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Geophysical investigations of the Cove Fort-Sulphurdale geothermal system, Utah

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ABSTRACT

The Cove Fort-Sulphurdale KGRA is part of one of the largest thermal anomalies in the western United States. Since 1975 an extensive data base has been developed which includes the results of detailed and regional geologic, gravity, magnetic, seismic, and resistivity investigations. Geologic studies have delineated the major tectonic elements of the thermal system and have led to the recognition of large-scale gravitational glide blocks that act as a leaky cap to portions of the geothermal system.

Gravity and magnetic data have delineated major throughgoing structures beneath alluvium and basalt cover, and have indicated the importance of the Cove Fort-Beaver graben in localizing the geothermal reservoir. The presence of these structures and a high level of microearthquake activity suggest other target areas within the larger thermal anomaly. Electrical resistivity surveys and thermal gradient holes both contribute to the delineation of the known reservoir.

Four deep exploration wells which test the geothermal system were drilled between 1975 and 1979. One well, CFSU 42-7, recorded temperatures of 178°C. The high cost of drilling, high corrosion rates, low reservoir pressures, and the apparent limited extent of the high-temperature reservoir led to a premature conclusion in 1980 that the field was not economic for large-scale electric power production. More recent drilling in the vicinity of CFSU 42-7 resulted in the discovery of high-temperature (200°C?) geothermal fluids at a depth of approximately 350 m. A well-head generator was installed and power production is expected in 1985. Additional development of the geothermal reservoir is anticipated in the 1985 to 1987 time frame.

INTRODUCTION

During the past several decades most of the known hot spring systems in the Basin and Range province have been systematically drilled to test their potential for producing geothermally generated electricity. The Cove Fort-Sulphurdale thermal anomaly, located on the eastern margin of the province (Figure 1), is one of the largest of the thermal systems discovered as a result of these efforts. Exploration of this thermal system was initiated in 1975. There are abundant indications of high subsurface temperatures, including numerous gas seeps, intense surficial acid alteration, high thermal gradients, and measured subsurface temperatures of 178°C. Nevertheless, it was not until 1983, when a shallow well capable of producing an estimated 114 000 kg/hr of "dry steam" at a wellhead temperature estimated at 200°C (DiPippo, 1984) blew out that the true potential of the resource was demonstrated.

Since 1975, the field has been the subject of numerous geologic, geophysical, and geochemical investigations by both the geothermal industry and federally funded organizations. As a result of a cost-sharing agreement between the Department of Energy (DOE) and Union Oil Company, a significant number of proprietary data, including all data obtained during the drilling of four deep wells, were placed in the public domain (Union Oil Company, 1978a, b, c; 1979a, b). Other investigations principally by the Earth Science Laboratory of the University of Utah Research Institute (ESL/UURI) (Ross et al., 1982; Moore and Samberg, 1979), and the U.S. Geological Survey (Steven and Morris, 1981; Steven et al., 1979), were conducted to augment this data base. Here we present the results of the geologic and geophysical investigations and offer a conceptual model of the thermal system.

GEOLOGY

Geologic setting

The Cove Fort-Sulphurdale thermal anomaly is located near the junction of the Pavant Range and Tushar Mountains on the eastern margin of the Basin and Range province. These highlands, composed largely of Paleozoic to Mesozoic sedimentary rocks and Tertiary volcanic rocks, form part of the High Plateaus subprovince (Figures 1 and 2) that marks the transition between the Colorado Plateau and the Basin and Range provinces.

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The sedimentary rocks of the Cove Fort-Sulphurdale area are part of a broad, north-trending thrust belt deformed during the Late Cretaceous Sevier orogeny (Crosby, 1959; Armstrong, 1968). Rocks penetrated to depths of 2 358 m in the deep geothermal wells consist largely of limestone and dolomite that were variably metamorphosed during Tertiary intrusive activity. Comparison of the lithologies encountered within the wells with unmetamorphosed stratigraphic sections from the Pavant Range described by Crosby (1959) and Hintze (1973) suggests that the reservoir rocks are Cambrian to Triassic in age.

The Tertiary volcanic rocks were erupted between about 30 and 19 m.y. ago from widely scattered centers in two distinct volcanic terranes—the Marysvale volcanic field of the southwestern High Plateaus to the east of Cove Fort and the Basin and Range to the west (refer to Figure 1; Steven et al., 1979; Steven and Cunningham, 1979). The base of the volcanic sequence near Cove Fort consists of locally derived propylitically altered lava flows and breccias of intermediate composition (Caskey and Shuey, 1975; Steven et al., 1979). Ash-flow tuffs predominate in the upper parts of the Tertiary volcanic sequence. These distinctive marker horizons allowed detailed mapping of important structures within the geothermal field (Moore and Samberg, 1979; Steven and Cunningham, 1979; Steven et al., 1979).

The lower portion of the volcanic sequence (Tb and Tc in Figures 2 and 3) and the underlying sedimentary rocks of the thermal reservoir were metamorphosed and mineralized by a hypabyssal pluton of monzonite between 22 and 27 m.y. ago (Moore and Samberg, 1979). Although the main body of the intrusion is not exposed, numerous latite porphyry dikes and plugs are exposed in the northwestern Tushar Mountains (Figure 2) and, near Sulphurdale, well CFSU 42-7 intersected several thin monzonite dikes in recrystallized limestone. In places, the dikes fed lava flows which were locally preserved beneath the unaltered Osiris tuff dated at 22 m.y. by Fleck et al. (1975).

Renewed volcanic activity spanned the interval between 1 m.y. and 0.3 m.y. ago (Best et al., 1980) producing a shield volcano in the Cove Fort basalt field (Condie and Barskey, 1972; Clark, 1977; Steven and Morris, 1981). Callaghan (1973) and Steven et al. (1979) have suggested that the heat source of the Cove Fort-Sulphurdale geothermal system may be related to this basaltic volcanism.

Structure and alteration

Geologic and geophysical data indicate that permeability within the geothermal system is controlled by faults and fractures. The oldest structures are thrust faults which disrupted the sedimentary rocks during the Sevier orogeny. Thrust faults, although not conspicuous in the area shown in Figure 2, may be widely distributed in the reservoir rocks of the thermal area at depth. They occur to the north in the Pavant Range (Steven and Morris, 1981) and have been intersected at depth on the northern edge of the Tushar Mountains. In well CFSU 31-33, Paleozoic dolomites have been thrust over Triassic siltstone and limestone.

Since Basin and Range tectonism began in the mid-Miocene (Steven et al., 1979), rocks of the Cove Fort area have been disrupted by both high- and low-angle northerly and easterly trending normal faults. Continued activity is indicated by fault scarps in the alluvium and lava flows of the Cove Fort basalt field (Steven and Morris, 1981; Clark, 1977; Zimmerman, 1961) and by a high level of microearthquake activity in the vicinity of Cove Fort (Smith and Sbar, 1974). Here, at Sulphurdale, and along the western margin of the Pavant Range, the trends of the faults are marked locally by the alignment of sulfur deposits, acid-altered alluvium, and gas seeps.

Low-angle faults bound gravitational glide blocks between Sulphurdale and the Cove Creek fault (Figure 2). These westerly dipping faults (Figure 3) display pronounced arcuate trends in plan view (Figure 2). An interpretation of the subsurface geometry of the gravitational glide blocks near Sulphurdale is illustrated in cross-section A-A', Figure 3. The youngest rocks preserved within the fault blocks are basalt and sandstone that overlie the Joe Lott Tuff (not present along section A-A'). These rocks have been assigned to the Sevier River formation of late Cenozoic age.

The gravitational glide blocks form a nearly impermeable cover over the geothermal system which has profoundly influenced the distribution of the surficial alteration, temperatures, and thermal gradients along the northwestern flank of the Tushar Mountains. Geochemical and mineralogical analyses of drill cuttings from shallow gradient holes within the gravitational glide blocks suggest that the near-surface rocks be-

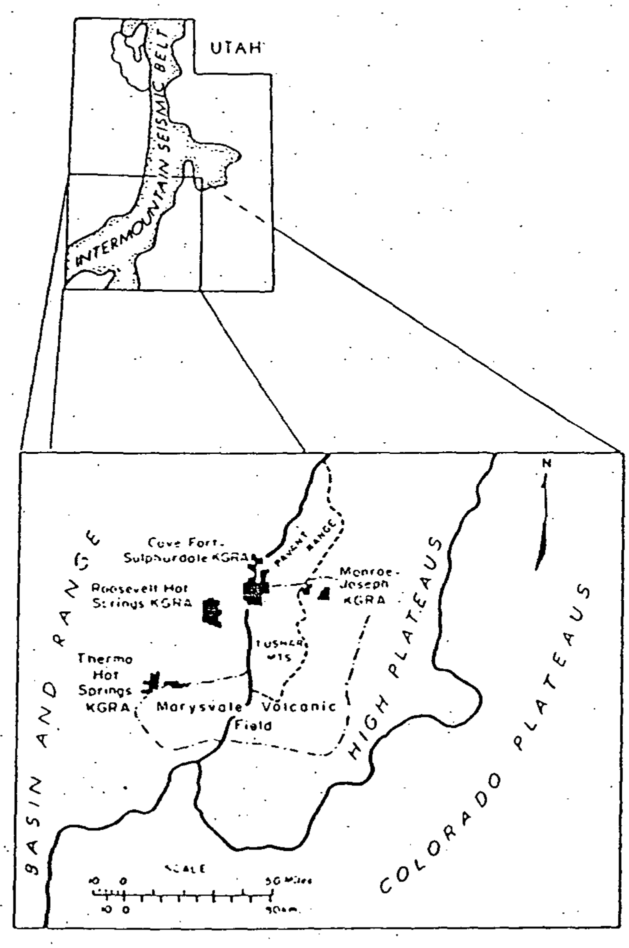

FIG. 1. Index map showing the location of Cove Fort-Sulphurdale KGRA with respect to regional geology and seismicity. Geologic province boundaries are indicated by solid lines, and the mountain ranges by dashed lines.

tween Cove Fort and Sulphurdale have not been appreciably altered by the present geothermal system. Locally intense alteration does occur on the periphery of the glide blocks at Sulphurdale. These data indicate that vertical permeabilities are low throughout most of the area covered by the glide blocks, in spite of the locally intense fracturing that we mapped within them.

The surface manifestations of the active geothermal system at Sulphurdale and north of the glide blocks near Cove Fort include sulfur deposits, acid-altered ground, and active gas seeps (Figure 2) which emit some hydrogen sulfide. These features occur in an area covering approximately 47 km^2 and reflect the degassing and perhaps boiling of a chloride brine located at a depth of approximately 400 m. The acid-altered areas are conspicuous white deposits consisting predominantly of siliceous residues derived from the preexisting rocks and containing variable amounts of clays, sulfur, gypsum, pyrite, marcasite, and mercury. These are surficial features that do not extend below the water table.

Anhydrite occurs in the metamorphosed limestones beneath

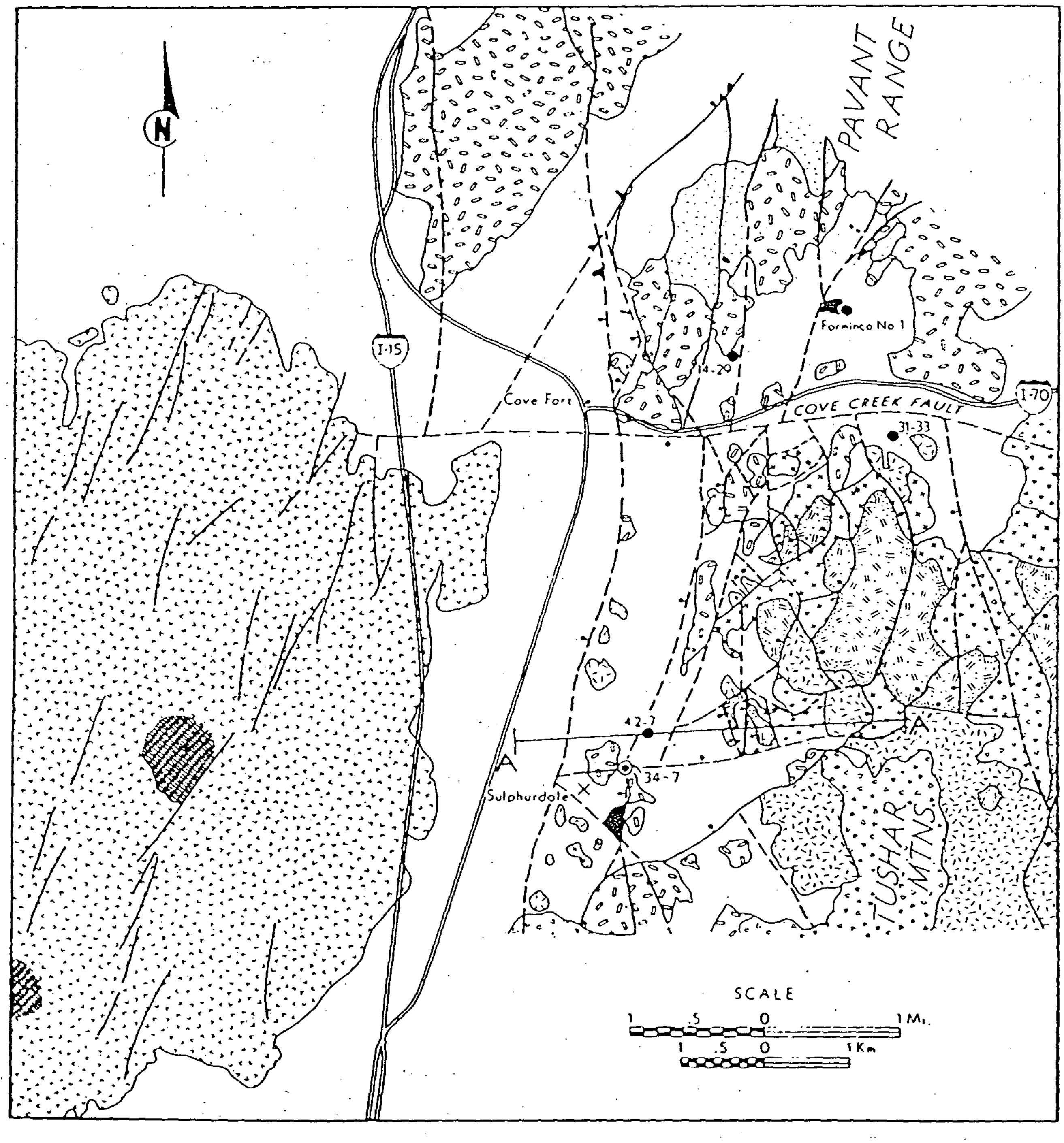

FIG. 2. Detailed geologic map of the Cove Fort-Sulphurdale area showing the location of the deep exploration wells and cross-section AA' (after Moore and Samberg, 1979; Steven and Morris, 1981).

the glide blocks in well CFSU 42-7. The presence of anhydrite as open-space fillings and the absence of other minerals typical of base-metal porphyry systems suggest that the anhydrite is related to the active geothermal system. While anhydrite is a common mineral of many geothermal fields (Browne, 1978), it is characteristically not in equilibrium with the high-temperature fluids from the interior of these systems. Because the solubility of anhydrite decreases with increasing temperature, anhydrite is most likely to precipitate on the margins of geothermal systems where heating of nonthermal waters can occur.

GEOPHYSICS

A variety of geophysical data is available as the result of regional investigations and site-specific exploration of the geothermal reservoir. Passive seismic and gravity data provide considerable insight into the deeper structural setting of the Cove Fort-Sulphurdale area and are considered first.

Seismic setting

The Cove Fort-Sulphurdale and Roosevelt Hot Springs geothermal areas are located along the western margin of the active Intermountain seismic belt (Smith and Sbar, 1974), a major zone of earthquake activity which extends northward from Arizona through Utah and eastern Idaho into western Montana (Figure 1). In Utah this zone is roughly coincident with the transition zone between the Basin and Range province on the west and the Colorado Plateau to the east. Within this broad region of active seismicity, the area between and including Roosevelt Hot Springs and Cove Fort-Sulphurdale appears to be less seismically active than the Sevier and Tushar fault zones and the Marysvale volcanic center 40 km to the east (Olson and Smith, 1976).

In 1974 and 1975, an array of up to 12 portable, high-gain seismographs was established within the Roosevelt Hot Springs and Cove Fort-Sulphurdale areas (Olson and Smith, 1976). One hundred sixty-three earthquakes of magnitude $0.5 < M < 2.8$ were recorded in two survey periods totaling 49 days. Most of the earthquake activity occurred as a series of swarms with shallow (less than 5 km) focal depths around the Cove Fort area. The maximum calculated depth was 16 km. Only four events could be associated with the 20 km length of the western flank of the Mineral Mountains which includes the Roosevelt Hot Springs geothermal area (Ward et al., 1978). Composite fault-plane solutions indicated normal faulting with generally east-trending T-axis. A high b-value of 1.27 and statistical analyses of mode of event occurrence indicated swarm-like activity near Cove Fort. Most prominent is a northeast-trending cluster of earthquakes which extends northward from an area centered 3 km northeast of Cove Fort.

More recent observations, recorded as part of an induced-seismicity study at Roosevelt Hot Springs, showed a similar pattern of active seismicity at Cove Fort (Schaff, 1981). One hundred-eighty events were recorded for the 12 month period October 1979 through September 1980. The highest density of epicenters occurred near Cove Fort, with 71 events within a 10 km radius of the Cove Fort highway intersection (Figure 2). This seismicity suggests continued reopening of fractures at depth within the reservoir.

Gravity studies

Regional gravity surveys (Cook et al., 1975) have also provided additional data on some of the major regional tectonic elements present in the Cove Fort area. A prominent north-trending 35 to 50 mGal gradient bends eastward at Cove Fort, then trends northeast along the margin of the Colorado Plateau. A gravity study by Cook et al. (1980) documents this

Key to lithologic symbols used in Figure 2.

Qal	Alluvium (Quaternary)	Tc	Clinoptilolite-bearing ash-flow tuff (Miocene)
Qls	Landslide deposits (Quaternary)		
Qb	Cinder cones of the Cove Fort basalt field (Pleistocene)	Tb	Older volcanic rocks and ash-flow tuffs (Oligocene to Miocene); includes lava flows, breccias and the Three Creeks Tuff Member of the Bullion Canyon Volcanics and the Tuff of Albinus Canyon
Qb	Lava flows of the Cove Fort basalt field (Pleistocene)		
Tjm	Ash-flow tuffs (Miocene); includes the Joe Lott Tuff of the Mount Belknap Volcanics and the Osiris Tuff	Kpr	Price River Conglomerate (Cretaceous)
Ti	Dikes, flows and stocks ranging from latite porphyry to monzonite (Miocene)	PMs	Paleozoic and Mesozoic sedimentary rocks, undivided; includes metamorphosed equivalents at depth
●	Union Oil Company geothermal well		Faults, dashed where covered; ball and bar on downthrown side
⊙	Mother Earth Industries, Inc. geothermal well		Area of acid alteration

transition in detail (Figure 4) and indicates several major structural features. Approximately 700 gravity stations provide control for the gravity contours. Interpreted faults are shown as heavy lines.

The dominant feature is the north-trending Beaver-Cove Fort graben, filled with more than 1 km of volcanic rocks and Quaternary alluvium. The interpreted structures shown on Figure 4 are generalized from the 2-D model results of Cook et al. (1980) supplemented by our 3-D modeling and geologic mapping. Paleozoic sedimentary rocks which outcrop north of Cove Fort and granitic intrusives of the Mineral Mountains exhibit densities of approximately 2 670 kg/m^3. Limited density measurements of the Tertiary volcanics, which consist of tuffs and rhyolites, suggest an average density of 2 250 to 2 400 kg/m^3. Quaternary alluvium and valley fill can be expected to vary from 2 000 to 2 300 kg/m^3. An average density contrast of 500 kg/m^3 between bedrock range blocks and Tertiary volcanics and/or alluvium was used in the numerical modeling, which then indicated a 1 km to 2 km thickness (increasing to the south) of low-density rocks in the eastern portions of the graben. The positions of major structures are substantially accurate, but uncertainties in density contrasts may result in a minimum estimate of graben fill. The gravity data, when quantitatively interpreted, indicate a major structural feature with fault displacements of several kilometers. The interpreted depth extents and ages of the faults suggest that these faults may be the principal conduits which tap a deep-seated geothermal reservoir.

Magnetic studies

High-altitude aeromagnetic data on a statewide (1 : 1 000 000) scale map (Zietz et al., 1976) indicate a prominent east-trending discontinuity over 160 km long which passes through the Cove Fort-Sulphurdale area and delineates the northern margin of the Pioche-Beaver mineral trend (Rowley et al., 1978). To the north, magnetic values are lower and only isolated anomalies occur. To the south numerous intrusive- and volcanic-caused anomalies are present. The aeromagnetic data shown in Figure 5 are part of a detailed survey flown in 1978 (Univ. Utah Res. Inst., Earth Sci. Lab., 1978). North-south profiles were flown approximately 0.5 km apart at about 300 m (smoothly draped) above the surface. The Cove Fort basalt field and the major interpreted structures are superimposed over the 100 nT magnetic contours in Figure 5 to facilitate comparison with the detailed geologic map in Figure 2. The IGRF has been removed from the observed total intensity values. A simple, low-intensity magnetic pattern in the northern third of the mapped area arises from Paleozoic and Cretaceous sedimentary rocks with considerable topographic relief on the east, and from Tertiary volcanic rocks and alluvium in areas of low topographic relief to the west.

A complex magnetic pattern with residual total intensity values varying from +450 to −770 nT occurs over a 70 km^2 area of the Cove Fort basalt field in the west-central portion of the map. In general this magnetic pattern reflects the distribution of intersecting northwest- and northeast-trending faults. Although most of the faults are characterized by relatively small displacements, many have pronounced topographic expresssions. A conspicuous low of more than 400 nT near the center of the basalt field occurs over the 150 m topographic high of Cinder Crater. Numerical modeling yields an equivalent susceptibility of −.063 (−.005 cgs), indicating strong permanent magnetization directed approximately opposite the Earth's present field direction. Another smaller, reversely magnetized cinder cone is noted at the southern edge of the basalt field. The remainder of the basalt field appears to be normally

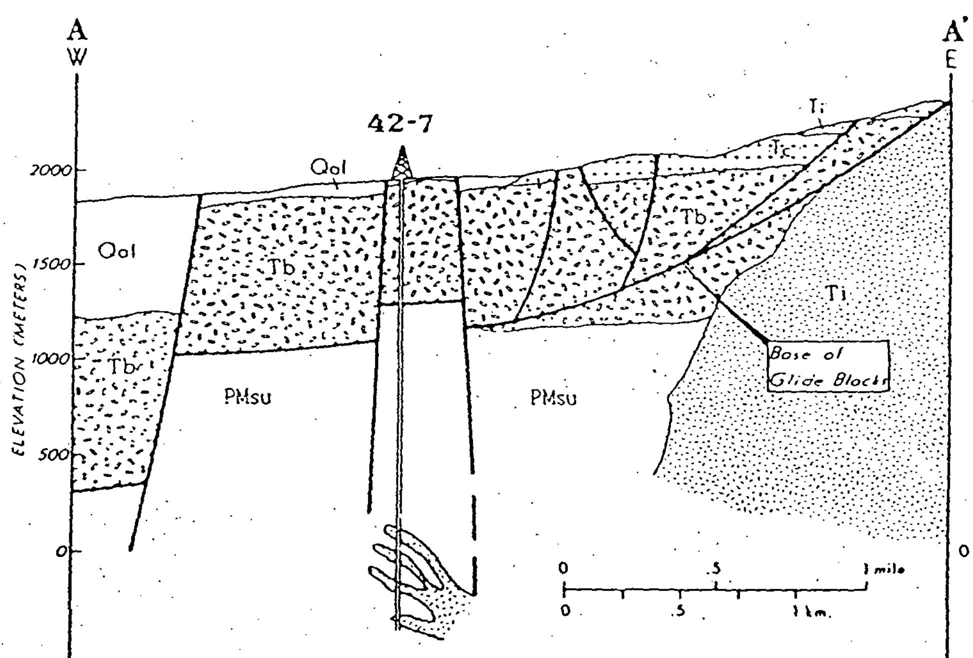

FIG. 3. Simplified geologic cross-section of the glide blocks and CFSU 42-7 lithologies. Faults are shown by heavy lines. Lithologic symbols are the same as in Figure 2.

magnetized, based on a positive correlation between reduced terrain clearance and increased magnetic intensity. The Cinder Crater magnetic source is cut by a northeast-trending fault but is itself elongate northwest.

The southeastern portion of the survey area is dominated by an elliptically shaped magnetic anomaly with a maximum value of 970 nT. Three-dimensional numerical modeling indicates a complex magnetic source with a geometry as indicated by the patterned area in Figure 5. Reduced terrain clearance over the Tertiary ash-flow tuffs and andesites of the Tushar Mountains contributes to this irregular magnetic anomaly. However, the dominant source is attributed to a buried intrusion 100 to 1 000 m below the surface, which dips to the north and extends to depths greater than 3 000 m. The equivalent susceptibility for the magnetic source, as determined from modeling, varies from approximately 0.063 (0.005 cgs) near the surface to 0.126 (0.010 cgs) at depths below 1 000 m. The high average magnetization suggests the possibility of magnetic skarn mineralization. The widespread and locally high-grade contact metamorphism and hydrothermal alteration, and the presence of monzonite dikes intersected in drilling provides geologic support for the intrusive-skarn interpretation. Tertiary latite porphyry rocks which outcrop north of the interpreted source are only weakly expressed (40 to 50 nT) in the magnetic data.

The lowest total intensity values (−942 nT) recorded in the survey occur in an area of low magnetic relief between Sulphurdale and Cove Fort. Here weakly magnetic and extensively altered Tertiary volcanics overlie the Paleozoic carbonates which host the geothermal reservoir. The low magnetic values occur as a polarization low from the intrusive source to the south.

Several northwest- and northeast-trending structures which cut the Cove Fort basalt field and the buried intrusive source are readily identified from the magnetic data. Only short segments of the north-trending faults apparent in the gravity data (Figure 4) are well-defined by the magnetic contours. These structures, which may be important to the localization of geothermal fluids, are well defined: northwest and north-northwest trending structures which cut the magnetic intrusive body, one of which extends into the Sulphurdale alteration area; and an east-trending fault which cuts across the graben between well CFSU 42-7 and Sulphurdale. All three trends are Tertiary or younger in age and must represent some substantial offset to be expressed in the aeromagnetic data.

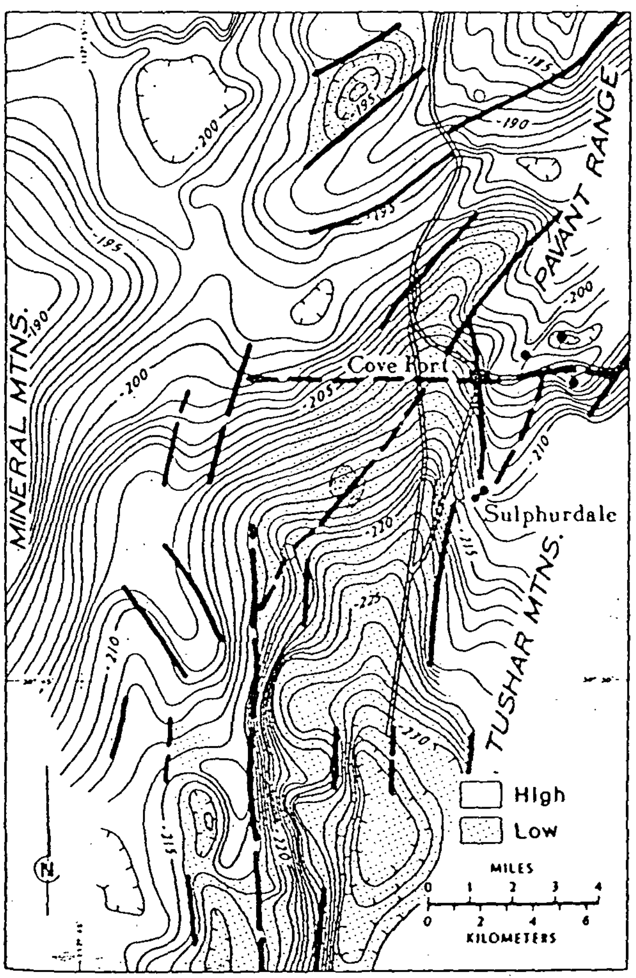

FIG. 4. Terrain corrected bouguer gravity anomaly map of the Cove Fort-Sulphurdale region, Beaver and Millard Counties, Utah (modified from Cook et al., 1980). Contour interval is 1 mGal. Interpreted faults are shown as heavy lines. The locations of the deep exploration wells are shown as filled circles. Refer to Figure 2 for well numbers.

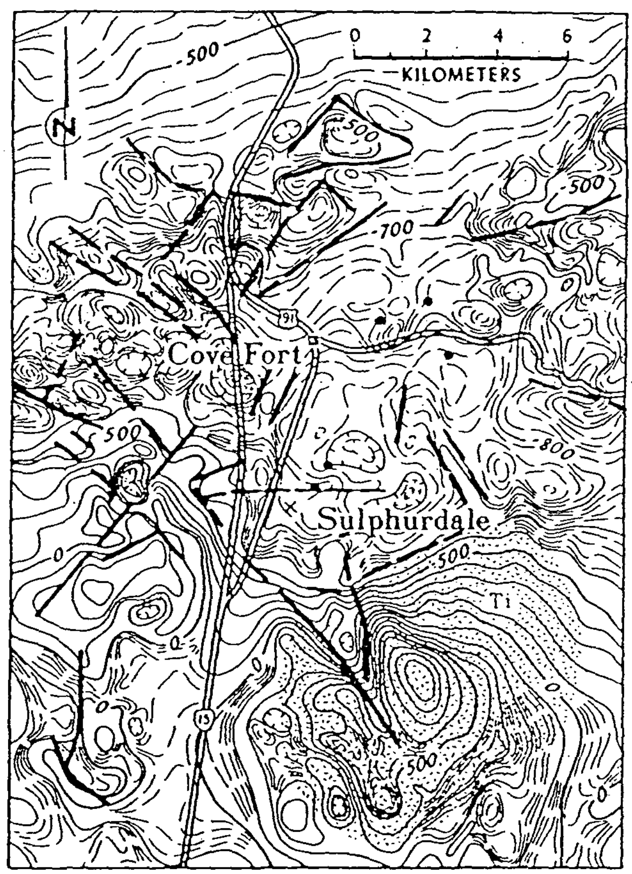

FIG. 5. Total magnetic intensity map for the Cove Fort-Sulphurdale area showing interpreted faults and buried intrusive (Ti). Contour interval 100 nT (solid); 20 nT (dashed). The locations of the wells are shown as filled circles. Refer to Figure 2 for well numbers.

Thermal studies

The shallow thermal gradient anomaly determined from 24 drill holes is shown in Figure 6. The thermal data presented are part of a Union Oil Company (1978a) data package made available through the DOE Industry Coupled Program. The thermal gradient values shown are not corrected for topography and correspond to stable temperature gradients at 30 to 76 m depths. An average Basin and Range gradient for Tertiary tuffs and alluvium materials (i.e., thermal conductivities of 1.5 to 2.2 W/m K) would be approximately 50°C/km. The 200°C/km contour of Figure 6 defines an area of about 60 km ^{2}. This is a fraction of the less well-defined 200 to 300 km^2 anomalous thermal area, including Dog Valley to the north of the map area and Beaver Valley to the west, where anomalous well temperatures are also known to occur.

Many of the higher thermal gradients (383°, 328°, 364°, 301°C/km) were recorded in drill holes located along fractures. Convenient drill hole locations were often areas of low topographic relief along mine or prospect roads in areas of fracturing and alteration. Consequently, they test a more direct leakage from the hydrothermal system.

A map of temperatures at a depth of 76 m (which corresponds to the maximum depth for most of the gradient holes) shows a pattern very similar to the thermal gradient contours. Twice background values of 30° to 40°C occur as highs north and south of the area covered by the gravitational glide blocks. The average (nonanomalous) surface temperatures are about 15°C. The excellent agreement between the gradient and temperature maps indicates an absence of near-surface hydrologic disturbance (due to the deep water table), but both parameters are affected by vapor leakage along structures.

Electrical resistivity surveys

Two dipole-dipole resistivity surveys were completed as part of the exploration effort. The first survey of three long, widely spaced profiles (UOC AA', BB', LL'; Figure 7) was completed in November 1976, and a second survey of six additional profiles was completed in September 1978. Both sur-

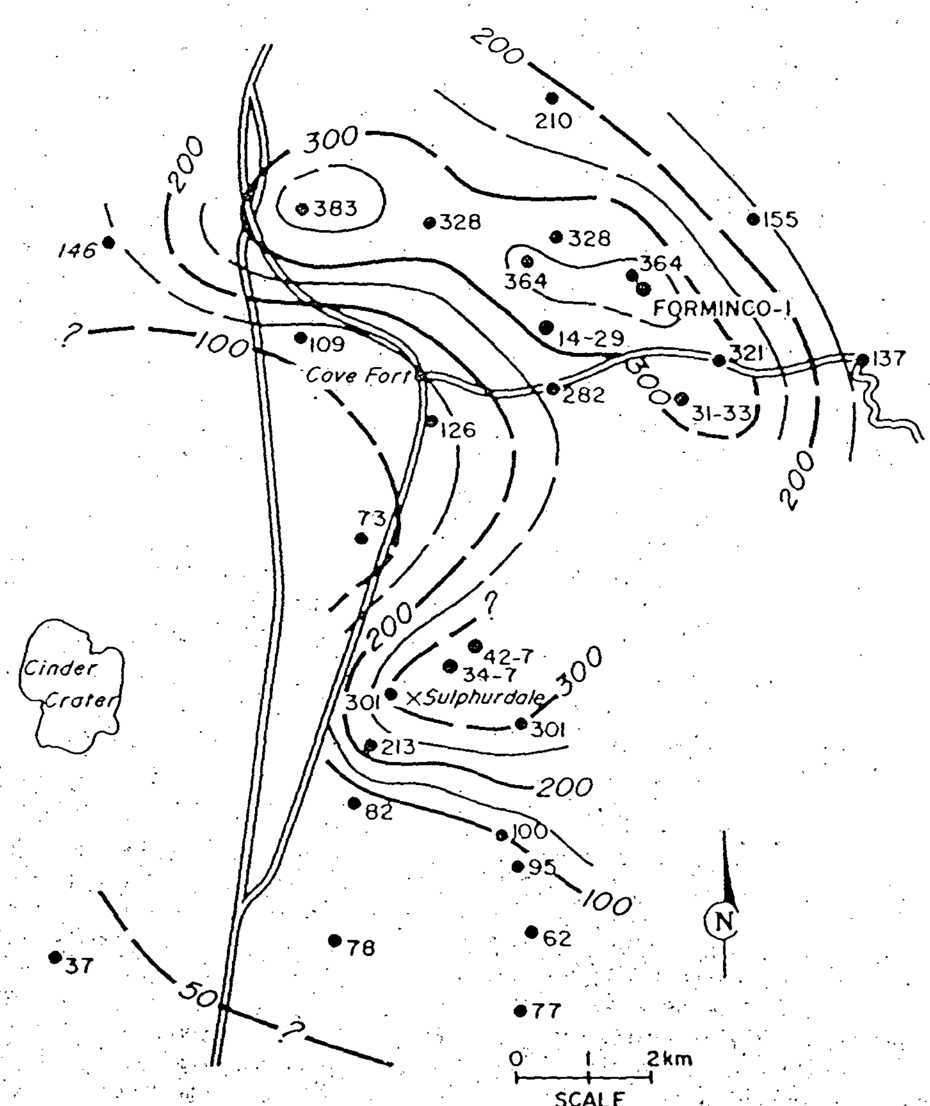

FIG. 6. Shallow thermal gradient map as determined for the depth interval 30–76 m; °C/km.

veys used 305 m dipoles and each survey yielded 31.4 line-km of profile data. Apparent resistivity values were recorded for $N = 1$ to 6 or $N = 1$ to 7. The locations of all lines and a summary of interpreted resistivity values for the 460 to 610 m depth interval are shown in Figure 7.

All of the dipole-dipole resistivity data were interpreted using an interactive computer modeling process (Ross, 1979) which assumes a 2-D geometry. Apparent resistivity values were computed by a finite-element program initially developed by Rijo (1977) and subsequently modified by Killpack and Hohmann (1979).

The apparent resistivity values were computed for dipole separations $N = 1$ to 6 and compared with the observed data to determine the goodness of fit and the model changes needed to achieve a better fit. The interpretation rarely proceeds to a perfect match of observed and model data because of the time involved. The 3-D aspects of the actual resistivity distributions and the ambiguities of position, intrinsic resistivity, and size of bodies cannot be resolved (i.e., are not unique). A satisfactory fit was judged to have been obtained when a majority of the pseudosection data values were within 10 percent of the observed resistivity values and when the directions of the observed resistivity changes were matched.

Two of the nine interpreted resistivity profiles are shown in Figure 8. The computed resistivity values corresponding to the model shown closely match the observed data (Ross, 1979). Although the interpretation of resistivity data is not unique, careful modeling of dipole-dipole resistivity data can provide a satisfactory representation of earth resistivity distribution to depths equal to twice the dipole length. The nonuniqueness is reduced by utilizing a network of profiles, several of which intersect, and the integration of geologic data such as the 1 : 24 000 scale map of Moore and Samberg (1979).

Line 6 (Figures 7 and 8), located approximately 2 km north of Cove Fort, trends east-west and crosses a series of high-angle normal faults near station 1 east. The Cretaceous and Paleozoic sedimentary rocks are seen to be resistive (50 to 300 Ω·m) from the surface to depths greater than 600 m. The leakage of low-resistivity thermal fluids is indicated by 5 Ω·m resistivity bodies at stations 0 to 1 E and from stations 1 to 3 W. Geologic confirmation for this interpretation includes alteration along the trace of the north-trending fault 500 m to the south. The resistivity model for the western half of line 6 suggests the westward migration of these fluids at depths of 200 m or greater within the alluvium. The low-resistivity zones noted here and on line LL′ to the south are important to the target concept for untested portions of the geothermal system. Resistivities of 50 Ω·m and 20 Ω·m on the west correspond to alluvium and volcanic rocks, probably unsaturated or containing low-salinity waters to depths of 200 to 300 m, and more conductive waters at greater depth.

Line AA′ trends N50°W approximately 600 m north of Sulphurdale and is the southernmost survey line. The modeled resistivity distribution indicates a background level of 20 Ω·m resistivity extending to depth which can be associated with the alluvium and Tertiary volcanics (see Figure 2). Superimposed on this background are areas of 100 Ω·m along the eastern end of the line which are probably due to the densely welded Three Creeks Tuff (unaltered) and possibly to latite porphyry stocks which extend to depth. A thin resistive zone (100 Ω·m) northwest of Sulphurdale corresponds to the Cove Fort basalt flows. A well-defined area of 4 Ω·m which occurs immediately north of Sulphurdale is approximately 1 300 m across and extends from the surface to depths exceeding 600 m. The low resistivities are believed to result from extensive clay alteration of volcanic rocks and high-temperature brines which rise from depth to the top of the water table.

Table 1 presents a summary of resistivity properties determined from the comparison of a detailed geologic map and the modeled resistivity distribution for the 0 to 100 m depth interval. Many resistivity changes are closely associated with mapped lithologic changes in areas of outcrop. The projections of several faults on lines 6, 2, AA′, and 4 (Figure 7) are indicated as pronounced resistivity changes in areas of alluvial cover. It is noteworthy that resistivities for most of the surveyed area are below 50 Ω·m even though the continuous water table is 100 m to over 300 m deep. Substantial moisture must be present either as vadose water or as locally perched aquifers. The low-resistivity zone associated with the known thermal fluids at Sulphurdale covers more than 5 km^2.

Figure 7 shows the modeled resistivity distribution for the depth interval 460 to 610 m. This interval, corresponding to 1.5 to 2.0 times the dipole length, is the deepest depth interval which can be modeled with reasonable confidence, and corresponds to depths below the water table. Dominantly high (50 to 300 Ω·m) resistivities are mapped north and east of Cove Fort on lines 1, 2, 3, 6, BB′ and LL′. The geothermal system, if present in this area, is poorly expressed in these electrical data. Resistivities of 100 to 300 Ω·m are incompatible with porous rock filled with conductive thermal waters. Drill holes Forminco 1 and CFSU 14-29 were terminated by drilling problems before testing the deep reservoir potential in this area (Union Oil Company, 1978b; 1979a). A coherent 5 km^2 area of 4 to 5 Ω·m resistivities around Sulphurdale is bordered by 20–30 Ω·m resistivites. The low resistivities arise from the clay alteration of the volcanic rocks and the conductive geothermal fluids. Five Ω·m resistivities on the western portions of lines 6, LL′, and 4 define a zone of conductive thermal waters rising along a covered Basin and Range fault.

Initial plans for the second resistivity survey included induced polarization measurements for several lines with the aim of documenting sulfide and/or alteration product responses from the geothermal system. Low signal strengths were observed in low-resistivity areas and caused very long reading times which forced a cutoff of the IP measurements. Ross (1979) reported observed apparent polarization values of 3 to 16 ms on lines 1 and 3, with 3 to 6 ms considered background (Table 1). The model interpretation indicates intrinsic polarizations of 15 to 30 ms, which suggest substantial zones of 1 to 2 weight percent sulfides.

Drilling results

Union Oil Company drilled four exploration test wells in their evaluation of the Cove Fort-Sulphurdale geothermal system. The locations of all wells are indicated on Figure 2 and serve as position reference points for additional data sets in Figures 6 and 7. Table 2 summarizes principal results for these four wells. Only two of the four wells, CFSU 42-7 and CFSU 31-33, reached target depth (Ash et al., 1979) due to severe drilling problems associated with numerous, uncontrollable lost-circulation zones.

No temperature data or geophysical logs were obtained in well Forminco 1 (abandoned at 320 m). Well CFSU 42-7

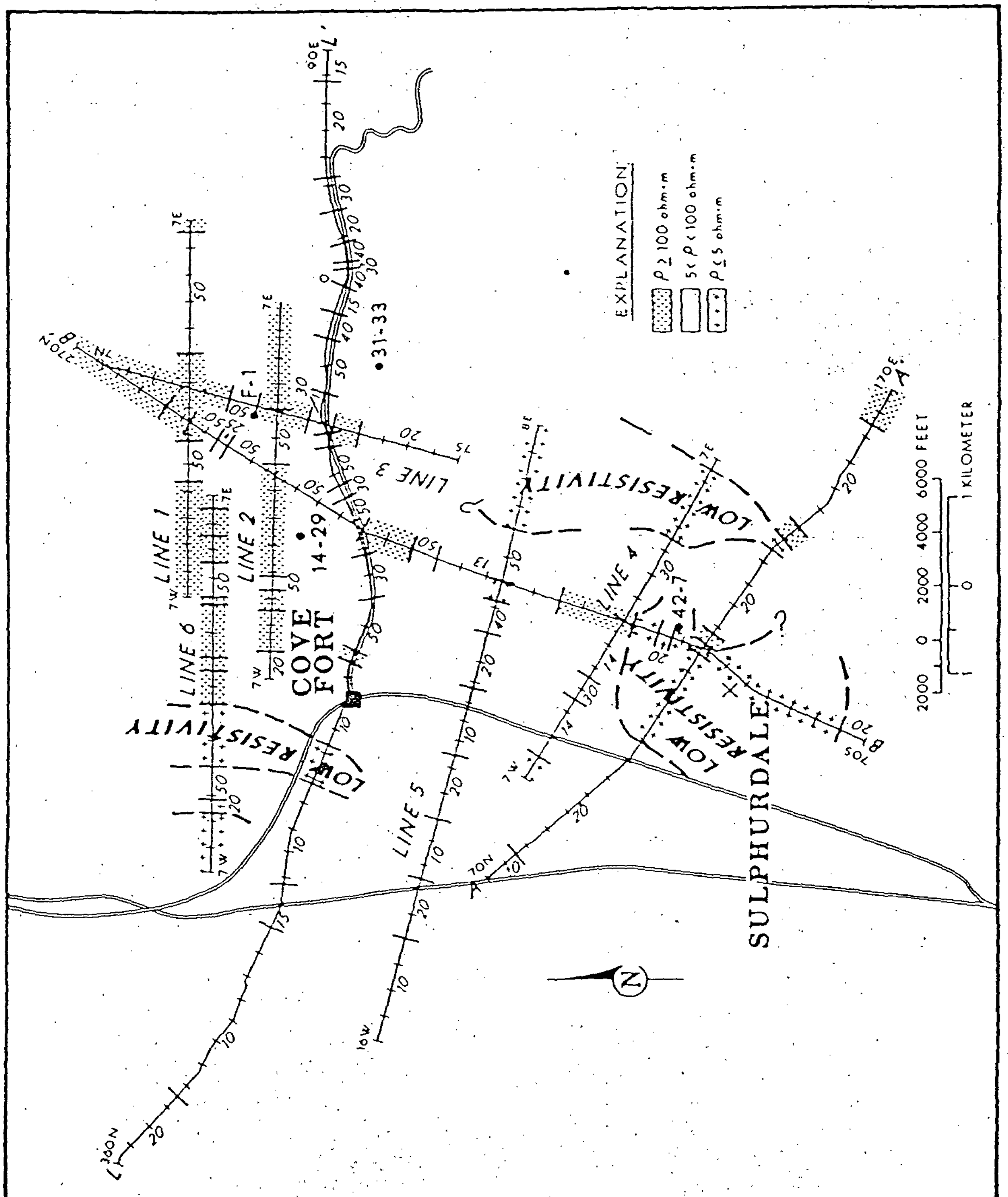

FIG. 7. Electrical resistivity survey. The locations of all lines are shown as are the interpreted resistivity distribution for the depth interval 460 to 610 m as determined by numerical modeling. All lines had a dipole length of 305 m.

reached a maximum observed temperature of 178°C at 2 231 m 13 hours after circulation. A temperature of 146°C was recorded in CFSU 31-33 at 1 433 m 7 hours after circulation. Somewhat higher reservoir temperatures are to be expected. Temperatures are nearly isothermal in the lower portion of both holes (Figure 9) where the wells penetrate rocks beneath the gravitational glide blocks. Intraformational flow was identified in CFSU 31-33 and CFSU 42-7. Ash et al. (1979) concluded that these temperature profiles probably reflect the highly convective nature of the reservoir, and we concur.

Geophysical log interpretation

A wide variety of open-hole, production, and cased-hole well logs were obtained in three wells and interpreted in detail in Glenn and Ross (1982). These logs included a geothermal mud log with drilling rate, rock density, mud temperatures (in and out), lithology, H_2S, and CO_2; dual induction spherically focused log with linear correlation log (SP); compensated neutron-formation density with caliper and gamma ray. Multiple temperature surveys were recorded in each well and each well was surveyed with a four-arm, high-resolution, continuous dipmeter-directional log. A fluid migration survey (temperature and spinner) was recorded in CFSU 31-33 to determine flow directions in this borehole. An acoustic log was recorded in CFSU 42-7.

In their well log interpretation, Glenn and Ross (1982) characterized the tool responses of the major geologic units identified by Moore and Samberg (1979), then refined the depths of lithologic changes, identified major structures, and

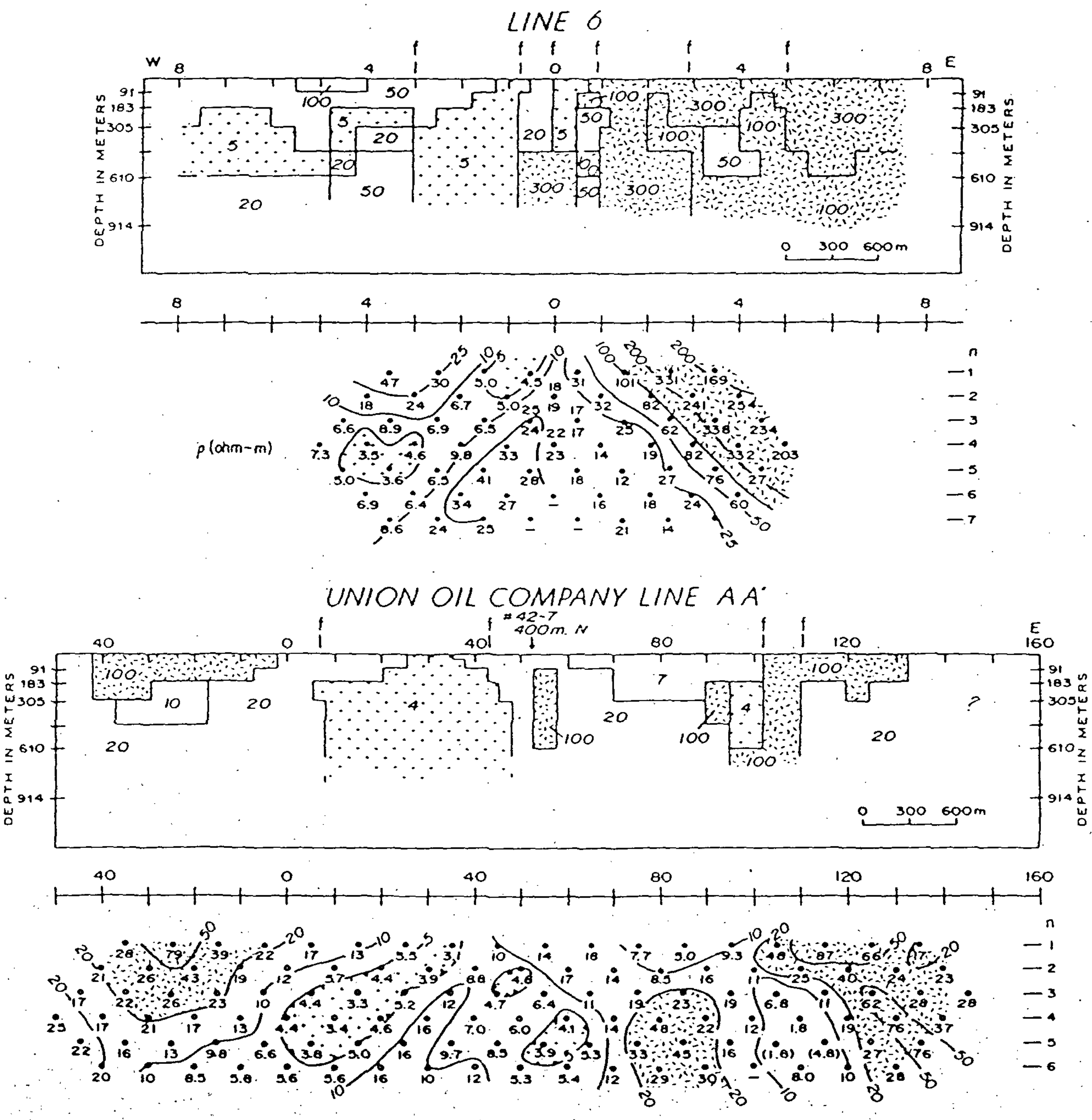

FIG. 8. Observed apparent resistivity data and interpreted resistivity distribution for lines AA' and 6. The dipole length is 305 m.

interpreted lithologies for the large intervals of no cuttings return. Table 3 summarizes formational properties derived in these studies as determined by lithologic interpretation and cross-plot analysis.

Figures 10a and 10b from Glenn and Ross (1982) present cross plots of gamma ray versus bulk density and neutron porosity for the depth interval 536.5 m to 1 578.9 m in CFSU 31-33 and illustrate the utility of cross-plot analysis in unit discrimination. Both figures demonstrate a strong correlation, as indicated by straight lines in each figure, between the gamma-ray data and bulk density and neutron porosity. An increase in gamma-ray response is, in most instances, accompanied by a decrease in density and an increase to neutron porosity. The cross plots illustrate the different responses of the carbonates and siltstones, and the presence of silty limestone and fracture effects as labeled in Figures 10a and 10b. The well-log interpretations identified several fractured intervals which control the fluid flows in these drill holes and contributed to our understanding of reservoir rock properties. Nonfracture porosity is generally less than 4 percent. Thus permeability, lost circulation zones, and solution cavity phenomena are all controlled by major structures and fractures (Glenn and Ross, 1982).

DISCUSSION AND CONCLUSIONS

Surface manifestations, reconnaissance geologic mapping, and shallow thermal-gradient data are routinely used by the geothermal industry to prioritize drilling targets and predict the quality of the geothermal resource. Cove Fort-Sulphurdale provides an instructive illustration of a geothermal field where the surface features of the thermal system do not adequately reflect the conditions within the reservoir.

The surface expressions of the Cove Fort-Sulphurdale geothermal system include numerous gas seeps and intensely altered alluvium produced by gases which evolve from a deep thermal water table. Geologic mapping has shown that leakage of gases to the surface occurs along faults located on the flanks of the Pavant Range and on the periphery of large-scale gravitational glide blocks near Sulphurdale (Moore and Sam-

Table 1. Interpreted electrical resistivities for geologic units at Cove Fort-Sulphurdale.

Geologic unit	Electrical resistivity (Ω · m)	Polarization (ms)	Line coverage
Alluvium-Qal			
Near-surface, above water table	20–50	—	W/2 6, LL', 5, AA'
Below water table	10–20	—	W/2 6, LL', 5, AA'
Tertiary volcanics			
Tbj-Tb—ash flow tuffs	5–10	—	S/2 3; E/3 5, 4
Tb— lava flows	20–100	6–10	1, 2, 3, 6, AA'
Tb—ash flow tuff	100	—	E end AA'
Cretaceous sedimentary rocks			
Kpr—Price River Conglomerate	30–50	6–15	W/2 1, N/2 3
Mesozoic and Paleozoic sedimentary rocks			
PMsu—siltstones, sandstones, limestones, and shales	100–130	15–30	1, 6
Hydrothermal alteration areas			
Tb	4–5	—	AA', BB', 4
Qal	5	—	4, 6

Table 2. Basic data for the four test wells at Cove Fort-Sulphurdale KGRA. (Data from Ash et al., 1979 and Union Oil Co. 1978a, b, c; 1979a, b.)

Drill hole name and spud date	Depth drilled (m)	Average cost per meter	No. of days to drill	Logged	Max. temp. and depth (°C @ m)	Water level (m)	Hole status
Forminco 1 7/26/76	320.3	$1 949	34	NO	ND	ND	Abandoned
*CFSU 42-7 11/29/77	2 357.6	$ 873	105	YES	178 @ 2 231	409	17.8 cm liner and tie back, surface to T.D.
*CFSU 31-33 5/24/78	1 591.4	$ 797	64	YES	146 @ 1 433	427	Plugged at 792.5 m; 7.3 cm tubing to T.D.
*CFSU 14-29 5/25/79	798.6	$1 335	45	YES	91 @ 664	427	Abandoned

*All depths referenced top RKB.

berg, 1979; Nielson and Moore, 1979). The glide blocks form a cap to portions of the thermal system located beneath the western flank of the Tushar Mountains. Areas of surface leakage are characterized by anomalously high thermal gradients, pronounced mercury anomalies, and deposits of native sulfur. Extrapolation of the measured shallow thermal gradients to the water table suggests that temperatures may be high enough to cause boiling under atmospheric conditions, but these gradients provide no information on the true reservoir temperature.

The distribution of thermal fluids and hydrothermally altered rocks at depths to 600 m is most evident in electrical resistivity data. Resistivities of 4 to 5 Ω · m occur over an area of more than 5 km² which includes Sulphurdale. At Sulphurdale, intense acid leaching of the rocks has occurred above the boiling water table and along narrow elongate zones which match the trends of fault zones. East-west resistivity lines cross the dominant structural trends and suggest that the number of faults carrying thermal waters decreases northward from the Sulphurdale area. The deep, throughgoing structural zones are most clearly reflected in the magnetic and gravity data.

The gravity and aeromagnetic data, both regional and detailed, indicate major structural zones which have probably localized the geothermal resource. Quantitative interpretation of the detailed-scale data indicates the position of several relatively young (Tertiary or younger) faults beneath the Quaternary alluvium and basalt cover. Many of these faults align with structures mapped in the Tertiary volcanics to the east and north. Mother Earth Industries, Inc. well 34-7 was drilled near the projected intersection of three such structures in October 1983 and produced "dry steam" at temperatures estimated to be 200°C under high pressure. The integration of the detailed geologic and geophysical data has thus contributed to the discovery of what may be a major geothermal reservoir.

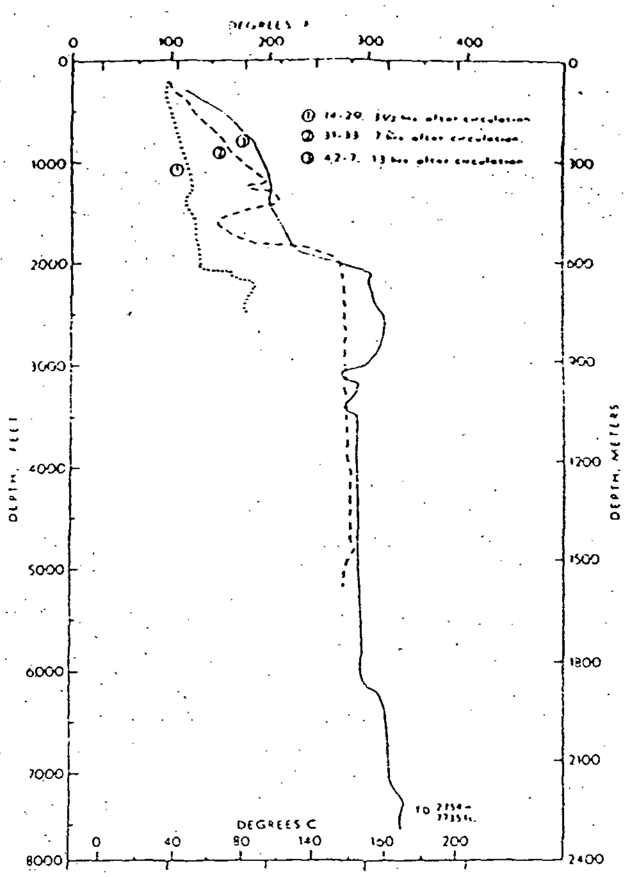

FIG. 9. Temperature-depth profiles for exploration wells CFSU 14-29, 31-33 and 42-7. Holes were circulated prior to each temperature survey.

Table 3. Rock property estimates from well logs: range, average.

Rock unit	Gamma ray (API units)	Porosity (%)	Bulk density (kg/m³)	Resistivity (Ω · m)	Acoustic velocity (km)
Alluvium	no data	no data	no data	no data	no data
Bullion Canyon volcanics	80–130; 105	15–25; 20	no data	10–30; 15	no data
Triassic sedimentary rocks					
Dolomite	30–140; 80	1–4	2 700–2 850; 2 770	18–64; 40	no data
Shale	90–150; 110	1–4	2 670–2 850; 2 760	12–30; 20	no data
Limestone	35–130; 90	1–4	2 650–2 830; 2 740	15–80; 35	no data
Permian sedimentary rocks					
Coconino sandstone	20–50; 30	2–15; 8	no data	6–80	no data
Pakoon limestone					
Limestone	20–50; 30	no data	no data	3–25	no data
Sandstone	105–145; 125	no data	no data		no data
Paleozoic rocks, undifferentiated					
Dolomite	20–50; 30	0–2	2 780–2 950; 2 850	40–150; 75	
Limestone	20–100; 40	undetermined	no data	undetermined	undetermined
Quartzite	50–160	1–6; 2	2 500–2 650; 2 610	no data	no data
Metamorphic rocks					
Marble	10–120	1–7; 2	2 650	125–250; 190	5.0–6.9
Serpentine marble	1–280	1–4; 2	2 580	40–225; 90	5.0–6.1
Intrusive rocks					
Monzonite	110–160	undetermined	2 650	~190	~6.1

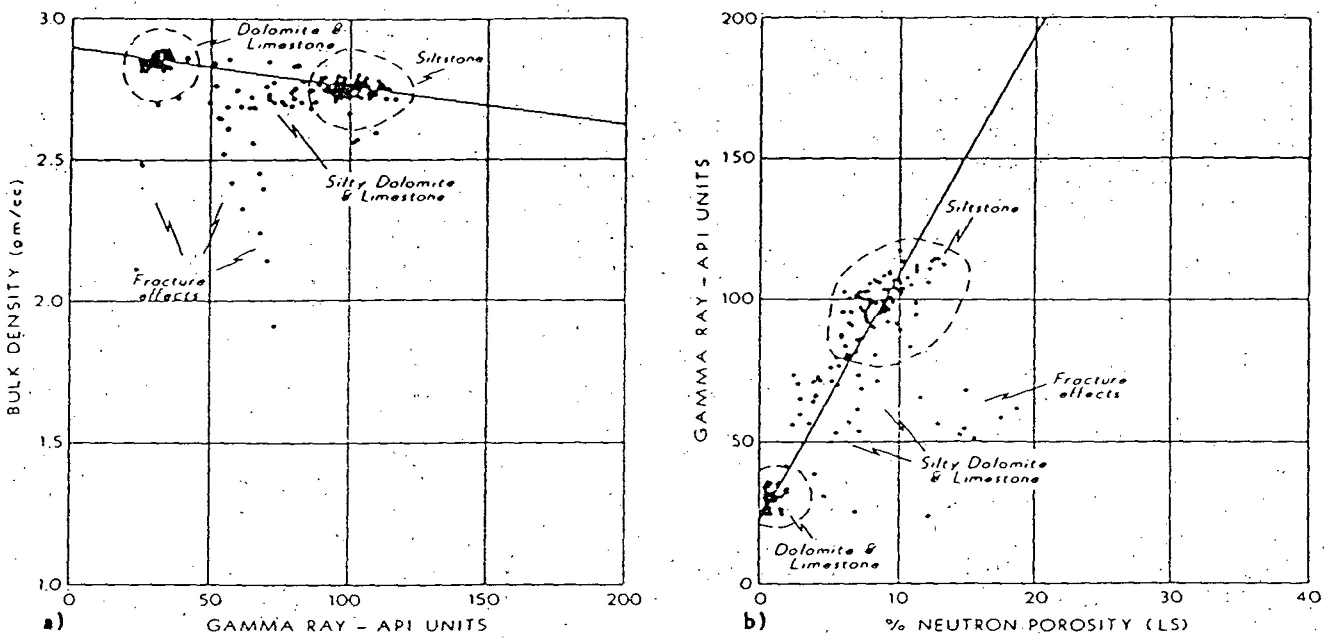

FIG. 10. Cross plots of gamma-ray response versus: (a) bulk density and (b) neutron porosity for the depth interval 536 to 1 579 m in CFSU 31-33. Data are 6.1 m averages.

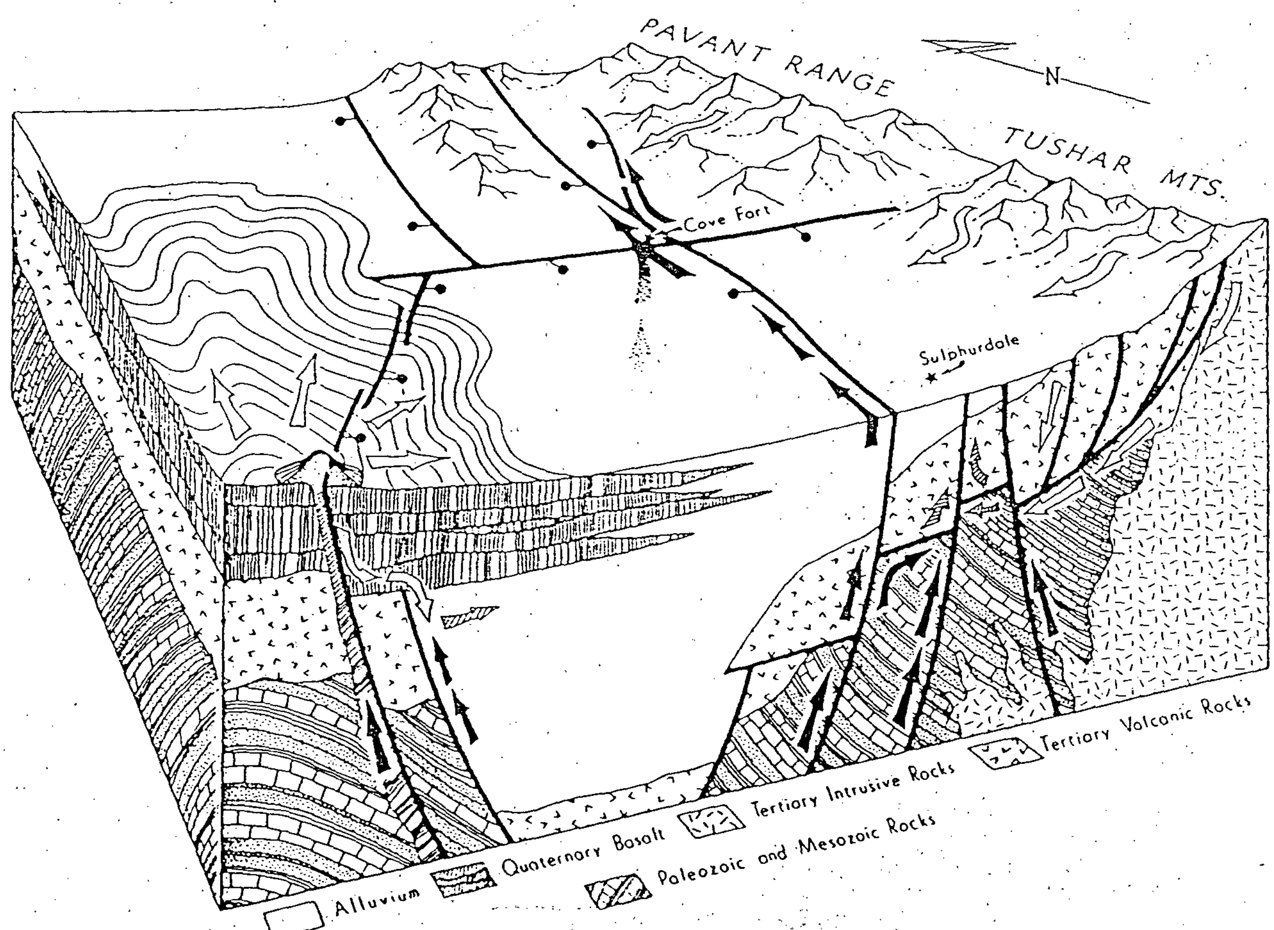

FIG. 11. Schematic model of the Cove Fort-Sulphurdale geothermal resource showing the structural relationship between high-temperature fluids in faults and the previously known moderate-temperature reservoir. Vertical scale is exaggerated with the depth to the base of the glide blocks being about 700 m. The distance from the Cinder Crater to CFSU 42-7 is about 5 km. The filled arrows indicate upwelling thermal brines, cross-hatched arrows represent fluids formed by the mixing of the thermal waters with nonthermal groundwater (open arrows). Faults are shown in heavy black lines with the ball and bar on the downthrown side.

Collectively, the geologic and geophysical data suggest that the Cove Fort-Sulphurdale KGRA is located on the periphery of a much larger geothermal anomaly that extends at least 15 km northward into Dog Valley (Crosby, 1959) along major faults, and possibly westward beneath the Cove Fort basalt field where additional exploration has been conducted. A conceptual model of the geothermal system based on these data is illustrated in Figure 11. In this model, thermal fluids are channeled upward principally along faults on the eastern boundary of the Cove Fort graben. We suspect that one center of upwelling is located at the intersection of the northerly trending boundary faults with a major northwest-trending fault zone that passes through the acid alteration and gas seeps at Sulphurdale and cuts a buried intrusive to the southeast. Both easterly and northerly trending structures, as well as permeable zones along the base of the glide blocks and within the volcanic rocks of the basalt field, may serve as aquifers for the thermal fluids. Cool groundwaters enter the thermal fluid from the high mountains which border the graben on both sides as well as from the south. Heating of groundwaters on the margin of the thermal system provides a likely explanation for the occurrence of anhydrite in open fractures at depth in well CFSU 42-7.

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