hydrostatic gradient at approximately 500°F. The initial temperature contours constructed from the downhole data dome upward, and an initial two-phase region at the crest of the dome is penetrated by several Baca wells (Fig. 8). All of the Baca wells induce flashing in the near-wellbore formation upon production.

Chemical analyses of the discharge fluids from Baca wells indicate that the reservoir fluid has relatively low salinity (< 9000 ppm) with a noncondensible gas content (principally CO_2) of about 0.4 to 1.5 percent by mass. The effect of the noncondensible gas content on the fluid state has been examined using an equation of state for a mixture of pure water and carbon dioxide (Pritchett et al., 1980). The probable extent of the two-phase region in the Baca reservoir is found to be very sensitive to the CO_2 content of the fluid. The boiling pressure for the mixture is significantly greater than for pure water. The two-phase region at Baca is larger than would be anticipated if the pressure-temperature were interpreted without accounting for the presence of the CO_2.

Various tests have been performed on the wells in the Redondo Creek area to evaluate the productivity of the wells and the reservoir characteristics. Production tests performed include two-phase tests, separator tests, pressure drawdown and buildup tests (and chemical analyses of the produced fluids). In a two-phase test of productivity the well is flowed to the reserve pit, and the pressure drop across an orifice plate is used to estimate the flow rate. A typical separator test consists of flowing the well through a separator

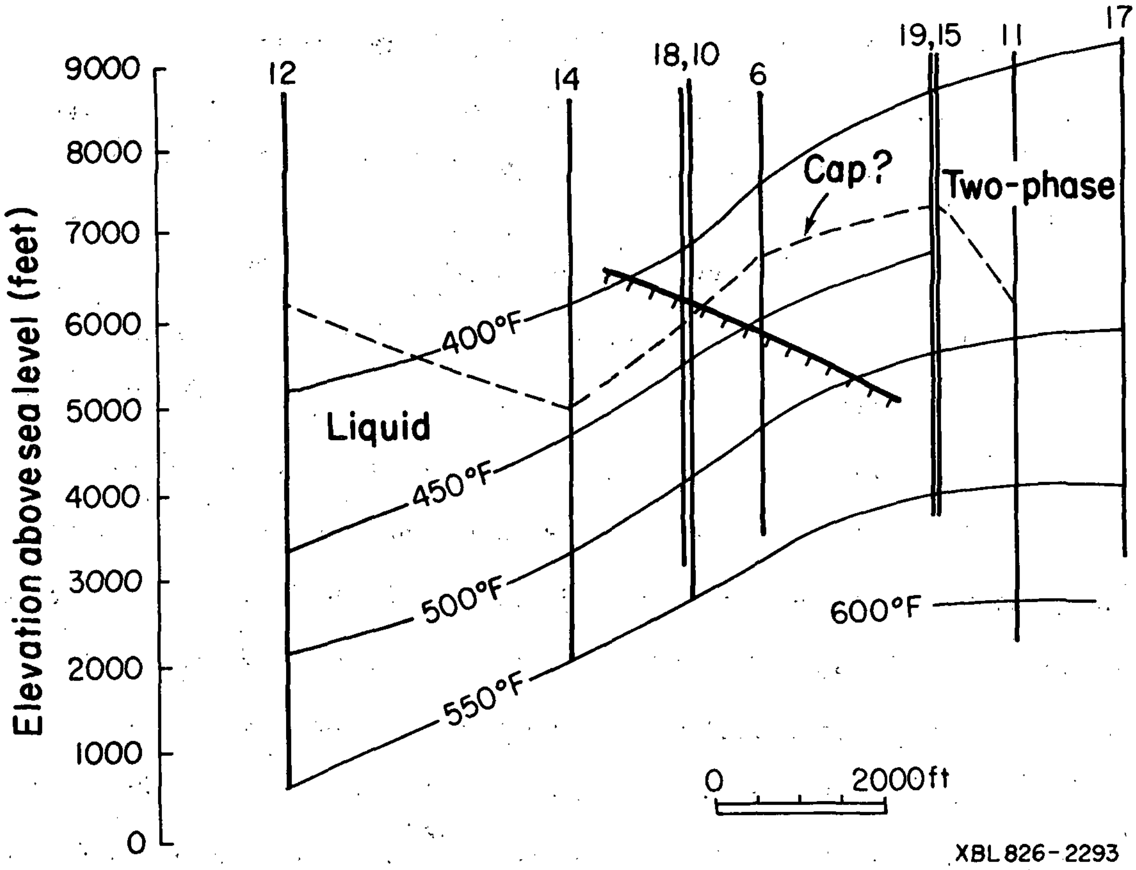

Figure 8. Inferred reservoir temperature along a section between wells Baca 12 and Baca 17, showing the boundary between the liquid and two-phase regions. The reservoir fluid is assumed to contain 0.8% CO_2 by mass.

vessel and measuring steam and water phases individually to evaluate the well's flowing capacity with respect to producing pressure and time, steam fraction, fluid enthalpy, and composition of fluids. The separator tests provide sufficient flow data for analysis of the downhole pressure data during buildup. Lack of downhole measurements during production preclude reliable analysis of the drawdown data.

Analysis of the buildup behavior of the wells has been completed for most of the wells on which separator tests were performed (Riney and Garg, 1982). The interpretation relies on simulated two-phase well-test calculations for guidance (Garg and Pritchett, 1980) and analysis of the downhole measurements to establish the reservoir conditions in the production zone. It considers the effects of the CO_2 content and fracture permeability of the reservoir, the two-phase and single-phase portions of the buildup response, and the fact that the downhole pressure/temperature gages are usually located hundreds of feet from the primary production zone. A summary of the results is shown in Table 4. Lack of data for the effective porosity and compressibility of the fractured reservoir formation, and the flashing of pore fluid near wellbore, make calculation of the skin effect (impairment or improvement in the near-wellbore permeability) meaningless.

In addition to the above described flow tests on individual wells, two field-wide pressure interference tests were conducted (1975-1976 and 1981) to evaluate the hydraulic connectivity of the fracture network. Analysis of the 1975-1976 test yielded a permeability-thickness product (kh) of around 6000 md-ft (Hartz, 1976; Garg and Rice, 1982). This value is significantly lower than the permeability-thickness product measured at other geothermal fields, where products range from 20,000 to more than 100,000 md-ft.

Non-productive Baca wells have been used as injection wells. The ability of these wells to accept high injection rates implies that all permeable zones may not be productive zones. Detailed analysis of Baca 20 (prior to hydrofracturing) shows that the primary production zone is at ~ 4000 ft depth, whereas most of the injected fluid enters a deeper fractured zone below ~ 5000 ft (Riney and Garg, 1982). The fracture produced during the stimulation of Baca 20 apparently intersects the lower fluid-accepting zone, rather than a production zone.

In summary, analysis of the downhole data and fluid production/ injection data for the Baca wells indicates the following:

1. Performance of a well in the Redondo Creek area depends primarily upon whether it intersects one or more fractures and how well the fracture(s) is connected to the rest of the fracture network.

2. Production from these wells is primarily from the shallower of two fractured or permeable statigraphic zones in the Bandelier Tuff.

3. There is a two-phase region initially present near the top of the Baca reservoir system. All of the Baca wells induce flashing in the near-wellbore formation during production.

4. The effective values of the key parameters kh and ϕh are significantly lower at Baca than at other, more productive geothermal systems.

Table 4. Depth, temperature, pressure, and kh of production zones for Baca wells.

	Permeable horizons					
Well	Thickness (ft)	Elevation (ft ASL)	T (°F)	P (psig)	kh (md-ft)	Remarks
4	4800	4546	~500	1170	5050	Commercial
6	3700	5058	524	968	6480	Commerical
	4750	4033	----	---		
10	3000	5746	~500	750	5100	Productivity damage
	4500	4252	~535	1260	(Union)	during drilling
11[a]	4000	5075	>525	1100	3500	Commercial
	6000	3102	~575	1850	(Union)	
13[a]	4500	4836	491	1100	2600	Commercial
	6000	3377	>500	1600		
15	2525	6610	~500	450	23,800	Commercial
	5505	3755	----	1405		
20	4000	5165	488	975	3030	Marginal[b]
	5750	3567	549	1443		
	5000	4237	507	1313	----	Sub-commercial[c]
21	2840	6559	436	519	10,250	Sub-commercial
22	Insufficient data for analysis.		----	----	----	Sub-commercial
23[c]	3250	5526	450	835	4340	Sub-commercial
24	5502	3273	>500	1525	15,900	Commercial

[a] Wells cycle. kh values may be suspect.
[b] Prior to hydraulic fracturing.
[c] After hydraulic fracturing.

PREDICTION OF RESERVOIR PERFORMANCE

G. S. Bodvarsson and C. F. Tsang

Two of the most important factors that control the producibility of a geothermal resource are the reservoir capacity and the generating capacity. The reservoir capacity may be defined as the mass of hot fluid in place, whereas the generating capacity is a measure of the rate at which energy can be extracted from the reservoir. Reliable estimates of these factors must be obtained before a proper development plan for a resource can be designed; these estimates must also be periodically updated as more field data become available during exploitation of the field.

Union (1978) used two different methods to estimate reservoir capacity: a depletion equation (mass balance) and analysis of interference test data. Calculations based on the depletion equation assume that the reservoir is fully confined; i.e., no recharge. Interference test data from well Baca 10 were used to estimate the reservoir capacity on the basis of a simple reservoir model (Theis solution). Both methods yielded 4.7×10^{12} lb of fluid in place. However, both methods are based solely on pressure measurements, and do not distinguish between hot and cold fluid in place.

Bodvarsson et al. (1980) estimated the reservoir capacity by volumetric means using existing geological, geophysical, and well data. Magnetotelluric data (line B-B') were used to estimate the north and south boundaries. The eastern boundary of the reservoir was assumed to coincide with a major fault zone of the medial graben; the western boundary, with the ring-fracture zone (Fig. 9). Using results from core data analyzed by Core Laboratories, Inc. in 1975 and resistivity logs, the porosity-thickness product was estimated

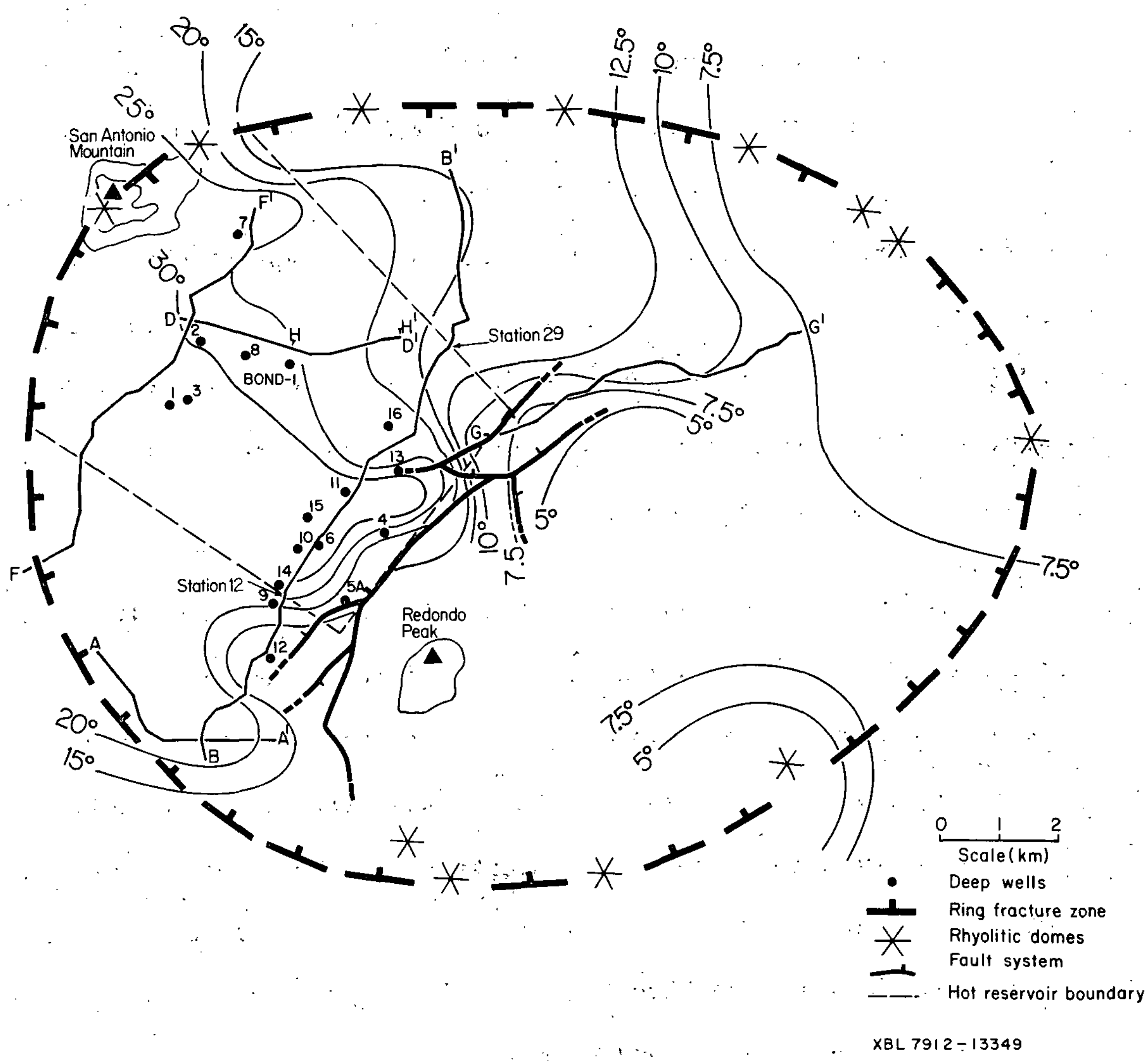

Figure 9. Base map of the Valles Caldera showing shallow temperature gradients (°F/100 ft), geophysical survey lines (e.g., A-A'), and specific faults. The estimated hot reservoir boundary is indicated by broken lines.

to be 100 ft. Using all these factors, they calculated a reservoir capacity of 2.2×10^{12} lb of hot fluid in place.

In light of the ambiguity of the data and the many assumptions used in each approach, the reservoir capacity estimates agree reasonably well with each other.

Two independent studies have addressed the question of the generating capacity of the Baca field. Union (1978) used a lumped-parameter model, and Bodvarsson et al. (1980) used a distributed parameter model. A lumped parameter model is one in which the entire reservoir is considered as one (or several) mixing cell(s), thus neglecting spatial variations of reservoir parameters and the thermodynamic evolution during exploitation. Lumped-parameter techniques were developed in the oil and gas industry, and are presently widely used in the evaluation of geothermal systems. The results based on the lumped-parameter model indicate that the Baca reservoir could ultimately sustain a 410-MWe power production over 30 years without injection, and 900 to 1200 MWe if injection were employed.

Bodvarsson et al. (1980) used a distributed model, which considers spatial variations in dependent variables and reservoir parameters, to estimate the performance of the reservoir on the basis of a power production of 50 MWe. Because data were limited, they used a rather coarse grid-block representation of the reservoir and an optimistic modeling of the production region. All wells were located within a 500-acre area. The results of the simulations showed that for cases of variable mass flow and constant steam production, very limited waste water would be available for injection. Consequently, injection was not considered. On the basis of these assumptions, their results indicated that the wells within this production area may sustain 50 MWe of power production for 25 to 50 years. They concluded that the main factor controlling the generating capacity of the Baca reservoir was its low transmissivity (permeability-thickness) value inferred from well-test data. The low transmissivity would cause very localized boiling in and around the production region and, consequently, a very rapid pressure decline. The low transmissivity indicates a rather coarsely fractured system, and thus it is not altogether surprising that the success rate of intercepting permeable, fluid-filled fractures has been low in the new wells.

Comparison of the studies by Bodvarsson et al. (1980) and Union (1978) shows that the generating capacity estimates are an order of magnitude higher in the case of the lumped-parameter model. The reason for this large discrepancy is that the lumped-parameter method inherently assumes that a uniform pressure decline will occur in the reservoir; the transmissivity of the reservoir does not enter the calculations. In cases of localized boiling (low transmissivity), the lumped-parameter method will grossly overestimate the ultimate generating capacity of the reservoir. Thus we believe that the distributed-parameter model estimates of the generating capacity of the Baca reservoir are the more realistic of the two.

In summary, studies of the reservoir capacity and generating capacity of the Baca reservoir have indicated the following:

1. Three different methods for estimating the reservoir capacity all gave results in the range of 2 to 4 x 10^{12} lb of fluid in place.

2. Although such a reservoir capacity should be adequate to produce approximately 400 MWe for 30 years, the actual generating capacity is much less because of the low transmissivity of the Baca reservoir.

3. The low transmissivity requires the use of distributed parameter models rather than the simpler, lumped-parameter models for estimating the generating capacity of the reservoir.

4. Using a distributed parameter model, Bodvarsson et al. (1980) estimated that a 500-acre production area at Baca may sustain 50 MWe power production for 25 to 50 years. This assumes the reservoir has infinite transmissivity in the 500-acre production area. If one includes the effects of individual wells, the estimate should be lower.

5. In general, it may be advantageous to develop a geothermal field as a phased process, beginning with an initial power production of 10 or 20 MWe and building to a large power production in several stages. In this way, the developer obtains data and gains experience at each stage that helps to determine how to advance the power production to the next stage.

SUMMARY AND CONCLUSIONS

Despite the high temperatures encountered at depth, the geothermal resource underlying Redondo Creek has proved to be difficult to develop and exploit because of low permeability, scarcity and unpredictability of the major production zones, and difficult drilling. The low reservoir pressure requires very high temperatures just to drive fluid to the surface.

The complexity and limitations of the major production zones were not recognized until Union began infill drilling in 1979. Union recognized that productivity was impaired in some of the earlier wells. However, it took extensive drilling throughout the project area to define the areal extent of productivity impairment factors (M. Gulati and R. Dondanville, 1982, personal commun.).

Failure of many infill wells forced Union to develop a well-targeting model (Behrman and Knapp, 1980) that emphasizes fracture permeability along the major faults that form the structural graben. Other potential avenues of fluid flow, such as the east-west faults, columnar jointed units, or permeable sands, were not integrated into the targeting of subsequent wells.

The failure of this fault model to successfully target production wells appears to have been the major contributor to Union's decision to halt developmental drilling in May 1981. Attempts to explore for deeper production zones were unsuccessful, and the DOE Project was terminated by mutual agreement in January 1982.

The extensive data made available by Union's development of the Baca project area has significant value for understanding this and similar geothermal reservoirs. Further conclusions of the Review Team are:

- Geochemical conclusions from the Baca wells were very limited. Further sampling and interpretation of such data can yield valuable information regarding conditions within the reservoir, as has been illustrated for many geothermal fields.

- Careful analysis of well data has shown that a two-phase zone is present in some part of the reservoir, and that the extent of this zone is very sensitive to the CO_2 content of the reservoir. Identification of two-phase zones in a geothermal reservoir is necessary to understand its behavior under exploitation.

- Although geophysics helped Union Geothermal locate a low-resistivity anomaly at depth beneath Redondo Canyon, the initial surveys were not followed up with more detailed investigations that might have delineated the extent of the resource.

- Stimulation of sub-commercial geothermal wells is a possible alternative to drilling new wells. Although two stimulation tests at Baca were technically successful, sustained commercial production was not obtained. For low-permeability reservoirs, hydraulic fracturing will yield commercial production only if the induced fracture intercepts major avenues of fluid flow.

- The early estimate that the ultimate power-generating capacity of the Baca reservoir would be 400 MWe for 30 years is believed to be far too high. The estimate was based on a lumped-parameter model that greatly overestimated the generating capacity of the resource. Subsequent studies have shown that in dealing with low-permeability reservoirs such as Baca, a distributed parameter model is necessary for a realistic assessment of the reservoir.

- The project has yielded very important information regarding exploration and exploitation of low-permeability, fractured geothermal reservoirs.

APPENDIX 1. LIST OF CONTRIBUTORS

Geologic Exploration

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APPENDIX 2. DRILLING PROBLEMS, BACA PROJECT

Baca well	TD (ft)	BHT (°F)	Steam (lb/hr)	Notes
4 OH	5048	N/A	N/A	Deep drilling halted by steam/water
4 deep	6378	>532	47,500	entry. Possible "internal discharge."
5 OH	2878	N/A	-	2459' drillpipe in hole.
5 A	6973	~ 485	-	Temperature reversal @ 3500'.
6 OH	3715	~ 500	45,400	30% liner slots plugged with clay
6 deep	4810	~ 505	38,500	powder. Attempts to run slotted liner failed, bridged, casing collapsed, closed in.
9 OH	3518	N/A	-	Bad sloughing, extensive fishing.
9 RD	5303	N/A	-	Sidetracked 250' stuck pipe, hazardous conditions from worn and damaged casing.
10	6001	~ 555	44,000 @ 16 psi	Planned for 7500', production interval damaged during fishing.
11	6924	>627	116,000	Drilling stopped because of sloughing redbeds, "interval discharge." Severe production decline from carbonate scale deposit.
12 OH	9212	~ 585	-	
12 RD	10,637	646	-	Limestone and basement granite test.
13	8228	~ 580	54,000	
14	6824	~ 545		Plugged back to 5780' due to sloughing. Serious scaling (silica) from injected fluid.
15	5505	~ 540	105,000	"Interval discharge" indicated @ 2525' near casing shoe.
16	7002		44,000	Possible "interval discharge," with water existing wellbore @ 3600' and 5400'.
17 OH	5791		N/A	Plugged back and sidetracked
17 RD	6254		N/A	@ 3056'; initially productive, casing collapsed.

APPENDIX 2 (continued)

Baca well	TD (ft)	BHT (°F)	Steam (lb/hr)	Notes
18 OH	4597		N/A	Potentially productive, drill pipe and tools left in hole.
18 RD1	2766		-	Lost bit in hole, sidetracked.
18 RD2	5250		-	Non-productive.
19	5610		32,000 @ 10 psi	Junk and fish recovered, sub-commercial.
20 OH	6863		-	542' fish sidetracked in hole.
20 RD	6374	549	30,000	
21	3000	436	34,000 @ 75 psi	Sub-commercial.
22 OH	6017		N/A	Potentially productive, 1771' fish in hole.
22 RD1	6485		41,000 @ 45 psi	Sub-commercial.
22 RD2	6006		20,000 @ 8 psi	Sub-commercial.
22 RD3	8846		-	Deep production test, stopped by fish in hole.
23	5746		-	Non-productive.
23 Recompl.	3515	450	48,000 @ 51 psi	Possibly commercial.
24	5502		33,000	Deep production test, stuck drill pipe @ 5502'.

Subtotals	19	Original holes (OH)
	10	Redrills (RD)
	2	Deepenings
Total	31	Drilling actions

REFERENCES

Albright, J. N., and Pearson, C. F., 1982, Acoustic emission as a tool for hydraulic fracture location, the experience at the Fenton Hill Hot Dry Rock Site: Paper SPE 10898, Soc. Pet. Eng. Jour., in press.

Bailey, R. A., Smith, R. L., and Ross, C. S., 1969, Stratigraphic nomenclature in the Jemez Mountains, New Mexico: U.S. Geol. Survey Bull. 1274-P, 19 p.

Behrman, P. G., and Knapp, R. B., 1980, Structure of the Redondo Creek area, Baca project, New Mexico--implications concerning the nature of permeability/production and recommendations for future drilling: Union Oil Co., Geoth. Div., Private Rept., 43 p.

Bodvarsson, G.S., Vonder Haar, S.P., Wilt, M.J., and Tsang, C.F., 1980, Preliminary estimation of the reservoir capacity and the longevity of the Baca Geothermal Field, New Mexico: Paper SPE 9273, presented at 55th Annual Fall Technical Conference SPE-AIME.

Christensen, B., and Atkinson, P., 1981, Baca-20, Redondo Creek Field: summary and analysis of flowtests 1 through 4; 4/80 to 1/81: Union Oil Company, Internal Report.

Corwin, R.F., and Hoover, D.B., 1979, The self-potential method in geothermal exploration: Geophysics, v. 44, no. 2, p. 226-245.

Doell, R. R., Dalrymple, G. B., Smith, R. L., and Bailey, R. A., 1968, Paleomagnetism, potassium-argon ages, and geology of rhyolites and associated rocks of the Valles Caldera, New Mexico, in Coats, R. R., Hay, R. L., and Anderson, C. A., eds., Studies in volcanology: Geol. Soc. America Mem. 116, p. 211-248.

Dondanville, R. F., 1971, The hydrothermal geology of the Valles Caldera, Jemez Mountains, New Mexico: unpublished manuscript, 36 p.

Dondanville, R. F., 1978, Geologic characteristics of the Valles Caldera geothermal system, New Mexico: Geoth. Resources Council, Trans., v. 2, p. 157-160.

Fournier, R. O., and Truesdell, A. H., 1973, An empirical Na-K-Ca geothermometer for natural waters: Geochim. et Cosmochim. Acta., v. 37, p. 1255-1275.

Garg, S. K., and J. W. Pritchett, 1980, Pressure transient analysis for hot water and two-phase geothermal wells: some numerical results: Topical Report No. DOE/ET/27163-5, Systems, Science and Software (S-Cubed), La Jolla, Calif.

Garg, S. K., and Rice, L. F., 1982, Interference test data and analysis for Baca wells in the Redondo Creek area: Topical report, S-Cubed (formerly Systems, Science and Software), La Jolla, Calif.

Goff, F. E., and Gardner, J. N., 1980, Geologic map of the Sulphur Springs area, Valles Caldera geothermal system, New Mexico: Los Alamos Sci. Lab. Map LA-8634.

Goff, F., and Kron, A., 1980, In-progress geologic map of Canon de San Diego, Jemez Springs, New Mexico, and lithologic log of Jemez Springs geothermal well: Los Alamos Sci. Lab. Map LA-8276.

Grant, M.A., and Garg, S.K., 1981, Baca geothermal demonstration project: interpretation of downhole data from the Baca Geothermal Field: Systems, Science and Software (S-Cubed), La Jolla, California.

Hartz, J. D. 1976, Geothermal reservoir evaluation of the Redondo Creek area, Sandoval, County, New Mexico: Union Oil Company, Internal Report.

_____________, 1977, Baca-15 production test and reservoir evaluation: Union Oil Company, Internal Report.

Jiracek, G.P., Smith, C., and Dorn, G., 1975, Deep geothermal exploration in New Mexico using electrical resistivity: Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources, v. 1, p. 1095-1103.

Morrison, H. F., and Corwin, R.F., 1981, Interpretation of self-potential data from geothermal areas: Final Technical Report, Engineering Geosciences, University of California, Contract 14-08-0001-16546, U.S.G.S. Geothermal Research Program.

Pearson, C. F., 1981, The relationship between microseismicity and high pore pressures during hydraulic stimulation experiments in low permeability granitic rocks: Jour. Geophys. Res. v. 86, p. 7855-7864.

Pritchett, J. W., M. H. Rice and T. D. Riney, 1980, Equation-of-state for water-carbon dioxide mixtures: implications for Baca reservoir: Topical Report No. DOE/ET/27163-8, Systems, Science and Software (S-Cubed), La Jolla, Calif.

Pye, S., 1981, Drilling, completing and maintaining geothermal wells in Baca, New Mexico: Proceedings, International Conference of Geothermal Drilling & Completion Technology, Albuquerque, NM, Jan. 21-23, Sandia National Laboratory Report, SAND81-0036C.

Riney, T. D., and S. K. Garg, 1982, Pressure tests for individual Baca wells in the Redondo Creek area: Topical Report, S-Cubed (formerly Systems, Science and Software), La Jolla, Calif.

Ross, C. S., and Smith, R. L., 1961, Ash-flow tuffs--their origin, geologic relations and identification: U. S. Geol. Survey Prof. Paper 366, 81 p.

Segar, R., 1971, Quantitative gravity interpretation Valles Caldera area, Sandoval and Rio Ariba Counties, New Mexico: Union Oil Company, Internal Report.

Smith, R. L., and Bailey, R. A., 1968, Resurgent cauldrons, in Coats, R. R., Hay, R. L., and Anderson, C. A., eds., Studies in volcanology: Geol. Soc. America Mem. 116, p. 613-662.

Smith R. L., Bailey, R. A., and Ross, C. A., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geol. Survey Misc. Inv. Map I-571.

Truesdell, A. H., 1976, Summary of Section III- Geochemical techniques in exploration, Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, v. 1, p. liii.

Union Oil Company, Geothermal Division, 1973-1981, "Mud" logs (generalized lithology, drilling rate, and temperature) for wells Baca 4 through 24.

Union Oil Company of California and Public Service Company of New Mexico, 1978, Geothermal Demonstration Plant: Technical and Management Proposal to DOE.

Wilt, M., and Vonder Haar, S., 1982, A geological and geophysical study of the Baca Geothermal Field, Valles Caldera, New Mexico: Lawrence Berkeley Laboratory Report LBL-12966.

DOCUMENTS NOT CITED IN TEXT

Republic Geothermal Inc., 1980, Proposal for producing well hydraulic fracture stimulation treatment - Baca project area: Internal document, Republic Geothermal Inc., Santa Fe Springs, California.

Republic Geothermal Inc., 1980, Proposal for producing well hydraulic fracture stimulation treatment - Baca project area: Internal document, Republic Geothermal Inc., Santa Fe Springs, California.

Republic Geothermal Inc., 1982, Post-stimulation reports on Baca 23 and 20: Internal document, Republic Geothermal Inc., Santa Fe Springs, California.

Union Geothermal Division

Union Oil Company of California
Union Oil Center, Box 7600, Los Angeles, California 90051
Telephone (213) 977-6260

Baca, New Mexico
Geoth

UNION 76

Carel Otte
President

February 3, 1982

Mr. Joe La Grone
Manager
San Francisco Operations Office
U.S. Dept. of Energy
1333 Broadway
Oakland, CA 94612

Dear Mr. La Grone:

RE: Baca GDPP Project Meeting, January 19, 1982

A meeting was held in Union's Los Angeles office on January 19, 1982 to consider what course of action to take regarding the Baca Geothermal Demonstration Power Plant (GDPP) Project. Attending the meeting were management, technical and legal representatives from each of the three parties involved in the GDPP Project (Union, DOE and PNM). At the conclusion of the meeting it was mutually agreed by the three parties to terminate the project.

Prior to the start of the GDPP Project, Union had drilled eleven wells, five of which had proven productive. One wellbore had collapsed but the remaining four wells were producible at a combined rate of 320,000 lbs/hr. of steam or about one-third of the required steam supply. We estimated that up to ten more successful wells would be required to supply an additional 600,000 lbs/hr. of steam to meet the total requirement of the proposed 50 MW plant. From the time work began under the cooperative agreement to April 1981, twelve bottom hole locations had been drilled from seven wells, but only 30,000 lbs/hr. of additional steam had been developed.

In April 1981, a thorough technical review of drilling and testing activities was conducted. The results of this review were set forth in my letter of May 1, 1981 to you (see Appendix I). The principle conclusions derived from the review were:

1. The resource is an extensive, high temperature hydrothermal system containing fluids with benign chemical characteristics.

2. Geochemical data suggest produced fluids are originally from a common aquifer at depths below the then current completion depths in the lower Bandelier Tuff in Redondo Creek.

3. The lower Bandelier Tuff in Redondo Creek possesses insufficient distribution of natural fractures to justify the drilling and completion of future development wells solely in this zone.

4. Continued experimentation with existing wells to refine and improve hydraulically fracturing of wells appeared justified based on the qualified success of a recent first attempt in Redondo Canyon.

Based on this technical review, Union proposed a $6.5 million program for the remainder of 1981, the successful completion of which would dictate the viability of resumption of all phases of the project. The program consisted of drilling three deep attempts to test the productivity of the Magdalena Limestone and the upper part of the basement complex (mostly granite), and to hydraulically fracture two existing wells in the Bandelier Tuff and lower competent formations.

During the remaining eight months of 1981, this program was implemented and the disappointing results are described in "1981 Baca GDPP Project Interim Test Program" (see Appendix II). Three deep drilling attempts were made to achieve a Magdalena Limestone/granite formation producer but none was successful. Further drilling to deep horizons can no longer be justified as the cost of a completed well, now estimated at $3.0 million, would be economically prohibitive. One frac stimulation was performed and also did not result in a commercial producer. The drilling rig was released on December 18, 1981. The total cost of this interim program was about $6.9 million.

The overall drilling history of the GDPP project is presented in Appendix III. In summary, prior to DOE participation, Union had drilled eleven wells, one of which, Baca No. 12, was off the shallow high temperature anomaly. Five wells were successfully completed in the Bandelier Tuff reservoir yielding a total of 353,000 lbs/hr. steam at line pressure; the casing in Baca 6 subsequently collapsed, reducing the steam count to 320,000 lbs/hr. After DOE participation, the Bandelier Tuff reservoir was penetrated thirteen times, counting original holes and redrills. Of these, only two wells, Baca Nos. 20 and 24, were successfully completed for a total of 63,000 lbs/hr. additional steam. The overall success ratio in the Bandelier Tuff reservoirs is seven completions out of twenty-three penetrations.

All of the above information was considered at the January 19, 1982 meeting and formed the basis for the mutual agreement by all three of the parties that the project was no longer commercially viable and should be terminated.

Appropriate representatives from each of the three parties involved in the project have been designated to prepare the necessary documents to fulfill terms regarding termination of the Cooperative Agreement. These activities are currently in progress and we will be sending you a proposal soon.

Sincerely yours,

Carel Otte

CO/jh
attachments

cc: Dr. James Bresee, w/attach.
Mr. Art Wilbur "
Mr. Jack Wilkins "
Mr. W. Manning "
Mr. D. Bedford "
Mr. J. Maddox "

APPENDIX I

Union Geothermal Division

Union Oil Company of California
Union Oil Center, Box 7600, Los Angeles, California 90051
Telephone (213) 977-6260

Carel Otte
President

May 1, 1981

Mr. Joe La Grone
Acting Deputy Under Secretary
United States Department of Energy
Forrestal Building, Rm. 7B226
Washington, D.C.

Dear Mr. La Grone:

This is to advise you that Union Geothermal Company of New Mexico must recommend to the Department of Energy a deferment in the planned construction schedule of the 50 MW Baca Geothermal Demonstration Power Plant (GDPP). We are making this recommendation because at this time we have no assurance of our ability to develop an adequate steam supply for an October, 1982 plant start-up.

At the start of the GDPP project, Union had drilled 10 wells, half of these had proven to be productive and Union had 4 producing wells ready with 320,000 lbs/hr of steam for the 50 MW plant. We have only developed 30,000 lbs/hr more steam since work began under the Cooperative Agreement, although we have drilled to 12 bottom-hole locations from 7 new wells. The cost of drilling these wells has escalated rapidly during the project life, and, when coupled with the lack of successful well completions, has placed a cloud of uncertainty over proceeding with the project unless we can drill wells more successfully. The project needs to develop about 600,000 lbs/hr more steam supply. It will take up to 10 more successful wells to achieve this supply for a plant start-up.

Our Union Geothermal Division staff has recently completed a thorough technical review of the results of our drilling and well testing activities. Listed below are the principal conclusions derived from this review.

1. All available evidence indicates that we are still dealing with an extensive, high temperature hydrothermal system containing fluids with benign chemical characteristics.

2. Geochemical data suggest produced fluids are from a common aquifer of about 624 degrees F. Since the vast majority of the measured bottom-hole temperatures of the wells in Redondo Creek range from 500 to 550 degrees F, it is reasonable to conclude that the fluids are being heated to stable temperatures

at depths below the current well depths and are convecting up into the lower part of the Bandelier Tuff.

3. The lower part of the Bandelier Tuff in Redondo Creek does not contain sufficient distribution of natural fractures to economically justify the drilling and completion of future development wells solely in this zone. Until a method is proven economically feasible to artificially induce fractures in this zone, subsequent drilling should seek more productive formations below the Bandelier Tuff.

4. The first attempt to hydraulically fracture a well in the Redondo Creek area appears at least initially to have been a success. Continued experimentation with existing wells to refine and improve this technique seems justified.

These conclusions of our technical review have brought us to where we are today, recommending that plant and field facility construction be deferred until an adequate steam supply can be assured. More details of our technical review are included in the attachments.

We are still convinced that a significant geothermal resource exists at the Baca Ranch. We are recommending that the project proceed with a program of both deep drilling and hydraulic fracturing to test both of these concepts in as short a time as possible. The program consists of drilling 3 deep attempts to test the productivity of the Magdalena Limestone and the upper part of the basement complex (mostly granite), and to hydraulically fracture 2 existing wells in the Bandelier Tuff and lower competent formations. The program will take about 6-7 months and cost about $6.5 million, but this may change somewhat if specific parts of the program are altered during implementation, or the program may be terminated if additional information is developed along the way that would indicate that further expenditures are not justified.

Significant success with this program should allow us to recommend resumption of all phases of this project. It should also be noted that this program will also provide industry at large with technical data and information on various new drilling, completion and well stimulation techniques.

Union Oil is commencing this program by drilling of well Baca #24 located in the high heat flow area of this prospect and programmed to a depth of 8500 feet to the top of the granite.

In anticipation of the success of the drilling test program, Union Oil is also proceeding with its legal preparation for the Santa Ana Pueblo Appeal of the State Engineer's water rights decision.

We recommend that the DOE also vigorously resist the lawsuit by the All Indian Pueblo Council.

It is our hope that DOE will continue to participate in the project and in our planned program. We invite you and your staff to review our information and records on the Redondo Creek wells to determine your own conclusions regarding this project.

Yours very truly,

UNION OIL COMPANY OF CALIFORNIA

ORIGINAL SIGNED BY
CAREL OTTE

Carel Otte
President
Union Geothermal Division

CO/jh
attachments

cc: Messrs. J. Salisbury - DOE, w/attachments
W. Manning - DOE "
A. Wilbur - DOE "
D. Bedford - PNM "
J. Wilkens - PNM "
J. Maddox - PNM "

bcc: Messrs. R. Burke - Union, w/attachments
J. Harrell - Dunigan, w/attachments
S. Lipman - Union "
V. Suter - Union "
R. Engebretsen - Union "
R. Dondanville - Union "
R. Lindwall - Union "

APPENDIX A

GEOLOGIC SYNOPSIS

The location of the proposed Redondo Creek, New Mexico, 50 MW geothermal demostration plant is situated in a volcanic structure known as the Valles Caldera. The Valles Caldera is a subcircular depression, 12 to 15 miles in diameter, in the center of the Jemez Mountains. Volcanic activity, which began in the Jemez Mountains about twelve million years ago, culminated about one million years ago with the formation of the caldera. At that time huge explosive eruptions produced a widespread deposit of rhyolitic tuff and pumice (Bandelier Tuff). Simultaneously with the eruptions, the eruptive area collapsed along a ring-fracture zone. Because of the simultaneous eruptions-collapse, the Bandelier Tuff is over 6000 feet thick with in the caldera, but only about 1000 feet thick outside. Volcanism, in the form of rhyolite domes, continued until as recently as 100,000 years ago. To date, exploration for geothermal resources in the Valles Caldera has been concentrated in the Bandelier Tuff reservoir.

Evidence that the Valles Caldera is an excellent geothermal prospect is abundant within the caldera. The principal surficial geothermal features, illustrated on Figure 1, are:

a. Widespread distribution of rhyolitic volcanics in space and time.
b. Large areas of hydrothermally altered rock.
c. Abundant hot spring and gas vents.

Shallow temperature gradient holes show that anomalously high temperature gradients extend over much of the western portion of the caldera, both inside and outside of the ring fracture zone. At depth, measured temperatures exceed 600°F. At the Los Alamos dry-hot rock project, just west of the caldera, 620°F has been measured at a depth of 16,700 feet. Within the caldera, the maximum temperature measured is 625°F in Union's Baca-11 well at a depth of 6931 feet.

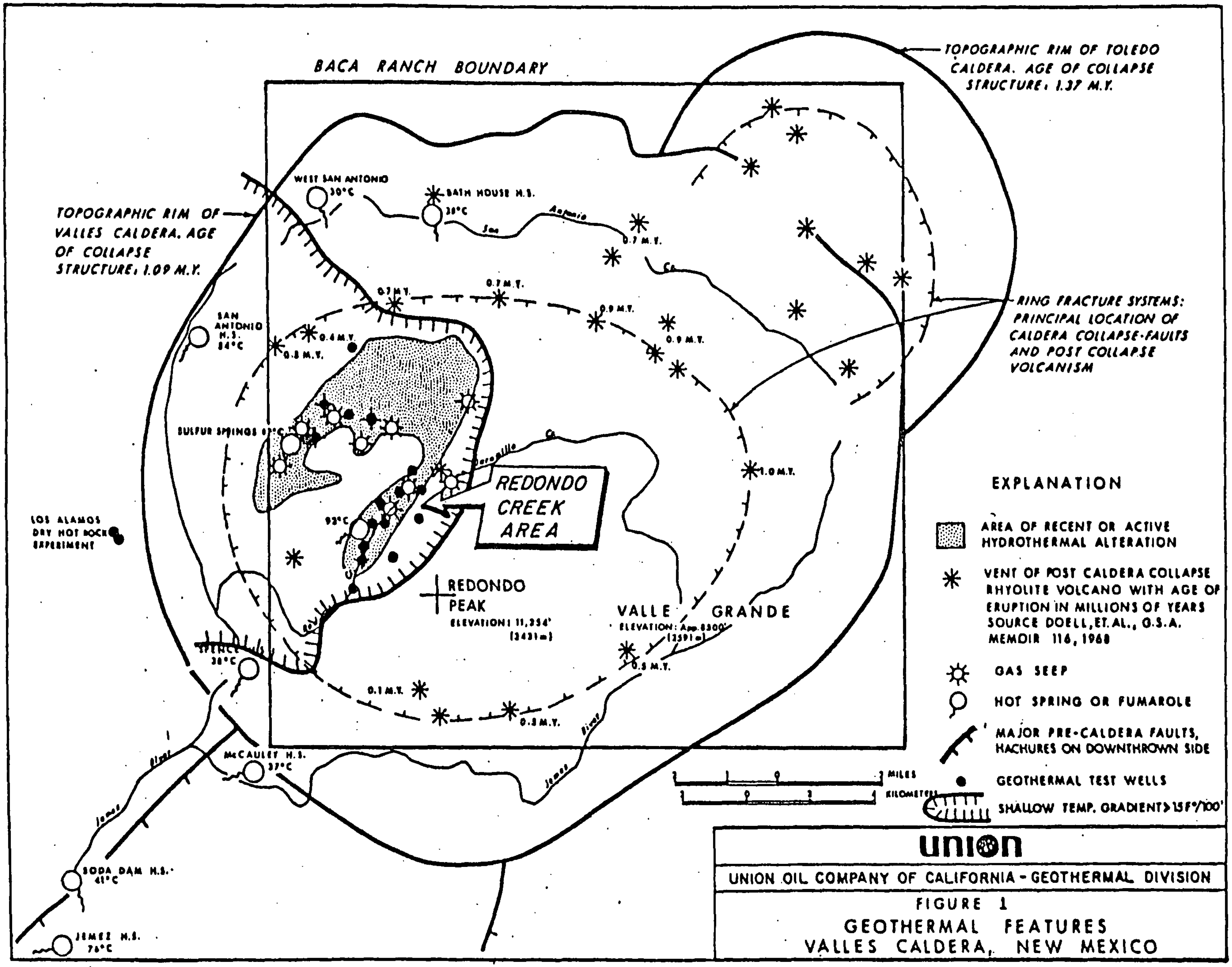


FIGURE 1
GEOTHERMAL FEATURES
VALLES CALDERA, NEW MEXICO

Dondanville

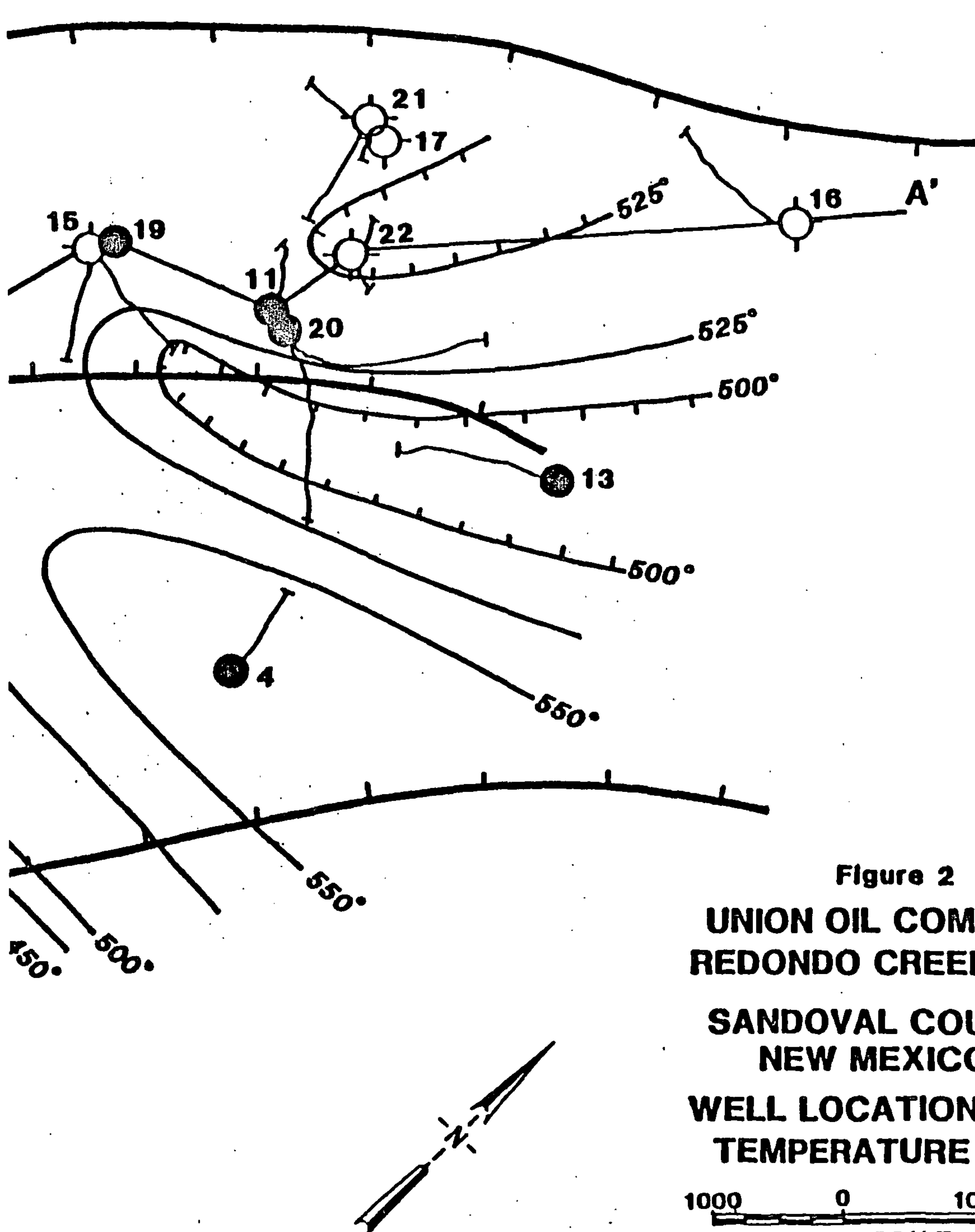


Figure 2

UNION OIL COMPANY
REDONDO CREEK AREA

SANDOVAL COUNTY, NEW MEXICO

WELL LOCATION and TEMPERATURE MAP

1000 0 1000 2000
SCALE

APRIL, 1981

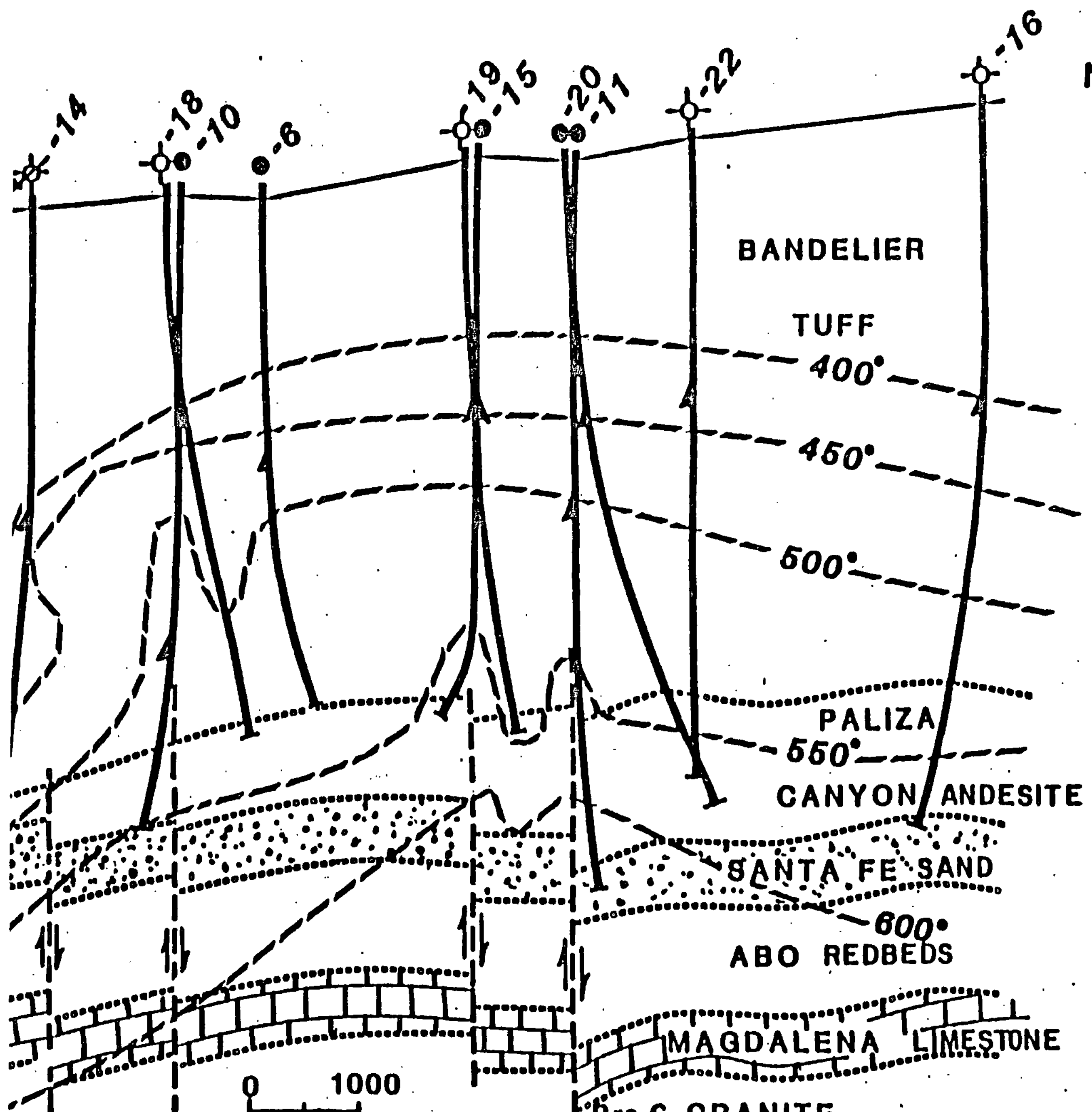


Figure 3

GEOLOGIC & ISOTHERMAL CROSS SECTION of REDONDO CREEK BACA, NEW MEXICO

(WELL TEMPERATURES PROJECTED ONTO SECTION)

APPENDIX B

DRILLING HISTORY

It is apparent from the geologic discussion in Appendix A that drilling success in the Bandelier Tuff depends upon intersecting the fractures which act as conduits to the deeper source formations. The drilling history has been summarized in Tables I and II. Table I summarizes results before DOE participation. Table II summarizes results after DOE participation. Prior to DOE participation, 8 penetrations of the high temperature reservoir resulted in 5 successful completions, for a total potential production of 353,000 lbs/hr steam at line pressure. The casing in Baca 6 subsequently collapsed, reducing the steam count to 320,000 lbs/hr. After DOE participation, the high temperature reservoir has been penetrated twelve times, counting original holes and redrills. Of these, only one well, Baca 20, was successfully completed at a rate of 30,000 lbs/hr steam. The overall successful completion is 6 completions out of 19 reservoir penetrations. From the drilling history and the geologic observations concerning the irregularity of fractures in the Bandelier Tuff, we conclude that the Bandelier Tuff may not contain an adequate distribution of natural fractures to justify development. Until a method is found to artificially induce fractures in the Bandelier, subsequent drilling probably should seek productive formations below the Bandelier Tuff.

TABLE I

PRE-DOE WELLS

WELL	T.D.	COST ($000)	STATUS	STEAM (At Line Pressure)
Baca 4	6378'		Commercial	
Baca 5A	6973'		Water Injector	Off High Temp. Reservoir
Baca 6	4810' (3455' Bridge)		Initially Commercial Collapsed	(33,000) Now Bridged
Baca 9	5303'	333	P&A	
Baca 10	6001'	635	Mechanical Problems	
Baca 11	6931'	425	Commercial	116,000 lbs/hr
Baca 12	9212'	542	Water Injector	(Off High Temp. Reservoir)
Baca 13	8228'	718	Commercial	54,000 lbs/hr
Baca 14	6824' (5780' cmt.)	908	Water Injector	
Baca 15	5505'	610	Commercial	105,000 lbs/hr
Baca 16	7002'	557	Non-Productive	
			TOTAL:	320,000 lbs/hr

TABLE II

POST-DOE WELLS

WELL	T.D.		COST ($000)	STATUS	STEAM
Baca 17	*OH 5791'	1	914	Non-Productive	
	**RD 6254'	2	733	Initially Productive, Mechanical Problems	
			$1,647		
Baca 18	OH 4597'	3	996	Pot. Productive	
	RD 5250'	4	477	Lost Hole	
				Non-Productive	
			$1,473		
Baca 19	5610'	5	$ 999	Sub-Commercial	(32,000 @ 10 psi)
Baca 20	OH 6863'	6	905	Non-Productive	
	RD 6374'	7	791	Commercial	30,000 lbs/hr
			$1,696		
Baca 21	3000'	8	$ 875	Sub-Commercial	(34,000 @ 75 psi)
Baca 22	OD 6017'	9	$1,263	Pot. Productive, Lost Hole	
	RD1 6485'	10	400	Sub-Commercial	(41,000 @ 45 psi)
	RD2 6006'	11	531	Sub-Commercial	(20,000 @ 8 psi)
			$2,194		
Baca 23	TD 5746'	12	1,261	Non-Productive	
	Recpl.3515'		602	Possibly Commercial	(48,000 @ 51 psi)
			$1,863		
				TOTAL:	30,000 lbs/hr

* OH - Original Hole
** RD - Redrilled Hole

APPENDIX C

BACA RESERVOIR ENGINEERING

The permeability-thickness product of Baca reservoir has been derived from individual well tests and an interference test. It varies between 2000 and 6000 md-ft. The table below shows a comparison of the permeability-thickness product of Baca reservoir with other liquid-dominated geothermal reservoir, the Union Oil Company is associated with.

Reservoir	Average Permeability-thickness product, md-ft
Tiwi (Philippines)	50,000
Bulalo (Philippines)	20,000
Brawley	20,000
Heber	130,000
Baca	6,000

It is clear that the permeability-thickness product found so far in Bandelier Tuff in Baca is much less than comparable systems.

The initial reservoir pressure in Baca is less than the pressure corresponding to hydrostatic head of water. At 3000' below surface, Baca reservoir pressure is approximately 610 psig whereas, in the other liquid dominated systems, the initial pressure at that datum varies from 1270 to 1320 psig.

Thus, the Baca reservoir suffers from two drawbacks:

1. The permeability-thickness product is small, and,
2. The reservoir pressure is low.

The permeability in the wellbores is derived from fractures. If adequate number of fractures are not encountered in a well, the well becomes subcommercial.

There is not much that can be done to increase the reservoir pressure. However, we can try to find or create additional permeability. One place to look for additional permeability is in the zones below the current depth of the wells. We should also actively pursue well stimulation so that we can convert poor producers into good producers.

The Redondo Creeek area (Figure 1), is located in the center of the caldera near the eastern edge of the geothermal anomaly. Structurally, the Redondo Creek area is a northeasterly trending graben, which formed after caldera collapse. Displacement on the major graven faults, Figure 2, exceed 1000 feet, measured at the surface. Major regional faults (Figure 1) which pre-date the caldera and displace can be projected into the Redondo Creek area from the southwest along the Jemez River. Detailed analysis of dip-meter data from the geothermal wells in Redondo Creek shows a preferred northwest-southeast orientation of fractures intersecting the well bore. It would appear, therefore, that the geothermal anomaly in Redondo Creek occurs at the intersection of northeast-southwest trending faults, and northwest-southeast trending fractures, in response to a heat source from a widely distributed youthful magma.

The Redondo Creek geothermal reservoirs (Figures 2 and 3), as it exists in the Bandelier Tuff, is in the range of 500°- 550°F. In plan view (Figure 2), the isotherms are semi-parallel to the Redondo Creek graben faults and are also open to the northwest, indicating influence by the intersecting fracture set. In detail, the temperature distribution is irregular, being measurably hotter in successful wells then in nearby unsuccessful wells. The irregularity is illustrated in Figure 3. The highest measured temperature is 625°F in Baca-11 at total depth of 6931 feet. At this depth, the well bottomed in Tertiary sands of the Santa Fe Formation, about 1500 feet below the base of the Bandelier Tuff. Chemical geothermometry, using the Na-K-Ca geothermometer, of the fluids produced from the 500°- 550°F Bandelier Tuff reservoir indicates equilibration in a 625°F reservoir. The irregularity of the isotherms in the Bandelier Tuff, and the geochemical indication of higher temperatures lead to the conclusion that fluids are being heated to stable temperatures below current well depths and are convecting up along heterogeneously-distributed fractures into the lower part of the Bandelier. The Bandelier thus acts more like a leaky cap rock than a homogeneous reservoir.

Figure 3 also shows the distribution of rocks below the Bandelier Tuff. The Santa Fe sandstone is an excellent storage reservoir, but difficult to produce from because it is usually unconsolidated. The Abo Formation consists of mostly red shales and poorly sorted sandstones, and is probably not a major reservoir rock. The Magdalena limestone and Pre-Cambrian granite are competent rocks which should be able to sustain the fractures necessary for high permeability. All the formations below the Bandelier Tuff in Redondo Creek are inadequately tested.

APPENDIX D

BACA 23 STIMULATION

Baca 23 was stimulated with a hydraulic fracturing technique utilizing 8 stages as shown in the following table:

Stage Number	Mean Pressure Psi	Mean Rate BPM	Volume Pumped Gallons	Proppant Pumped	Remarks
1	3480	41.6	150,430	0	Pond water 25 #/1000 gal FLA
2	3100	72.2	21,000	0	Versagel pad
3	3390	65.0	21,100	2#/gal	100 mesh sand, primarily for fluid loss cont.
4	3290	62.4	22,000	0	Spacer between 100 mesh sand and proppant
5	3470	71.6	37,800	1#/gal	50/50 mixture of Bauxite and super sand
6	3410	71.9	42,000	2#/gal	same
7	3140	43.1	23,150	3#/gal	same
8	3240	53.0	2,500	0	flush
	TOTALS:		319,980	197,000 lbs.	

Two shutdowns occurred during Stage 1 which showed 0.8 psi/ft fracturing gradients. This indicates that the minimum principal stress is quite high compared to other areas we operate in such as The Geysers (.4 psi/ft) and the Imperial Valley (0.5 - 0.6 psi/ft).

The original completion on Baca 23 would not sustain flow, and the isolated fracturing interval from 3300 to 3525 feet was totally non-productive prior to fracturing. After fracturing, the well produced at a sustained rate of 121,000 #/hr total mass flow including 48,000 #/hr of steam, assuming a 40% flash, at 51 psig on the wellhead (two phase rig test using a 5" orifice plate.) This is not a commercial rate, and we are in the process of evaluating whether this is due to fracturing at an interval which is too low in temperature or too low in conductivity.

This stimulation treatment cost $441,000, and was totally paid for by DOE through their geothermal well stimulation program. Preparation and well testing with the rig cost $603,000, and was cost shared by DOE and Union through the Baca agreement.

APPENDIX II

Union Oil Company of California

In Reply Give No.

ROE2-009
4-405

January 29, 1982

TO: S.C. Lipman

FROM: R.O. Engebretsen *ROE*

RE: 1981 BACA GDPP PROJECT INTERIM TEST PROGRAM

In April, 1981, following our technical review of the GDPP Project, a $6.5 million program was proposed for the remainder of 1981 which, if successful, would demonstrate the viability of continuing the project. The proposed program was to drill three deep attempts to test productivity of both the Magdalena Limestone and the granite formations and to hydraulically fracture in the Bandelier Tuff and lower competent formations.

In the eight months following our proposed deep drilling and stimulation test program three attempts were made to achieve a Magdalena Limestone/granite formation producer and none proved successful. One frac stimulation was performed and it, too, did not result in a commercial producer. The total cost for this interim program amounted to approximately $6.9 million.

Further drilling to deep horizons can no longer be justified as the cost of a completed well, now estimated at $3.0 million, would be economically prohibitive for the remaining ten wells needed to supply the 50 Mw power plant. Consequently, in January, 1982, it was mutually agreed by all parties involved in the GDPP Project -- Union, DOE, and PNM -- that the project was no longer commercially viable and should be terminated.

The following is a detailed discussion of the drilling and stimulation work that was performed on each of the wells involved in the 1981 interim program.

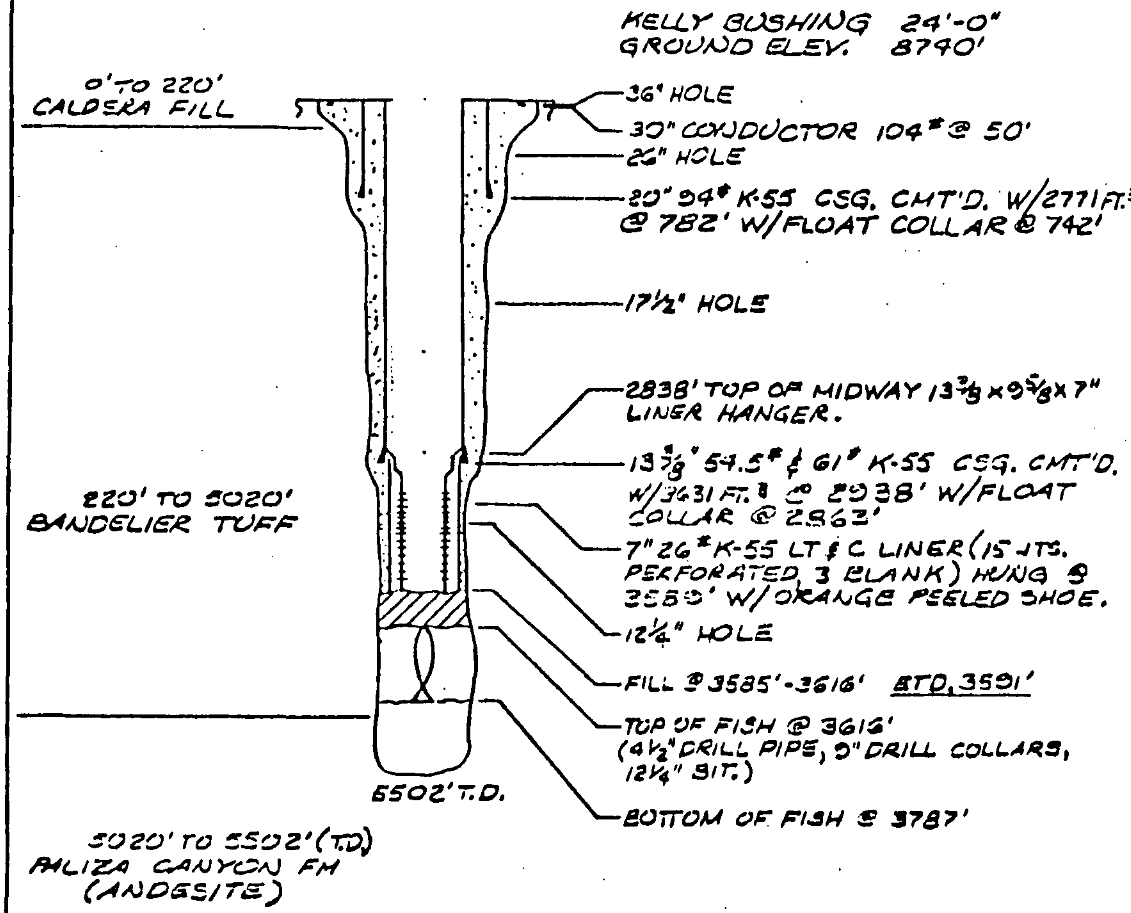
Baca No. 24 was spudded April 23, 1981, as the first attempt for deep production. The well was programmed to 8500' depth, approximately 1000' below the top of the granite. The drill pipe became stuck while drilling in highly altered Andesite at 5502'. The pipe was backed off and part of the fish was recovered, leaving the top of the fish at 4296'. The Andesite and Bandelier Tuff formations began sloughing severely while attempting to run wash pipe in the hole. Several cleanout runs were made with a bit and drilling assembly. While cleaning out at 3832' the well unloaded large amounts of formation, sticking the drill string and plugging surface equipment. The drill pipe was backed off at 3552', leaving a second fish in the hole. Part of the second fish was recovered down to 3616'. Continued severe formation sloughing precluded further fishing attempts. Baca No. 24 was completed June 3, 1981, with a 7" perforated liner run to 3589'. Total cost for the well was $2.0 million. A subsequent separator test on the well indicated it to be capable of producing about 33,000 lb/hr of steam. Figure 1 is a schematic diagram of the completed well.

The rig was then moved to Baca No. 12 and operations to deepen the well to granite commenced August 15, 1981. To facilitate the deepening it was necessary to remove the existing 7" perforated liner and replace it with a blank cemented 7" liner. In order to eliminate lost circulation following removal of the 7" perforated liner and before cementation of the blank liner could be assured, forty-three lost circulation cement plugs and thirty-two days rig time were required. Deepening of the well then progressed by drilling 6-1/8" hole from 9220' original T.D. to 10,637' which is 417' below top of the granite formation. Attempts to induce the well to flow proved unsuccessful. Subsequent injection into the well indicated the exposed limestone and granite formations had extremely low permeability. Drilling operations were discontinued and the well was completed open-hole on September 6, 1981. Total cost for the deepening operation was $1.6 million. A temperature survey run in January, 1982, measured 646°F at 10,190' depth. Figure 2 is a schematic diagram of the completed well.

Operations were then initiated September 12, 1981, to perform a hydraulic fracturing stimulation on Baca No. 20. The original 7" slotted liner (2390'-5812') was pulled and the well plugged back to 4890'. A 7" blank liner was cemented 2383'-4880'. The hole below the 7" liner was cleaned out to 5120'. A hydraulic fracture treatment was then performed using 42,000 lbs. $CaCO_3$ at 0.4 to 1.3 lb/gal in water followed by 344,000 lbs. of 16/20 and 12/20 mesh sintered bauxite at 0.5 to 4.2 lb/gal in gelled water injected at 40-80 BPM with 3800-1800 psig. The hole was then cleaned out and a 5-1/2" perforated liner was installed 4760'-5131'. Figure 3 contains schematic diagrams for the original completion, treatment configuration and final completion. Table I indicates the treating schedule and fluid volumes used to perform the job. Figure 4 shows a plot of the pressure/rate history during the treatment. Analysis of pressure buildup curve obtained following a forty-eight hour flow test indicated about 5,000 md-ft of fracture permeability had resulted from the stimulation. The recompletion was completed October 13, 1981. A subsequent fifteen day flow test indicated the well to be capable of only flowing about 47,000 lb/hr of steam at 28 psig wellhead pressure. Total cost of the stimulation was $1.4 million including $0.4 million which was paid by Republic Geothermal, Inc.

The rig was then moved to Baca No. 22 and operations to redrill the well to granite commenced October 18, 1981. The 7" perforated liner was pulled and the well was plugged back to 2525'. After kicking off at 2551' an 8-3/4" hole was directionally drilled to 8846', about twenty-six feet below the top of the Magdalena Limestone group. Drilling progress was hindered by severe lost circulation problems. A logging tool that was run at 8846' T.D. became stuck at 6525'. Attempts to recover the fish were unsuccessful and further drilling operations were discontinued and the rig released December 18, 1981. Total cost of the redrill/deepening effort was $1.9 million. Figure 5 is a schematic diagram of the Baca No. 22 well as currently completed.

REVISIONS				
REV	DESCRIPTION	DATE	BY	APP'D
0	RELEASED	7-21-81	[illegible]	



DRILLING DETAIL				
H2O & STEAM ENTRIES	FRACTURES	LOST CIR.	DRLG. BREAK	LOGS
3636'		923'	3658' (REPLACED ROTATING HEAD RUBBER) 3662' (TWISTED OFF REC'D FISH) 3730' (REPLACED ROTATING HEAD RUBBER) 4647' (UNSCREWED DRILL PIPE) 5490' (STUCK PIPE @ 5502)	HTR (TEMP.) @ 150°F 0'-2944' DI-GR. 782'-2944' @ 236°F

DATE SPUDDED	DATE COMPLETED	REMEDIALS	
		DATE STARTED	DATE COMPLETED
4-23-81	6-3-81		

FIGURE 1

UNION 76	Union Geothermal Company of New Mexico				
DESIGN		WELL SCHEMATIC BACA NO. 24			
DRAWN	S. FOUZAK-R.				
CHECK	G.I.	SIZE B	AFE NO.	DWG NO. RC1-DR-20	REV 0
DATE	7-21-81	SCALE 1"=1,000'		SHEET 1 OF 1	

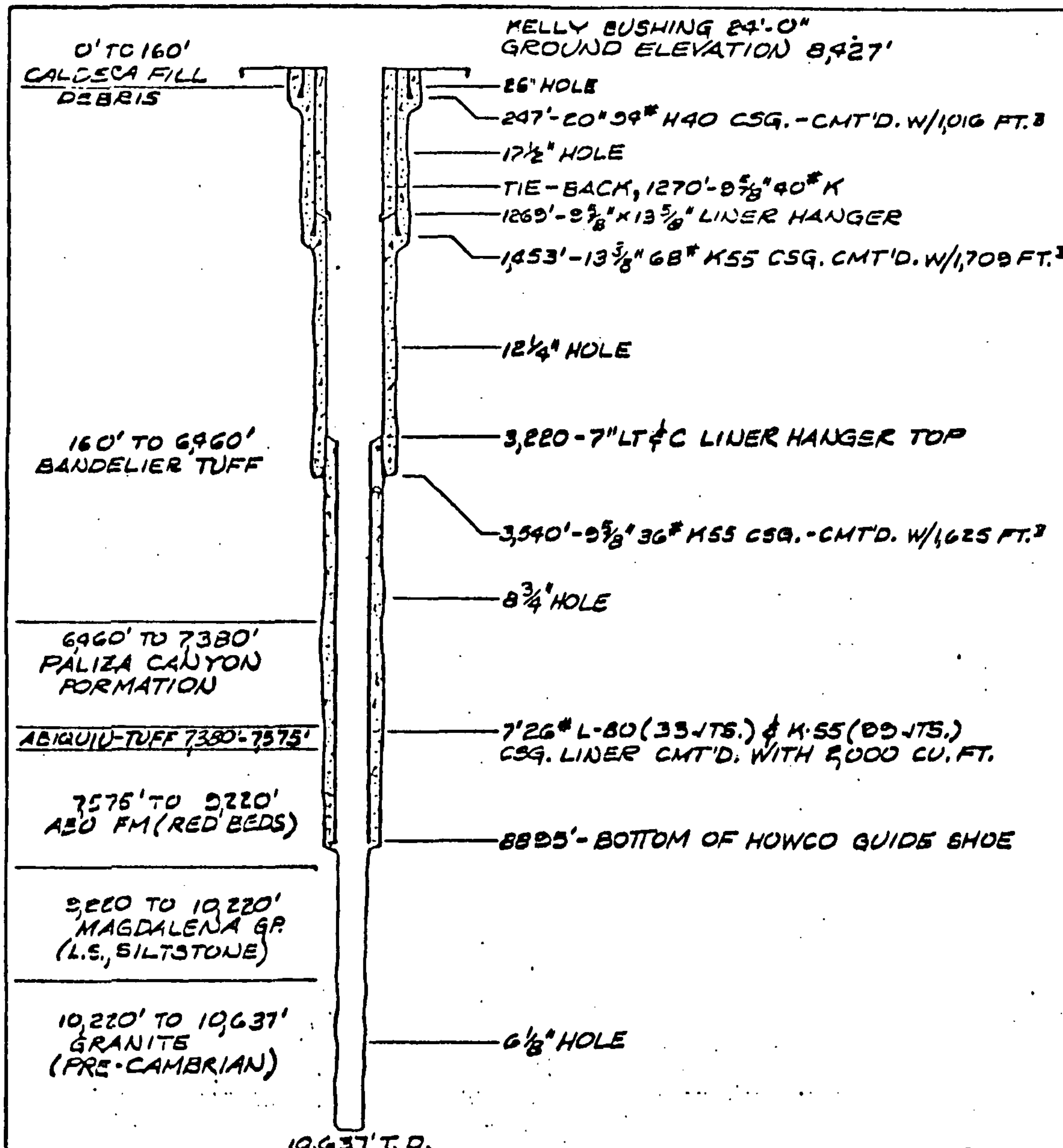


FIGURE 2

REVISIONS				
REV	DESCRIPTION	DATE	BY	APP'D
1	CHECK FOR ACCURACY	3-31-80	REG	
2	REDRAWN	11-13-81	[illegible]	

DRILLING DETAIL				
H_2O & STEAM ENTRIES	FRACTURES	LOST CIR.	DRLG. BREAK	LOGS
		3540'-9212' (SET 45 CMT. PLUGS)		NONE

DATE SPUDDED	DATE COMPLETED	DEEPENING	
		DATE STARTED	DATE COMPLETED
6-19-74	8-19-74	6-27-81	8-16-81

Union Geothermal Company of New Mexico

WELL SCHEMATIC
BACA NO.12

DESIGN	
DRAWN	S. FENZAK JR
CHECK	[illegible]
DATE	3-31-80

SIZE	AFE NO.	DWG NO.	REV
B	303005	RC1-DR-07	2

SCALE: N.T.S. | SHEET 1 OF 1

FIGURE 3

BACA 20
COMPLETION DETAILS

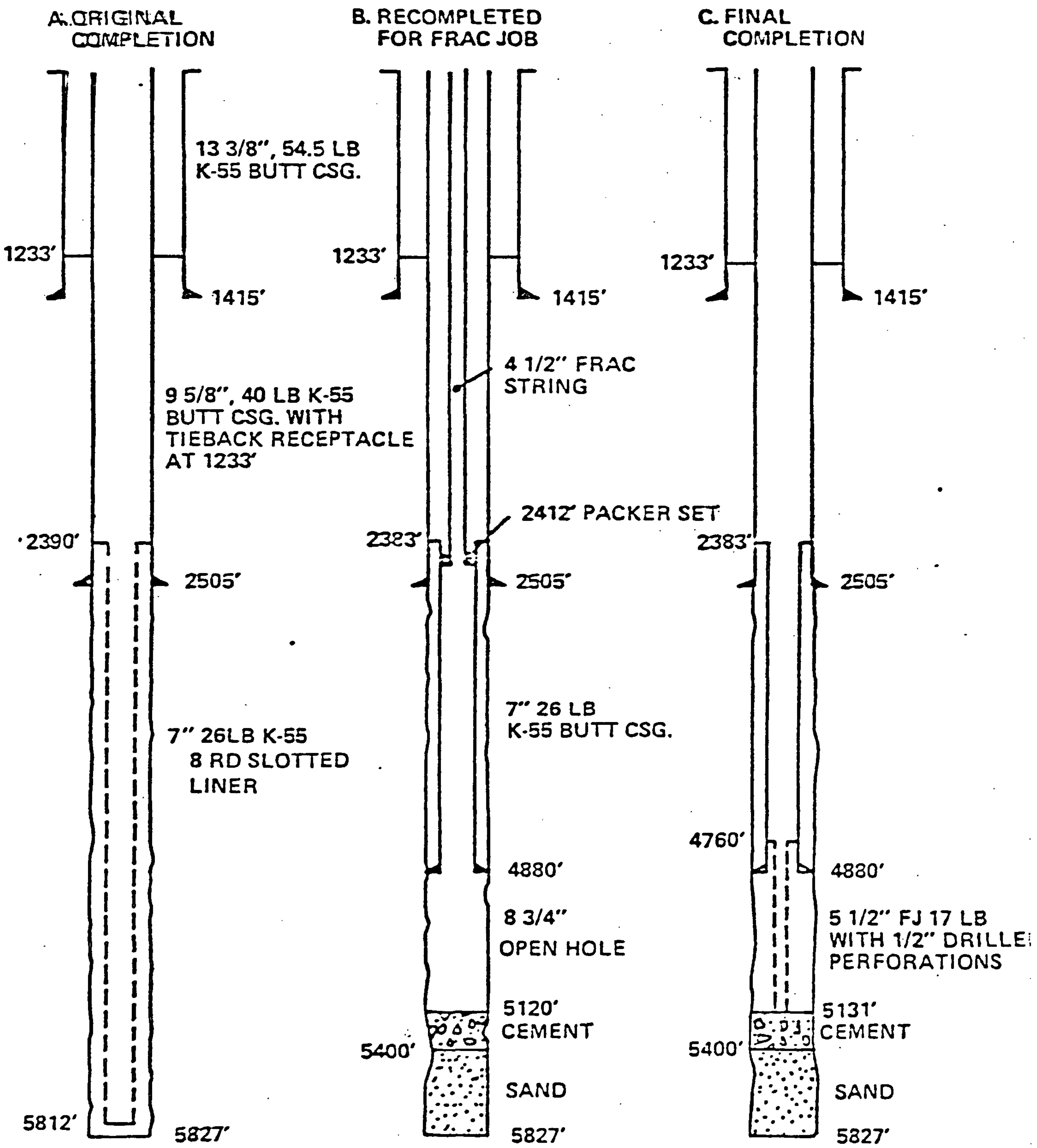


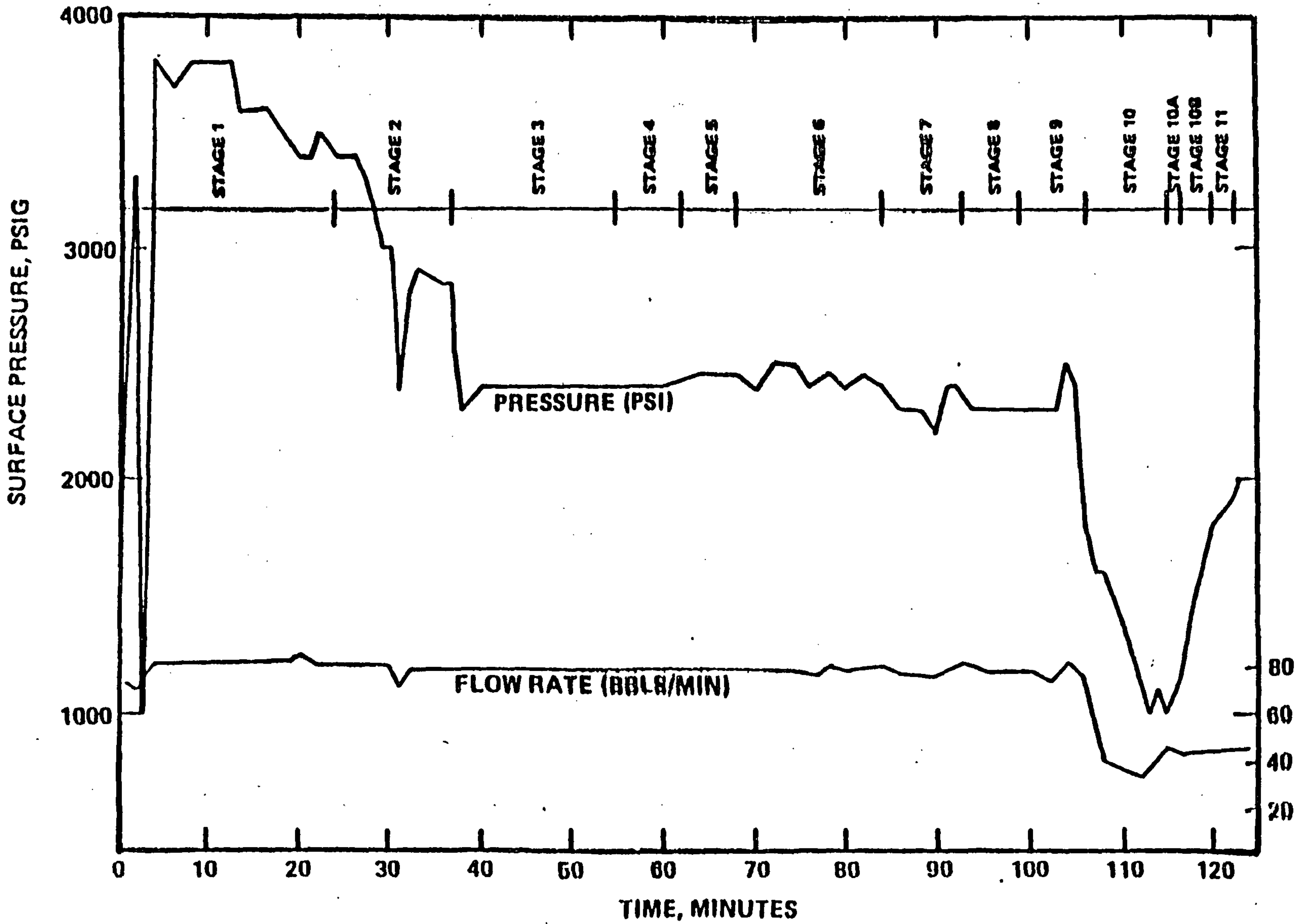
TABLE I

BACA 20 TREATING SCHEDULE
FLUID VOLUME

Stage No.	Planned Size (bbl)	Actual Size (bbl)	Proppant (lb/gal)	Proppant Size	Fluid
1.	2000	2000			FRESH WATER WITH FLUID LOSS ADDTIME (FLA)
2.	500	639	0.39	100-MESH $CaCO_3$ (10,500 LB)	FRESH WATER WITH FLA
3.	500	350			FRESH WATER WITH FLA
4.	1500	1400			POLYMER GEL WITH FLA
5.	500	566	1.33	100-MESH $CaCO_3$ (31,500 LB)	POLYMER GEL WITH FLA
6.	500	500			POLYMER GEL WITH FLA
7.	1150	1168	0.46	16/20-MESH BAUXITE (B)	POLYMER GEL
8. a	850	682	1.85	16/20-MESH (B)	POLYMER GEL
b		378	2.77	16/20-MESH (B)	POLYMER GEL
9.	300	450	2.11	12/20-MESH (B)	POLYMER GEL
10.	750	451	4.21	12/20-MESH (B)	POLYMER GEL
11.	150	151			FRESH WATER
	8700	8735			

FIGURE 4

FRACTURE STIMULATION PRESSURE/RATE HISTORY
UNION BACA 20



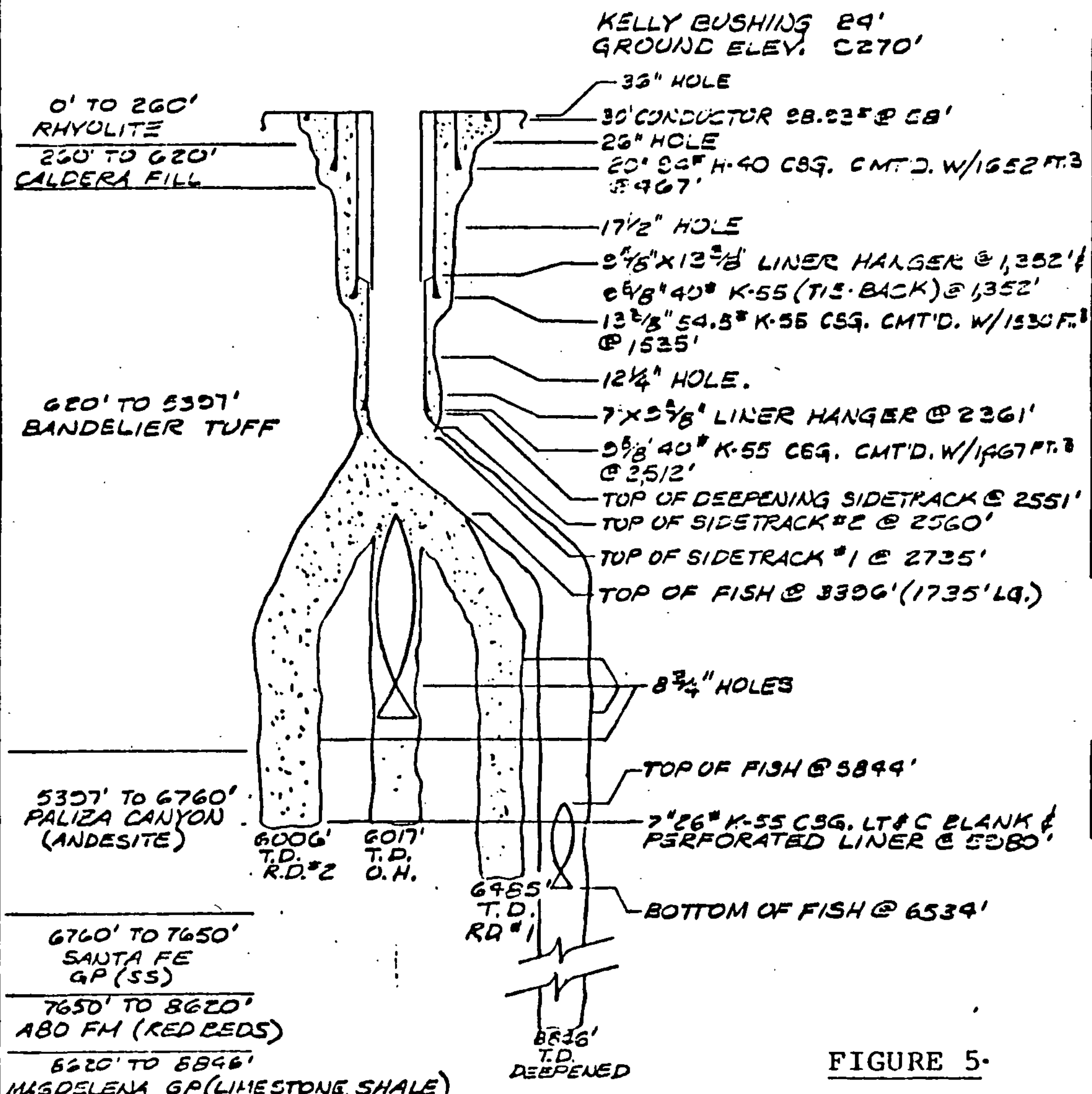


FIGURE 5·

REVISIONS				
REV	DESCRIPTION	DATE	BY	APP'D
0	RELEASED	7-16-81	[illegible]	[illegible]
1	DEEPENING CHANGES	1-15-82	[illegible]	

DRILLING DETAIL				
H2O & STEAM ENTRIES	FRACTURES	LOST CIR.	DRLG. BREAK	LOGS
		652' 685' 2056' 2049'-2120' 2122'-2144' 2144'-2255' DEEPENING 4240'-4250' 4764'-4955' 5365'-5900' 6017'-6071' 6745'-6765' 8130'-8237'	5000'-5060' CORED: 6011'-6017' 4470'-4481'	O.H.: DLL-GR 435'-1,535' HTR (TEMP) 1,492'-2,525' FIL-1531'-2530' CNL-FDC-GR 2512'-5946' I-G-2512'-[illegible] RD.#1 2512'-6253' DEEPENING DLL-GR 2512'-6535' (LOST TOOL)

DATE SPUDDED	DATE COMPLETED	REMEDIALS	
		DATE STARTED	DATE COMPLETED
10-12-80	1-3-81	10-18-81	12-18-81

UNION 76	Union Geothermal Company of New Mexico
DESIGN	WELL SCHEMATIC BACA NO. 22
DRAWN S. FENZAK, R.	
CHECK [illegible]	SIZE B · AFE NO. · DWG NO. RC1-DR-18 · REV 1
DATE	SCALE 1"=1,000' · SHEET 1 OF 1

APPENDIX III

DRILLING HISTORY OF THE UNION-DOE 50 MW BACA GEOTHERMAL DEMONSTRATION POWER PLANT (GDPP)

I. GEOLOGIC SETTING

The location of the proposed 50 MW Baca Geothermal Demonstration Power Plant is situated in a volcanic structure known as the Valles Caldera. The Valles Caldera is a subcircular depression, 12 to 15 miles in diameter, in the center of the Jemez Mountains. Volcanic activity, which began in the Jemez Mountains about twelve million years ago, culminated about one million years ago with the formation of the caldera. At that time huge explosive eruptions produced a widespread deposit of rhyolitic tuff and pumice (Bandelier Tuff). Simultaneously with the eruptions, the eruptive area collapsed along a ring-fracture zone. Because of the simultaneous eruptions-collapse, the Bandelier Tuff is over 6000 feet thick within the caldera but only about 1000 feet thick outside. Volcanism, in the form of rhyolite domes, continued until as recently as 100,000 years ago. To date, exploration for geothermal resources in the Valles Caldera has been concentrated in the Bandelier Tuff reservoir.

Evidence that the Valles Caldera is an excellent geothermal prospect is abundant within the caldera. The principal surficial geothermal features, illustrated on Figure 1, are:

a. Widespread distribution of rhyolitic volcanics in space and time.
b. Large areas of hydrothermally altered rock.
c. Abundant hot spring and gas vents.

Shallow temperature gradient holes show that anomalously high temperature gradients extend over much of the western portion of the caldera, both inside and outside of the ring fracture zone. At depth, measured temperatures exceed 600°F. At the Los Alamos dry-hot rock project, just west of the caldera, 620°F has been measured at a depth of 16,700 feet. Within the caldera, the maximum temperature measured is 646°F in Union's Baca-12 well at a depth of 10,190 feet.

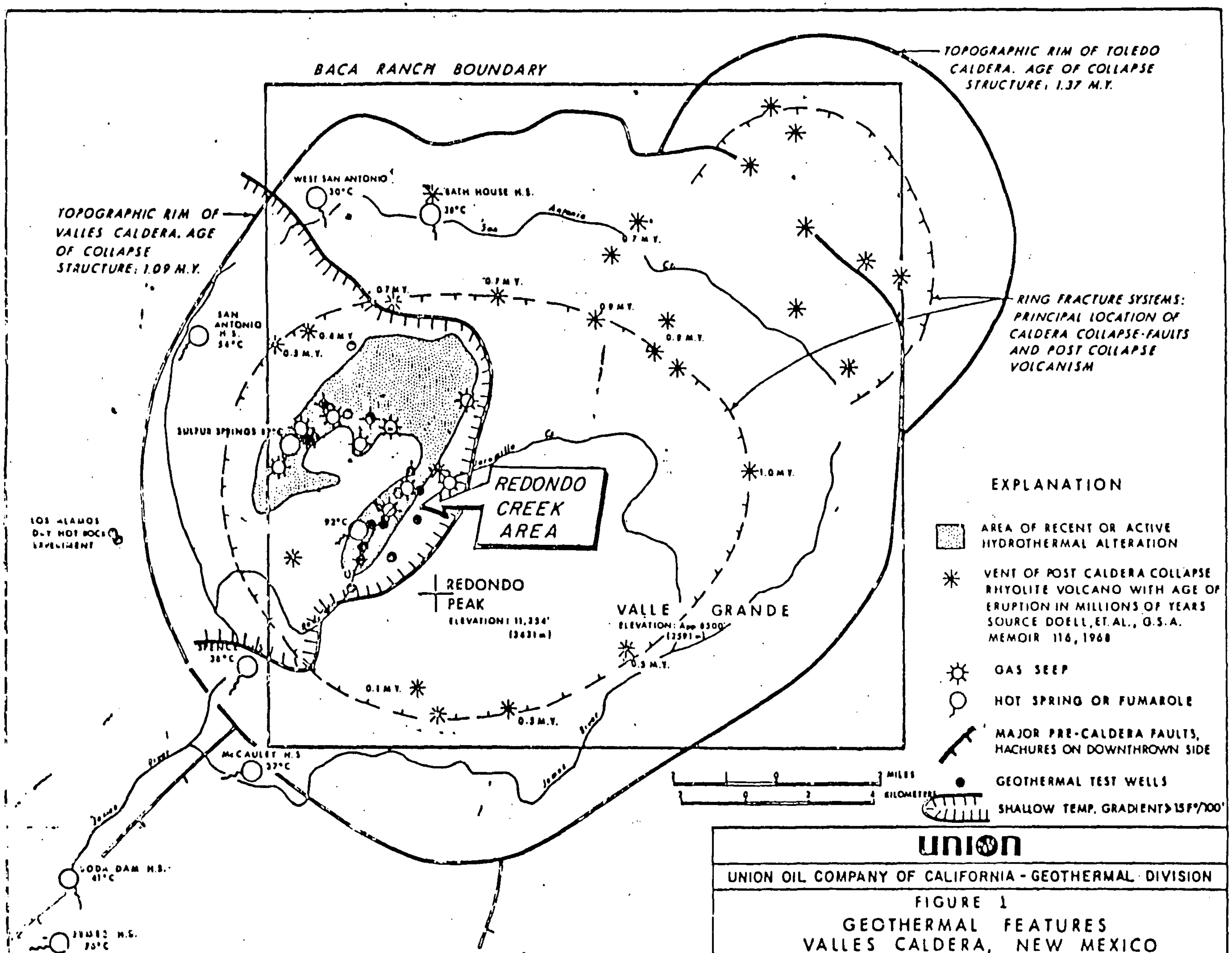


FIGURE 1
GEOTHERMAL FEATURES
VALLES CALDERA, NEW MEXICO

DRILLING HISTORY OF THE
UNION-DOE 50 MW BACA GEOTHERMAL
DEMONSTRATION POWER PLANT (GDPP)

II. DRILLING HISTORY

The drilling history of the GDPP is summarized in Tables I and II, and in Figures 2 and 3. Table I and Figure 2 show results prior to DOE participation, and Table II and Figure 3 show results after DOE participation.

Prior to DOE participation, Union had drilled eleven wells, one of which, Baca 12, was off the shallow high temperature anomaly. Five wells were successfully completed in the Bandelier Tuff reservoir, yielding a total of 353,000 lbs/hr steam at line pressure. The casing in Baca 6 subsequently collapsed, reducing the steam count to 320,000 lbs/hr.

After DOE participation, the Bandelier Tuff reservoir was penetrated thirteen times, counting original holes and redrills. Of these, only two wells, Baca 20 and 24, were successfully completed for a total of 63,000 lbs/hr additional steam. The overall success ratio in the Bandelier Tuff reservoirs is seven completions out of twenty-three penetrations.

Three wells were used in an attempt to achieve production from formations deeper than the Bandelier Tuff. Principal targets were considered to be the Paleozoic limestone and Pre-Cambrian granite. Baca 12 was deepened from 9212' to 10,637'; bottoming in granite. Although hot (maximum temperature 646°F) the deeper zones were impermeable. Baca 24 was drilled from the surface as a deep test, but mechanical problems led to completion in the Bandelier Tuff. Baca 22 was redrilled to 8846 feet, the top of the limestone. The hole was lost during logging operations.

RFD/ge
Attachments
0266g

TABLE I

PRE-DOE WELLS

WELL	T.D.	COST ($000)	STATUS	STEAM (At Line Pressure)
Baca 4	6378'		Commercial	45,000 lbs/hr
Baca 5A	6973'		Water Injector	Off High Temp. Reservoir
Baca 6	4810' (3455' Bridge)		Initially Commercial Collapsed	(33,000) Now Bridged
Baca 9	5303'	333	P&A	
Baca 10	6001'	635	Mechanical Problems	
Baca 11	6931'	425	Commercial	116,000 lbs/hr
Baca 12	9212'	542	Water Injector	(Off High Temp. Reservoir)
Baca 13	8228'	718	Commercial	54,000 lbs/hr
Baca 14	6824' (5780' cmt.)	908	Water Injector	
Baca 15	5505'	610	Commercial	105,000 lbs/hr
Baca 16	7002'	557	Non-Productive	
			TOTAL:	320,000 lbs/hr

TABLE II

POST-DOE WELLS

WELL	T.D.	COST ($000)	STATUS	STEAM
Baca 17	*OH 5791'	914	Non-Productive	
	**RD 6254'	733	Initially Productive, Mechanical Problems	
		$1,647		
Baca 18	OH 4597'	996	Pot. Productive	
	RD 5250'	477	Lost Hole Non-Productive	
		$1,473		
Baca 19	5610'	$ 999	Sub-Commercial	(32,000 @ 10 psi)
Baca 20	OH 6863'	905	Non-Productive	
	RD 6374'	791	Commercial	30,000 lbs/hr @ 125 psi
		$1,696		
Baca 21	3000'	$ 875	Sub-Commercial	(34,000 @ 75 psi)
Baca 22	OD 6017'	1,263	Pot. Productive, Lost Hole	
	RD1 6485'	400	Sub-Commercial	(41,000 @ 45 psi)
	RD2 6006'	531	Sub-Commercial	(20,000 @ 8 psi)
		$2,194		
Baca 23	TD 5746'	1,261	Non-Productive	
	Recpl.3515'	602	Possible Commercial	(48,000 @ 51 psi)
		$1,863		
Baca 24	TD 5502' Eff. TD 3591'	$1,895	Commercial	33,000 @ 131 psi
Baca 12 (deepening to granite)	TD10637'	$1,654	Non-Productive	
Baca 22 (deep re-drill)	TD 8846'	$1,993	Non-Productive	
			TOTAL:	63,000 lbs/hr @ linepressu

* OH - Original Hole
** RD - Redrilled Hole

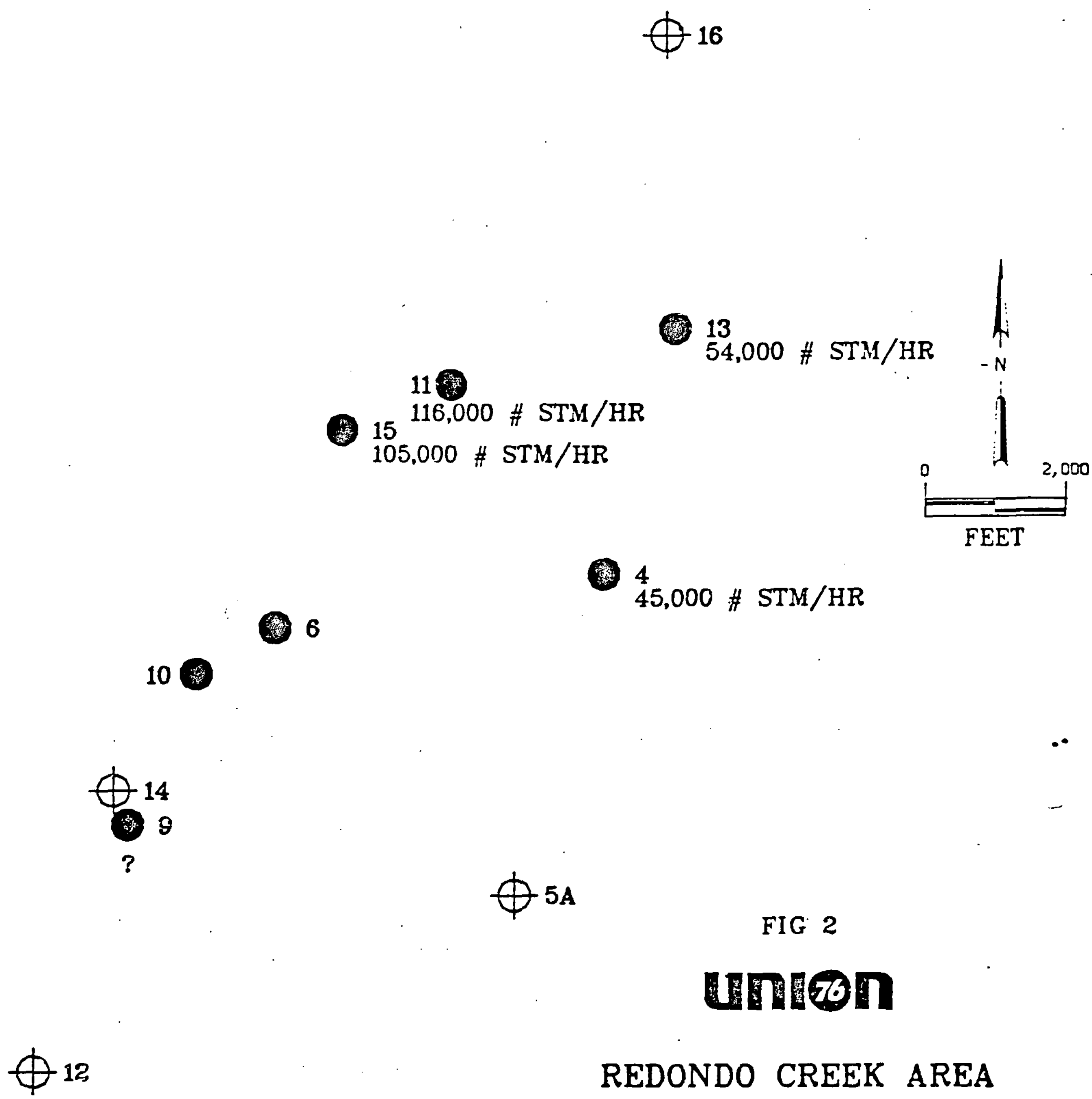


FIG 2

UNION 76

REDONDO CREEK AREA

VALLES CALDERA, NEW MEXICO

DISTRIBUTION AND GEOLOGIC RESULTS OF PRE-DOE WELLS, INCLUDING STEAM PRODUCTION RATE (LBS/HR AT LINE PRESSURE) OF PRODUCIBLE WELLS

● GEOLOGIC SUCCESS

⊕ GEOLOGIC FAILURE

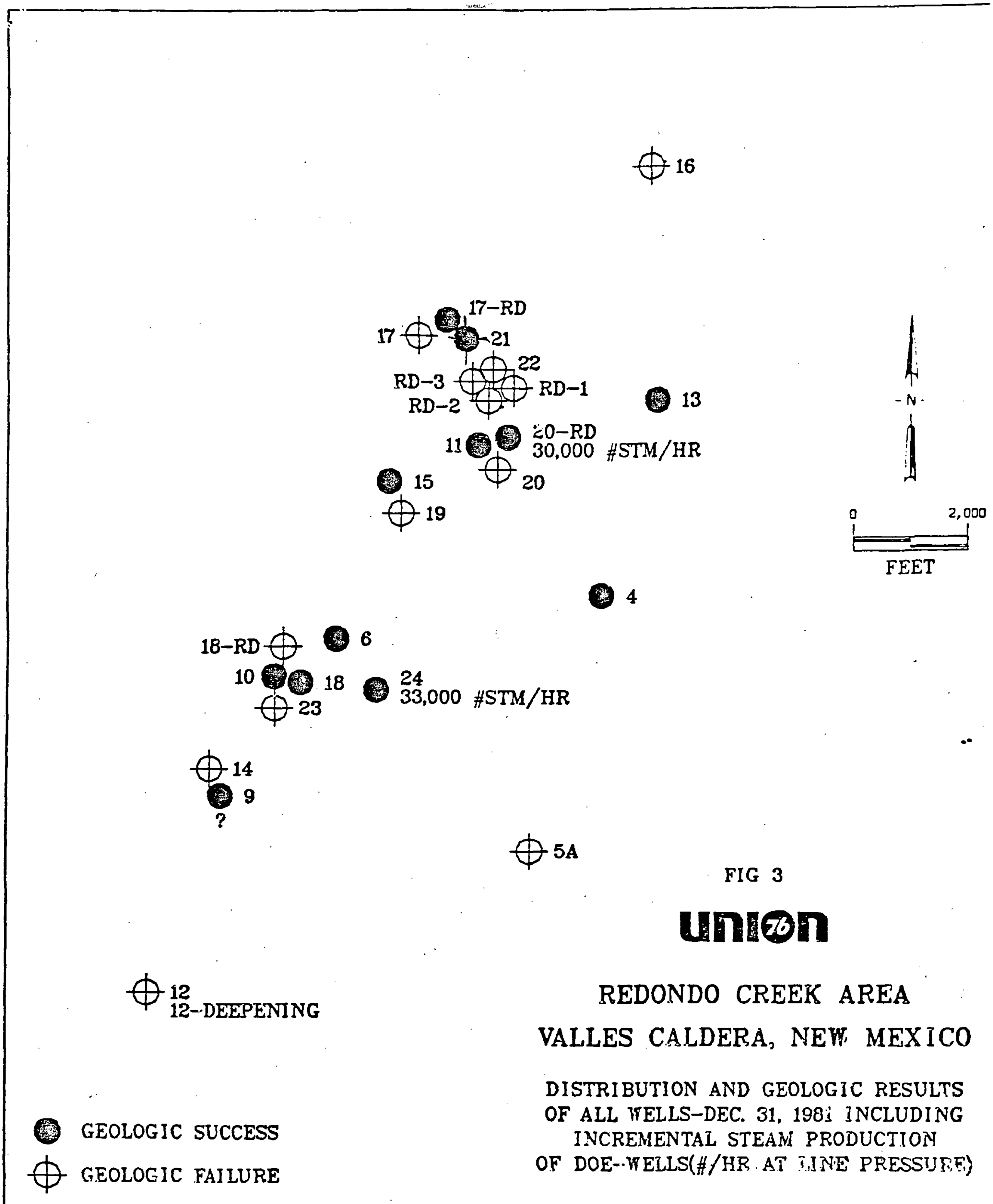


FIG 3

UNION 76

REDONDO CREEK AREA

VALLES CALDERA, NEW MEXICO

DISTRIBUTION AND GEOLOGIC RESULTS
OF ALL WELLS-DEC. 31, 1981 INCLUDING
INCREMENTAL STEAM PRODUCTION
OF DOE-WELLS(#/HR AT LINE PRESSURE)

PHILLIP M. WRIGHT

LBL-16883
UC-66a

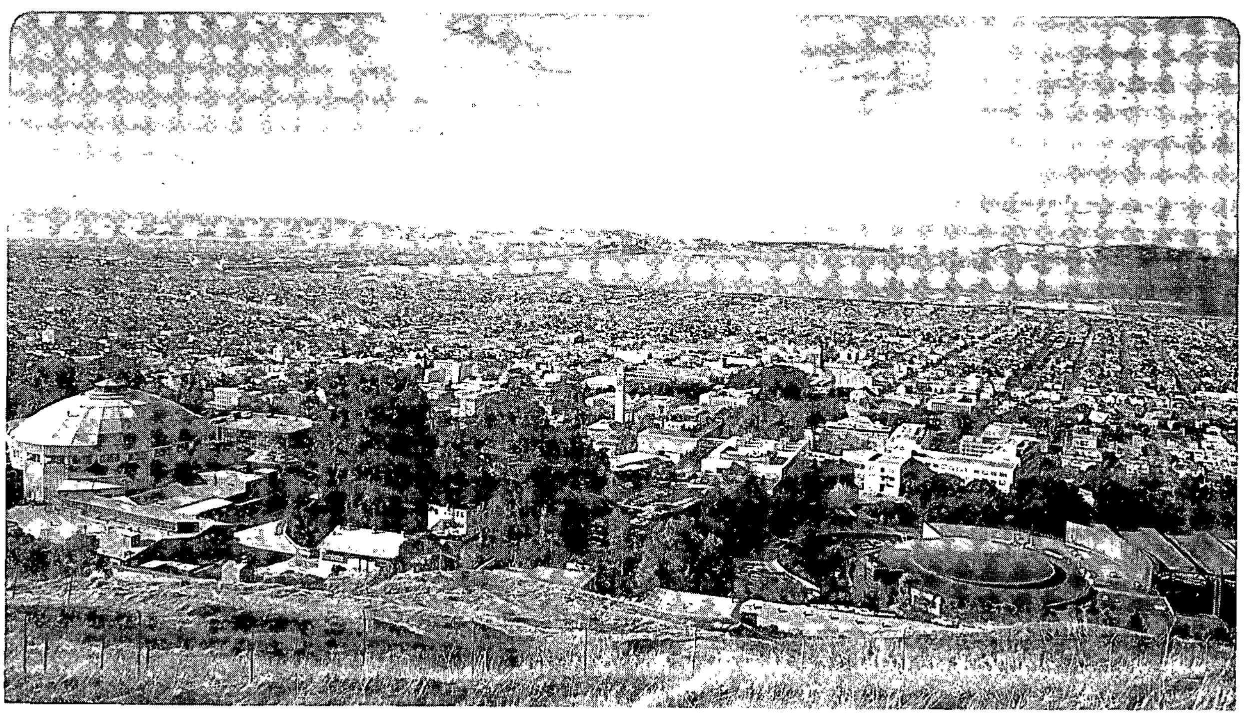
Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

EARTH SCIENCES DIVISION

HYDROTHERMAL ALTERATION IN WELL BACA 22,
BACA GEOTHERMAL AREA, VALLES CALDERA, NEW MEXICO

D.J. Fox

January 1984



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Hydrothermal Alteration in Well Baca 22
Baca Geothermal Area, Valles Caldera,
New Mexico

by
Dennis James Fox*
Earth Sciences Division
University of California
Lawrence Berkeley Laboratory

January 1984

*This work was originally a Masters of Science thesis for the Department of Geology and Geophysics, University of California, Berkeley.

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Acknowledgements

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Hydrothermal Alteration in Well Baca 22, Baca Geothermal Area, Valles Caldera, New Mexico

Dennis James Fox

Introduction

The Baca geothermal area is located in the Valles caldera in the Jemez Mountains of north-central New Mexico. Union Geothermal Company drilled a number of exploration wells to supply steam for a proposed electric generating plant. Drill cuttings from one of these wells, Baca 22 (see Figure 1), were studied with a petrographic microscope and by x-ray diffraction to determine the nature of the original rocks and of the hydrothermal alteration. The hydrothermal alteration will be used to determine the temperatures of alteration which can then be compared with borehole temperatures to determine if the mineral assemblages are compatible with present day temperatures. It will be shown that there is evidence indicating that the upper 2000 feet of borehole is cooler now than it has been in the past.

Sample sizes were limited in this study (usually less than 5 grams). In most cases, one quarter of the sample was used to make the thin section while the remainder was reserved for x-ray analysis. Samples were mounted in epoxy and cut to a thickness of 30 microns for petrographic study. X-ray diffraction patterns were obtained using a Debye-Scherrer camera and Fekα radiation.

The Valles caldera is considered a promising area for geothermal development for several reasons. The recency, magnitude, and duration of volcanic activity in the Jemez Mountains combined with the surficial rock alteration and numerous hot springs and fumaroles all suggest a large heat source located at a shallow depth—presumably the same magma chamber which

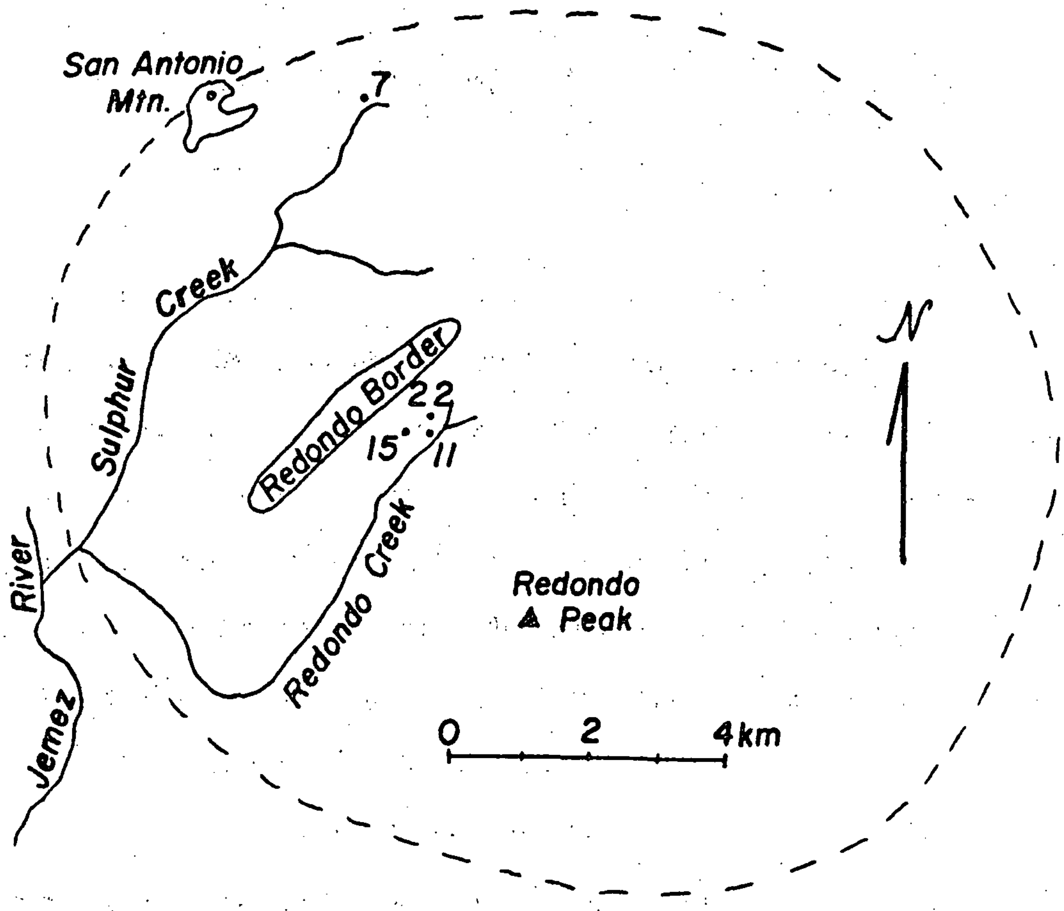

Figure 1. Location map. The location of four wells in the Baca geothermal area are shown. The broken circle indicates the approximate location of the ring fracture system of the latest caldera.

produced the voluminous volcanic rocks. Recent flow testing by Union Geothermal Company did not produce the large amounts of steam which were expected. Thus, this area has a low potential for generating electricity. However, low temperature geothermal resources are being investigated for use in space heating and Hot Dry Rock research is being conducted by the Los Alamos National Laboratory (Laughlin, 1981).

The Jemez Mountains are composed of late Miocene to Pleistocene volcanic rocks overlying older sedimentary rocks of the middle Miocene to upper Pliocene Santa Fe Group, the Abo Formation of Permian age, and the Carboniferous age Magdelina Group which rests on Precambrian granite. Volcanism began with the eruption of the Keres Group over 9 million years ago (m.y.a.) (Bailey et al., 1969). The Keres Group comprises the basalts of Chamisa Mesa, the Canovas Canyon Rhyolite, the Paliza Canyon Formation, and the Bearhead Rhyolite-Peralta Tuff Member. The basalts and rhyolites were erupted from numerous centers over a wide area. A thick sequence of andesite tuffs, flows, and breccias form coalesced composite cones overlying the earlier basaltic shields (Ross et al., 1961). Between 7.4 and 2.0 m.y.a. the Lobato Basalt, the Tshicoma Formation, and the El Rechuelos Rhyolite were erupted to form the Polvadera Group which overlies the andesites of the Keres Group (Bailey et al., 1969). The Tewa Group represents the latest stage of volcanism in the Jemez Mountains. This group is composed of the Bandelier Tuff, the Cerro Toledo Rhyolite, the Cerro Rubio Quartz Latite, and the Valles Rhyolite (Bailey et al., 1969). The volcanic rocks penetrated by Baca 22 are the Paliza Canyon Formation, the Bandelier Tuff, and the Valles Rhyolite.

The Toledo caldera, which is truncated by the north-east rim of the Valles caldera, was formed 1.4 m.y.a. during the eruption of the lower member (Otowi Member) of the Bandelier Tuff (Doell et al., 1968). The Valles caldera was formed during the eruption of the upper member (Tshirege Member) 1.1 m.y.a. (Doell et al., 1968). The Valles caldera was occupied by a lake soon after subsidence which persisted until near the end of the late rhyolite stage of volcanism (~0.5 m.y.a.). The lake was drained by headward erosion of the Jemez River and San Antonio Creek (Ross et al., 1961). The caldera floor was locally buried by more than 2000 feet of caldera fill before formation of a resurgent dome. Many of the post-caldera rhyolites erupted between 1.1 and 0.4 m.y.a. flowed into the lake (Doell et al., 1968). The source of these post-caldera lavas is presumed to be the same magma chamber which produced the Bandelier Tuff. Figure 2 shows a columnar section of Baca 22 and two adjacent wells.

Determination of Sample Depth and Temperature

Samples from Baca 22 were taken at 20 foot intervals with depth measured along the wellbore. The nature of the samples (drill cuttings) lends a measure of uncertainty to the results. At the time of sample collection no correction is made for travel time from bit to surface so a sample from a specified interval will not necessarily contain cuttings representing or exclusively from that entire interval.

Corrections to vertical depth can usually be accomplished with a dip-log which measures inclination within the wellbore. Dip-logs are available for Baca 22 for the original hole and the first two redrills but not for redrill 3 which was the source of all samples below 2700 feet for this study. The dip-log for the original hole (which was the source of all samples above 2700 feet) showed that a measured depth of 2528 feet corresponded to a vertical depth of 2523 feet. The error (5 feet) is less than the sample interval so it is considered negligible in this study. Errors within redrill 3 are not available so these depths are given as depth along wellbore.

Temperatures were obtained from a pressure/temperature gradient survey conducted in redrill 2. No temperature data are available below 5900 feet.

All of the photomicrographs shown in this paper have a sample number such as [1065A335]. "1065" is the U.C. Berkeley Geology Department collection number, "A" refers to Baca 22, and "335" refers to the depth interval of the sample. This number is obtained by

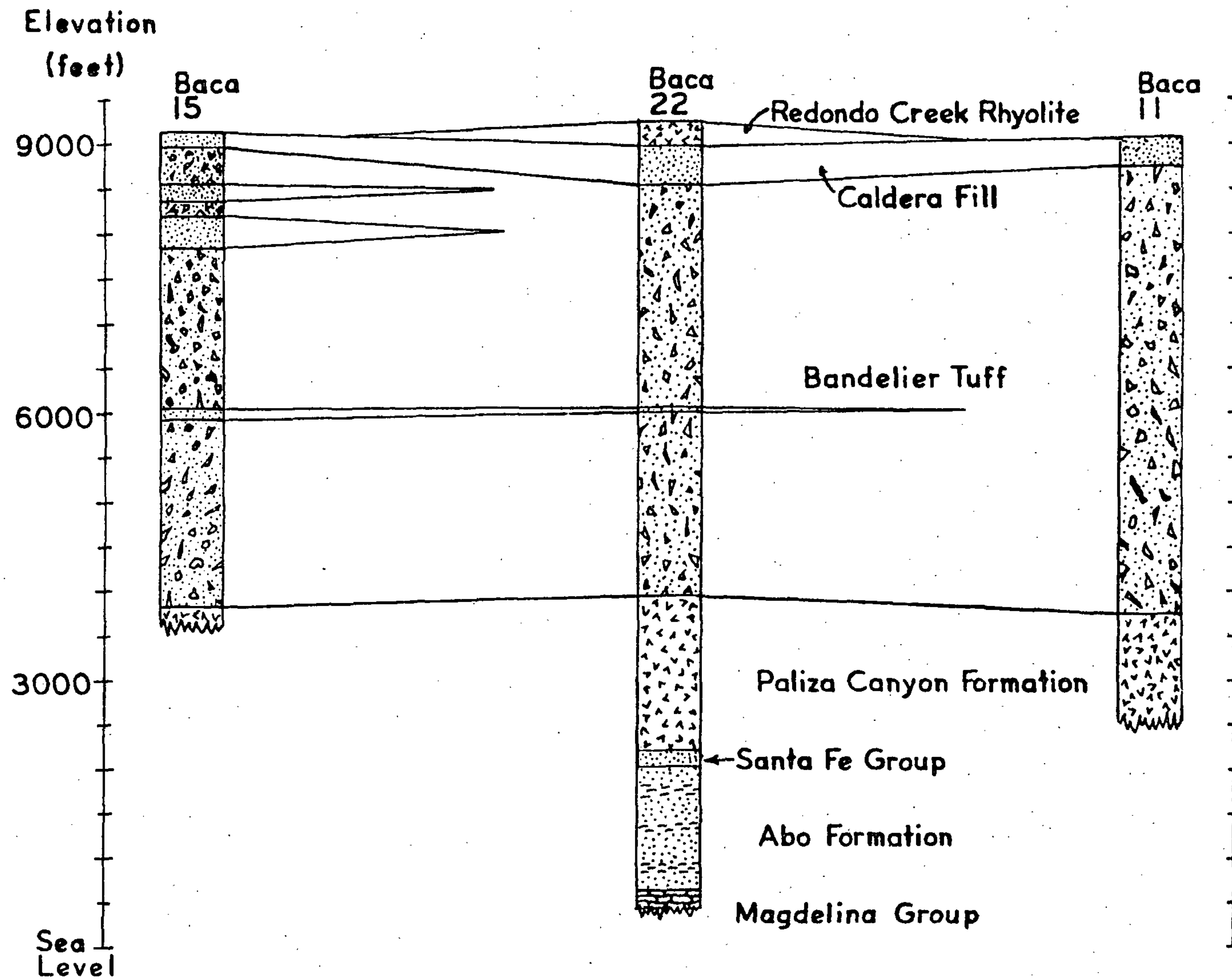

Figure 2. Baca 22 local stratigraphy. Columnar sections of Baca 22, Baca 15, and Baca 11 are shown here. Locations for these three wells are shown in Figure 1.

averaging the upper and lower limits of the sample interval and dividing the average by 10. Therefore, 335 would refer to the sample interval from 3340 to 3360 feet.

Petrographic and X-ray Analysis

Redondo Creek Rhyolite

The Redondo Creek Rhyolite is the uppermost unit penetrated by Baca 22. This 250 foot thick member of the Valles Rhyolite is readily distinguishable from all other members by the presence of plagioclase phenocrysts mantled with sanidine, large biotite phenocrysts, and by the absence of quartz phenocrysts (Bailey et al., 1969). The groundmass is primarily fresh clear glass with numerous areas of spherulitic devitrification which are most evident around phenocrysts. A typical sample of this rock is shown in Figure 3.

Alteration within the Redondo Creek Rhyolite is limited to about 1% of the glass and comprises opal and a green phyllosilicate. Smectite is thought to be the most likely composition of this phyllosilicate based on its color and depth of occurrence and on the composition of the original glass. The opal forms spheres similar to those described by Honda and Muffler (1970). As shown in Figure 4, the alteration is confined to fractures and the width of the zone is on the order of 50 microns. Orpiment and realgar were precipitated in trace amounts below 110 feet.

Caldera Fill

Below the Redondo Creek Rhyolite is Caldera Fill about 450 feet thick consisting of fine sand and silt sized particles of quartz, plagioclase, microcline, granitic rock fragments, and minor magnetite. Calcite cement is common and is accompanied by illite in the matrix of some samples. The illite was identified by x-ray diffraction and appears to be of both sedimentary and hydrothermal origin. The illite in the matrix shows no evidence of having grown in place

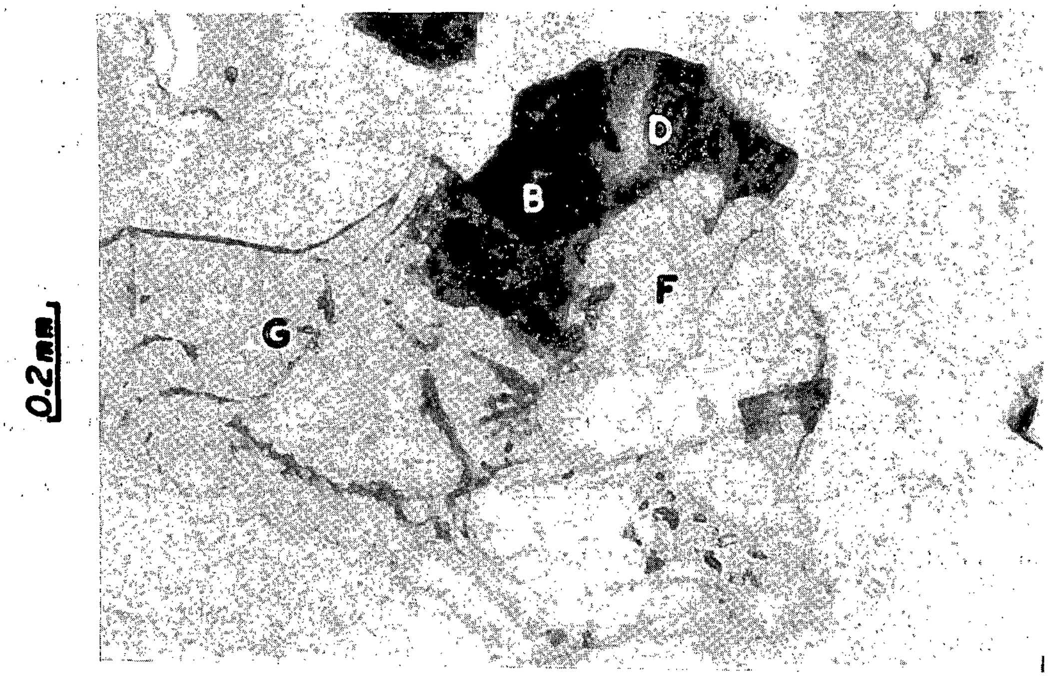

Figure 3. Redondo Creek Rhyolite. G-glass, B-biotite, D-devitrified glass, F-feldspar. Plane polarized light. [1065A010]

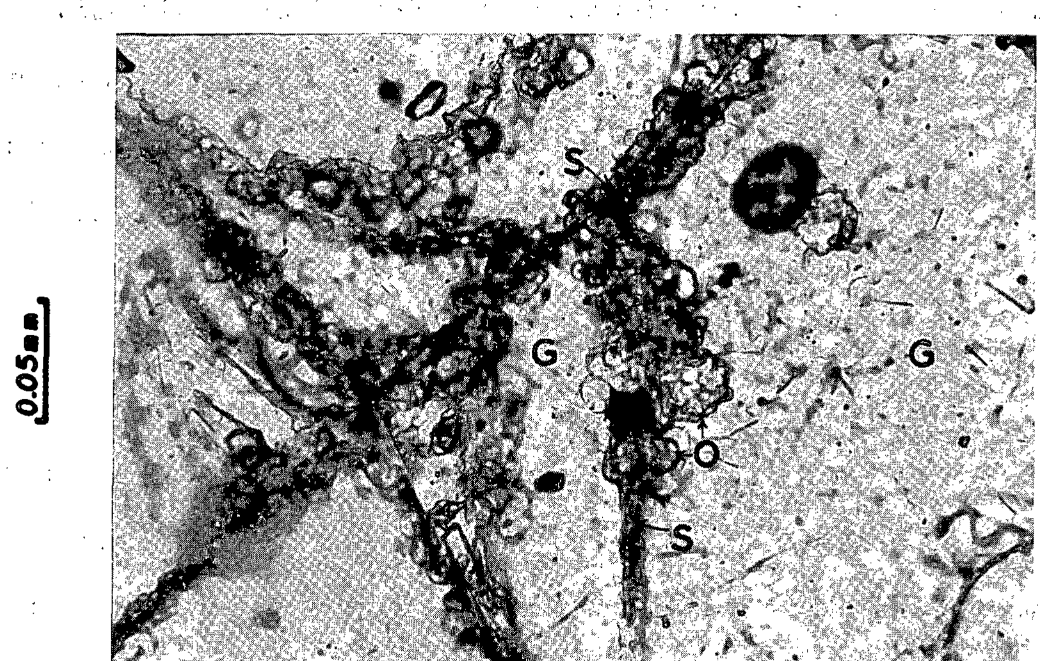

Figure 4. Opal and smectite in the Redondo Creek Rhyolite. The spherical alteration of the glass (G) is opal (O) and the darker alteration is smectite (S). Plane polarized light. [1065A010]

and appears to support grains in some cases so is probably detrital in origin. Lambert and Epstein (1980) describe the carbonates in the Caldera Fill as having $\delta^{18}O$ values which indicate deposition in an environment similar to that found in a freshwater lake. Therefore, the calcite is probably unrelated to hydrothermal activity.

Hydrothermal minerals in the Caldera Fill are orpiment, realgar, hematite, pyrite, and illite. Orpiment and realgar were recognized by their color and association. Hematite and pyrite were recognized by powder diffraction. The concentration of the hydrothermal alteration products is highest in the center of the unit (500 feet deep) where orpiment, realgar, and hematite make up about 3% of the rock.

Bandelier Tuff

Underlying the Caldera Fill is the Bandelier Tuff of rhyolite composition. The combined thickness of the two members is approximately 4700 feet in Baca 22. The tuff is densely welded, devitrified, and hydrothermally altered throughout most of its thickness. Ignimbrites of this great thickness are not widely known. A mechanism for forming a deposit of this magnitude would involve eruption of vast amounts of ash during the foundering of the roof of the magma chamber. Ponding of ash flows within the developing caldera could easily produce deposits of this size. Bailey et al. (1976) describe a similar thickness of ash flows (1000 to 1500 meters) within the Long Valley caldera in California. The bulk of the Bandelier Tuff in Baca 22 is probably Tshirege Member since it was erupted concurrent with the subsidence of the Valles caldera. The Otowi Member in this area is found on the flanks of the volcano so it should be much thinner. Smith and Bailey (1966) show that where the Tshirege Member is found on the flanks of the volcano, it is normally less than 600 feet thick and locally attains a thickness of 800 feet where it has filled in former valleys.

The primary minerals of the Bandelier Tuff are quartz, plagioclase, sanidine, pyroxene, minor magnetite, and minor lithic fragments. The anorthite content of the plagioclase was not determined due to the highly altered state of the phenocrysts. The pyroxene phenocrysts are totally replaced by chlorite, sphene, and epidote. Thin sections of the Tshirege Member borrowed from Fraser Goff of the Los Alamos National Laboratory contain pigeonite which exhibits the same crystal habit as the chlorite pseudomorphs in the Baca 22 samples. Smith and Bailey (1966) also noted hypersthene, fayalite, and anorthoclase at various levels in the Tshirege Member. Above 1400 feet the devitrified groundmass (probably containing cristobalite and alkali feldspar) retains its axiolitic and spherulitic texture. Below this point to a depth of 3000 feet the devitrified groundmass has been recrystallized to a clear featureless mosaic of fine-grained quartz and albite.

A layer of fine sandstone is located between 3190 and 3240 feet. The grains are made up of quartz, microcline, plagioclase, and sanidine. The sandstone is cemented by quartz overgrowths, calcite, and phyllosilicate. The sand is well sorted, subangular, well indurated and is mineralogically and texturally similar to the Caldera Fill.

Above and below the sandstone, between 3000 and 3400 feet, the rhyolite tuff is only partly (or locally) recrystallized as shown in Figure 5. The welding and devitrification textures are well preserved here although x-ray diffraction patterns indicate that some of the groundmass has been recrystallized to quartz and albite. Below 3400 feet the recrystallization texture appears again and continues throughout the remainder of the formation.

Hydrothermal alteration within the Bandelier Tuff has been quite extensive. In addition to the recrystallized groundmass discussed above, pyrite, illite, and hematite which were present in the Caldera Fill, continue into this formation. The hematite is not found below 1000 feet but pyrite continues to be present throughout the total depth of the hole with the exception of the interval between 2850 and 3150 feet. Calcite is commonly present as a replacement of plagioclase phenocrysts and groundmass. Illite replaces feldspar in minor (less than 5%) amounts throughout much of this formation.

Albitization of plagioclase begins at 700 feet and continues to the base of the Bandelier Tuff. A lower refractive index, higher birefringence, and a clouded appearance in plane light all make this replacement readily recognizable. Figure 6 shows a typical Bandelier Tuff plagioclase phenocryst which is partially albitized. The absence of polysynthetic twinning in the albite is

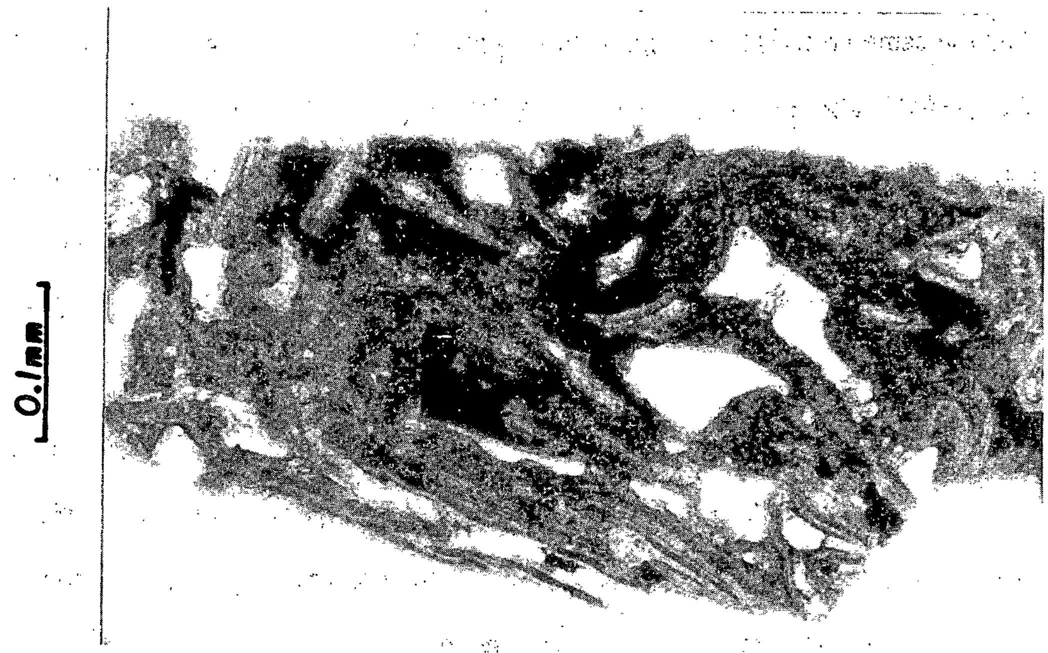

Figure 5. Welded-tuff texture in the Bandelier Tuff. This sample is from the interval between 3000 and 3400 feet where the groundmass has not been recrystallized. Plane polarized light. [1065A315]

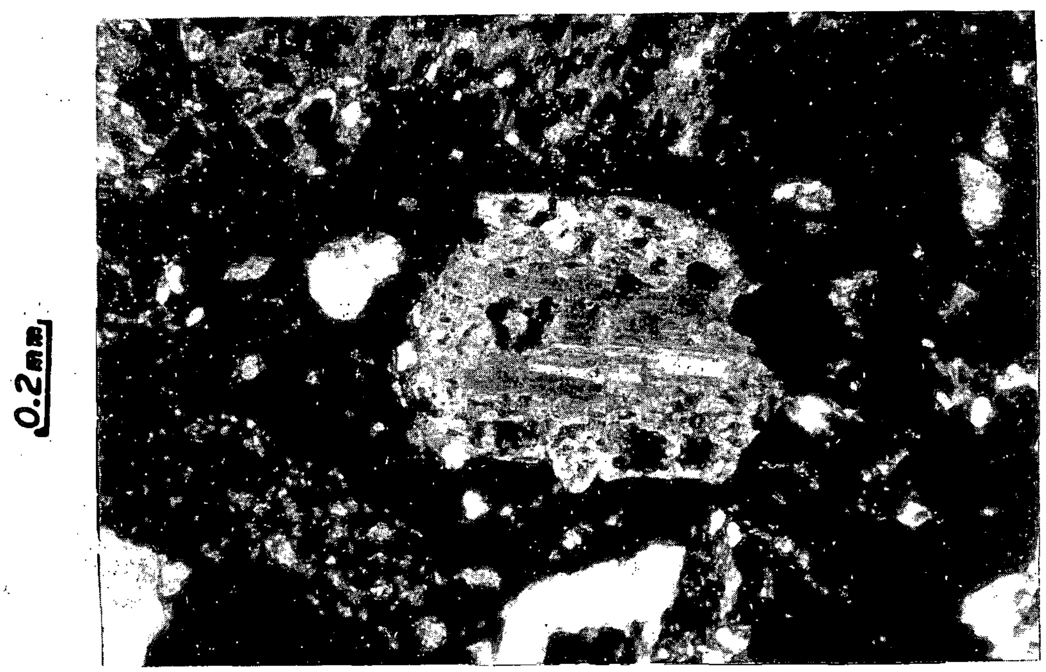

Figure 6. Albitized plagioclase in the Bandelier Tuff. This phenocryst of twinned plagioclase rimmed by untwinned albite demonstrates the loss of twinning and higher birefringence of the albitized plagioclase. Crossed nicols. [1065A075]

unusual in albitization of plagioclase. Usually, the twinning in the original phenocryst will continue into the albite. Twinning continues from the plagioclase into the replacement albite in only a few samples of the Bandelier Tuff. In these cases the albite is relatively clear and free of inclusions. The untwinned secondary albite is much cloudier and frequently contains inclusions. It is not known if this difference is caused by differing modes of albitization, differing temperatures, differences in original phenocryst composition, or some other factor.

In addition, albite begins to replace sanidine at a depth of 1300 feet. Figure 7 demonstrates that this albite is readily distinguishable from albitized plagioclase by the presence of chessboard-twinning (Callegari and De Pieri, 1967). As discussed above, albite and quartz occur as recrystallization products of the devitrified glass. This hydrothermal alteration gives the groundmass a finely crystalline texture in crossed nicols as shown in Figure 8. Although the recrystallization generally eliminates the devitrification texture, it does not completely remove the welded-tuff texture which can still be seen in plane light.

Chlorite first appears in the sample from 1100 feet. As shown in Figure 9, the most common habit of the chlorite is as pseudomorphs after pyroxene although it also occurs in the recrystallized groundmass. At depths in excess of 1700 feet, sphene occurs as numerous, brown, fine grained crystals grouped together into clusters. Epidote commonly occurs below 3400 feet with chlorite as prismatic crystals arranged in a radial pattern.

Paliza Canyon Formation

Three dacitic rocks in the 1300 foot thick Paliza Canyon Formation have been dated at 8.5, 8.8, and 9.1 million years old (Bailey et al., 1969). Andesite and dacite flows appear to be the dominant rock type in the Baca 22 samples. The mineralogy of the Paliza Canyon is dominated by zoned and twinned plagioclase with compositions determined by the Michel-Lévy technique of An_{24} to An_{55} with the most common anorthite content about An_{33}. Pyroxene is wholly altered throughout this formation. Magnetite is common and apatite can be found as small euhedral crystals.

Figure 7. Albitized sanidine in the Bandelier Tuff. This photomicrograph shows the sanidine (S) being replaced by albite (A) which displays chessboard-twinning. Crossed nicols. [1065A381]

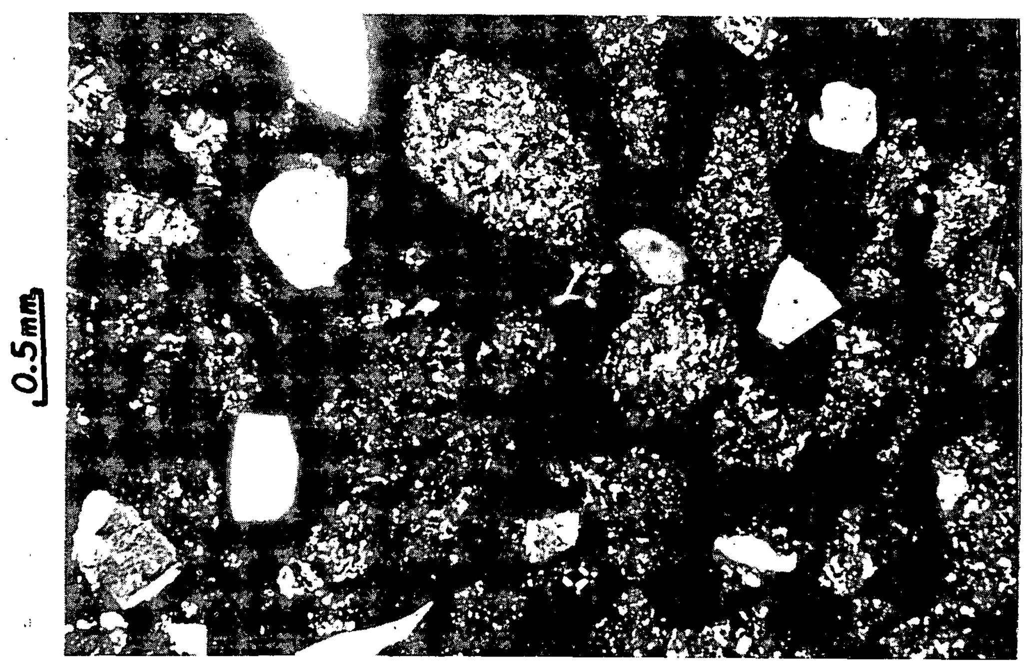

Figure 8. Recrystallized groundmass in the Bandelier Tuff. The groundmass is recrystallized to quartz and albite. Crossed nicols. [1065A533]

Figure 9. Chlorite after pyroxene in the Bandelier Tuff. This sample shows a pseudomorph of chlorite (C) after pyroxene. Plane polarized light. [1065A315]

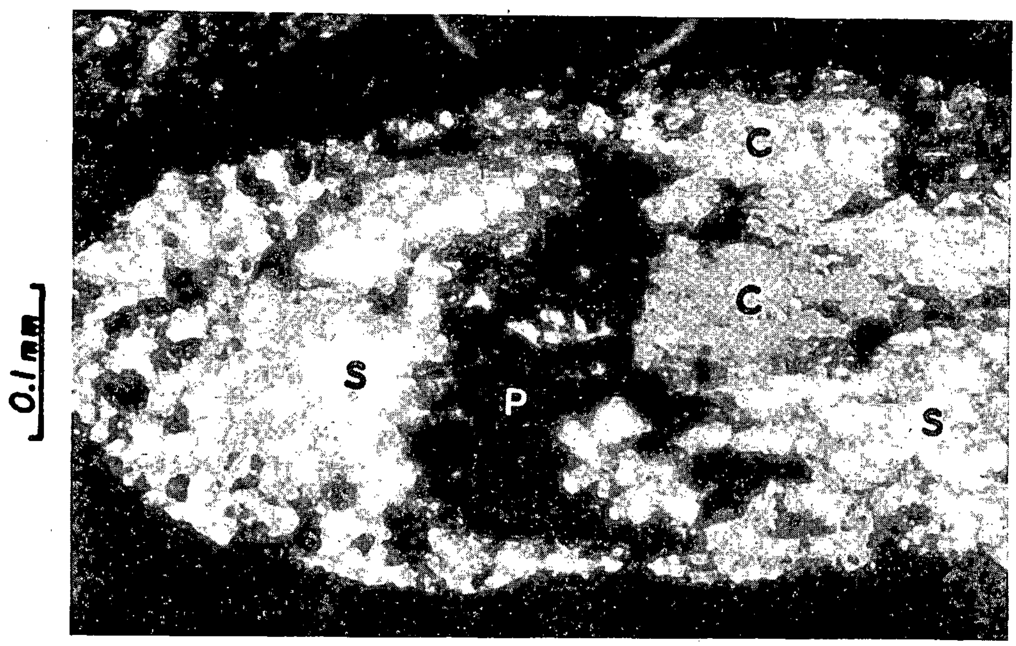

Figure 10. Calcite and sericite replacing plagioclase in the Paliza Canyon Formation. C-calcite, S-sericite, P-plagioclase. Crossed nicols. [1065A573]

Hydrothermal alteration in the Paliza Canyon includes sericite which is an extensive alteration product of plagioclase replacing half or more of some phenocrysts in many samples. Figure 10 demonstrates the large size of some of the sericite crystals. Calcite commonly replaces plagioclase although rarely more than about 15% of a phenocryst. Epidote is another common alteration product of plagioclase but in most samples its abundance is minor compared to sericite and calcite. However, a sample from 6270 feet (Figure 11) is unusual in that it contains much more epidote than sericite and calcite as alteration products of plagioclase.

Pyroxene has been completely altered to chlorite, epidote, sphene, and quartz in this formation. As shown in Figures 12 and 13, chlorite is the more common alteration product. Epidote, quartz, and sphene occur in lesser amounts than chlorite in most cases. Figure 14 illustrates that some of the chlorite replacements (after hypersthene?) are rimmed by quartz.

Much of the groundmass of the Paliza Canyon Formation has the same appearance as the recrystallized groundmass in the Bandelier Tuff. X-ray diffraction and oil immersion has shown this groundmass to be quartz and albite. Sphene clusters are common and pyrite continues to be present throughout the Paliza Canyon Formation.

Santa Fe Group

The Santa Fe Group, of Miocene age, comprises 200 feet of unconsolidated, well sorted fine sand made up of quartz, plagioclase, microcline, magnetite, and perthite. The quartz and feldspar occur in two varieties. One type is clear, subangular, and was probably deposited by stream. The second type is very well rounded, has small pits (percussion marks) in the surface, and has a faint hematite stain on the surface suggesting eolian transport.

Hydrothermal alteration is slight in these sediments. A minor amount of sericite (less than 1%) is seen in some of the plagioclase grains. Pyrite is present in trace amounts and epidote is found as small isolated crystals.

Figure 11. Epidote replacing plagioclase in the Paliza Canyon Formation. E-epidote, P-plagioclase. Plane polarized light. [1065A627]

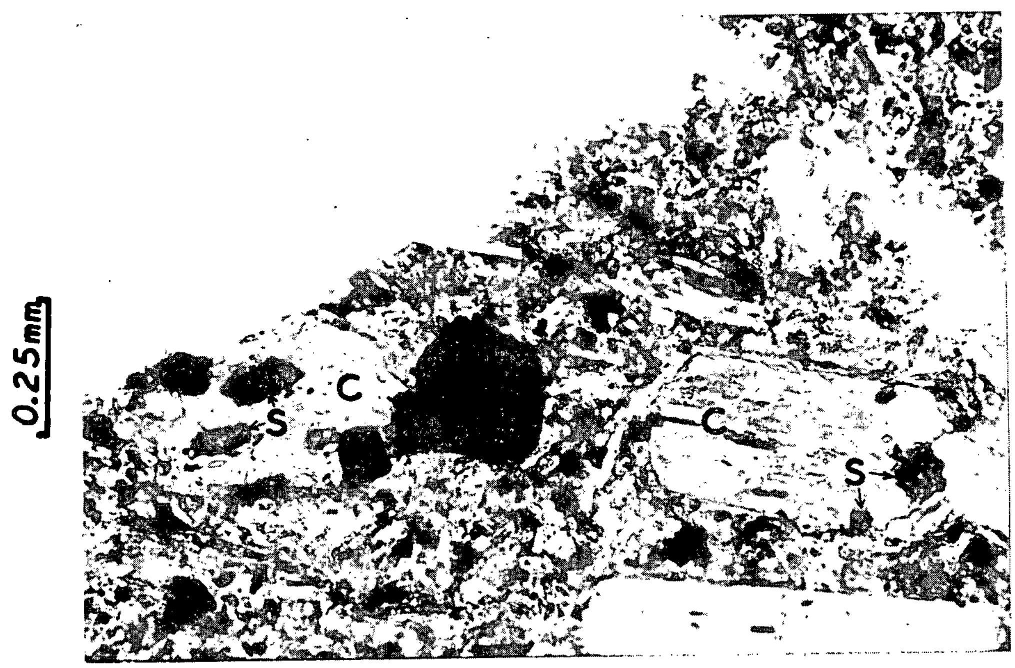

Figure 12. Chlorite and sphene after pyroxene in the Paliza Canyon Formation. S-sphene, C-chlorite. Plane polarized light. [1065A591]

Figure 13. Chlorite and epidote after pyroxene in the Paliza Canyon Formation. C-chlorite, E-epidote. Plane polarized light. [1065A591]

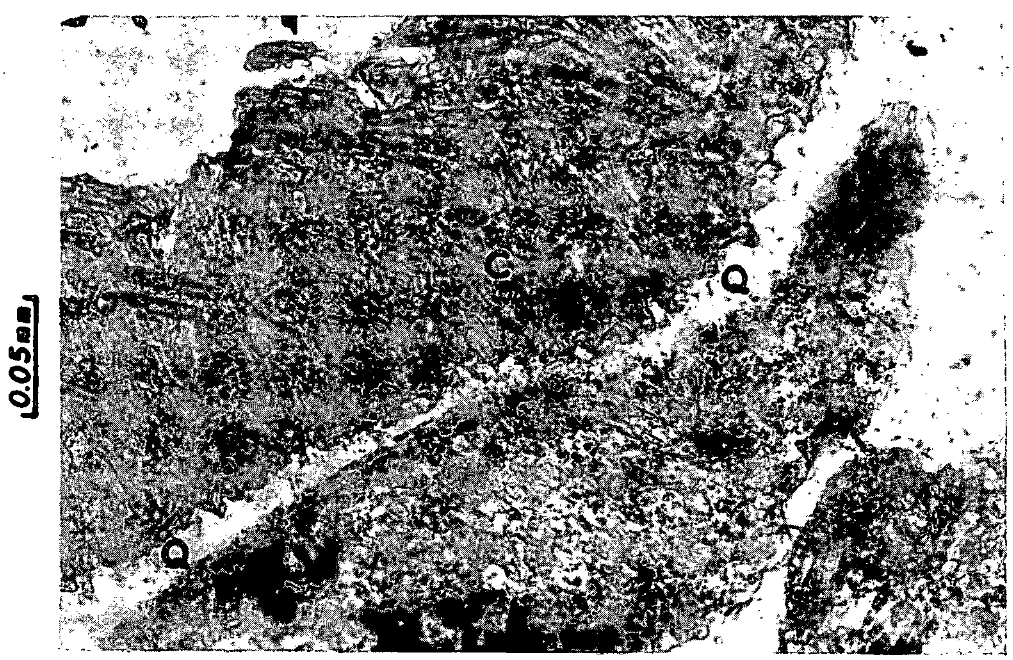

Figure 14. Chlorite and quartz replacing pyroxene in the Paliza Canyon Formation. Q-quartz, C-chlorite. Plane polarized light. [1065A559]

Abo Formation

The 1300(?) foot thick Abo Formation comprises calcite, epidote, and hematite cemented fine grained sandstones and siltstones of Permian age. The sand consists of subangular to subrounded well sorted quartz and feldspar grains. Hydrothermal alteration includes sericite replacing plagioclase in trace amounts and precipitation of minute subhedral to anhedral pyrite crystals and subhedral epidote crystals in the interstitial pore spaces.

Magdelina Group

One sample from the Magdelina Group has been studied. It comprises red argillite, brown mudstone with silt-sized quartz grains, and dense micritic limestone. Hydrothermal alteration has recrystallized some of the micrite to sparite and formed the zeolite wairakite.

Patterns of Hydrothermal Alteration

Opal and Green Phyllosilicate

Hydrothermal alteration of glass in the Redondo Creek Rhyolite is confined to fractures in the glass (see Figure 4). Alteration products comprise opal and a green phyllosilicate of undetermined composition, possibly smectite.

Sulfides and Oxides

Three sulfides and one oxide were precipitated in the rocks penetrated by Baca 22. Pyrite is found throughout the Baca 22 samples below 600 feet except for the interval between 2850 and 3150 feet. The pyrite occurs as minute cubic crystals (usually less than 0.5 mm) which are disseminated throughout the samples and exhibit no systematic relationship to any other mineral. Lambert and Epstein (1980) describe the occurrence of pyrite in Baca 7 below 3710 feet. Orpiment and realgar are two sulfides which are restricted to the upper portion of the well between 200 and 700 feet where they appear to have been precipitated in pores. Hematite was precipitated in pore spaces in the Caldera Fill and Bandelier Tuff between depths of 400 and 900 feet.

Illite and Sericite

Illite was detected with x-ray diffraction in the Caldera Fill and is visible in thin sections of the Caldera Fill and Bandelier Tuff. The illite in the Caldera Fill appears to be of sedimentary and hydrothermal origin. Hydrothermal illite has replaced feldspar grains which were present in the sandstones and siltstones. In the Bandelier Tuff the illite is most evident in the replacement of feldspar phenocrysts (see Figure 15) but is also present in minor amounts in the groundmass. Lambert and Epstein (1980) found kaolinite in the groundmass of Baca 7 but none was detected here.

A clear birefringent phyllosilicate occurs as a replacement of plagioclase in the Paliza Canyon Formation. The 2V was determined to be 32° using the method of Tobi (1956) which indicates that this mica is sericite (muscovite) as opposed to pyrophyllite (2V=53-60°) or illite (small 2V). Figure 10 shows the large crystal of sericite on which the axial angle measurement was made and illustrates the common association of sericite with calcite in the alteration of plagioclase.

It is not known at what point the illite grades into sericite or what structural types of muscovite these two minerals represent. Yoder and Eugster (1955) describe the range of compositions and structure types which are encompassed by these two mineral names.

Albite

Albite is formed from three different materials in the Baca 22 samples. Below 1300 feet the devitrified groundmass is altered from the original cristobalite and alkali feldspar to quartz, albite, and minor illite. The groundmass changes from the faintly birefringent dusty looking devitrified glass to a finely crystalline moderately birefringent clear aggregate of anhedral crys-

Figure 15. Illite replacing plagioclase in the Bandelier Tuff. The edges of this plagioclase phenocryst have been albitized and altered to illite. The albite retains the twinning present in the original phenocryst. A-albite, I-illite, P-plagioclase. Crossed nicols. [1065A089]

tals. This recrystallization does not disturb the welded-tuff texture or the glass shard outlines which can still be seen in the drill cuttings but it does eliminate the devitrification texture. Albitized plagioclase is first seen at 700 feet and is progressively farther advanced as one looks at deeper samples from the Bandelier Tuff.

Chessboard-twinned albite occurs as a replacement of sanidine in the Bandelier Tuff. Albite replaces sanidine below 1300 feet where some sanidine phenocrysts appear to be untouched and others appear to be completely replaced. Near the base of the Bandelier Tuff the sanidine has been replaced to a much greater extent but there are usually a few small patches of sanidine visible in some of the phenocrysts. Callegari and De Pieri (1967) have shown that chessboard-twinning in albite is a good indicator that the albite is more than 98% pure. It has been observed that chessboard-twinning only occurs in albite when it replaces K-feldspar so it can be used as an indicator of original mineralogy in a highly altered rock (Moore and Liou, 1979).

Calcite

Calcite is present in the Baca 22 samples from a depth of 300 feet to the bottom of the hole. Some of this calcite is sedimentary in origin (the calcite cement in the sandstones and the Magdelina Group limestones) while some is the product of hydrothermal activity. Hydrothermal calcite is found as a pore filling mineral and in the replacment of the groundmass and of plagioclase. Calcite is associated with albite, sphene, sericite, and illite as a replacement of plagioclase.

Quartz

Quartz formed by recrystallization under hydrothermal conditions was recognised through x-ray diffraction in the Paliza Canyon Formation and the Bandelier Tuff. The quartz occurs as an alteration product when the groundmass of these formations is recrystallized. Recrystallization takes place between 1300 and 6850 feet. Quartz also occurs with chlorite in the alteration of hypersthene.

Chlorite

Chlorite is found in most samples below 1100 feet as an alteration product of pyroxene and in minor amounts as a groundmass alteration. X-ray powder diffraction has yielded 001 and 002 reflections of 14.15å and 7.08å respectively. Optically, the chlorite occurs as fibrous radiating crystals with anomalous blue and green birefringence. The alteration of pyroxene to chlorite appears to involve little or no volume change. Both clino- and orthopyroxenes were altered to chlorite since both types of pyroxene were present in the Bandelier Tuff (discussed earlier) and the Paliza Canyon Formation. Two thin sections of fresh Paliza Canyon rocks on loan from the Los Alamos National Laboratory contain both clino- and orthopyroxenes. Unpublished microprobe data obtained from Jamie Gardner, a Ph. D. candidate at U. C. Davis, indicates that the pyroxene compositions within the Paliza Canyon Formation remain constant throughout all of the flows. These compositions are augite ($Ca_{45}Mg_{45}Fe_{10}$) and hypersthene ($Mg_{75}Fe_{25}$).

Sphene

Sphene occurs in the Bandelier Tuff (below 1500 feet) in and the Paliza Canyon Formation as minute brown anhedral crystals grouped into clusters. These clusters appear to form anywhere within the rock outside of the sanidine and quartz phenocrysts. The sphene is recognised by its very high relief which causes it to look white in reflected light, by its high birefringence, and by rare euhedra.

Epidote

Epidote first occurs in the Baca 22 samples below 3400 feet, primarily as a replacment of plagioclase and pyroxene. The epidote crystals occur in two habits. In the more common habit, the epidote occurs as prismatic to anhedral crystals in radial or aggregate form. More rarely, the epidote occurs as acicular crystals arranged in a radial pattern. Many of the larger crystals are zoned from a pleochroic yellow center to a colorless border. Figure 16 shows that epidote also occurs as a pore filling mineral in the Abo Formation.

Figure 16. Epidote cement in the Abo Formation. The epidote appears to form a cement between the detrital grains. E-epidote, Q-quartz. Crossed nicols. [1065A817]

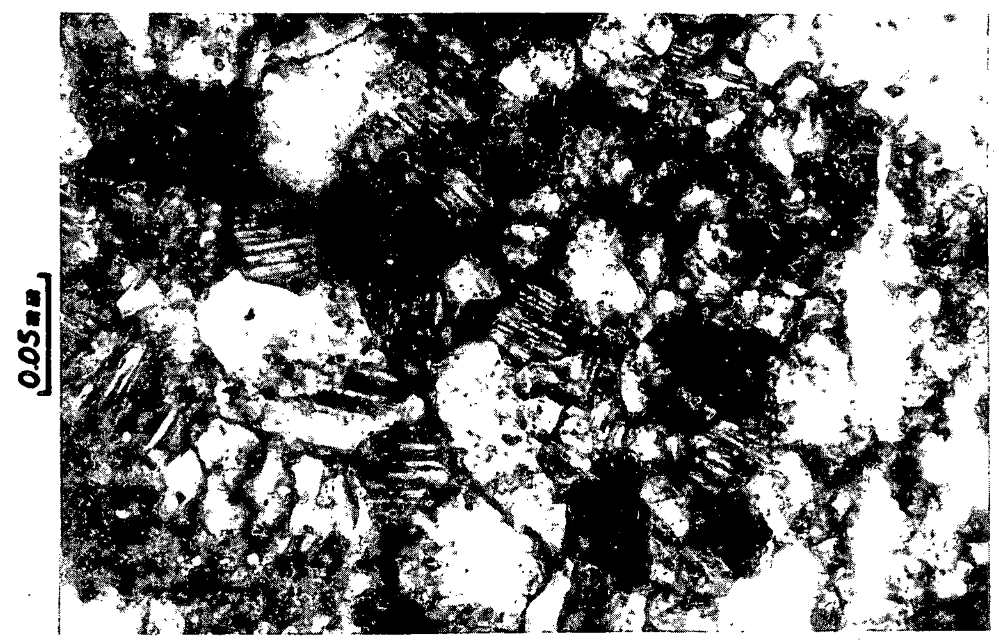

Figure 17. Wairakite in the Magdelina Group. The low birefringence and polysynthetic twinning make this zeolite easily recognizable. Crossed nicols. [1065A867]

Wairakite

Coarse-grained (0.35 mm) crystals of wairakite were seen in the one sample available from the Magdelina Group. The crystals occur in groups and were identified by their low birefringence and polysynthetic twinning (see Figure 17). The wairakite has formed primarily in the mudstone and to a lesser extent in the limestone.

Discussion of Alteration Conditions

Figure 18 shows the relationships of the different alteration products with each other, with lithology, and with depth along wellbore. There are minerals which appear only in specific lithologic types and minerals which occur independent of lithology. Orpiment, realgar, hematite, sericite, illite, pyrite, calcite, and epidote all seem to occur independent of lithology. Minerals which appear to be related to lithology include smectite and opal which occur only in the Redondo Creek Rhyolite. Cristobalite is a devitrification product in the Redondo Creek Rhyolite and the Bandelier Tuff. Chlorite and sphene occur only in the Bandelier Tuff and Paliza Canyon Formation. Hydrothermal quartz and albite were found primarily in the Bandelier Tuff and Paliza Canyon Formation where glass, devitrified glass, or fine grained groundmass was available for alteration.

Clays are relatively rare in the upper portion of this drillhole which contrasts with other hydrothermal areas such as Ohaki-Broadlands (Browne and Ellis, 1970), Wairakei (Steiner, 1977), and Yellowstone (Keith et al., 1978). The only clays detected in Baca 22 were the limited amounts of possible smectite in the Redondo Creek Rhyolite, the illite in the Caldera Fill and Bandelier Tuff, and the chlorite which is present in the deeper portions of the well.

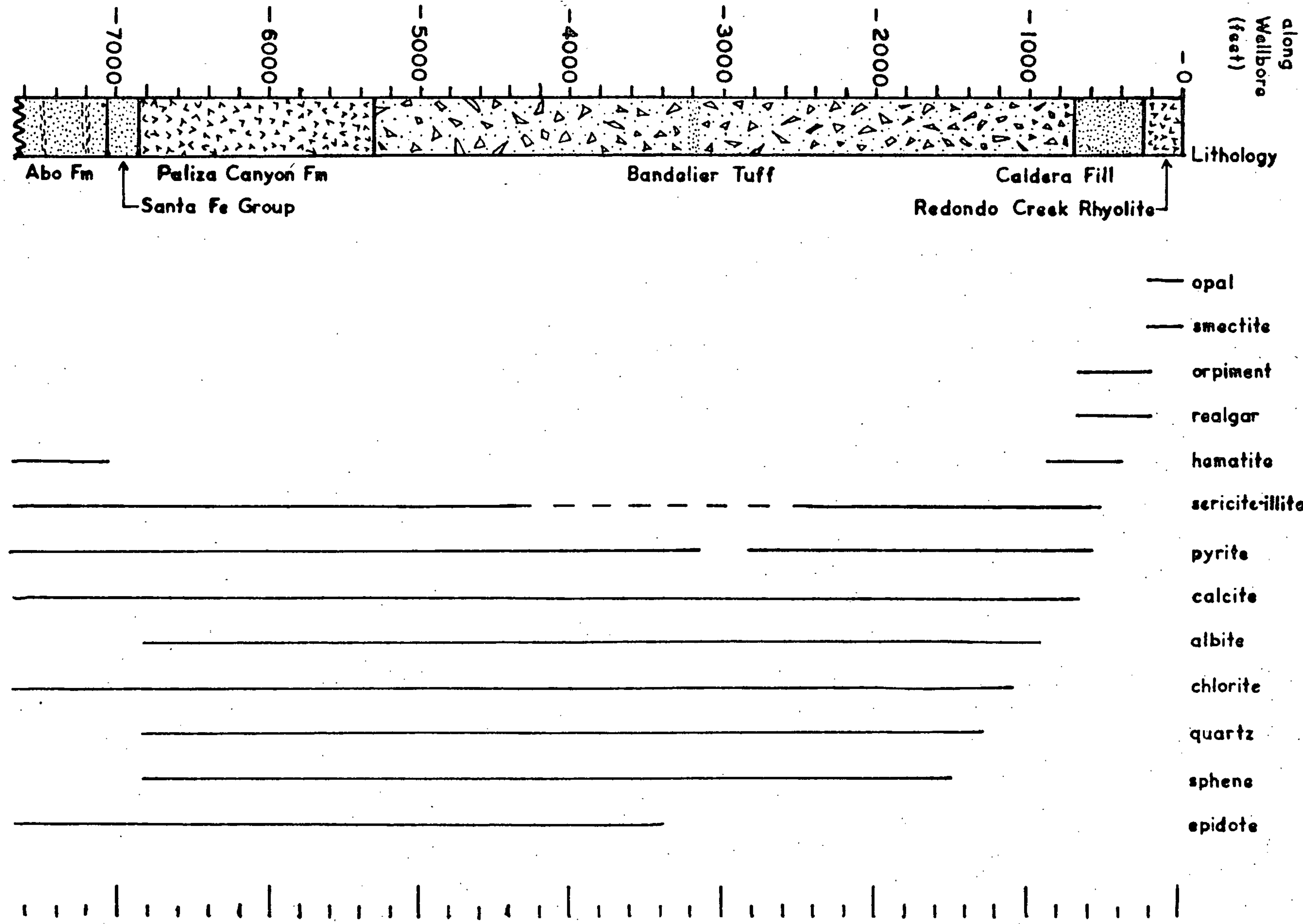

Figure 18. Occurrence of hydrothermal alteration minerals in Baca 22.

Two minerals in Baca 22 occur at temperatures significantly lower than is seen in other hydrothermal areas. These minerals are albite and chlorite.

Albite first occurs at a depth of 700 feet where the temperature is presently 75°C. Browne and Ellis (1970) noted that albite was first formed at temperatures near 120°C at Ohaki-Broadlands which is in agreement with temperatures reported by Iijima and Utada (1971) and Iijima (1975).

Chlorite generally forms at temperatures in excess of 120°C (Sigvaldason and White, 1962), (Honda and Muffler, 1970), (Keith et al., 1978), and (Cavarretta et al., 1982). In Baca 22 chlorite is seen at depths where the temperature is 100°C.

Figure 19 gives the downhole pressures and temperatures from Baca 22 redrill 2 which demonstrate the relationship between the water table depth and the temperature gradients due to the higher thermal conductivity of saturated rocks (Garg and Kassoy, 1981) and convection of fluids within the rocks. Until about 0.5 m.y.a. the Valles caldera contained a lake, below which the rocks were saturated. The presence of this water in the hydrothermal system may well have increased temperatures above the present water table so that the present placement of alteration minerals was more in keeping with other hydrothermal areas. The lowering of the water table to its present position would have lowered the conductivity and temperature of those rocks above the water table.

Another possibility explaining the occurrence of albite and chlorite at such low temperatures is given in Doell et al. (1968) who suggested that the caldera floor was buried by more than 2000 feet of caldera fill before the formation of the resurgent dome. This extra overburden, since thinned by erosion, may have insulated the rocks sufficiently to raise temperatures to the necessary levels to form albite and chlorite where we see them today. The formation of the resurgent dome also may have provided heat for the temperature increase.

Wairakite occurs in one sample near 8400 feet. Lambert and Epstein (1980) describe the initial occurrence of wairakite in Baca 7 at 4660 feet. The great difference in depth of occurrence can be attributed to the depth of the Magdelina Group rocks. The wairakite seen in

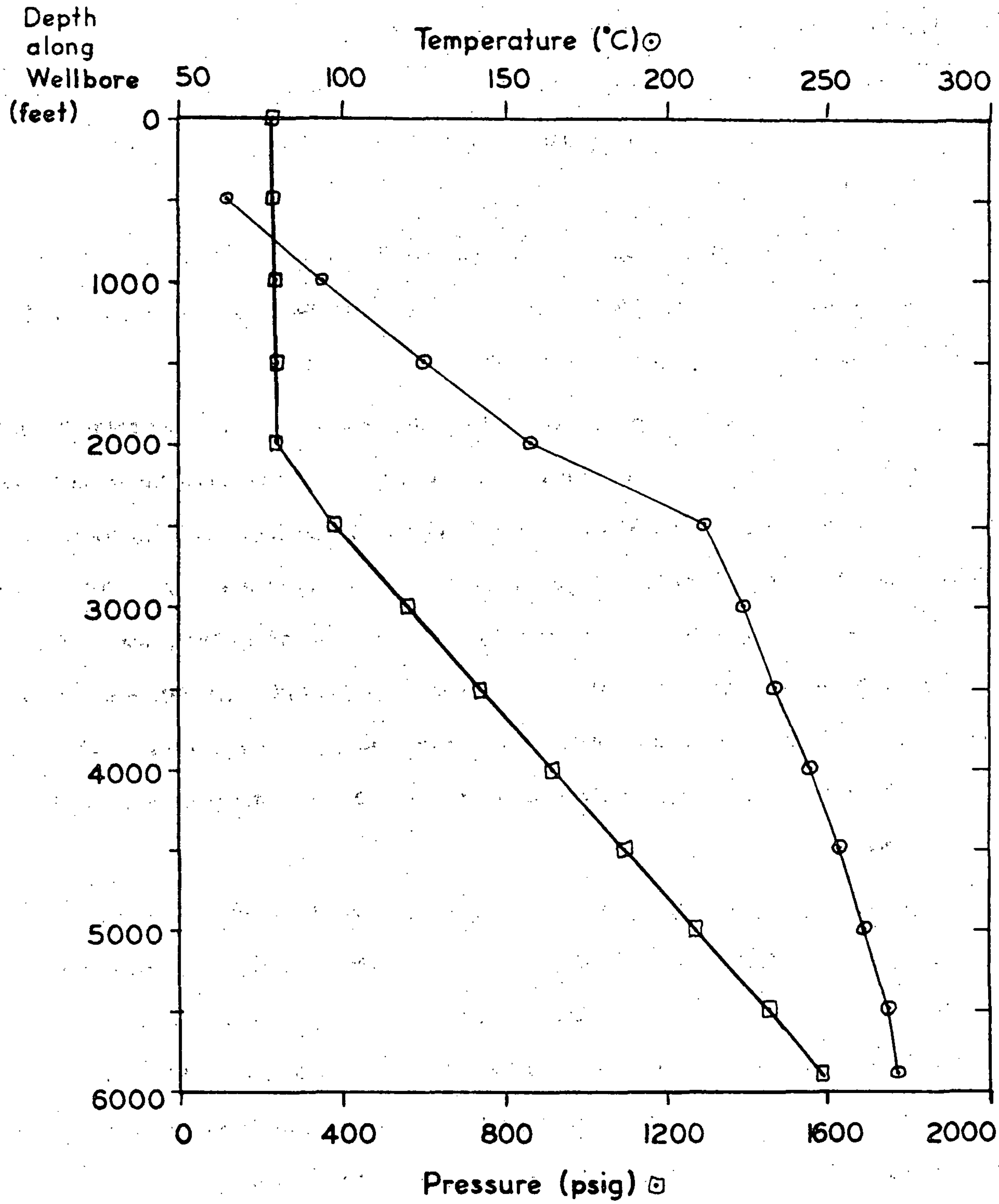

Figure 19. Temperature and pressure in Baca 22.

Baca 22 occurs within the Magdelina Group and the wairakite seen in Baca 7 occurs a short distance above the Magdelina Group.

With the exception of wairakite, zeolites are absent in the Baca 22 cuttings. This may be related to the cooling history of the Bandelier Tuff. Most of the tuff devitrified soon after emplacement and zeolites are not known to form from devitrified silicic glass.

Conclusions

1. The following minerals were formed in hydrothermal alteration of volcanic rocks: calcite, illite, quartz, chlorite, albite, epidote, sphene, opal, smectite, pyrite, orpiment, realgar, hematite, and sericite. Hydrothermal minerals formed in the sedimentary rocks are: calcite, illite, quartz, epidote, pyrite, orpiment, realgar, hematite, sericite, and wairakite.
2. Textural detail is lost in hydrothermal alteration of welded-tuff below a depth of 1400 feet.
3. Albite and chlorite are found at temperatures lower than usual for their formation in hydrothermal areas.
4. The draining of a lake in the caldera ~0.5 m.y.a. dropped the water table 2000 feet and consequently lowered the conductivity and the temperatures in the rocks above the present water table.
5. Albitization of sanidine and plagioclase phenocrysts is pervasive in the Bandelier Tuff but is absent in the Paliza Canyon Formation. The albitization of plagioclase is unusual here in that the polysynthetic twinning present in the original phenocryst is not retained in the pseudomorphic albite.

6. The Bandelier Tuff devitrified soon after emplacement which may account for the lack of hydrothermal zeolites such as are commonly found elsewhere in hydrothermal alteration of rhyolites.

7. Alteration reactions such as feldspar to illite; plagioclase to sericite, sphene, calcite, albite, and epidote; and sanidine to albite have not yet gone to completion.

References

Bailey, R. A., G. B. Dalrymple, and M. A. Lanphere, 1976. Volcanism, structure, and geochronology of Long Valley caldera, Mono County, California. *Jour. Geophys. Res.*, **81**, p. 725-744.

Bailey, R. A., R. L. Smith, and C. S. Ross, 1969. Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico. *U. S. Geol. Surv. Bull., 1274-P,* 19 pps.

Browne, P. R. L. and A. J. Ellis, 1970. The Ohaki-Broadlands hydrothermal area, New Zealand: mineralogy and related geochemistry. *Amer. Jour. Sci.*, **269**, p. 97-131.

Callegari, E. and R. De Pieri, 1967. Crystallographical observations on some chess-board twinned albites. *Schweiz. Mineral. Petrogr. Mitt.*, **47**, p. 99-110.

Cavarretta, G., G. Gianelli, and M. Puxeddu, 1982. Formation of authigenic minerals and their use as indicators of the physicochemical parameters of the fluid in the Larderello-Travale geothermal field. *Econ. Geol.*, **77**, p. 1071-1084.

Doell, R. R., G. B. Dalrymple, R. L. Smith, and R. A. Bailey, 1968. Paleomagnetism, potassium-argon ages, and geology of rhyolites and associated rocks of the Valles caldera. *Geol. Soc. Amer. Memoir 116,* p. 211-248.

Garg, S. K. and D. R. Kassoy, 1981. Convective heat and mass transfer in hydrothermal systems. In *Geothermal Systems: Principles and Case Histories.* L. Rybach and L. J. P. Muffler (Eds.), Wiley, Chichester, p. 37-76.

Honda, S. and L. J. P. Muffler, 1970. Hydrothermal alteration in core from drill hole Y-1, Upper Geyser Basin, Yellowstone National Park, Wyoming. *Amer. Mineral.*, **55**, p. 1714-1737.

Iijima, A., 1975. Effect of pore water to clinoptilolite-analcime-albite reaction series. *Journal of the Faculty of Science, Univ. of Tokyo,* Sec. II, **19**, p. 133-147.

Iijima, A. and M. Utada, 1971. Present-day zeolitic diagenesis of the Neogene geosynclinal deposits in the Niigata oil field, Japan. *Amer. Chem. Soc., Advances in Chemistry Series No. 101*, p. 342-349.

Keith, T. E. C., D. E. White, and M. H. Beeson, 1978. Hydrothermal alteration in Y-7 and Y-8 drill holes in northern part of Upper Geyser Basin, Yellowstone National Park, Wyoming. *U. S. Geol. Surv. Prof. Paper 1054-A*, 26 pps.

Lambert, S. J. and S. Epstein, 1980. Stable isotope investigations of an active geothermal system in the Valles caldera, Jemez Mountains, New Mexico. *Jour. Vulcan. Geother. Res.*, **8**, p. 111-129.

Laughlin, A. W., 1981. The geothermal system of the Jemez Mountains, New Mexico and its exploration. In *Geothermal Systems: Principles and Case Histories*. L. Rybach and L. J. P. Muffler (Eds.), Wiley, Chichester, p. 295-320.

Moore, D. E. and J. G. Liou, 1979. Chessboard-twinned albite from Franciscan metaconglomerates of the Diablo Range, California. *Amer. Mineral.*, **64**, p. 329-336.

Ross, C. S., R. L. Smith, and R. A. Bailey, 1961. Outline of the geology of the Jemez Mountains, New Mexico. In *New Mexico Geological Society, Guidebook of the Albuquerque Country, 12th Field Conf., Oct. 6-8, 1961: Socorro,* New Mexico Bur. of Mines and Mineral Resources, p. 139-143.

Sigvaldason, G. E. and D. E. White, 1962. Hydrothermal alteration in drill holes GS-5 and GS-7, Steamboat Springs, Nevada. *U. S. Geol. Surv. Prof. Paper 450-D*, p. 113-117.

Smith, R. L. and R. A. Bailey, 1966. The Bandelier Tuff: a study of ash-flow eruption cycles from zoned magma chambers. *Bull. Volcanol.*, Ser. 2, **29**, p. 83-104.

Steiner, A., 1977. The Wairakei geothermal area, North Island, New Zealand: its subsurface geology and hydrothermal rock alteration. *N. Z. Geol. Surv. Bull.*, **90**, 136 pps.

Tobi, A. C., 1956. A chart for measurement of optic axial angles. *Amer. Mineral.*, **41**, p. 516-519.

Yoder, H. S. and H. P. Eugster, 1955. Synthetic and natural muscovites. *Geochim. et Cosmochim. Acta*, **8**, p. 225-280.

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