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THE COVE FORT-SULPHURDALE KGRA
A GEOLOGIC AND GEOPHYSICAL CASE STUDY

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September 1982

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ABSTRACT

Geological, geochemical and geophysical data are presented for one of the major geothermal systems in the western United States. Regional data indicate major tectonic structures which are still active and provide the conduits for the geothermal system. Detailed geologic mapping has defined major glide blocks of Tertiary volcanics which moved down from the Tushar Mountains and locally act as a leaky cap to portions of the presently known geothermal system. Mapping and geochemical studies indicate three periods of mineralization have affected the area, two of which are unrelated to the present geothermal activity. The geologic relationships demonstrate that the major structures have been opened repeatedly since the Tertiary.

Gravity and magnetic data are useful in defining major structures beneath alluvium and basalt cover, and indicate the importance of the Cove Fort-Beaver graben and the Cove Creek fault in localizing the geothermal reservoir. These structures and a high level of microearthquake activity also 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.

Deep exploration wells which test the reservoir recorded maximum temperatures of 178°C and almost isothermal behavior beginning at 700 to 1000 m and continuing to a depth of 1800 m. Costly drilling, high corrosion rates and low reservoir pressure coupled with the relatively low reservoir temperatures have led to the conclusion that the reservoir is not economic for electric power production at present. Plans are underway to utilize the moderate-temperature fluids for agribusiness, and exploration continues for a deep high-temperature reservoir.

INTRODUCTION

The Cove Fort-Sulphurdale Known Geothermal Resource Area (KGRA) is perhaps the largest and least understood of the major thermal systems lying near the eastern edge of the Basin and Range Province. This area is central to several geothermal areas including the Monroe-Joseph KGRA to the east and the Roosevelt Hot Springs and Thermo KGRAs to the west and south (Fig. 1).

Fumaroles, sulfur deposits and altered alluvium are exposed over an area covering nearly 47 sq km in the southern Pavant Range and northern Tushar Mountains. Consequently, this area was initially targeted for detailed evaluation by the Union Oil Co. and was the site of intensive exploration efforts between 1975 and 1979. In 1977 Union Oil Company entered into a cost-sharing exploration and development program with the Department of Energy (then the Energy Research and Development Administration), Division of Geothermal Energy. The contract provided for the drilling of three deep exploration wells and the release to the public of the resulting technical data and certain preexisting surface and subsurface data (Union Oil Co., 1978a).

Thermal gradient measurements and deep drilling suggest that the geothermal system may extend northward into Dog Valley and westward into the Cove Fort graben where it is covered by young basalt flows and thick alluvial deposits. While our detailed studies deal mainly with the portion of the thermal field explored by Union Oil Company, the results of this work nevertheless provide a useful starting point for understanding the geometry and geologic controls of a much larger area of resource potential.

The purpose of this paper is to present an integrated summary and current interpretation of the geological, geophysical and geochemical data that has been collected during exploration in the Cove Fort-Sulphurdale KGRA. In addition we have tried to assess the utility of certain geophysical techniques in an area which may be similar to other parts of the Basin and Range.

GEOLOGY

Regional Stratigraphy

The Cove Fort-Sulphurdale KGRA 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 volcanics, form part of the High Plateaus Subprovince (Figs. 1 and 2) that marks the transition between the Colorado Plateau and the Basin and Range Provinces.

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 2358 m (7535 ft) in the deep geothermal wells consist largely of limestone and dolomite that was 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 Hintz (1973) suggests that the reservoir rocks are Cambrian to Triassic in age.

The sedimentary rocks are separated from the overlying Tertiary volcanic sequence throughout the region by the Late Mesozoic Price River Conglomerate (Crosby, 1959) which consists of conglomerate interbedded with minor sandstone and claystone (Fig. 3). The Price River Conglomerate was deposited after Late Cretaceous deformation on an erosional surface that cut across the thrust sheets.

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 and the Great Basin to the west (refer to Fig. 1; Steven and others, 1979; Steven and Cunningham, 1978). Although the volcanic relationships within these fields are complex, this complexity has little bearing on our understanding of the geothermal system at Cove Fort. Here, the volcanic rocks define a relatively simple stratigraphic sequence detailed in Fig. 3.

Propylitically altered lava flows and breccias of intermediate composition which accumulated around one of the oldest vent centers of the Marysvale field form the base of the volcanic sequence near Cove Fort (Caskey and Shuey, 1975; Steven and others, 1979). The lava flows unconformably overlie the Price River Conglomerate. Ash-flow tuffs predominate in the upper parts of the Tertiary volcanic sequence. These are distinctive marker horizons which have allowed us to map in detail critical structures within the geothermal field. Lithologic characteristics of the ash-flow tuffs are described by Moore and Samberg (1979), Steven and Cunningham (1978) and Steven and others (1979).

The Bullion Canyon Volcanics (Figs. 2 and 3) and the underlying sedimentary rocks of the thermal reservoir were metamorphosed and weakly mineralized by a hypabyssal pluton of quartz-monzonite after deposition of the clinoptilolite tuff (Tc; Fig 3). Although the main body of the intrusion is not exposed, numerous latitic dikes and plugs cut the clinoptilolite tuff in the northwestern Tushar Mountains (Fig 2) and, near Sulphurdale, well CFSU 42-7 intersected several thin quartz-monzonite dikes in recrystallized limestone. In places the latitic dikes fed lava flows which were locally preserved beneath the overlying 22 m.y. old Osiris Tuff (Fleck and others, 1975). The 27 m.y. old Three Creeks Tuff Member of the Bullion Canyon Volcanics (Steven and others, 1979) was intruded by the latitic dikes and places a lower age on this intrusive event.

Magnetic data (discussed below) suggest that the quartz-monzonite pluton is centered southeast of Sulphurdale and may be covered by less than 300 m of weakly magnetic rocks. The intrusive-metasedimentary contact appears to dip northward toward Sulphurdale. Higher metamorphic grades at depth in CFSU 42-7, compared to CFSU 31-33 and widespread recrystallization of carbonate rocks, and quartz-monzonite dikes in CFSU 42-7 are consistent with the geometry of the intrusive inferred from the geophysical data.

Renewed volcanic activity spanned the interval between 1 m.y. and 0.3 m.y. ago (Best and others, 1980) producing a shield volcano in the Cove Fort Basalt Field (Condie and Barskey, 1972; Clark, 1977; Steven and Morris, 1981). The petrochemistry of the basaltic andesite which filled the Cove Fort Graben west of the Tushar Mountains is described by Clark (1977). Callaghan (1973) and Steven and others (1979) have suggested that the Cove Fort geothermal system may be related to basaltic volcanism.

Structure

Geological 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 widely 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 CFSU 31-33, Paleozoic dolomites have been thrust over Triassic siltstone and limestone.

Since Basin and Range tectonism began in the mid-Miocene (Steven and others, 1979), rocks of the Cove Fort area have been extensively disrupted by both high- and low-angle northerly and easterly trending normal faults. Continued activity is indicated by fault scarps within 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. Here 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 fumaroles.

Low-angle faults bound gravitational glide blocks which extend from Sulphurdale northward to the Cove Creek Fault (Fig. 2) and cover the reservoir rocks in the northwestern part of the Tushar Mountains. The glide blocks are bounded on the north by an east-trending normal fault that separates rocks of the Tushar Mountains from those of the Pavant Range. An interpretation of the subsurface geometry of the gravitational glide blocks near Sulphurdale is illustrated in cross section A-A', Figure 4. The youngest rocks preserved within the fault blocks are basalt and sandstone which overlie the Joe Lott Tuff (not present along section A-A') and 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 high temperature and thermal gradient values in the shallow thermal gradient holes. The surface features of the geothermal system are discussed more fully below.

Hydrology

The Cove Fort-Sulphurdale area is located in the northeastern portion of the Cove Creek basin, a rectangular-shaped area roughly 26 km long (east-west) and 19-23 km wide. The Tushar Mountains rise to elevations of 2,440 to 3,050 m along the eastern margin of the basin and provide most of the recharge for the local ground water system. Mower's (1978) study of the Beaver Valley system, immediately south of the Cove Creek basin, suggests an average annual precipitation of 41 to 76 cm in the foothills and mountains compared with 30 to 41 cm at the valley level.

Numerous springs occur along the west flank of the Tushar Mountains but stream flow along Cove Creek is ephemeral and all streams become dry where they enter alluvium of the valley. Ground-water flow within the alluvium is believed to be north (or south from the northern portion of the basin) to the Cove Creek drainage, then west along the drainage to the Mineral Mountains (Union Oil Co., 1979a). Several wells produce from perched aquifers at depths of 24 to 100 m. No wells are known to penetrate the true water table in the central or western portions of the basin, so little is known about the deep ground-water hydrology. Three geothermal well tests by Union Oil Company in the northeastern portion of the basin record water table depths of 366 to 427 m. Although the total area of the Cove Creek basin, at about 573 sq km is fairly small, the average annual precipitation rate is much higher than most

Basin and Range areas. The thick section of unconsolidated sediments in the Beaver Valley graben and the porous Paleozoic carbonates store large volumes of water for recharge of the geothermal reservoir.

GEOCHEMISTRY AND HYDROTHERMAL ALTERATION

The distribution and chemical characteristics of the hydrothermally altered rocks in a geothermal prospect area are frequently used as an exploration guide during the assessment programs. The geologic setting of the Cove Fort area is complex, and at least three hydrothermal events have been documented as a result of downhole lithologic and geochemical investigations. Consequently, a simple geochemical zonation does not exist in the area.

The oldest hydrothermal event accompanied emplacement of the intermediate-composition stocks and dikes exposed east and south of Sulphurdale and penetrated in CFSU 42-7. This event was characterized by contact metamorphism of the Paleozoic and Mesozoic sedimentary rocks, propylitic alteration of the volcanic rocks, silicification, and deposition of pyrite, galena, sphalerite, pyrrhotite, bornite and chalcopyrite. The relationship between base metal mineralization and the intrusive rocks is clearly illustrated by the distributions of lead and zinc. Figure 5 shows that anomalous lead and zinc concentrations are located within the southeastern portion of the area about the margin of the exposed latite stocks and inferred subjacent quartz-monzonite. Anomalous zinc concentrations are generally zoned outward from the high lead values.

A second hydrothermal event was marked by the deposition of fluorite along a normal fault bounding the southern part of the Pavant Range. Although the age of this event has not been established, the absence of fluorite in carbonate rocks affected by the hypabyssal intrusions and its occurrence in Basin and Range structures suggest that fluorite deposition is no older than mid-Miocene. Sulfur deposits related to active fumaroles are clearly younger than the fluorite and indicate that the fluorite deposits must predate the present stage of geothermal activity. Arsenic appears to have been mobilized by hydrothermal fluids which deposited both the base metals and fluorite (Fig. 5).

The active geothermal system is characterized by sulfur deposits, acid-altered ground, and active fumaroles which occur in an area covering approximately 47 sq km. These features reflect the degassing and 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 pre-existing rocks and containing variable amounts of clays, sulfur, gypsum, pyrite and marcasite. These are surficial features and do not extend below the water table. At depth anhydrite has been deposited in some of the fracture zones in the carbonate reservoir rocks by the geothermal fluids.

High concentrations of mercury, an element which is readily transported within a vapor (Fig. 5), are diagnostic of rocks hydrothermally altered by the geothermal system. Lesser concentrations of the chalcophile elements arsenic, lead, and zinc in some samples probably result from the scavanging of these elements along with iron from the host rock during the formation of pyrite. Mercury concentrations in drill hole cuttings are greatest near areas of active hydrogen sulfide discharge and sulfur deposition northwest of Cove Fort and near Sulphurdale.

GEOPHYSICS

A variety of geophysical data are available for study as the result of regional studies and the site-specific exploration for the geothermal reservoir. Passive seismic and gravity data provide considerable insight into the deeper structural setting of the Cove Fort-Sulphurdale area and are here 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 (Fig. 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 Roosevelt Hot Springs-Cove Fort-Sulphurdale area is less 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-axes. 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 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. This continuing seismicity suggests open structures at depth within the reservoir.

Gravity Studies

Regional gravity data (Cook et al., 1975) also provide evidence for 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 more detailed gravity study by Cook et al. (1980) documents this transition in detail (Fig. 6) 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 over one km of volcanics and Quaternary alluvium. The interpreted structures shown on Figure 6 are generalized from the two-dimensional model results of Cook et al. (1980) supplemented by our three-dimensional modeling. Paleozoic sedimentary rocks which outcrop north of Cove Fort and granitic intrusives of the Mineral Mountains exhibit densities of approximately 2.67 g/cm^3. Limited density measurements of the Tertiary volcanics, which consist of tuffs and rhyolites, suggest an average density of 2.25-2.4 g/cm^3. Quaternary alluvium and valley fill can be expected to vary from 2.0-2.3 g/cm^3. An average density contrast of 0.5 g/cm^3 between bedrock range blocks and Tertiary volcanics and/or alluvium was used in the numerical modeling. Some inaccuracy in depths of alluvial fill may result from incorrect density contrasts, but the positions of major structures are substantially accurate. The gravity data when quantitatively interpreted provide a major contribution to understanding the structural setting of the Cove Fort-Sulphurdale geothermal resource.

Magnetic Studies

High-altitude aeromagnetic data on a statewide (1:10^6) scale (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). North of this discontinuity magnetic values are lower and only isolated anomalies occur. South of the discontinuity numerous intrusive- and volcanic-caused anomalies are noted. The aeromagnetic data shown in Figure 7 are part of a detailed survey flown in 1978 (Earth Science Laboratory, 1978). North-south profiles were flown approximately 0.5 km apart, approximately 300 m (smoothly draped) above the surface. The Cove Fort basalt field and interpreted structures are superimposed over the 100 gamma magnetic contours in Figure 7 to facilitate comparison with the detailed geologic map, 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 volcanics and alluvial areas of low topographic relief to the west.

A complex magnetic pattern with residual total intensity values varying from +450 to -770 gammas occurs over a 70 sq km area in the west central portion of the map. This is the area of the Cove Fort basalt field, shown in the shaded pattern on Fig. 7. Most of the complex magnetic pattern is explained by intersecting sets of northwest-and northeast-trending faults, most with relatively small displacements, but often expressed in the topography. A conspicuous low of more than 400 gammas near the center of the basalt field occurs over the 150 m topographic high of Cinder Crater. Numerical modeling indicates an equivalent susceptibility of -5000 cgs indicating strong permanent magnetization directed approximately opposite to 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 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 maximum values of 970 gammas, approximately 1600 gammas above regional background levels. Three-dimensional numerical modeling indicates a complex magnetic source. Although reduced terrain clearance over the Tertiary tuffs and andesites of the Tushar Mountains contributes to this irregular magnetic anomaly, most of the source is attributed to buried intrusive rocks 100 to 1000 meters below the surface, which dip to the north and extend to great depth (i.e., greater than 3000 m). The equivalent susceptibility for such a body, as determined from modeling, varies from approximately 5000 cgs near the surface to 10,000 "cgs for the deeper portions of the body. A Tertiary quartz-monzonite intrusive (as intersected at depth in CFSU 42-7) is the probable source. The high average magnetization suggests some possibility of magnetic skarn. Tertiary latite porphyry rocks which outcrop north of the interpreted source are only weakly expressed (40-50 gammas) in the magnetic data.

The lowest total intensity values (-942 gammas) 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 of the intrusive source to the south.

Thermal Studies

The KGRA boundaries are based on the shallow thermal gradient anomaly and correspond closely to the 200°C/km contour shown in Figure 8. The thermal data presented here are part of a Union Oil Company (1978a) data package made available through the DOE/DGE Industry Coupled Program. The gradients, not corrected for topography, correspond to uniform gradients at 30-76 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 defines an area of about 60 sq km. This is a fraction of the less well defined 200-300 sq km 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 gradients (383, 328, 364, 301°C/km) were recorded in drill holes located along geologic structures. Convenient drill hole locations were often areas of low topographic relief along mine or prospect roads, consequently they test a more direct leakage from the hydrothermal system.

A map of temperatures at a depth of 76 m corresponding to total depth for most of the gradient holes, shows a pattern very similar to the thermal gradient contours. Twice background values of 30-40°C occur as highs north and south of the area covered by the gravitational glide blocks. The average 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') was completed in November 1976 and a second survey of six additional profiles in September 1978. Both surveys used 305-m dipoles and each survey yielded 31.4 line km of profile data. Apparent resistivity values were recorded for N=1-6 or N=1-7. The location of all lines and a summary of interpreted resistivity values are shown in Figure 9.

All of the dipole-dipole resistivity data were interpreted using an interactive computer modeling process (Ross, 1979) which assumes a two-dimensional 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 program uses a fine mesh near the electrodes (i.e., near the surface) where the current density is large and potentials are rapidly changing, and becomes coarser with increased distance from the electrode positions (at depth).

The apparent resistivity values were computed for dipole separations N=1 to 6 and visually 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 three-dimensional aspects of the actual resistivity distributions, and the ambiguities of position, intrinsic resistivity, and size of body that cannot be resolved (i.e., are not unique). A satisfactory fit was obtained when a majority of the pseudosection data values were within 10% 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 10. The computed resistivity values corresponding to the model shown closely match the observed data (see Ross, 1979). Although the interpretation of resistivity data is not unique, careful modeling of dipole-dipole resistivity data may offer a more accurate representation of earth resistivity distribution than any other electrical method. The non-uniqueness is reduced by utilizing a network of profiles, several of which intersect. The integration of geologic data, such as the 1:24,000 scale map of Moore and Samberg (1979), can further reduce interpretational ambiguities.

Line 6 (Figs. 9, 10), 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 ohm-m) from the surface to great depth (> 600 m). The leakage of low-resistivity thermal fluids is indicated by 5 ohm-m resistivity bodies at stations 0-1 E and from stations 1-3 W. Geologic confirmation for this interpretation includes alteration along the trace of the 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 zone 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 and 20 ohm-m on the west correspond to alluvium and volcanic rocks, probably unsaturated or containing low-salinity waters for the upper 200-300 m, and more conductive waters at depth.

Line AA' trends approximately N50°W approximately 600 m north of Sulphurdale and is the southernmost survey line. The modeled resistivity distribution indicates a background level of 20 ohm-m resistivity extending to depth which can be associated with the alluvium and Tertiary volcanics (see Figure 2). Superimposed on this are areas of 100 ohm-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 ohm-m) northwest of Sulphurdale corresponds to the Cove Fort basalt flows. A well defined area of 4 ohm-m which occurs immediately north of Sulphurdale is approximately 1300 m across and extends from the surface to great depth (> 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 I presents a summary of resistivity properties determined from the comparison of a detailed geologic map and the modeled resistivity distribution for the 0-100 m depth interval. Many resistivity changes are closely associated with mapped lithologic changes in areas of outcrop. In areas of alluvial cover the projections of several faults are noted as pronounced resistivity changes on lines 6, 2, AA', and 4 (Figure 9). It is surprising that resistivities for most of the surveyed area are below 50 ohm-m when the continous water table is 100 m to over 300 m deep. Substantial moisture must be present as vadose water or as locally perched aquifers. The low-resistivity zone associated with the known thermal fluids at Sulphurdale covers more than 5 sq km.

Figure 9 shows the modeled resistivity distribution for the depth interval 460-610 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 (50-300 ohm-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 100-300 ohm-m seem incompatible with highly 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 sq km area of 4 to 5 ohm-m resistivities around Sulphurdale is bordered by 20-30 ohm-m resistivities. The low resistivities arise from the clay alteration of the volcanic rocks and the conductive geothermal fluids. Five ohm-m resistivities on the western portions of line 6 and of AA' 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) reports observed apparent polarization values of 3 to 16 milliseconds (ms) on lines 1 and 3, with 3-6 ms considered background. His model interpretation indicates intrinsic polarizations of 15 to 30 ms which suggest substantial zones of one to two weight per cent sulfides.

RESERVOIR EVALUATION

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 these serve as position reference points for additional data sets in Figures 8 and 9. Table II 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. Table II records drilling costs far above the average cost per meter of geothermal wells. A wide range of lost circulation materials had virtually no effect and cement plugs had only marginal success. A total of 91 cement plugs were placed in attempts to control lost circulation which occurred in carbonates, particularly dolomites. Drillstrings were observed to drop as much as 9 m in some lost circulation zones, indicating that the carbonates were cavernous. Drilling with aerated mud created unacceptable and uncontrollable corrosion problems (Ash et al., 1979).

No temperature data or geophysical logs were obtained in well Forminco #1 (abandoned at 320 m). The maximum temperatures observed in the completed wells were 178°C at 2231 m (42-7) and 146°C at 1433 m (31-33). Isothermal behavior dominates the lower portion of both holes (Fig. 11). The highest temperatures were encountered in wells beneath the gravitational glide blocks. The measured temperature differences between the deep wells can be best explained as resulting from the loss of heat by convective movement of heated gases to the surface on the periphery of the caprock, in contrast to the thermal blanketing effect of the volcanic rocks within the glide blocks.

Geophysical Log Interpretation

A wide variety of open hole, production and cased hole well logs were obtained in three wells and are interpreted in detail by Glenn and Ross (1982). These logs included a geothermal mud log with drilling rate, rock density, temperature 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.

The well log interpretation (Glenn and Ross, 1982) characterizes the tool responses of the major geologic units identified by Moore and Samberg (1979), then goes beyond this to refine the depths of lithologic changes, to identify major structures and to interpret lithologies for the large intervals of no cuttings return. Table III summarizes formational properties derived in these studies as determined by lithologic interpretation and cross plot analysis.

Figures 12 (a) and 12 (b) 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 1578.9 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 in 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 12 (a) and 12 (b). The well log interpretations identified several fractured intervals and their control of the fluid flows for three drill holes, and have lead to a better understanding of the lithologies intersected, fracturing, and reservoir rock properties. Non-fracture porosity was determined to be generally less than 4%. Thus permeability, lost circulation zones, and solution cavity phenomena are all controlled by major structures and fractures (Glenn and Ross, 1982).

Reservoir Tests

Union Oil Company (1979a,b) carried out production logging tests in CFSU 31-33 and CFSU 42-7. Temperature injection profiling, pressure gradient surveying, and spinner and tracer logging in CFSU 31-33 revealed significant permeability and fluid production from 1463 to 1524 m. Fluids moved up hole at a rate of 500 bbl/hr and exited at 613 m and moved downhole at 10 to 20 bbl/hr, exiting at 1571 m. This strong intraformational flow and cooler fluids entering near total depth prompted the plugging of the hole back to 792 m.

In addition to temperature injection, production profiling, and spinner and tracer logging, a nitrogen lift flow test was conducted in CFSU 42-7 on May 16, 1978. Flow was initiated using the nitrogen lift and the well later flowed unassisted at 43,000 lb/hr with a wellhead pressure of 3 psi. After shut in and release of a non-compressible gas head, the wellhead pressure dropped to 0 psi. The wellhead temperature was about 93°C. Given the low flow rate, temperature, and probable low percent flash, the well was deemed non-commercial for electric power generation under present economic conditions and the Union Oil Company leases were terminated.

DISCUSSION

During the last several years an extensive data base, both regional and detailed, has been developed for the area including the Cove Fort-Sulphurdale geothermal system. These data present a picture of great geologic complexity resulting from numerous intrusive and tectonic disturbances since Cretaceous time. While many aspects of the regional geology are peripheral to our understanding of the geothermal resource, they provide the initial data for selecting exploration targets. More detailed aspects such as recognition of the extent of fracturing and dissolution of the reservoir rocks and the identification of lateral and vertical barriers to the movement of thermal fluids are critical to the development of an effective exploration model.

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 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 manifestations of the Cove Fort geothermal system are produced by heated 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 periphery of large-scale gravitational glide blocks which form an impermeable cap above the central portion of the thermal system (Moore and Samberg, 1979; Nielson and Moore, 1979). Areas of intense surface alteration 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 are close to boiling under atmospheric conditions but provides no information on the true reservoir temperature.

Geochemical analyses of drill cuttings from shallow gradient holes in the gravitational glide blocks suggest that near-surface rocks between Cove Fort and Sulphurdale have not been affected by the present geothermal system. These data provide additional evidence of low permeability within the glide blocks, in spite of the locally intense fracturing that we have mapped within them. Anhydrite is a common mineral in the deep portions of CFSU 42-7 occurring in metamorphosed Paleozoic limestones. Its absence in rocks of the impermeable caprock and presence as open-space fillings suggest that anhydrite is not related to one of the older hydrothermal events which affected this area. While anhydrite is a common mineral of many geothermal systems (Browne, 1978), it is characteristically not in equilibrium with the relatively reducing fluids from the interior of these systems. Giggenbach (1980) suggests that more oxidizing conditions which favor deposition of anhydrite are more likely to be encountered on the margins of active systems where mixing of thermal and nonthermal waters can occur.

Detailed numerical modeling of a substantial resistivity data base has permitted a detailed characterization of the electrical resistivity to depths of 600 m. A low resistivity (4-5 ohm-m) area of more than five sq km is associated with the Sulphurdale area. The dipole-dipole resistivity data also define faults beneath alluvial and volcanic cover and indicate their extension to depths exceeding 600 m. The known geothermal resource is reasonably well defined by the thermal gradient data and the electrical resistivity work. None of the thermal gradient holes reached the ground-water table. Perched water tables and cold water overflow are present in alluvium west of the known thermal anomaly, so the actual limits of the thermal anomaly are not well known.

Deep exploration wells which were drilled to 2358, 1591, and 799 m were observed to have maximum temperatures of 178, 146, and 91°C, respectively, and to indicate a low-pressure, isothermal hot water reservoir below the gravitational glide blocks. From these results Union Oil Company concluded that the unit was not economic as an electric power producer at the present time (Ash et al., 1980). However, fluids of less than 180°C are being utilized for power production at the Brawley Field in California. Other factors in the economic evaluation were the extreme drilling difficulties and high costs.

CONCLUSIONS

The size and geometry of the total thermal system is poorly understood even after three deep exploration wells have been drilled. One interpretation of the geoscience data base is that a higher temperature geothermal system may occur at depth peripheral to the 60 sq km area that has been reasonably well tested. A deeper reservoir would also account for anomalous borehole temperatures to the north in Dog Valley (Crosby, 1959) and to the west in Beaver Valley where other exploration efforts are underway. A relationship between the Cove Fort thermal fluids and a regional reservoir has not been documented, but the low pressures encountered and the presence of anhydrite in the Cove Fort wells also suggest that this area may lie on the periphery of a larger convective system.

The detailed gravity, magnetic, seismic, and resistivity data help to define two target areas which offer some promise for a high-temperature (>200° C) reservoir (Fig. 13). These are: 1) the west side of the graben where graben bordering faults are indicated by gravity and magnetic data and basalt crops out at the surface; 2) the western continuation of the Cove Creek fault, between the eastern flank of the Mineral Mountains and Cove Fort. The near-surface thermal expression of the system may be obscured by the Cove Fort basalt field and cooler recharge waters in the alluvium. A modest program of deep thermal gradient testing (depths well below the water table) and additional resistivity surveys with dipole lengths of 300 to 600 m are suggested for these areas.

The Cove Fort-Sulphurdale geothermal reservoir, as presently defined, is considered subeconomic for electrical power generation. Developments in down-hole pump technology and Rankine binary cycle energy conversion may make this reservoir economic for power production some time in the future. Plans are presently underway for direct heat utilization including ethanol production, mineral processing, and agribusiness using existing wells. At this time exploration continues in the search for a higher temperature geothermal reservoir.

ACKNOWLEDGEMENTS

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TABLES

Table I. Interpreted Electrical Resistivities Geological Units at Cove Fort-Sulphurdale.

Geologic Unit	Electrical Resistivity (ohm-m)	Polarization (ms)	Line Coverage
Qal-alluvium			
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			
Tmj, To, Ttc, - ash flow tuffs	5-10	-	S/2 3; E/3 5, 4
Tb, lava flows	20-100	6-10	1, 2, 3, 6, AA'
Tbt - ash flow tuff	100	-	E end AA'
Cretaceous Sediments			
Kpr - Price River Conglomerate	30-50	6-15	W/2 1, N/2 3
Mesozoic and Paleozoic Sediments			
PMsu - siltstones, sandstones, limestones, and shales	100-300	15-30	1, 6
Hydrothermal Alteration Areas			
Tbt, Tb	4-5	-	AA', BB', 4
Qal	5	-	4, 6

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

Drill Hole Name and Spud Date	Depth Drilled (meters)	Average cost per meter	No. of days to drill	Logged	Max. Temp. & depth °C @ m	Fluid Depth meters	TDS @ depth ppm	Hole Status
Forminco #1 7/26/76	320.3	$1,949	34	NO	ND	ND	ND	Abandoned
*CFSU #42-27 11/29/77	2357.6	$873	105	YES	178 @ 2231 m	409	9405 4775	17.8 cm liner & tie back, surface T.D.
*CFSU #31-33 5/24/78	1591.4	$797	64	YES	146 @ 1433 m	427	1320 10,000	Pugged 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 m	427	4776	Abandoned

* Also named Utah State Geothermal Wells 42-27, 31-33 and 14-29.
All depths referenced top RKB.

Table III: Rock Property Estimates From Well Logs: Range, Average.

Rock Unit	Gamma Ray API Units	Porosity %	Bulk Density gm/cc	Resistivity ohm-m	Acoustic/Velo. km/sec
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	2.70-2.85; 2.77	18-64; 40	no data
Shale	90-150; 110	1 - 4	2.67-2.85; 2.76	12-30; 20	no data
Limestone	35-130; 90	1 - 4	2.65-2.83; 2.74	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	2.78-2.95; 2.85	40-150; 75	
Limestone	20-100; 40	undetermined	no data	undetermined	undetermined
Quartzite	50-160	1-6; 2	2.50-2.65; 2.61	no data	no data
Metamorphic Rocks					
Marble	10-120	1-7; 2	_2.65	125-250; 190	5.0-6.9
Serpentine Marble	1-280	1-4; 2	_2.58	40-225; 90	5.0-6.1
Intrusive Rocks					
Quartz Monzonite	110-160	undetermined	_2.65	_190	_6.1

FIGURE CAPTIONS

Fig. 1 Index map showing the location of Cove Fort-Sulphurdale KGRA with respect to regional geology and seismicity.

Fig. 2 Detailed geologic map of the Cove Fort-Sulphurdale Area showing the location of exploration wells and cross section AA' (after Steven and Cunningham, 1978).

Fig. 3 Illustrative stratigraphic section for the Cove Fort-Sulphurdale area.

Fig. 4 Simplified geologic cross section illustrating glide blocks (movement was from south to north into page) and 42-7 lithologies.

Fig. 5 Summary of arsenic, mercury, lead and zinc geochemistry for shallow thermal gradient holes.

Fig. 6 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 milligal. Interpreted faults are shown as heavy lines.

Fig. 7 Total magnetic intensity map for the Cove Fort-Sulphurdale area showing interpreted faults and buried intrusive. Contour interval: 100 gammas (solid); 20 gammas (dashed).

Fig. 8 Shallow thermal gradient map as determined for the depth interval 30-76m; °C/km.

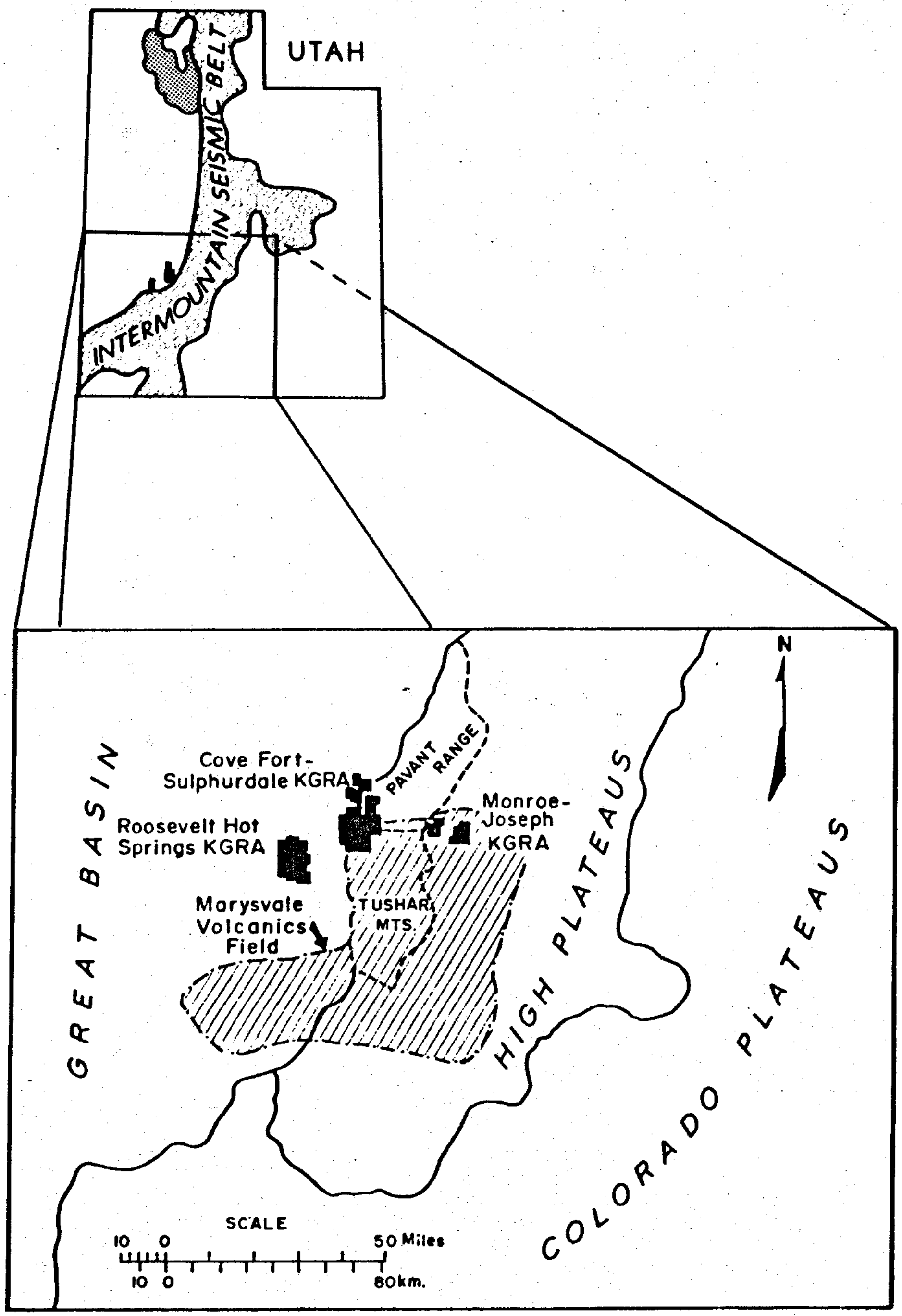
Fig. 9 Electrical resistivity survey. The locations of all lines are shown as are the interpreted resistivity distribution for the depth interval 460-610 m as determined by numerical modeling. All lines were 305 m dipoles.

Fig. 10 Observed apparent resistivity data and interpreted resistivity distribution for lines AA' and 6.

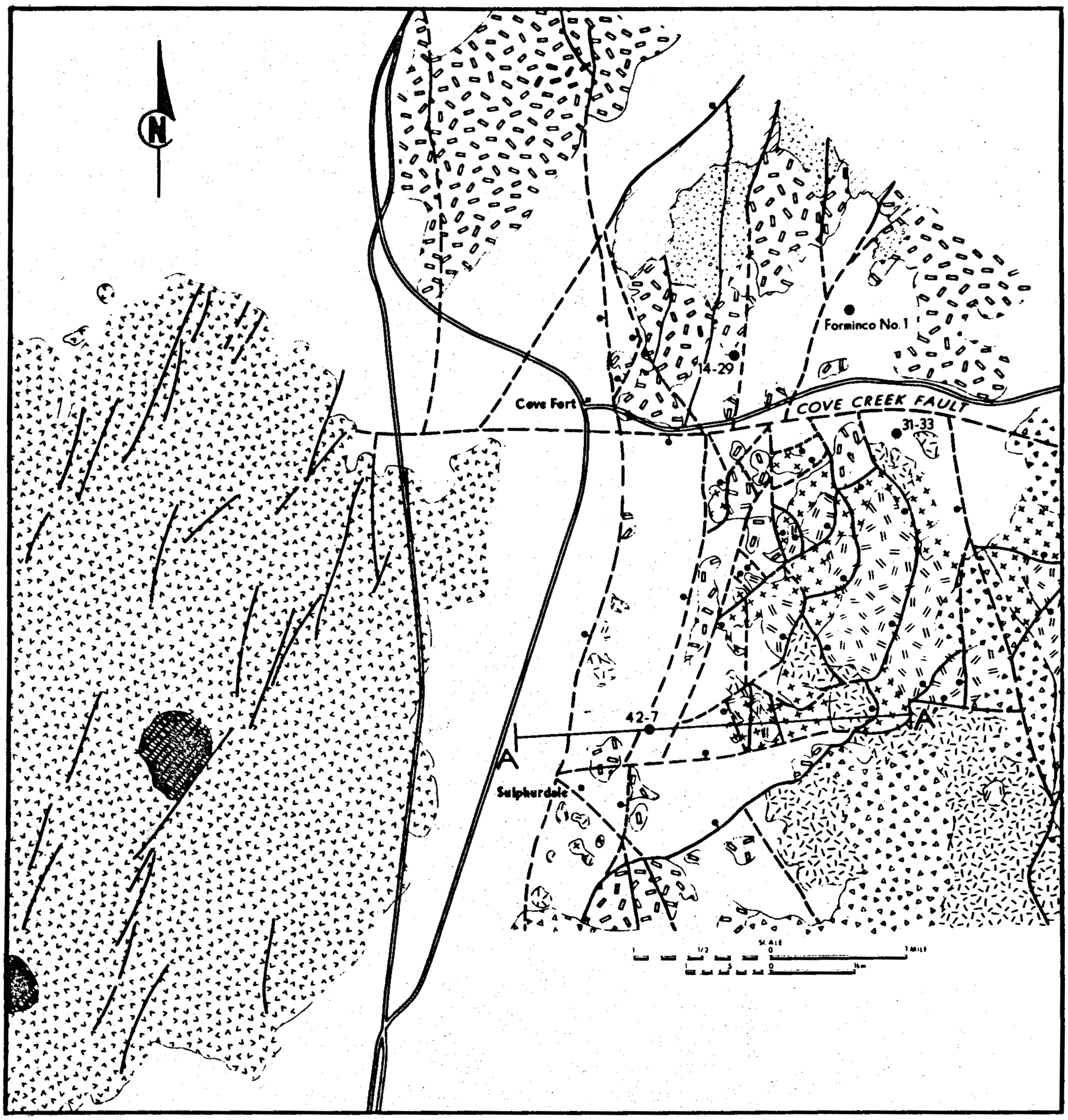
Fig. 11 Temperature-depth profiles for exploration wells CFSU 14-29, 31-33 and 42-7.

Fig. 12 Cross plots of gamma ray response versus: a) bulk density and b) neutron porosity for the depth interval 536 to 1579 m in CFSU 31-33. Data are 6.1 m averages.

Fig. 13 Integrated data summary showing major structural features, the known resource area, and remaining targets for a high-temperature resource.

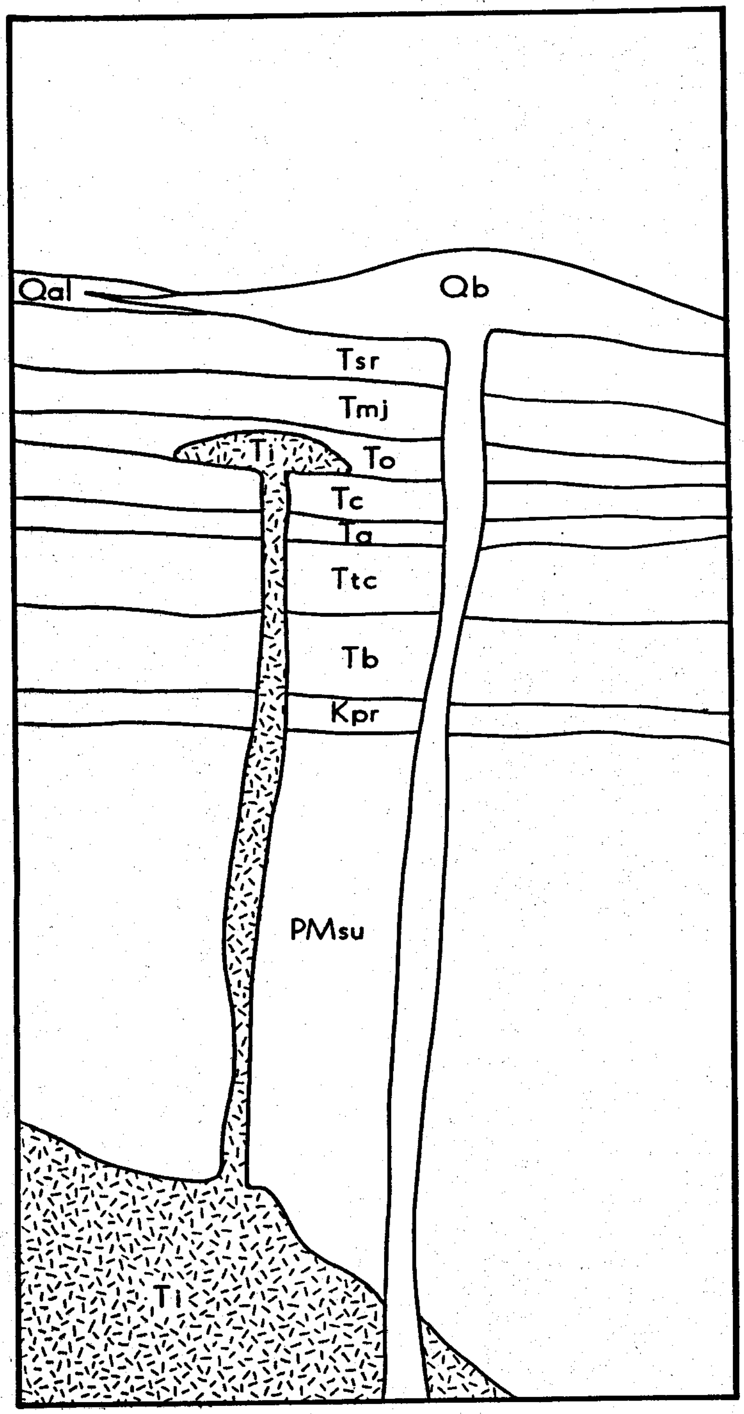


UTAH
INTERMOUNTAIN SEISMIC BELT
GREAT BASIN
Cove Fort-
Sulphurdale KGRA
PAVANT RANGE
Roosevelt Hot
Springs KGRA
Monroe-
Joseph
KGRA
TUSHAR
MTS.
Marysvale
Volcanics
Field
HIGH PLATEAUS
COLORADO PLATEAUS
N
SCALE
10 0 50 Miles
10 0 80km.



EXPLANATION

- Alluvium (Quaternary)
- Landslide deposits (Quaternary)
- Cinder cones of the Cove Fort basalt field (Pleistocene)
- Lava flows of the Cove Fort basalt field (Pleistocene)
- Ash-flow tuffs (Miocene); includes the Joe Lott Tuff of the Mount Belknap Volcanics and the Osiris Tuff
- Dikes, stocks and flows of latitic composition (Miocene); includes quartz-monzonite dikes at depth
- Clinoptilolite-bearing ash-flow tuff (Miocene)
- 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
- Price River Conglomerate (Cretaceous)
- Paleozoic and Mesozoic sedimentary rocks, undivided; includes metamorphosed equivalents at depth



EXPLANATION

Qal Alluvium (Quaternary)-Includes sands, silts, and gravels of alluvial fans and landslide deposits

Qb Cove Fort Basalt Flows (Pleistocene)-Basaltic andesite lava flows (Clark, 1977) ranging in age from 1 to 0.3 m.y. (Best and others, 1980)

Tsr Sevier River Formation (Pliocene and Miocene)-Partly consolidated fluviatile and lacustrine sandstone, conglomerate, and siltstone, with interbedded mafic lava flows and air-fall tuffs. Tuffs near the base and top have K-Ar ages of about 14 and 7 m.y. respectively (Steven and others, 1979)

Tmj Joe Lott Tuff Member of Mount Belknap Volcanics (Miocene)-Poorly welded, crystal-poor, rhyolite ash-flow tuff. K-Ar age is about 19 m.y. (Steven and others, 1979)

To Osiris Tuff (Miocene)-Densely welded crystal-rich rhyodacite ash-flow tuff. K-Ar age is about 22 m.y. (Fleck and others, 1975)

Ti Intrusive Rocks (Miocene)-Dikes, stocks, and flows of latite porphyry and quartz monzonite

Tc Clinoptilolite Tuff (Miocene)-Poorly welded, crystal-poor altered ash-flow tuff

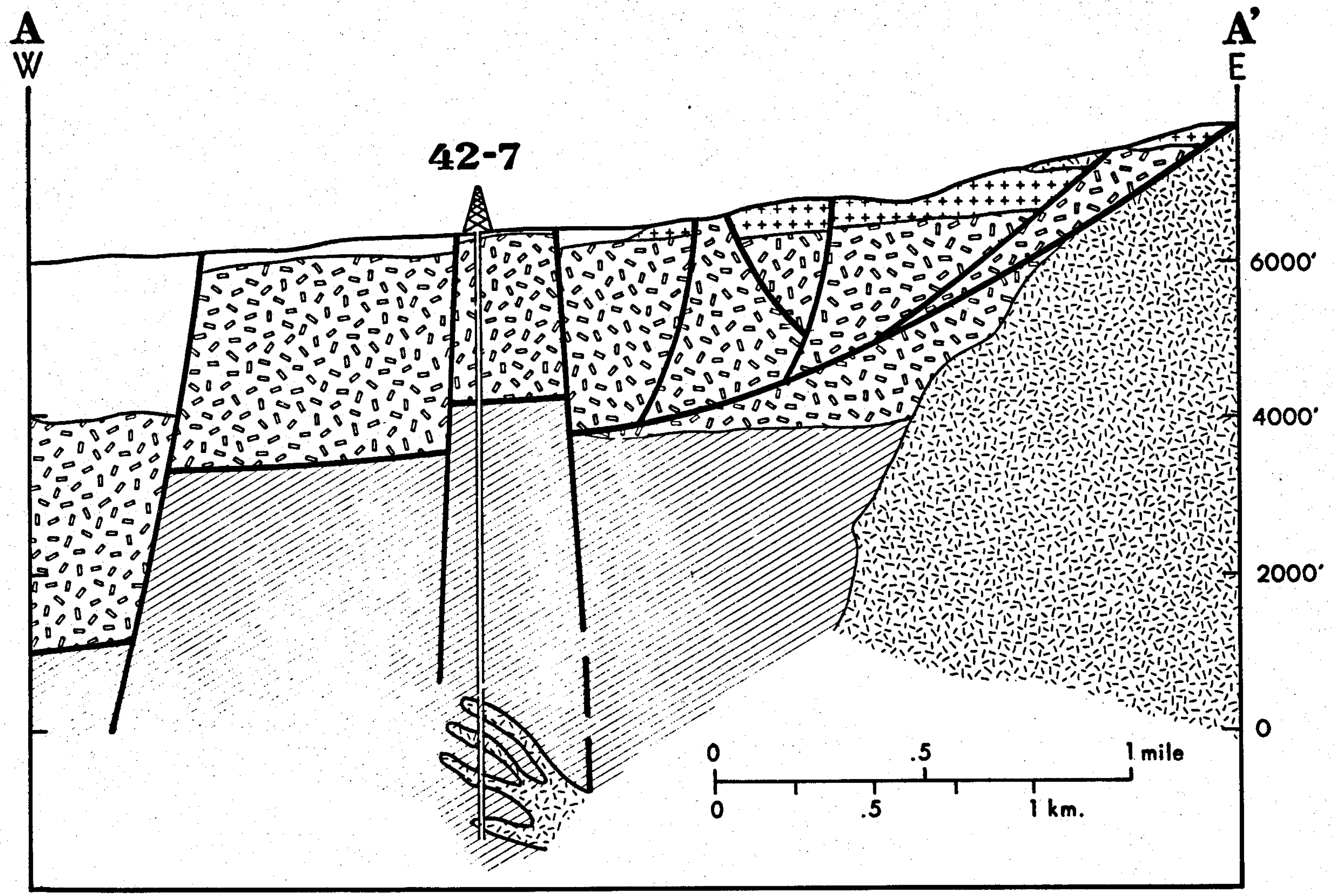
Ta Tuff of Albinus Canyon (Miocene)-Densely welded, crystal-poor ash-flow tuff (Steven and Cunningham, 1979; red tuff of Moore and Samberg, 1979)

Ttc Three Creeks Tuff Member of the Bullion Canyon Volcanics (Oligocene)-Densely welded, crystal-rich latite ash-flow tuff. K-Ar age is about 27 m.y. (Steven and others, 1979)

Tb Lower Bullion Canyon Volcanics (Oligocene)-Intermediate composition lava flows, flow breccias and ash-flow tuffs; Dog Valley volcanics of Steven and Cunningham (1979)

Kpr Price River (Cretaceous)-Conglomerate and minor sandstone, shale

PMsu Undivided Paleozoic and Mesozoic Sedimentary Rocks-Includes contact metamorphosed equivalents



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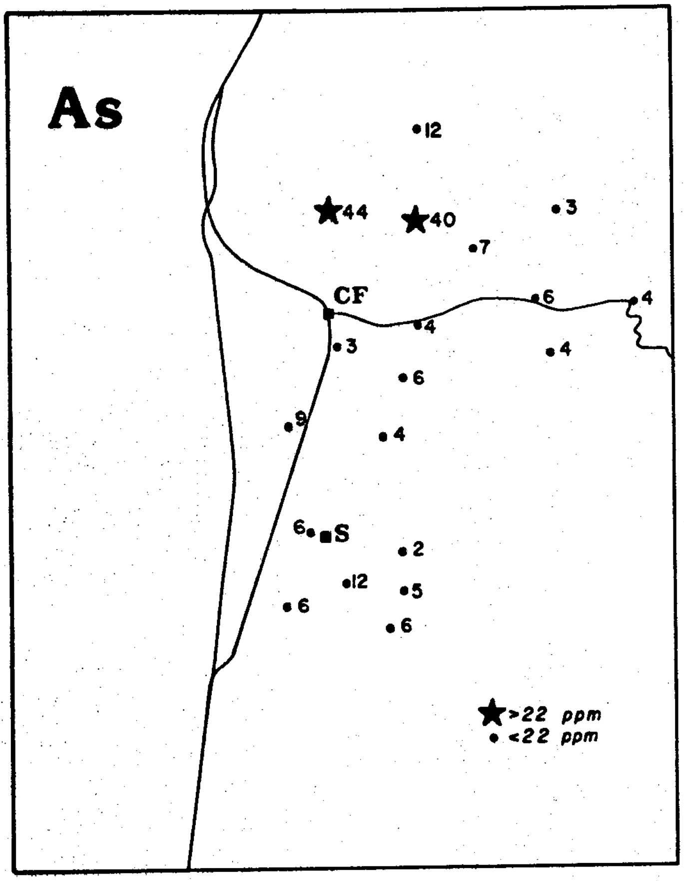
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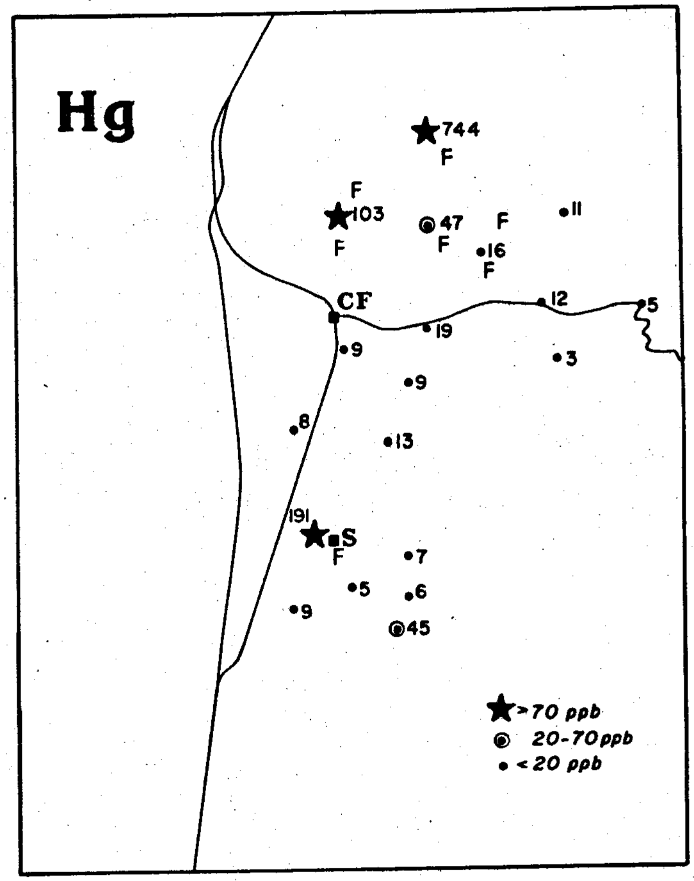
Hg
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20-70ppb
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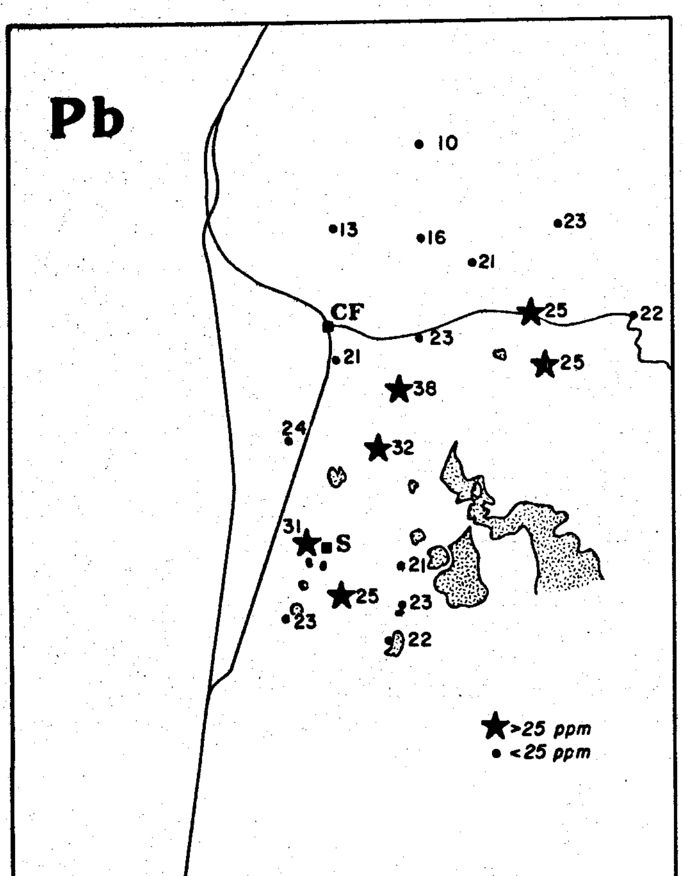
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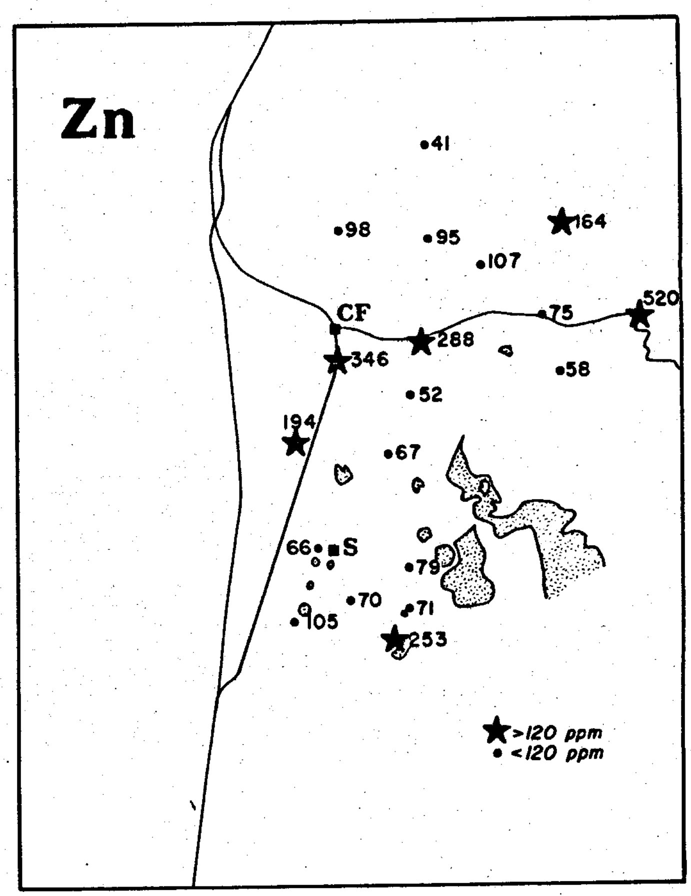
Zn
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98
95
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107
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S
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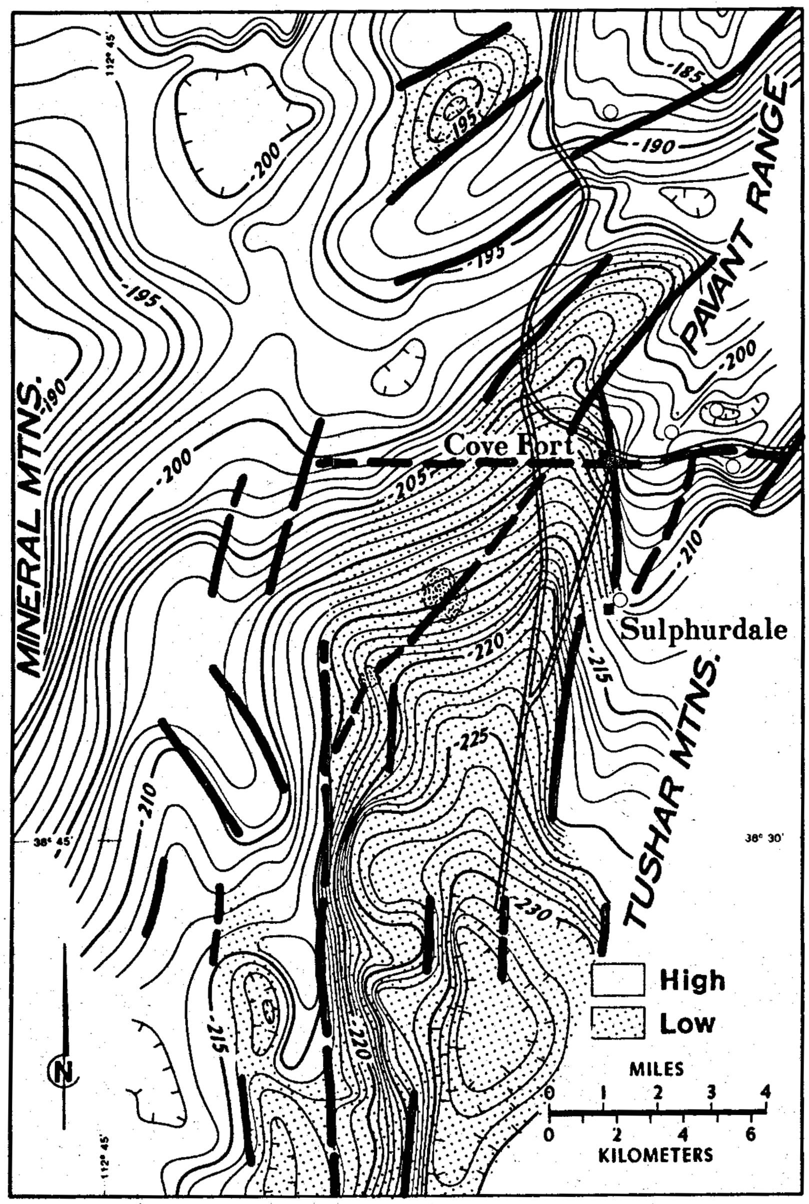
253
>120 ppm
<120 ppm



MINERAL MTNS.
PAVANT RANGE
TUSHAR MTNS.
Cove Fort
Sulphurdale
High
Low
MILES
0 1 2 3 4
0 2 4 6
KILOMETERS
N
112° 45'
38° 45'
38° 30'
-185
-190
-195
-200
-205
-210
-215
-220
-225
-230


0 2 4 6
KILOMETERS
N
-500
500
-700
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91
Cove Fort
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-800
Sulphurdale
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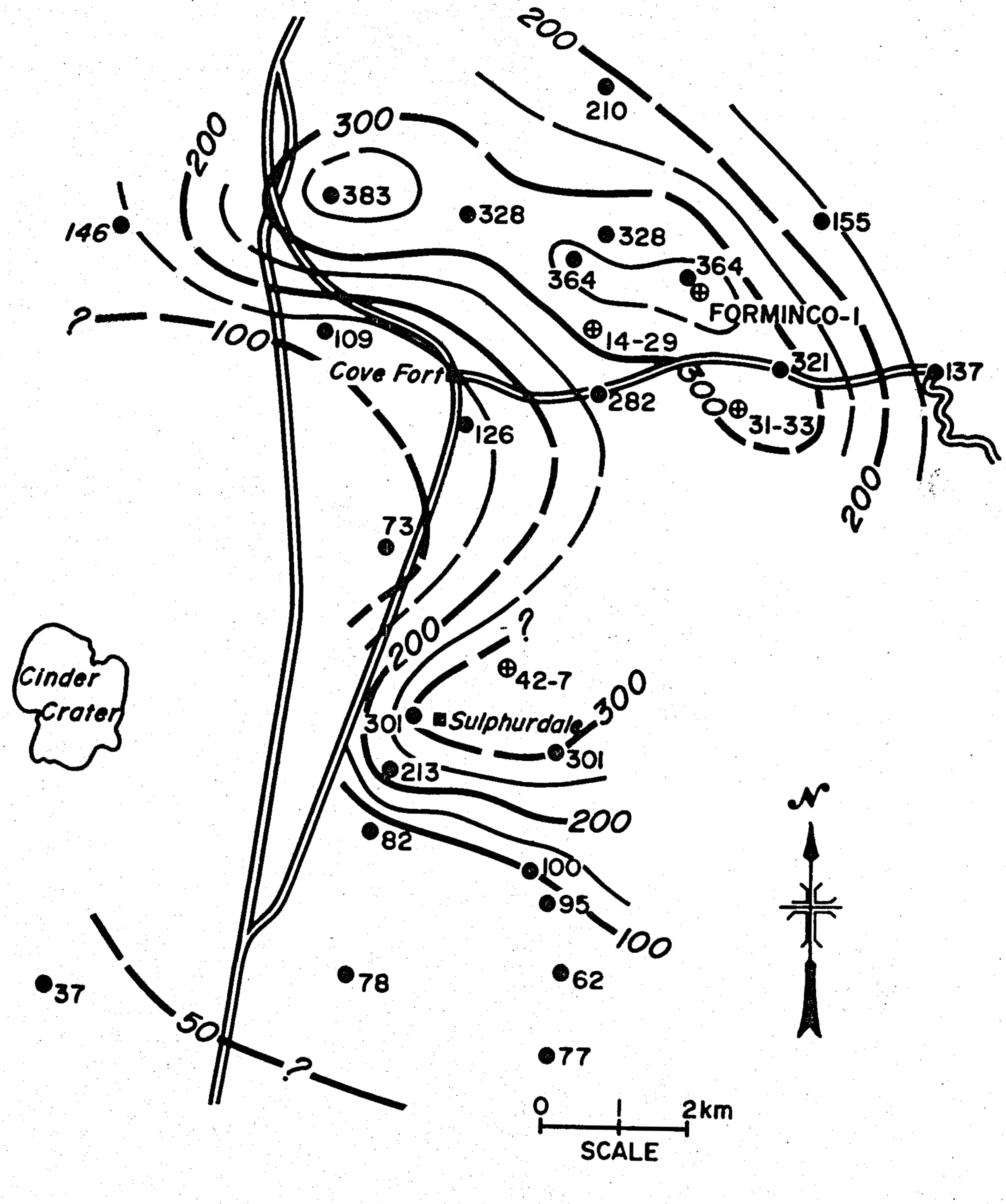

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383
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FORMINCO-1
?
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109
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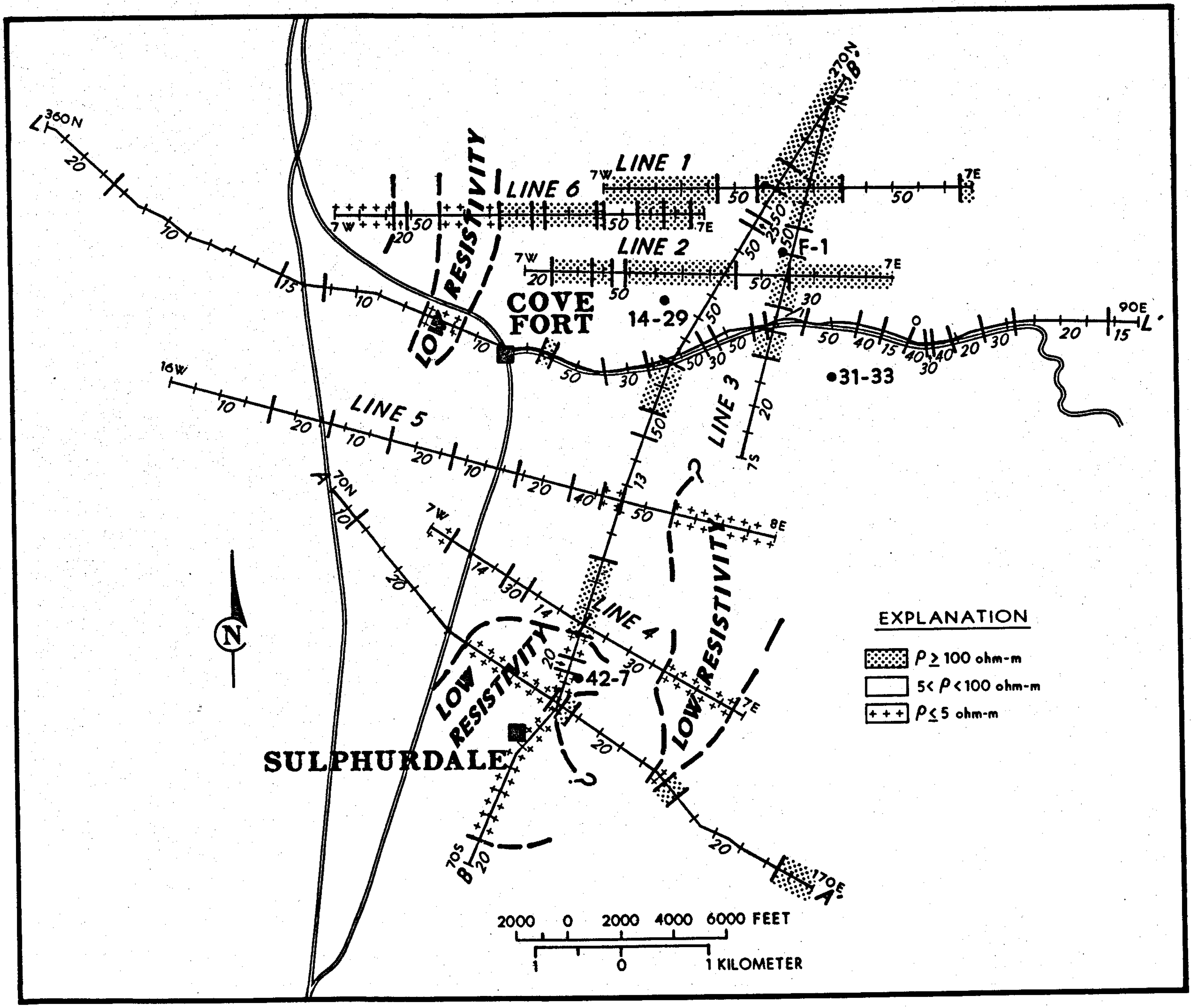
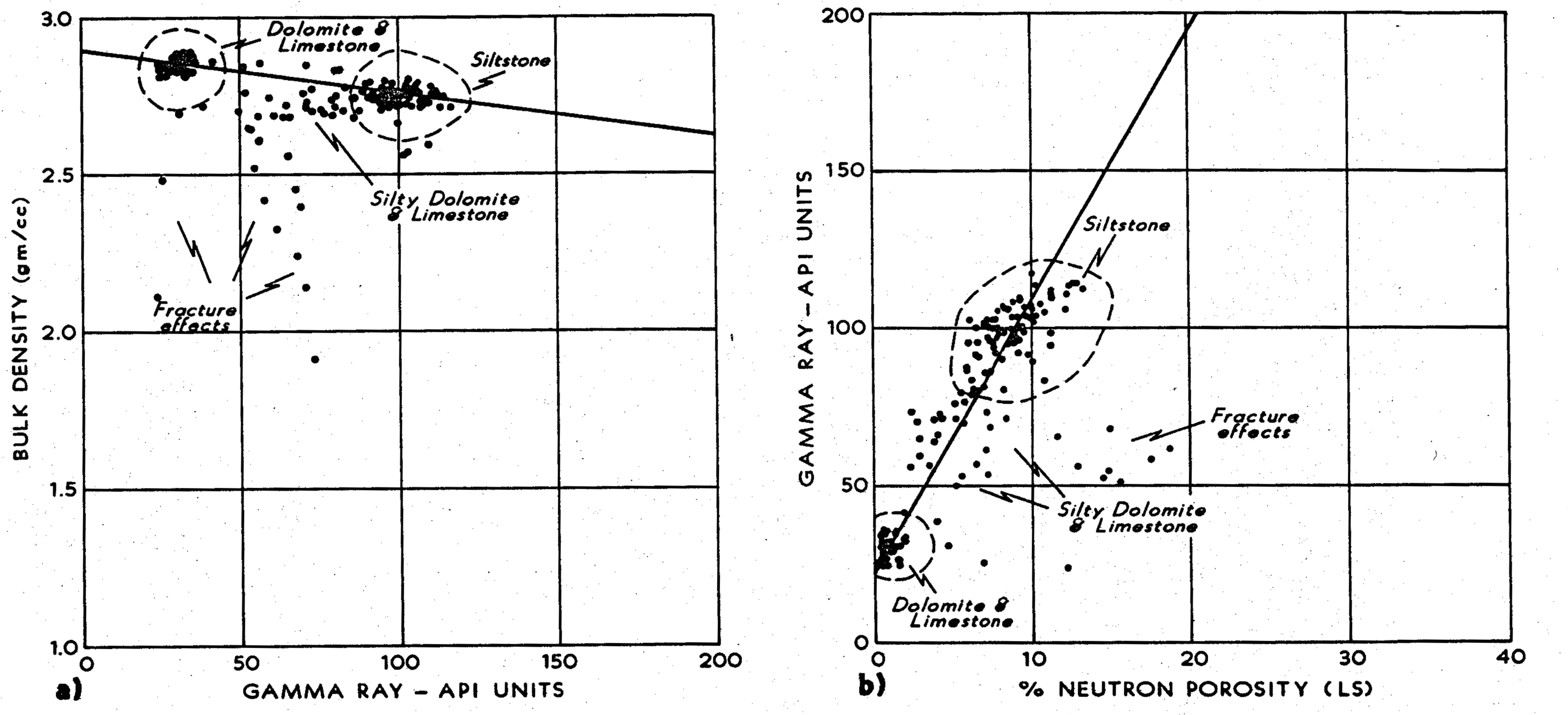
Cove Fort
282
300
31-33
126
200
73
?
200
42-7
Cinder Crater
300
301
Sulphurdale
301
213
200
82
100
95
100
78
62
37
50
?
77
N
0
1
2km
SCALE

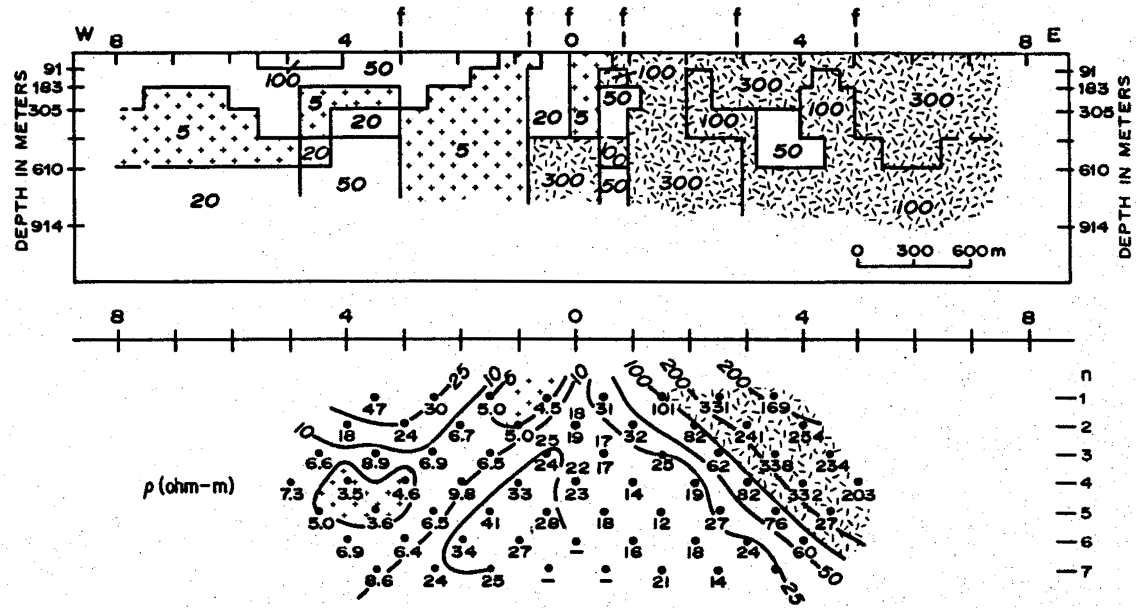


LINE 1
LINE 6
LINE 2
LINE 3
LINE 4
LINE 5
LOW RESISTIVITY
COVE FORT
SULPHURDALE
F-1
14-29
31-33
42-7
EXPLANATION
ρ ≥ 100 ohm-m
5< ρ <100 ohm-m
ρ ≤ 5 ohm-m
2000 0 2000 4000 6000 FEET
1 0 1 KILOMETER

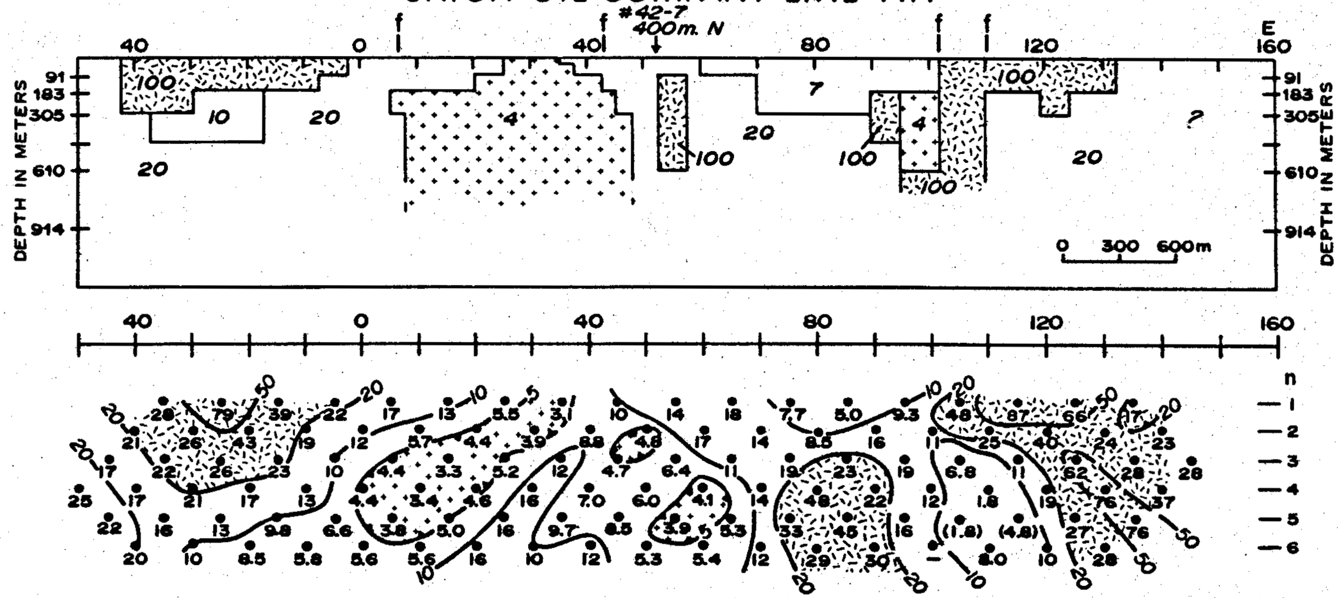


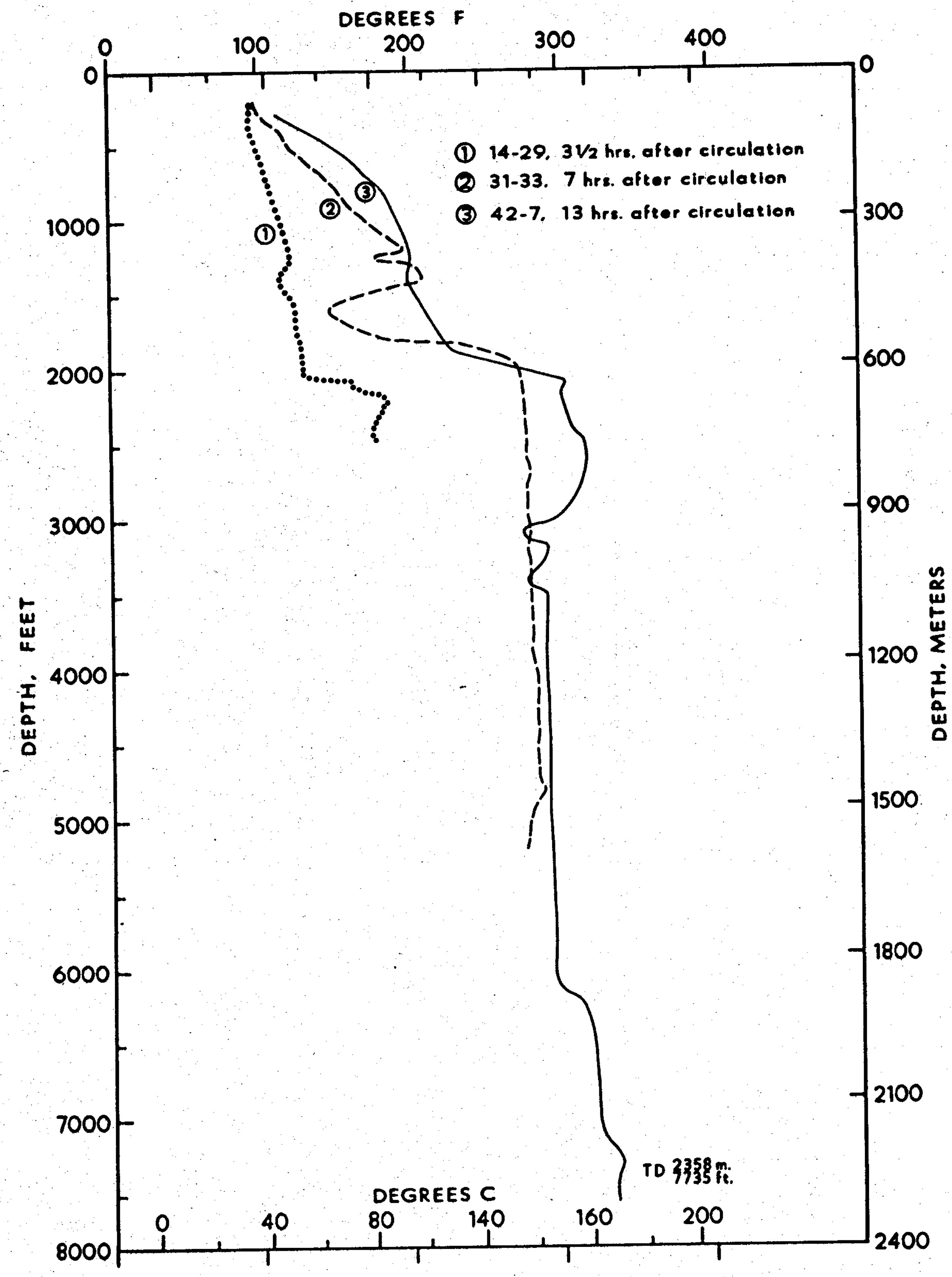
3.0
2.5
2.0
1.5
1.0
BULK DENSITY (gm/cc)
0
50
100
150
200
GAMMA RAY – API UNITS
Dolomite & Limestone
Siltstone
Silty Dolomite & Limestone
Fracture effects
a)
200
150
100
50
0
GAMMA RAY – API UNITS
0
10
20
30
40
% NEUTRON POROSITY (LS)
Siltstone
Fracture effects
Silty Dolomite & Limestone
Dolomite & Limestone
b)

LINE 6

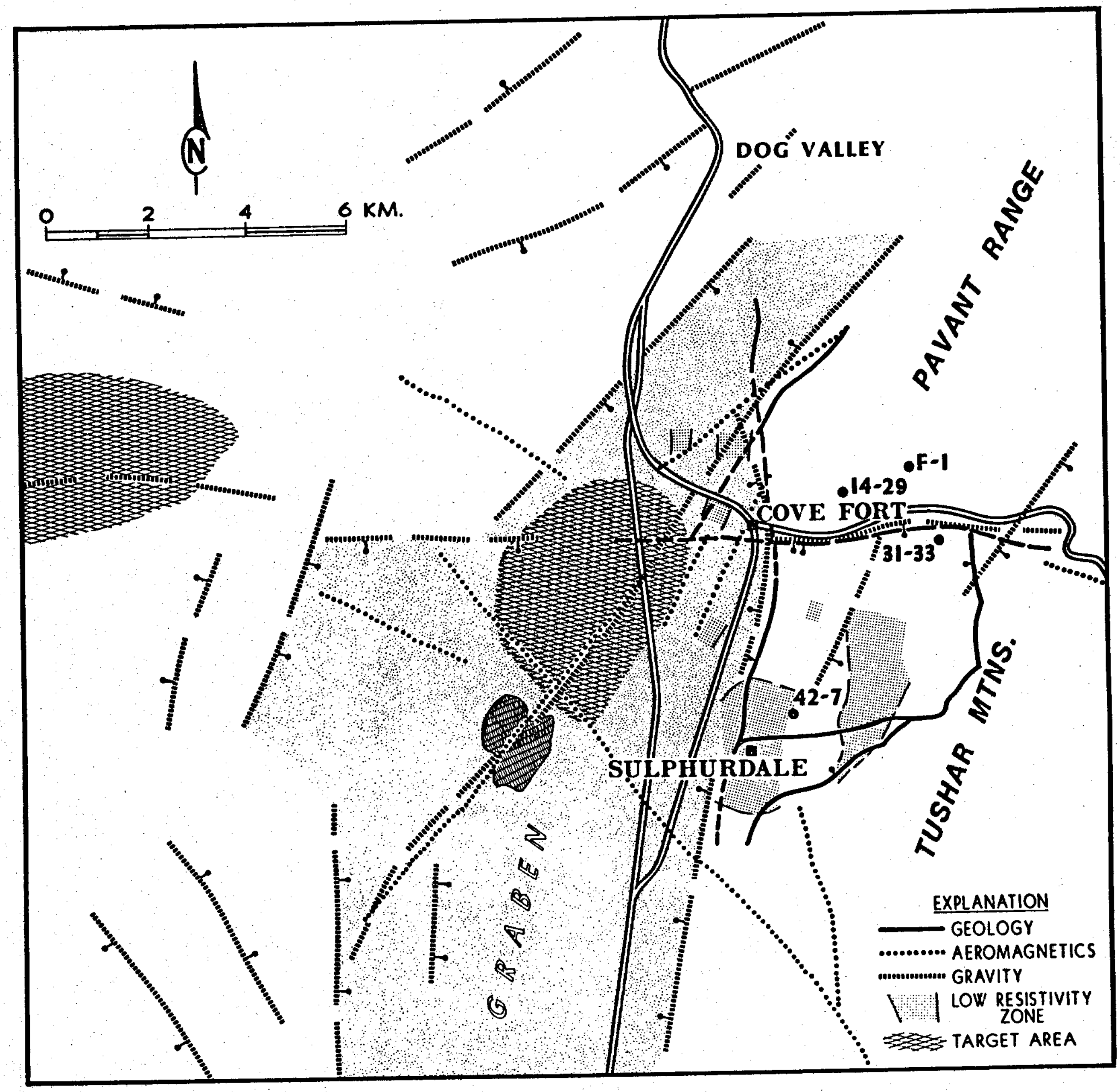


UNION OIL COMPANY LINE AA'





DEGREES F
0
100
200
300
400
0
1000
2000
3000
4000
5000
6000
7000
8000
DEPTH, FEET
0
300
600
900
1200
1500
1800
2100
2400
DEPTH, METERS
① 14-29, 3 1/2 hrs. after circulation
② 31-33, 7 hrs. after circulation
③ 42-7, 13 hrs. after circulation
TD 2358 m. 7735 ft.
DEGREES C
0
40
80
140
160
200



N
0 2 4 6 KM.
DOG VALLEY
PAVANT RANGE
F-1
14-29
COVE FORT
31-33
42-7
SULPHURDALE
GRABEN
TUSHAR MTNS.
EXPLANATION
GEOLOGY
AEROMAGNETICS
GRAVITY
LOW RESISTIVITY ZONE
TARGET AREA