GL04075

Retrospective Case Study of the Marysville, Montana Geothermal System as a Low- to Moderate-Temperature Resource

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ILLUSTRATIONS

INTRODUCTION

This report is one of a series of exploration case histories being prepared by the Earth Science Laboratory (ESL) in support of the Department of Energy (DOE)/Division of Geothermal Energy's (DGE) User-Coupled Confirmation Drilling Program, the purpose of which is the encouragement of direct utilization of low- to moderate-temperature (<150^{o}C) geothermal energy. Synthesis of these case histories should provide a useful data base for evaluation of proposals to DOE/DGE for participation in the program.

The Marysville geothermal area (Figure 1) was discovered in 1966 by D. D. Blackwell of Southern Methodist University during his investigation of regional heat flow in the northwestern United States (Blackwell, 1969). In several mineral exploration holes drilled just west of the town of Marysville Blackwell measured near-surface heat flow values averaging 6.5 HFU, over three times the already anomalous regional heat flow in western Montana (1.9 HFU; Blackwell and Baag, 1973). Additional measurements in existing and newly-drilled holes defined a 35 square kilometer anomaly with values up to 19.5 HFU. The size and intensity of the anomaly led Blackwell and Battelle Pacific NW Laboratories (1973) to request funding from the National Science Foundation for a detailed multidisciplined research program to characterize the geothermal source responsible for the high heat flow. Approval of the request allowed completion of the research program, which culminated in a deep drill test of the Marysville heat flow anomaly during the summer of 1974.

The heat source for the heat flow anomaly at Marysville was originally conceived as either a concealed, convecting hot water system or a shallow (1-1

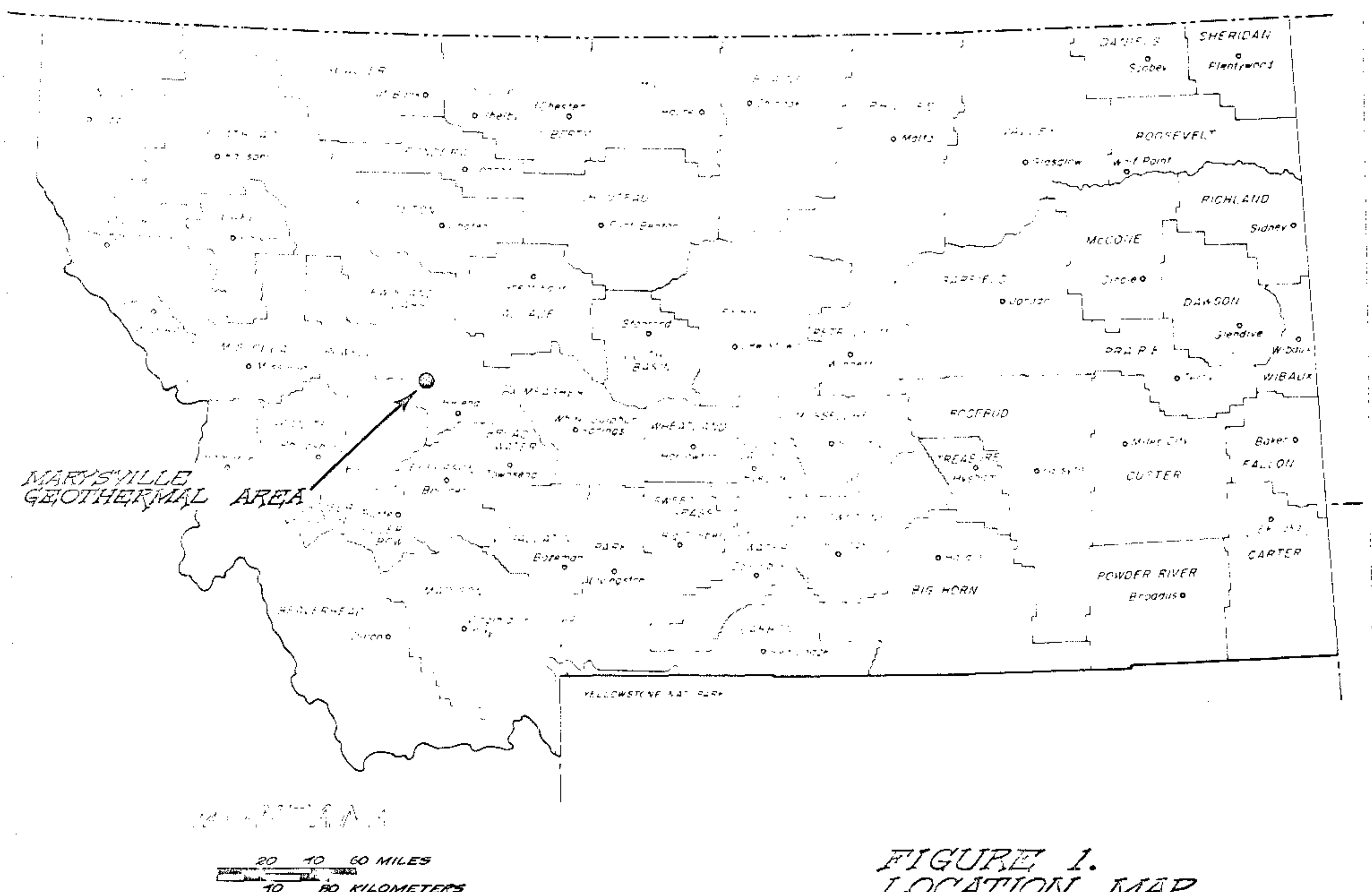


FIGURE 1.
LOCATION MAP

1/2 km) magma chamber (Blackwell and Baag, 1973; Battelle Pacific NW Laboratories, 1973). The magma chamber hypothesis was considered more likely because of the absence of hot springs, fumaroles or other surface hydrothermal phenomena within a 30-km radius of the heat flow anomaly. Thus Marysville was considered likely to be a hot, dry rock system, in which temperatures within a few kilometers of the surface might be expected to reach 500°C (Blackwell et al., 1974) or higher (Batelle NW Laboratories, 1973).

Deep drilling showed the heat flow anomaly to be produced by a convecting warm water system ($\leq$ 99°C) selectively developed in a concealed granite porphyry stock.

The Marysville geothermal project is documented in a series of technical reports coordinated by Battelle NW Laboratories (1973, 1974, 1975) and partially summarized by Blackwell and Morgan (1975). The interested reader is referred to these sources and others cited in this paper for details of individual exploration techniques used at Marysville.

This paper briefly sumarizes these exploration techniques and discusses the value of each technique in predicting the low- to moderate-temperature resource defined by deep drilling. Significant results for each technique are illustrated relative to the near-surface heat flow anomaly in a series of accompanying figures.

REGIONAL SETTING

The Marysville thermal area is situated roughly 20 km north of the large Late Cretaceous Boulder batholith in the northern Rocky Mountains structural and physiographic province. The batholith intrudes sedimentary rocks of Lower Precambrian through Cretaceous age. During the Late Cretaceous and possibly Paleocene (in part contemporaneous with emplacement of the batholith) these rocks were tightly folded and extensively disrupted by normal and overthrust faulting. The overthrust faults crop out in a narrow belt at the eastern margin of the Rocky Mountains roughly 40 km east of Marysville (Robinson et al., 1968). They are not exposed in the geothermal area but could be present at depth (Blackwell and Morgan, 1975).

The Boulder Batholith and its deformed Precambrian through Cretaceous host rocks are locally concealed beneath intermediate through felsic volcanic rocks of Eocene through Oligocene age. These volcanics may in part be the extrusive equivalents of spatially associated stocks, dikes and plugs of similar age and composition (Knopf, 1963, Robinson et al., 1968; Blackwell et al., 1975).

GEOLOGY

Stratigraphy and Structure

Marine sediments of the upper Precambrian Belt Supergroup (Ross, 1963; Knopf, 1963) are the oldest and most extensively exposed rocks in the Marysville geothermal area (Fig. 2). They comprise a conformable sequence including, in order of decreasing age: The Empire Formation (P€e), a siliceous to calcareous shale to argillite; the Helena Formation (P€h), a thick (roughly 4000 feet) siliceous dolomite to limestone; and the Marsh Shale, Greenhorn Mountain Quartzite and Black Mountain Quartzite, which have been grouped on Figure 2 as "P€s". The Spokane Shale (P€sp), an argillite

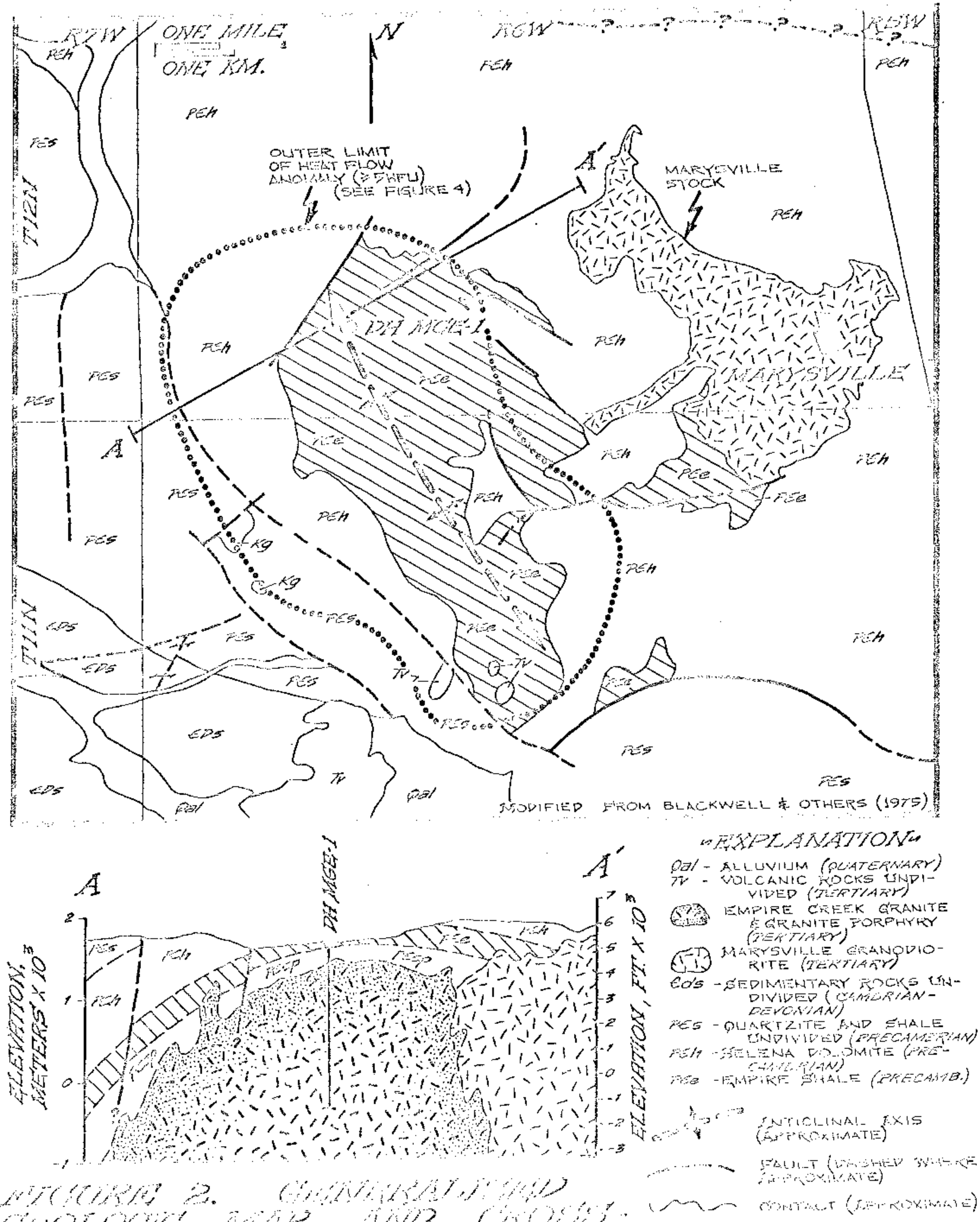


FIGURE 2. GENERALIZED GEOLOGIC MAP AND CROSS-SECTION OF THE MARYSVILLE GEOTHERMAL AREA

underlying the Empire Formation, is not exposed, but has been penetrated in drill holes and mine workings. Lower Paleozoic marine sedimentary rocks (€Ds) rest with slight angular unconformity on Belt rocks in the southwestern corner of the map area (Figure 2).

Belt formations in the Marysville area host numerous intrusions of diverse compositions and ages. The oldest are microdiorite sills confined to the Empire Formation and tentatively assigned on Upper Precambrian age. These sills are cut by the Marysville granodiorite stock (Figure 2), radiometrically dated at 79 $\pm$ 4 m.y. (Baagsgard et al., 1961), and considered an early satellite of the Boulder Batholith. Two concealed granite porphyry stocks were penetrated at shallow levels in exploration drill holes just southwest of the Marysville stock. The older of these, the Bald Butte stock, was radiometrically dated at 47.8 $\pm$ 2 m.y.; the younger, the Empire Creek stock, yielded a date of 40 m.y. (Ratcliff, pers. comm. _in_ Blackwell et al., 1974, and Blackwell and Morgan, 1975). The Empire Creek stock grades with depth from granite porphyry through porphyritic granite into equigranular granite (Blackwell et al., 1974). Northwest-trending quartz porphyry dikes above the two concealed stocks (not shown on map) and the Hope Creek rhyolite (Tv) in the south-central portion of the mapped area are apparently contemporaneous -- both have been dated at roughly 37 m.y. (Ratcliff, pers. comm. _in_ Blackwell et al. 1974 and Blackwell and Morgan 1975).

Structure in the Marysville area is dominated by an elliptical dome trending north-northwest just southwest of the Marysville stock (Fig. 2). The core of the dome is delineated at the surface by the outcrop and subcrop of the Precambrian Empire Formation. The dome may have been created in part by foreceful intrusion of the Empire Creek and Bald Butte granite porphyries (Blackwell and Morgan, 1975). Gentle open folding predominates away from the dome within the map area.

All mapped faults within the geothermal area are of normal displacement. One fault disrupts a contact metamorphic aureole developed around the Marysville stock, and so is post-Late Cretaceous. Another truncates Oligocene volcanics. Otherwise, absolute and relative ages of the faults could not be established. Study of geophysical well logs, cuttings and core from deep drill hole MGE-1 indicates that the Empire Creek granite porphyry is highly fractured relative to its Precambrian sedimentary host rocks (Blackwell et al., 1975).

Alteration, Mineralization and Contact Metamorphism

Cretaceous and early to middle Tertiary igneous activity in the Marysville area was accompanied by extensive contact metamorphism, mineralization and hydrothermal alteration, much or all of which, however, is not genetically related to the presently active geothermal system. Rich gold- and silver-bearing quartz veins clustered around the Marysville stock were mined during the late 19th and early 20th century (Barrel, 1907; Knopf; 1913). These veins may have formed contemporaneously with the stock (Mantei and Brownlow, 1967) during the Late Cretaceous or may be related to Oligocene igneous activity (Knopf, 1950; Blackwell, et al., 1979). The Marysville veins may also be related to the Oligocene (Ratcliff *in* Blackwell et al., 1974) gold-quartz-adularia veins emplaced in and around the Hope Creek rhyolites

("Tv" on Figure 2).

Molybdenum mineralization associated with the concealed Oligocene Empire Creek stock and Eocene Bald Butte stock was extensively investigated by private industry during the 1960's. Exploration drill holes completed during these investigations were utilized for Blackwell's initial heat flow studies in the Marysville area.

Alteration and mineralization in deep test well MGE-1 have not been dated and their relationship to the active geothermal system is not clear. Many of the veinlets encountered in the drill hole, however, contain minerals such as phlogopite and tremolite, which certainly reflect deposition at higher temperatures than encountered in the drill hole (99^{o}C).

An extensive contact metamorphic zone developed in precambrian Belt sediments surrounds the Marysville stock and extends southwest into the heat flow anomaly (Figure 3). Blackwell et al. (1974) separated this contact metamorphic zone into diopside and lower-temperature tremolite grade subzones based on characteristic metamorphic mineral assemblages. They correctly inferred that the southwestern portion of the metamorphic zone indicated a concealed intrusive partially coextensive in plan with the heat flow anomaly.

GEOPHYSICAL STUDIES

Heat Flow

Discovery of the Marysville thermal anomaly in 1966 led to detailed heat flow studies by D. D. Blackwell and associates from Southern Methodist University (Blackwell and Baag, 1973; Blackwell et al., 1974, 1975). These

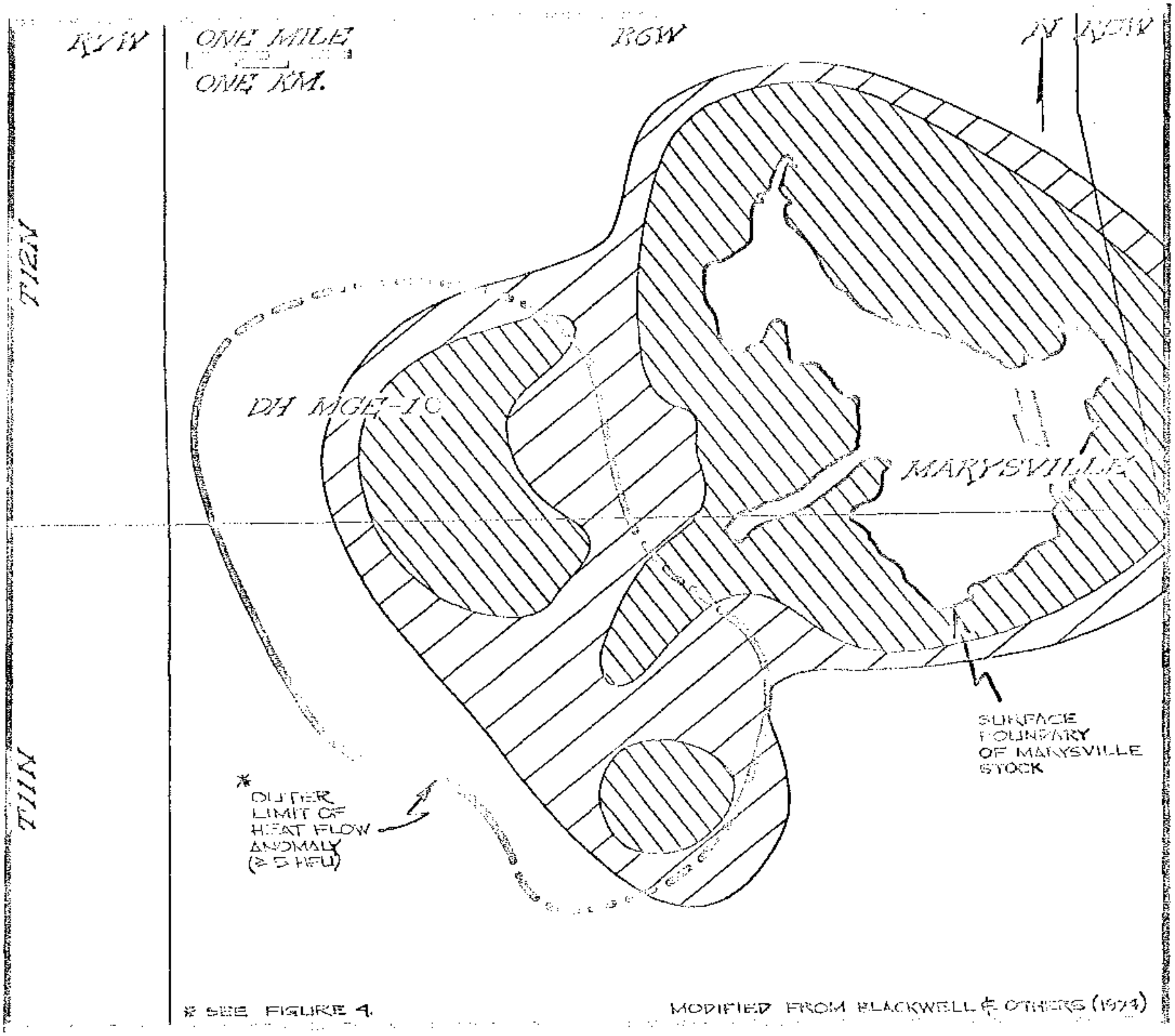


FIGURE 3. CONTACT METAMORPHISM IN THE MARYSVILLE GEOTHERMAL AREA.

(SOUTHWESTERN LOBE OF CONTACT METAMORPHIC ZONE RESTS ABOVE THE CONCEALED EMPIRE CREEK STOCK PENETRATED BY DEEP DRILL HOLE MGE-1)

EXPLANATION

DIOPSIDE-GRADE HORNFELS

TREMOLITE-GRADE HORNFELS

studies, completed between fall 1972 and summer 1974 were carried out on existing mineral exploration drill holes and on eight additional shallow (≤ 135m) holes drilled specifically for the project. All measurements were taken over shallow (≤ 280m), but not consistent, depth intervals. Many of the mineral exploration holes are inclined, and are felt to yield less reliable heat flow data than the vertical holes (Blackwell and Baag, 1973). All heat flow determinations were terrain-corrected using the methods of Birch (1950) and Blackwell (1973). Thermal conductivities were obtained from drill cuttings utilizing techniques outlined by Sass et al. (1971).

Heat flow values for all but two drill holes[1], are shown on Figure 4, which also shows the position of the heat flow anomaly relative to the town of Marysville and the surface expression of the Marysville stock. The anomaly is contoured at the 5 and 10 HFU values (slightly modified from Blackwell et al., 1975). The 5 HFU contour will be compared with results of other geophysical and geological investigations in subsequent figures.

Gravity

A detailed gravity survey comprising 210 stations was completed in the area of the Marysville thermal anomaly by Mazella (1973) during the summer of 1971. The survey was expanded twofold in area with another 150 stations during the summer of 1973 (Blackwell et al., 1974), and fifty three stations were added during the summer of 1974 (Blackwell et al., 1975). Most of these stations were either located on or leveled from benchmarks for precise

[1]These two holes, drilled in an area of high microearthquake activity about six miles southeast of Marysville, yielded values of 1.8 HFU, which is normal for west-central Montana (Blackwell and Robertson, 1973).

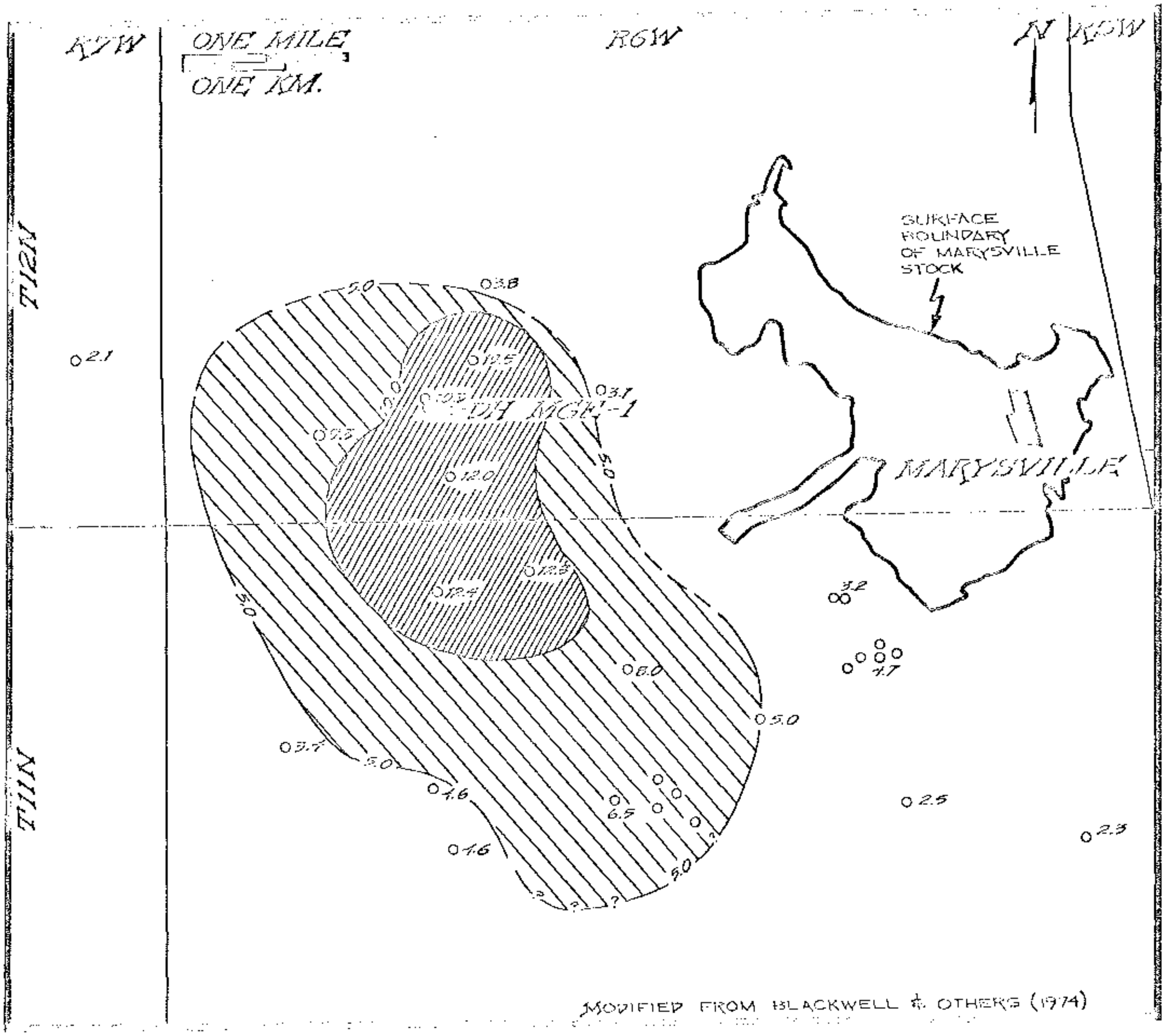


FIGURE 4. SHALLOW HEAT FLOW MAP OF THE MARYSVILLE GEOTHERMAL AREA.
VALUES RECORDED ARE HEAT FLOW UNITS (HFU = $\mu cal/cm^2 sec$)

elevation control. Elevations for 43 of Mazella's (1973) original stations were barometrically determined.

Complete Bouguer gravity values were determined for all stations. Terrain corrections were computer-calculated for most stations, but hand calculated for stations within and near the heat-flow anomaly. A residual gravity map was prepared by mathematically removing a strong regional gravity gradient from a map of complete Bouguer values.

Figure 5 shows a portion of the residual gravity map centered on the Marysville heat flow anomaly. The map reveals some correlation of high heat flow with a negative gravity anomaly which, however, extends out of the map area several miles to the south. This partial correlation led to initial speculation that the gravity low might be produced by a shallow, low-density, conductively cooling magma chamber (Mazella, 1973; Blackwell and Baag, 1973). Deep drilling results (Blackwell et al., 1975) coupled with earlier density measurements (Mazella, 1973) indicated the gravity low to be largely the result of density contrast between the concealed, partly altered Empire Creek stock (mean density 2.54 g/cm^3) and enclosing Precambrian sediments (measured formations in contact with the stock average 2.69-2.89 g/cm^3).

Ground Magnetics

During the summer of 1973, SMU personnel completed a total field intensity ground magnetic survey of 800 stations covering roughly 35 square miles centered on the Marysville heat flow anomaly (Blackwell et al., 1974). The survey was interpreted with the aid of a computer program based on the

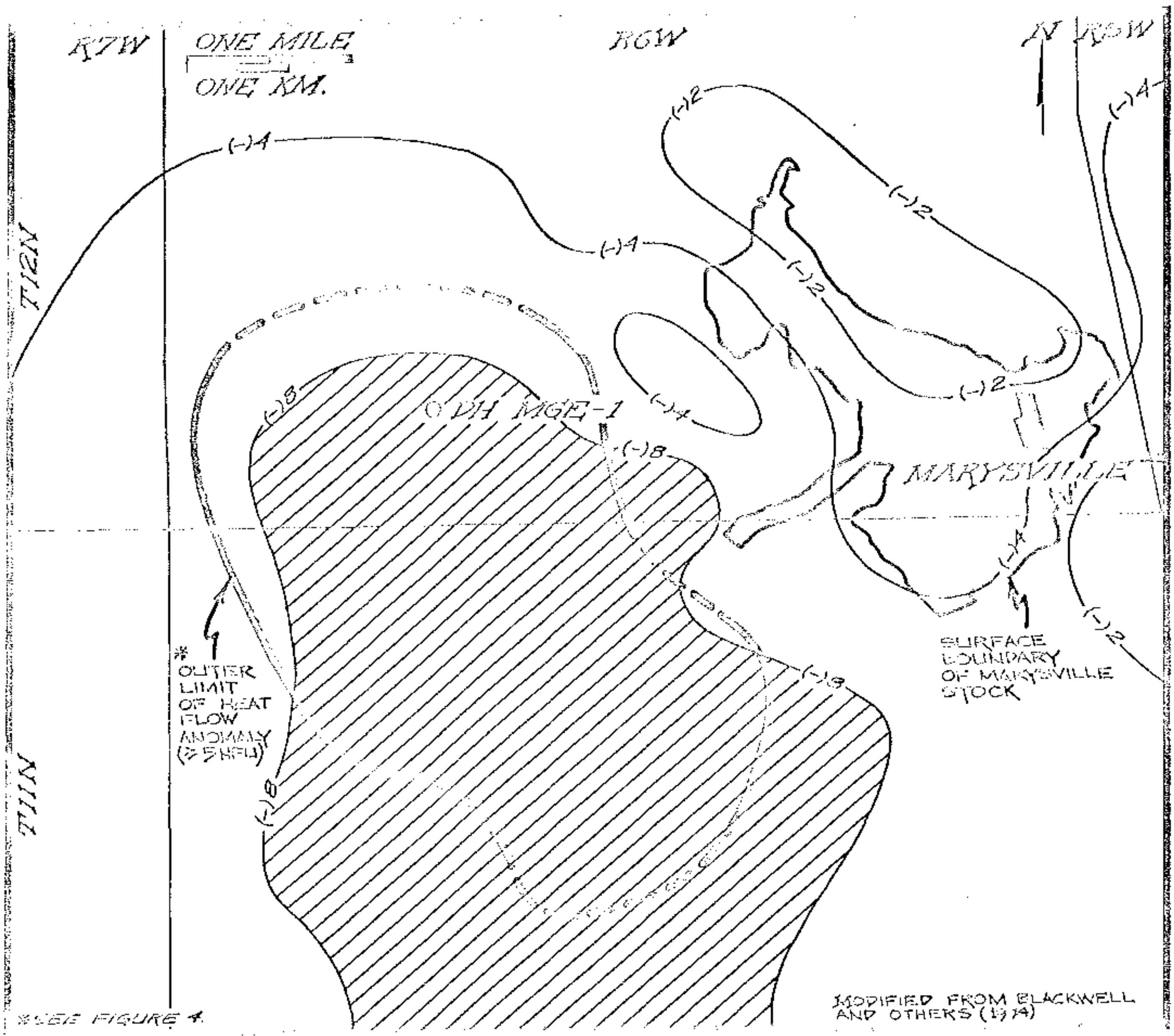


FIGURE 5. RESIDUAL GRAVITY MAP OF THE MARYSVILLE GEOTHERMAL AREA.
VALUES ARE IN MILLIGALS. NORTHERN PORTION OF THE CENTRAL GRAVITY LOW REFLECTS IN PART THE CONCEALED PRESENCE OF THE FELSIC EMPIRE CREEK STOCK IN HIGHER-DENSITY PRECAMBRIAN BELT SERIES SEDIMENTS.

algorithm of Talwani (1965). Interpretations were modified by results of a low-altitude (152m above topography) total field aeromagnetic survey flown earlier by private industry. Precision for the survey is estimated to be ± 5 Regional magnetic background in the Marysville area is roughly 57,900 with a declination in 1973 of 20°E and an inclination of 72.5°. Regional magnetic gradient is 3 /km to the northeast.

Figure 6 summarizes results of the ground magnetic survey. The outstanding feature of the survey is a strong positive anomaly, up to 1600 above background, obviously produced by the Marysville stock. Values west of the stock range narrowly between 57,900 and 58,000 and form no coherent anomalies in the area of the heat flow high.

The main result of the magnetic survey was discovery that the subsurface southwestern boundary of the Marysville stock delineates the northeastern margin of the heat flow anomaly. Deep drilling results indicate this margin to be the concealed contact between the relatively unbroken Marysville stock and the fractured Empire Creek stock, which hosts the thermal fluid reservoir responsible for the heat flow high.

Roving Dipole Resistivity Survey

A roving dipole resistivity survey was carried out in the Marysville area during the Fall of 1972 by Jackson (1972) of the U. S. Geological Survey. Details of instrumentation and interpretation for the survey are unpublished. Survey results are summarized in Blackwell et al. (1974). Source-receiver separations of up to several kilometers were used. Effective penetration of

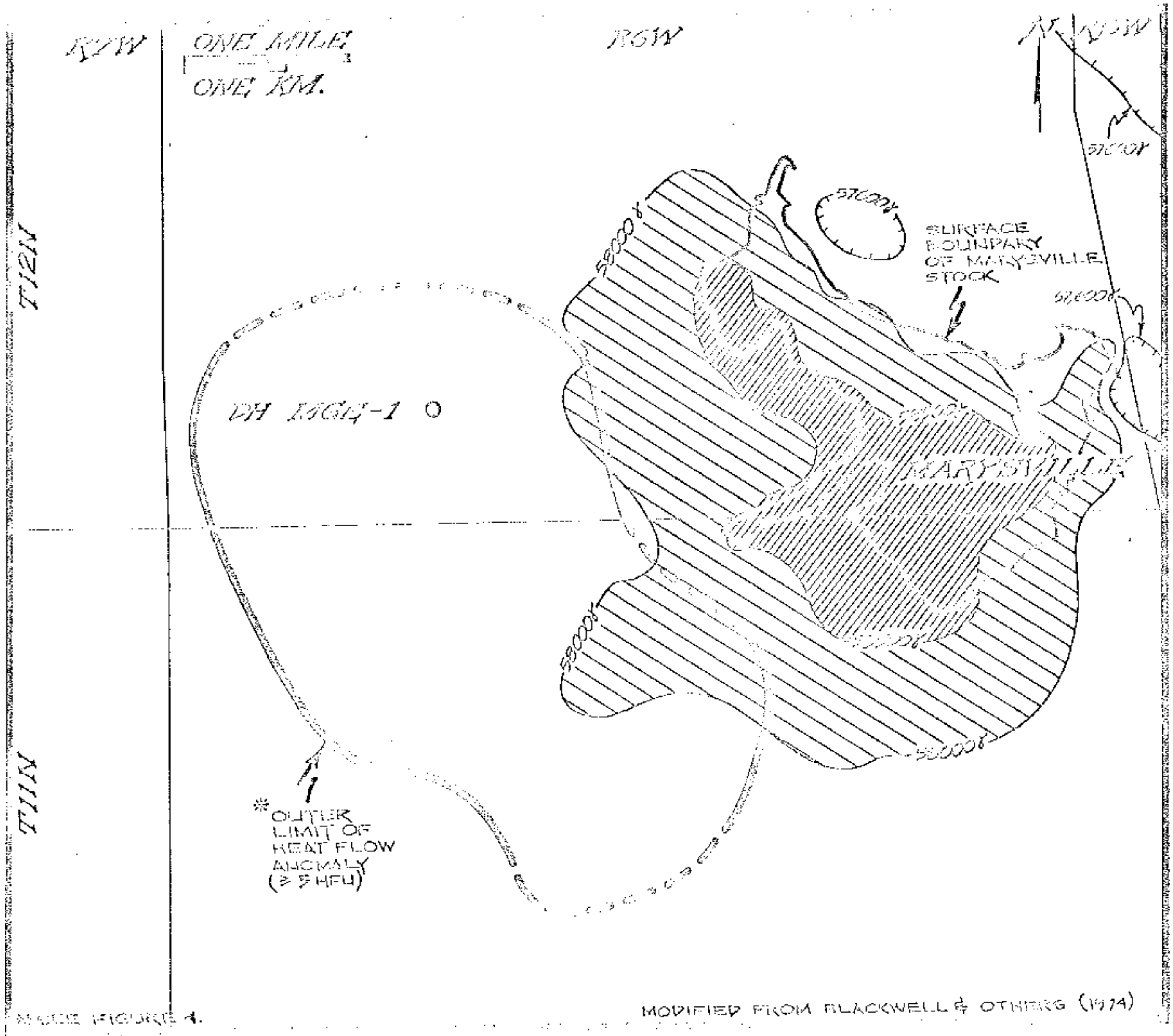


FIGURE 6. SIMPLIFIED GROUND MAGNETIC TOTAL FIELD INTENSITY IN THE MARYSVILLE GEOTHERMAL AREA. VALUES ARE IN GAMMAS (γ). ALL VALUES OUTSIDE AND WEST OF THE 58,000γ CONTOUR ≥ 57,800γ.

the survey was originally estimated at 600 to 1000 meters (Blackwell et al., 1974), but later amended to "perhaps even as shallow as a few tens of meters" (Blackwell et al., 1975).

Figure 7 is a shallow apparent resistivity map based on Jackson's roving dipole survey. Resistivity values within the map area range from less than 50 ohm-meters just southwest of the heat flow anomaly to 1000 ohm-meters in the northwestern portion of the anomaly. Most of the heat flow anomaly is characterized by high resistivity.

Magnetotelluric and Audiomagnetotelluric Surveys

Magnetotelluric (MT) and audiomagnetotelluric (AMT) surveys centered on the Marysville thermal anomaly were completed during the summer of 1974. Details of these surveys are discussed in Peeples (1975) and Stodt (1975) and summarized in Blackwell et al. (1975).

The AMT survey comprised 81 stations at which the electrical and magnetic fields were measured and hand recorded for two perpendicular horizontal directions (N20^{o}W and N70^{o}E), chosen as roughly parallel and perpendicular to the regional structural trend. Apparent resistivities were calculated over the frequency range 20Hz to 10^4 Hz for each measuring direction. Figure 8 is a map of apparent resistivity in the N70^{o}E direction as measured at 20 Hz, the lowest AMT frequency available. Skin depth, or effective depth of current peneration, is estimated at Marysville to be at on the order of several kilometers at 20 Hz, (Blackwell et al., 1975).

Twelve MT stations were occupied. For each station MT data were

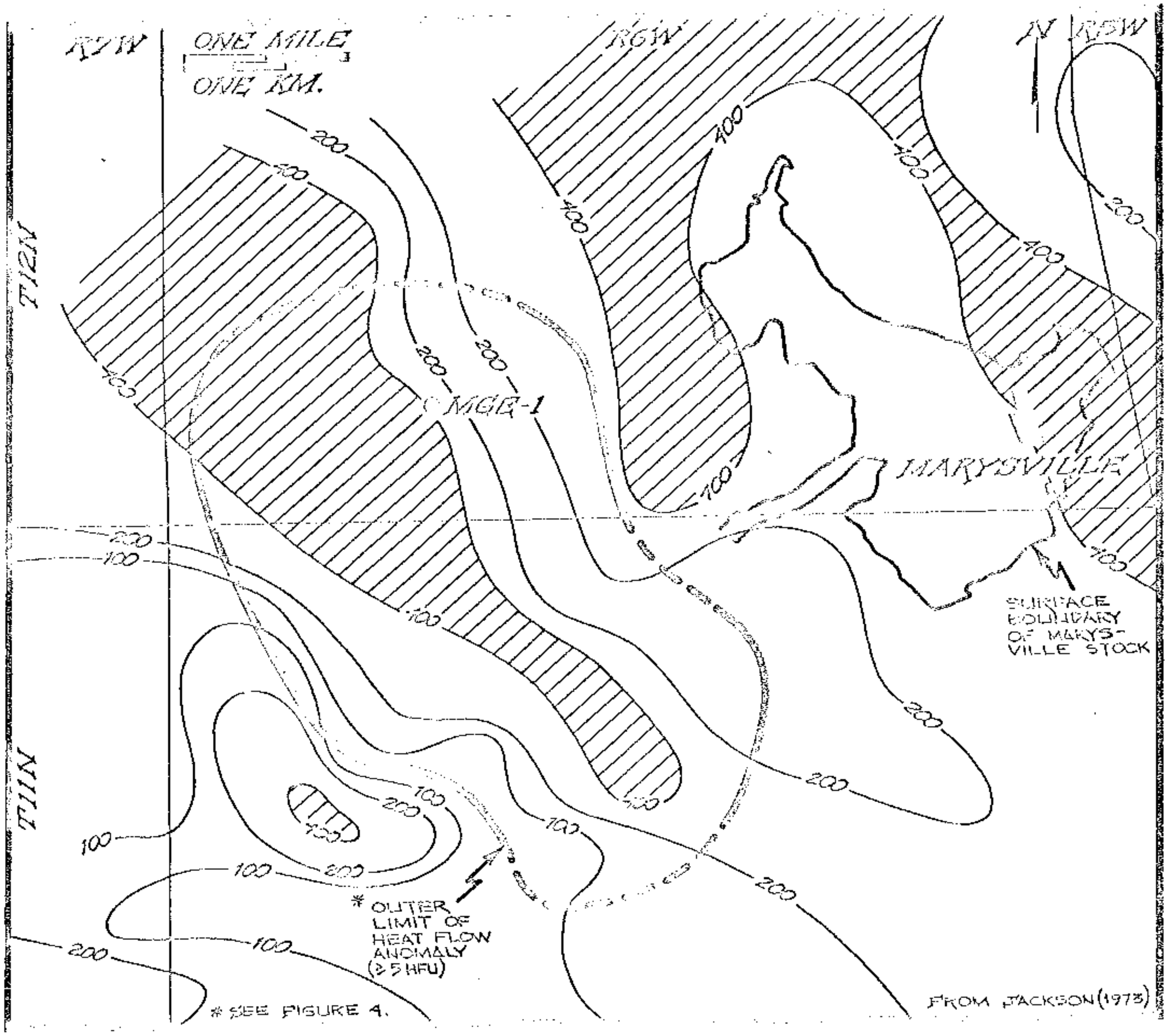


FIGURE 7. SHALLOW APPARENT RESISTIVITY MAP OF THE MARYSVILLE GEOTHERMAL AREA BASED ON ROVING DIPOLE RESISTIVITY SURVEY.
VALUES ARE IN OHM-METERS

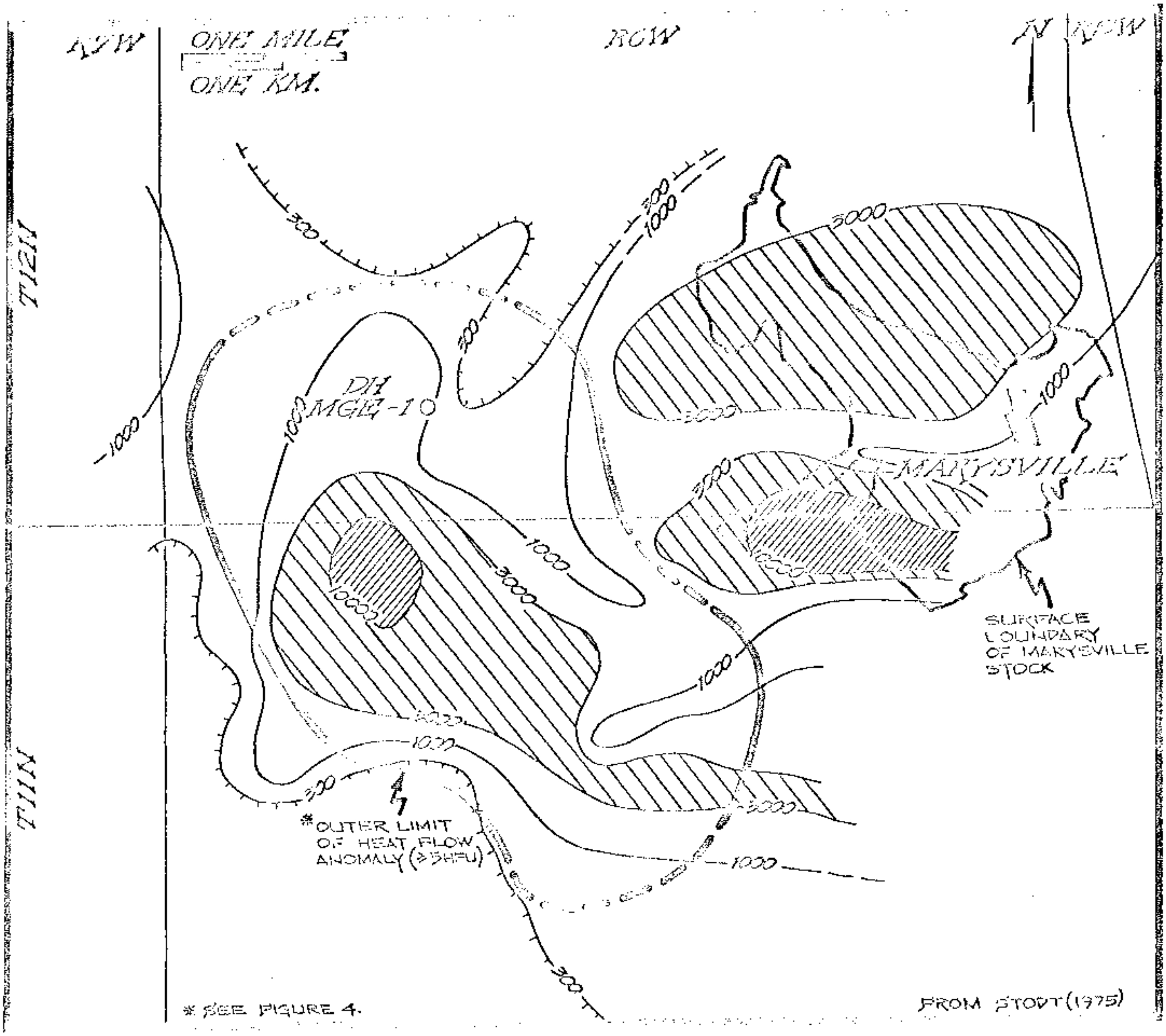


FIGURE 8. 20 Hz AUDIOMAGNETOTELLURIC APPARENT RESISTIVITY MAP (N10°E MEASUREMENT) OF THE MARYSVILLE GEOTHERMAL AREA.
VALUES ARE IN OHM-METERS

digitally recorded over the frequency range 0.1 Hz to 0.001 Hz in three orthogonal directions and tensor apparent resistivities were calculated. Figures 9 and 10 illustrate contoured apparent resistivities at MT frequencies of 0.10 and 0.01 Hz.

Curves of apparent resistivity versus frequency are similar for all stations. At highest frequencies (10^4 Hz), resistivities average about 100 ohm-meters, and are apparently associated with surficial material. At frequencies in the 10^2-10^3 Hz range, resistivities are very high (commonly measuring 10,000 ohm-meters) then diminish with decreasing frequency to the 100-1000 ohm-meter range.

The MT-AMT data were initially interpreted using one dimensional (1D) models. Results of the 1D modeling together with all other available geophysical and geological data were used to construct a two-dimensional (2D) model which is discussed in detail in Peeples (1975). Basically, both 1D and 2D models show a moderately conductive surficial layer above a thick highly resistive layer, in turn above a deep moderately conductive zone. Modeled depths to the base of the highly resistive layer are illustrated in Figure 11. Two prominent areas of deep and thick high resistivity are immediately apparent. The eastern of these two areas coincides with the Marysville stock. The second zone is confined to the area of anomalous heat flow.

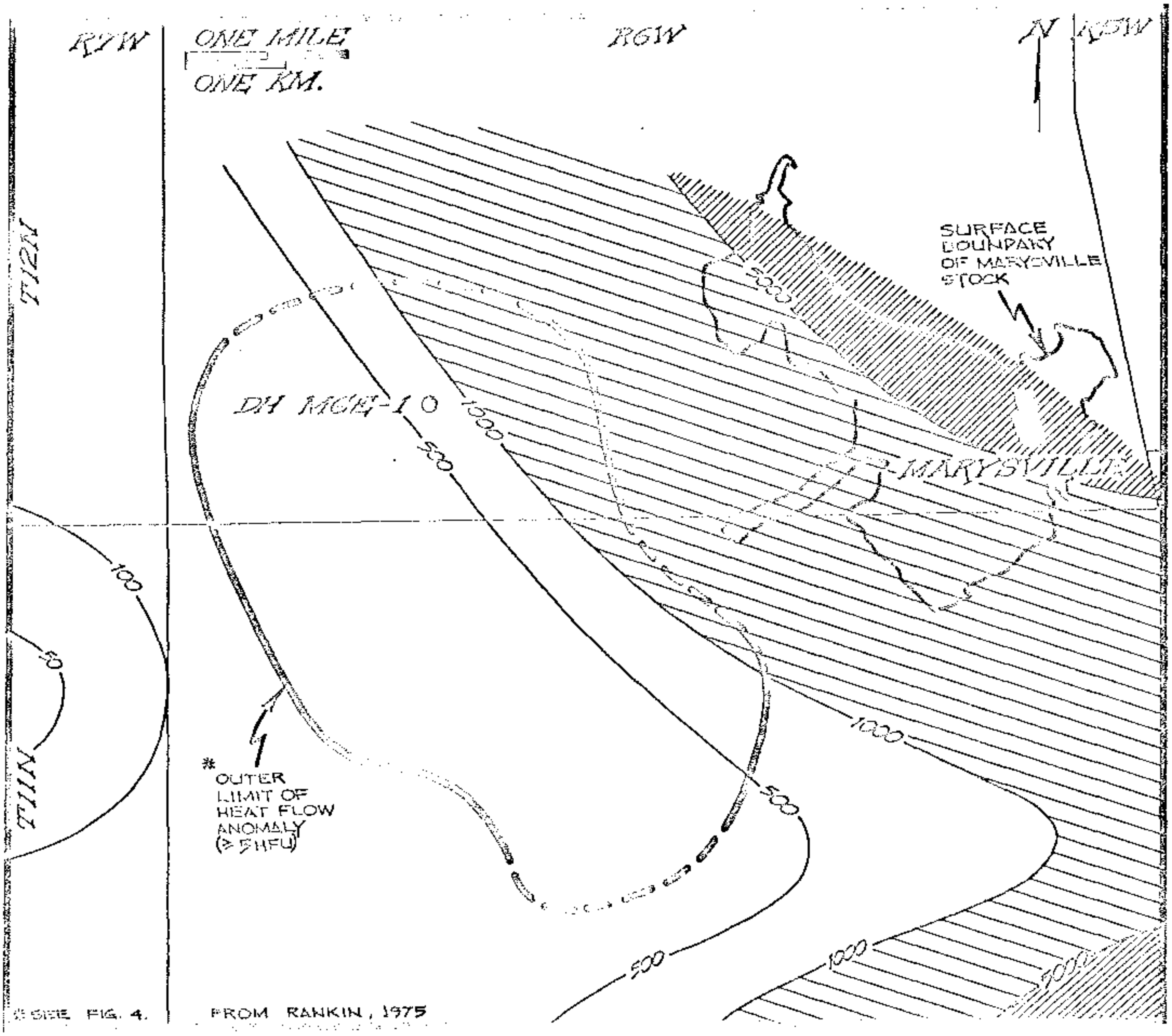


FIGURE 9. 0.10 Hz MAGNETOTELLURIC APPARENT RESISTIVITY MAP (N70°E DIRECTION) OF THE MARYSVILLE GEOTHERMAL AREA.
VALUES ARE IN OHM-METERS

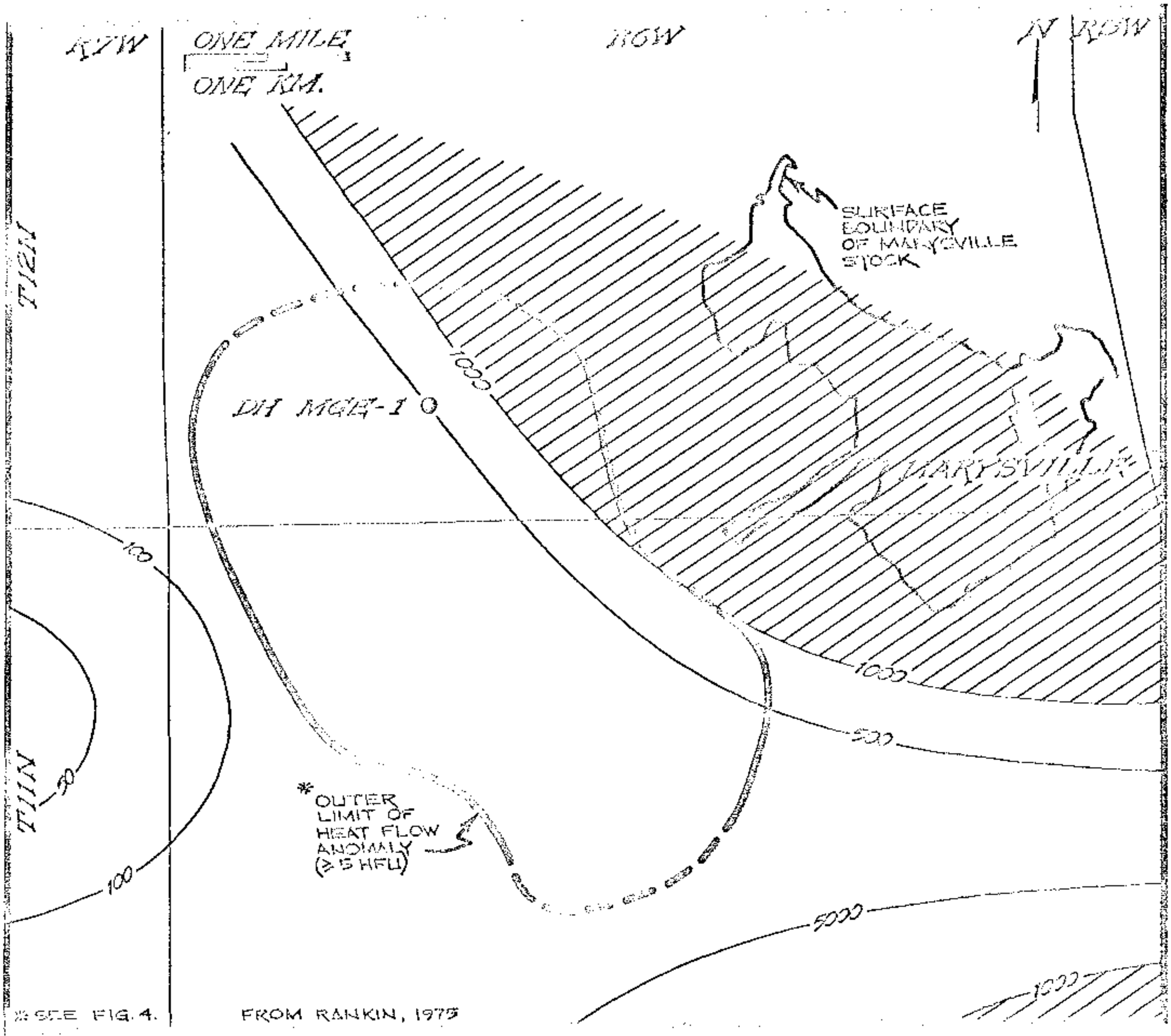


FIGURE 10. 0.01 Hz MAGNETOTELLURIC APPARENT RESISTIVITY MAP (N70°E DIRECTION) OF THE MARYSVILLE GEOTHERMAL AREA.
VALUES ARE IN OHM-METERS.

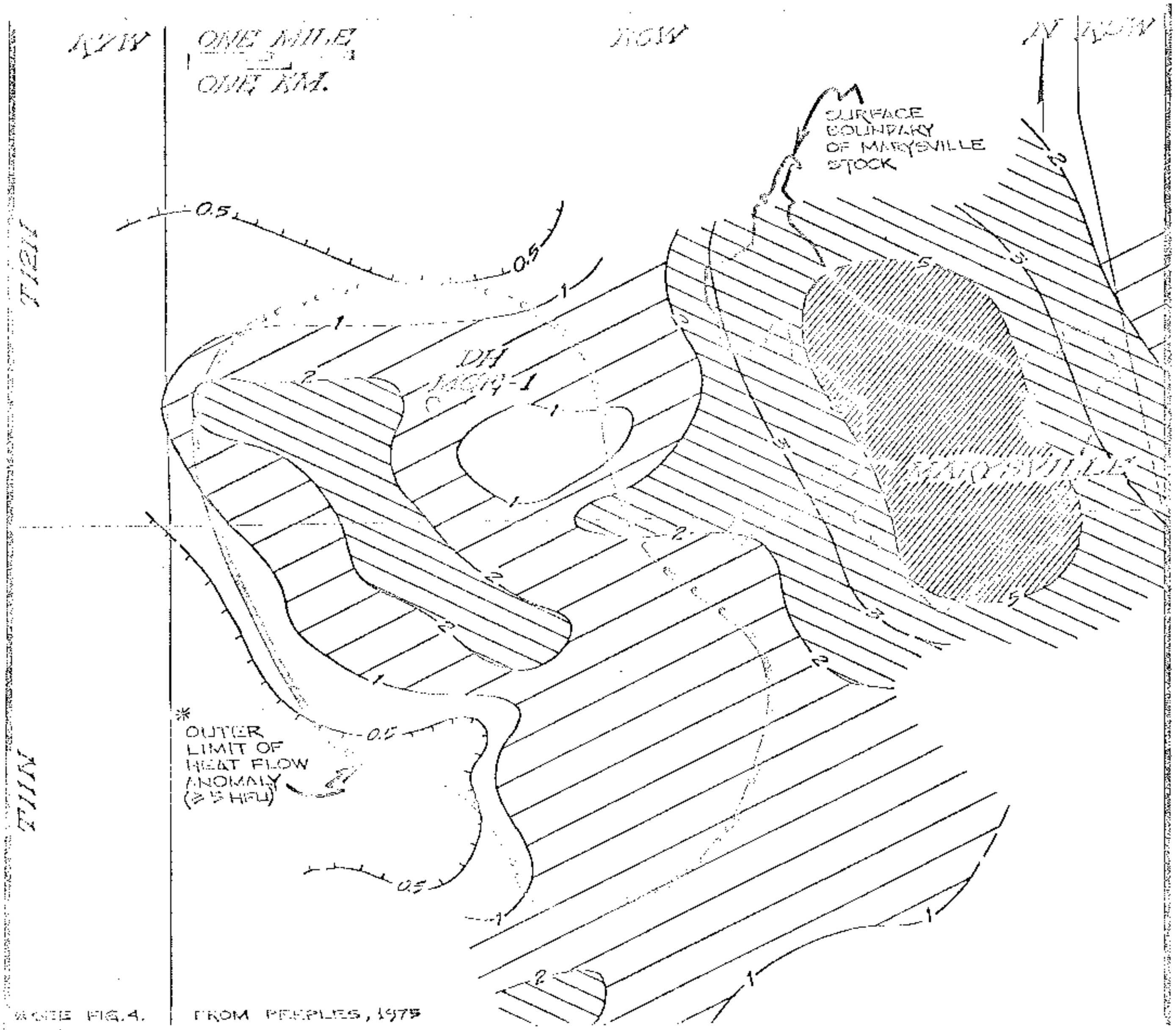


FIGURE 11. MODELED DEPTH TO BASE OF THICK, HIGHLY RESISTIVE LAYER (>1000-10,000 OHM-METERS) IN THE MARYSVILLE GEOTHERMAL AREA. DEPTHS CONTOURED ARE RECORDED IN KILOMETERS.

Ground Noise

During the summer of 1973, a seismic ground noise survey comprising 40 stations covering roughly 25 square miles was completed in the Marysville area (Blackwell et al., 1974). Previous work by Clacy (1968), Whiteford (1970), Goforth et al. (1972), and Combs and Muffler (1973) had shown some high-temperature convecting hydrothermal systems to be associated with high relative noise levels. The Marysville survey was undertaken both to test the possibility of such a relationship beneath the surficial heat flow anomaly and to investigate the source of that heat flow -- presumably either a convecting hot water system or a cooling magma chamber.

Details of the complex instrumentation and interpretation techniques employed for the survey are provided in Blackwell et al. (1974). Significant results of the survey are illustrated in Figure 12. The quantity contoured on the figure is ground noise as measured by the square of ground particle velocity calculated from the integral of power density observed in the frequency band 1-2 Hz.

Prominent ground noise lows are seen in the figure to correlate with both the heat flow anomaly and the surface expression of the Marysville stock. Since the heat flow anomaly actually reflects the concealed extent of the shallow Empire Creek/Bald Butte granite porphyry, it seems likely that ground noise at Marysville may be a function of rock type. The intrusives, being more competent than their Belt host rocks, are characterized by lower noise levels.

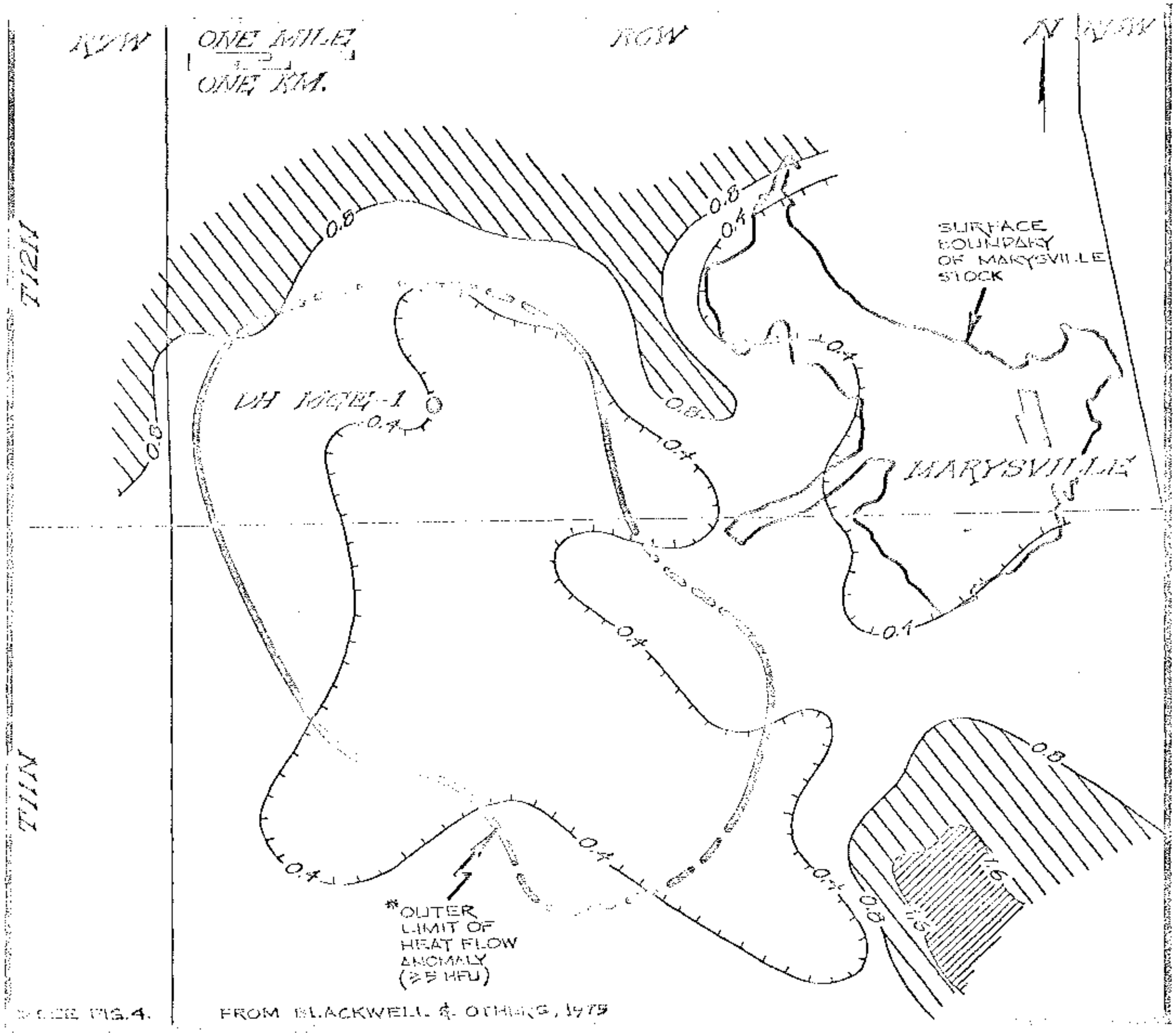


FIGURE 12. GROUND NOISE IN THE MARYSVILLE GEOTHERMAL AREA. QUANTITY CONTOURED IS GROUND NOISE AS THE SQUARE OF GROUND PARTICLE VELOCITY CALCULATED FROM THE INTEGRAL OF POWER DENSITY IN THE FREQUENCY BAND 1-2 Hz.

Blackwell et al. (1975) felt that low seismic noise associated with the heat flow anomaly was evidence against a concealed convecting hot water system. Deep drilling subsequently discovered just such a system, although at relatively low temperatures. High ground noise levels, therefore, may be produced only by high-temperature (and thus higher pressure) systems.

Microearthquake Studies

Microearthquakes in the Marysville region were monitored during two surveys completed in the summers of 1973 and 1974. Survey instrumentation and interpretation techniques are documented in Friedline (1974), Friedline and Smith (1974), and Friedline et al. (1974, 1975) and are summarized in Blackwell et al. (1974, 1975).

The surveys delineated a zone of microearthquake activity extending southeastward for 30 km from just outside the heat flow anomaly toward the town of Helena. Epicenter depths for the microearthquakes range from near-surface to 20 km. No microearthquakes, however, originated from within or near the heat flow anomaly.

Aerial Infrared and Direct Tree Temperature Survey

An aerial infrared survey of the heat flow anomaly and vicinity was carried out in the summer of 1973. (Batelle Northwest et al., 1974) The survey, completed in the 3-5μ and 8-19μ spectral bands, was flown at an approximate altitude of 10,000 feet. Sensitivity of the imaging system was $\leq$ 0.2^{o}C. The survey did not directly detect the heat flow high.

Eliason and Foote (1975), however, delineated an approximately 1.5°C thermal anomaly in the 8-14 band in tree canopies within the heat flow high. The tree canopy anomaly, subsequently confirmed by direct measurement, became apparent through altitude corrections and through comparison of sparsely and heavily vegetated areas within and outside the heat flow high. The anomaly apparently reflects removal of warm water from the zone of high heat flow by the trees' root systems.

DEEP DRILLING

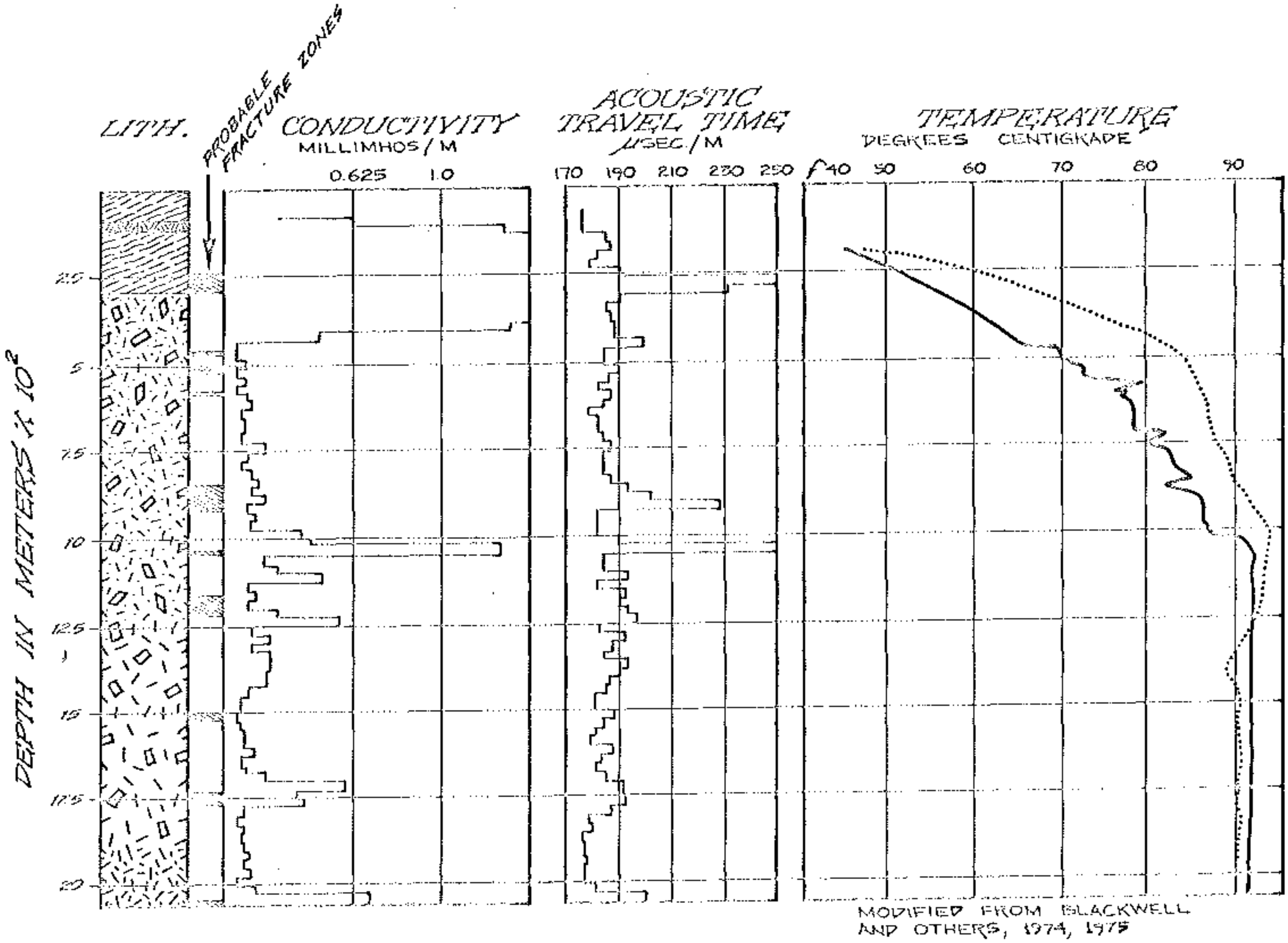
Geological and Geophysical Results

Exploration activities previously outlined culminated in a deep drill test during the summer of 1974. The deep drill hole (MGE-1) was collared in the most intense portion of the heat flow anomaly (Fig. 4) and completed at a depth of 2070 meters. Maximum temperature recorded in the hole within two months of completion was 94°C at 1000 meters (Fig. 13)(Blackwell et al., 1975). The hole remained nearly isothermal below this depth, although declining to 91.3°C at 1950 meters. A new temperature log in 1975 recorded a temperature of 99°C at 855 meters.

MGE-1 penetrated mostly tremolite-grade hornfels of the Precambrian Spokane and Empire formations to a depth of 294 meters (Fig. 13). Below 294 meters the well encountered the concealed Empire Creek stock, in which it remained to its total depth. In MGE-1, the stock grades with depth from granite porphyry through porphyritic granite into equigranular granite. Average porosity in the hornfels, as computed from sonic and resistivity logs, is about 20%; average porosity in the Empire Stock is about 3.5% (Blackwell et al., 1975).

The Empire Creek stock, where penetrated by MGE-1, is more or less kaolinized and cut by veinlets of diverse compositions and different ages along its entire intercept. Kaolinization affects mainly plagioclase phenocrysts, and diminishes with depth. Early veinlets cutting the stock consist of various combinations of quartz, adularia, calcite, and fluorite with minor galena sphalerite and (in the upper part of the hole) molybdenite. The early veinlets are cut by dolomite-calcite quartz and montmorillonite veinlets. As previously stated, much, and perhaps all alteration in MGE-1 probably antedates the presently active geothermal system.

Probable fracture/fault zones intersected by MGE-1 are illustrated in Figure 13. The fracture zones are interpreted from study of cutting and core in conjunction with various geophysical well logs. Three of these logs -- conductivity (reciprocal of resistivity), acoustic travel time and temperature -- are summarized in Figure 13. Conductivities are highest in the contact zone between the Empire Creek stock and superjacent hornfels. In this zone conductivities average about 3.3 millimhos/meter and reach as high as 40 millimhos/meter within a restricted zone directly above the stock contact. (Peeples, 1975) Within the stock, conductivities are low, averaging about 0.2 millimhos/meter (or a resistivity of about 5,000 ohm-meters) and commonly declining to 0.1 millimhos/meter (10,000 ohm-meter resistivity). Highest conductivity over a 25 meter interval in MGE-1 is 1.3 millimhos/meter between 1025 and 1050 meters. This relatively conductive zone (though still 770



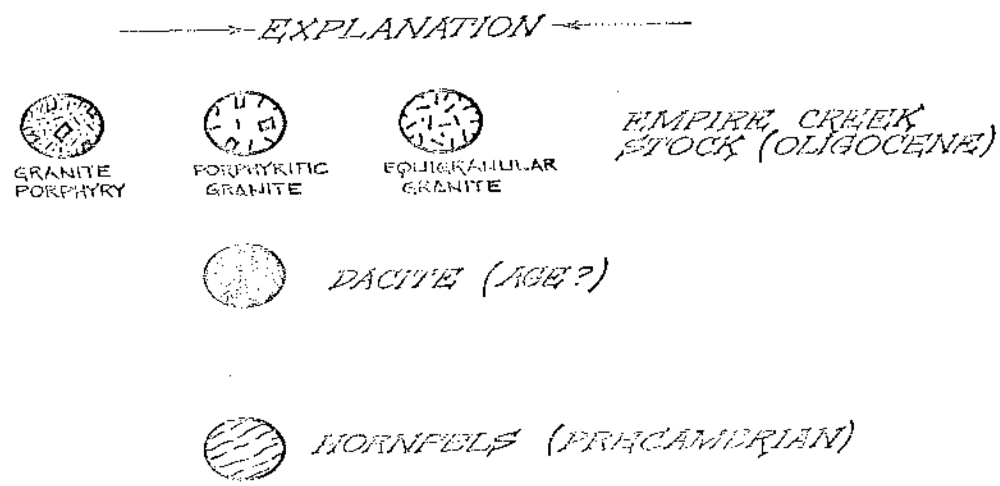


FIGURE 13. DRILL HOLE MCE-1, LOG SUMMARY
MARYSVILLE GEOTHERMAL AREA

ohm-meter material) corresponds with a steep increase in the temperature and acoustic travel time logs and has been interpreted as a fracture zone and warm water entry (Blackwell et al., 1975). Since the temperature log remains essentially isothermal below this probable fracture zone, it may be one of the main conduits along which thermal waters rapidly rise from depth.

Water Chemistry

Fluids collected from MGE-1 are all dilute sodium bicarbonate sulfate waters with low chlorine but high fluorine content (Blackwell, et al., 1975). The anomalous fluorine (up to 20 ppm), is probably derived from fluorite-bearing veins associated with intrusion of the Empire Creek granite porphyry.

Geothermometry

Thermal springs are absent within a 30 km radius of the Marysville heat flow high. Estimates of reservoir temperatures beneath the heat flow high are therefore based exclusively on chemical geothermometry applied to waters collected from fracture zones encountered in deep drill hole MGE-1. Details of MGE-1 water sample collection and analysis are provided in Blackwell et al. (1975).

Reservoir temperatures were estimated on the basis of SiO_2 solubility (Fournier and Rowe, 1966) and on the relative concentrations of sodium (Na) potassium (K) and calcium (Ca) (Fournier and Truesdell, 1973). SiO_2 estimated temperatures range from 110°C to 130°C; Na-K-Ca estimated temperatures from 165°C to 180°C. The SiO_2 temperatures are in fair agreement with the maximum temperature thus far recorded in the drill hole -- 99°C at 855 meters. The high Na-K-Ca temperatures may reflect contamination with drilling muds and additives or, according to Blackwell et al. (1975), may indicate derivation of the water from a higher-temperature portion of the geothermal system.

Oxygen Isotope Studies

Four water samples from MGE-1 and two surface water samples from within the heat flow anomaly were analyzed for oxygen isotopic composition. The samples were essentially identical in O^{18} content, with O^{18} values of about 19 ‰ -- normal for precipitation in the Marysville area (Blackwell et al., 1975). This relationship indicates that temperatures in the Marysville geothermal system do not exceed roughly 150°C, the temperature required to produce an O^{18} "shift" or enrichment (Craig, 1966).

DISCUSSION

Deep drilling conclusively demonstrated the heat source for the Marysville thermal anomaly to be a convecting warm water system selectively developed in the concealed Empire Creek Stock. Selective fracturing of the stock could reflect (1) greater brittleness and ease of fracturing relative to its host rocks in response to regional stresses, (2) shrinkage of the stock during cooling, or (3) explosive brecciation of the stock late in its intrusive history. Whatever the cause of the fracturing, it apparently allows deep and rapid circulation and heating of meteoric water in otherwise impermeable terrain.

Discovery of a convecting thermal water system as the heat source at

Marysville was considered unlikely prior to drilling because of the absence of surficial evidence (hot springs, etc.), high apparent shallow resistivity and low ground noise. The favored hypothesis placed a conductively cooling magma chamber or hot intrusive beneath the heat flow anomaly at depths as shallow as 1-1 1/2 km (3300-4500 feet). (Blackwell and Baag, 1973; Blackwell et al., 1974). The partial coincidence of a gravity low with the heat flow anomaly was considered good evidence in favor of the magma chamber model (Mazella, 1973; Blackwell et al., 1974).

The absence of any volcanic rocks in the Marysville area younger than 37 million years (Oligocene; Blackwell et al., 1974) could be considered strong evidence against the presence of a concealed magma chamber beneath the heat flow anomaly. A magma chamber still sufficiently hot to produce the observed heat flow would be much less than 37 m.y. of age (see, for instance, Smith and Shaw, 1975, 1978; Muffler, 1975). A young magma chamber, especially if as shallow as predicted at Marysville, would almost certainly have erupted correspondingly young volcanics.

Of all the exploration techniques used to investigate the Marysville geothermal system, only heat-flow determination in shallow drill holes and aerial infrared surveying (when supplemented by tree canopy temperature measurement) directly or indirectly detected the thermal anomaly prior to deep drilling. All other techniques, however, provided useful information on subsurface structural and lithologic configuration, such as the shape and extent of concealed intrusive masses.

Low subsurface resistivities are known to be characteristic of many geothermal areas (see for instance Keller, 1970; Merdan, 1970; Banwell and McDonald, 1965; Sill and Ward, 1976). The high subsurface resistivities beneath the Marysville heat-flow anomaly predicted by roving dipole and MT-AMT surveys (and confirmed by deep drilling) can be viewed as evidence against a warm or hot water reservoir with sufficient porosity and permeability to support commercial thermal fluid production. Resistivities measured in drill hole MGE-1 averaged about 5000 ohm-meters, and even in probable fracture and warm-water entry zones, (such as between 1025 and 1050 meters were no lower than 770 ohm-meters. Since the water saturating the rock in MGE-1 would measure about 5 ohm-meters at the reservoir temperature of 94°C (Birdwell, 1973, charts B-100 and B-110) porosity between 1025 and 1050 feet, the probable major warm water entry zone in the drill hole, would be no greater than 7.5% (Birdwell, 1973, chart ØF-30).

McNitt (1975) believes the roving dipole resistivity technique, which was used at Marysville, to be inferior to dipole-dipole resistivity surveying in producing geologically interpretable results in geothermal areas. In the Olkaria, Kenya geothermal field, for instance there is little correlation of results obtained by the two methods; only the subsurface resistivity configurations predicted by the dipole-dipole method have been borne out by drilling.

Many high-temperature geothermal areas are characterized by high microearthquake activity (i.e. Ward, 1972; Hamilton and Muffler, 1972, Combs and Hadley, 1976) and elevated ground noise levels (i.e. Clacy, 1968; Goforth, et al., 1972; Iyer and Hitchcock, 1974, 1975; Whiteford, 1970; Combs and

Muffler, 1973). The area of the Marysville heat flow anomaly, by contrast, is aseismic and anomalously low in ground noise production. The lack of microearthquakes in the immediate Marysville area may not be significant. In the Olkaria, Kenya geothermal area, for instance, a deep hole drilled on a microearthquake zone encountered only warm water, while another drilled 2 km outside the zone found temperatures up to 286°C (McNitt, 1975). The low noise levels at Marysville may be due to the relatively low reservoir temperature. Higher temperatures, and thus pressures, may be required to produce detectable seismic noise in geothermal systems.

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