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A BRIEF DESCRIPTION OF GEOLOGICAL AND GEOPHYSICAL EXPLORATION OF THE MARYSVILLE GEOTHERMAL AREA

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Extensive geological and geophysical surveys were carried out at the Marysville geothermal area during 1973 and 1974. The area has high heat flow (up to 20 μcal/cm^2-s), a negative gravity anomaly, high electrical resistivity, low seismic ground noise, and nearby microseismic activity. Significant magnetic and infrared anomalies are not associated with the geothermal area. The geothermal anomaly occupies the axial portion of a dome in Precambrian sedimentary rocks intruded by Cretaceous and Cenozoic granitic rocks. The results from a 2.4-km-deep test well indicate that the cause of the geothermal anomaly is hydrothermal convection in a Cenozoic intrusive. A maximum temperature of 95°C was measured at a depth of 500 m in the test well.

I. INTRODUCTION

The Marysville geothermal area is located about 30 km northwest of Helena, Montana, and about 4 km west of the old gold mining town of Marysville, Montana. The Continental Divide crosses the southern part of the area, so the terrain is mountainous, with a local relief in excess of 600 m (Fig. 1). The area had an extensive history of gold mining during the late 1800's and early 1900's. In the 1960's, the area was explored for disseminated molybdenum deposits by drilling at two locations. The existence of a geothermal anomaly in the area was discovered in 1966 during a regional heat flow study. Very high heat flow (6.5 μcal/cm^2-s) was measured at one of the sites of molybdenum exploration (the Bald Butte locality, Ref. 1). Subsequent measurements at the second molybdenum exploration site (Empire Creek) and in some holes drilled for gold exploration during the 1950's (Woodchopper Gulch and Ottawa Gulch localities) indicated heat flow values from 3.3 to 20 μcal/cm^2-s, over an area of several square kilometers (Ref. 2). The average background heat flow for western Montana is approximately 2.0 μcal/cm^2-s, while the world average heat flow is about 1.5 μcal/cm^2-s. Thus, the heat flow in the area is up to 10 times the already high background observed in western Montana.

Subsequent to the discovery of the geothermal anomaly, a detailed gravity study was carried out in the area by Mazzella (Ref. 3). Analysis of data from this survey indicated a negative gravity anomaly, and thus a region of mass deficiency, associated with the high values of heat flow. The correlation of a region of relatively low density with one of high heat flow was considered suggestive that the source of both anomalies might be a relatively shallow (<2 km) cooling chamber of recently molten igneous rock. Thus, extensive further geological and geophysical investigations were begun in 1973 in order to investigate the area in detail.

The Marysville geothermal area is unusual because, although the geothermal gradient is as high as 240°C/km, there are no surface *manifestations* of the anomaly. The hot spring nearest the geothermal area is 30 km away (the Broadwater Hot Spring, just west of Helena, Montana). The nearest recent volcanics are over 300 km away at Yellowstone National Park. Furthermore, the Precambrian sedimentary rocks and Mesozoic and early Cenozoic intrusive rocks of the area seem an unusual setting for a geothermal anomaly.

The geothermal reservoirs currently being exploited commercially have few common geological characteristics. For example, the Geysers field is in fractured graywacke and siltstones, the Larderello field is in carbonate rocks, the Wairakie field is in volcanic rocks, and the Imperial Valley and Cerro Prieto fields are in alluvial and deltaic sediments (Refs. 4 and 5). Similarly, the geophysical characteristics of these geothermal areas vary widely. Discussions of exploration techniques emphasize flexibility in the approach to geothermal exploration (Refs. 6 and 7). Study of the Marysville area was undertaken to provide a case history of geothermal exploration in an area with few surface clues, and to furnish deep hole data for comparison with surface geological and geophysical studies.

The studies carried out in the Marysville area have included geologic mapping, petrographic and chemical analyses, spring-water chemistry, gravity, magnetic heat flow, seismic ground noise, microearthquake, dipole-dipole resistivity, magnetotelluric and audio-magnetotelluric, and airborne infrared studies. During the summer of 1974, a 2.4-km-deep exploration hole was drilled to test the geothermal area at depth and the implications of the geological and geophysical studies. The results of these studies will be summarized briefly.

II. REGIONAL SETTING

The Marysville area is in the Northern Rocky Mountains physiographic and structural province (Ref. 8) and is about 40 km west of the extensive zone of large-scale thrust faulting (Ref. 9), which generally marks the eastern boundary of the Northern Rocky Mountains. Some of the thrust faults have displacements of tens of kilometers and could conceivably underlie the Marysville district. The country rocks of the district are Precambrian sedimentary rocks of the extensive Belt Series terrain of western Montana (Ref. 10). There has been extensive plutonic activity in the area and the large Boulder batholith (Ref. 11) of late Cretaceous age outcrops only 20 km south of the area (Ref. 12).

III. GEOLOGY

The geology in certain parts of the geothermal area has been studied in the past. An early study of the eastern part of the area by Barrell (Ref. 13) focused on the geology of the Marysville mining district as did the study of Knopf (Ref. 14). Bierwagen (Ref. 15) mapped a large area from Blossberg (10 km south of Marysville) to Lincoln, with particular emphasis on the stratigraphy of the sedimentary rocks. Ratcliff (1973, personal communication) studied an area which included the geothermal anomaly with a special emphasis on the bulk chemistry of the igneous rocks.

A. Sedimentary Rocks

The two formations which occupy most of the area on the geologic map (Fig. 1) are the Helena Limestone and the subjacent Empire Shale. Both formations are part of the Precambrian Belt Series, which is extensively exposed in northwestern Montana (Ref. 10). The Empire Shale is a biotite-rich siliceous to calcareous shale, and the Helena Limestone consists of siliceous limestone and dolomite with occasional interbeds of quartzite and shale. Other sedimentary rocks exposed in the area include the Spokane Shale, a purple to gray-green argillite, below the Empire Shale, and the Marsh Shale, a red to maroon argillite unit, the Greenhorn, and the Black Mountain Quartzites, above the Helena. Lower Paleozoic to Cretaceous units unconformably overlie the Belt rocks in a major syncline southwest of the geothermal area.

The geologic map (Fig. 1) incorporates the published work, but with significant modifications. In much of the area, the Helena and Empire have been contact metamorphosed into calcsilicate hornfels (Refs. 13 and 14) and are very difficult to distinguish. Detailed x-ray and petrographic studies of the contact metamorphic assemblages characteristic of each unit have resulted in criteria for differentiation of the two units, however, and their distributions are somewhat different than published mapping would suggest.

B. Contact Metamorphism

A broad zone of contact metamorphism extends to the southwest of the stock, as is indicated by the location of the diopside isograd (Fig. 2). Two other contact metamorphic zones with diopside grade metamorphism (the estimated temperature was 500°C at 750 bars) occur in the vicinity of Bald Butte and in Empire Creek. Exploration drilling at Bald Butte and in Empire Creek has intersected unexposed quartz porphyry intrusives beneath each of these contact zones. The large areas of contact metamorphism imply a much larger size for each of these quartz porphyries than is established by drilling. These two intrusive bodies occupy the dome in the sedimentary rocks southwest of the Marysville stock.

C. Igneous Rocks

The igneous history of the Marysville area has been quite complex. A summary of that history is shown in Table 1. The oldest igneous rocks are microdiorite sills in the upper part of the Empire Shale. These sills may be correlatives of the gabbro or diabase sills regionally developed at that stratigraphic horizon which have been dated as Precambrian. The next dated igneous event was the emplacement of the Marysville granodiorite at approximately 79 M.Y.B.P. (Ref. 16) as one of the early satellitic phases of the Boulder Batholith.

There appear to be at least two Tertiary igneous events, although the dating is preliminary (Rostad, personal communication, 1971; Ratcliff, personal communication, 1973). The intrusion of the Bald Butte quartz porphyry has been dated at 49 M.Y.B.P., but the most extensive activity apparently occurred between 37 and 40 M.Y.B.P. Numerous feldspar porphyry dikes and sills were emplaced during this episode, concentrated in an area southwest of the Marysville stock; a large (presently unexposed) quartz-feldspar porphyry body was intruded (the Empire stock), also in the area southwest of the Marysville stock; and extensive rhyolite flows and tuffs were extruded along a north-south axis west of the Marysville stock and over an area several tens of kilometers long. Considerable erosion has occurred since the episode of volcanism, and the present exposures are relatively isolated, but the volcanics may have been much more extensive in the past.

D. Structure

There have been several episodes of deformation in western Montana, and it is difficult to sort out the relative ages of the folds and faults in the Marysville area. The folds are mostly large-scale, open features. The basic structure of the map area is a dome in the sedimentary rocks. The core of this dome is shown on the geologic map by the exposures of the Empire Shale and Marysville stock. The northeastern half of the dome is occupied by the Marysville stock, and that portion of the dome may be related to the emplacement of the stock. The geothermal anomaly occurs in the southwestern portion of the dome. There is a pervasive fracture cleavage developed in most of the Belt rocks with general north-south orientation and west dip.

The contact metamorphic aureole of the Marysville stock has been offset in at least one location by faulting (near the Empire Mine), so some of the faulting is definitely post-79 M.Y.B.P. The area is still the site of tectonic activity, demonstrated by the occurrence of microearthquakes.

IV. GEOPHYSICS

A. Magnetic Surveys

The magnetic surveys (both ground and airborne studies) indicate anomalies associated with variations in the content of magnetic material in the rocks. Because igneous rocks usually contain more magnetic material than sedimentary rocks, magnetic anomaly maps commonly contain information on the distribution of igneous units in the map area. In the Marysville district, the only significant magnetic anomaly is associated with the Marysville stock. The quartz porphyries of Bald Butte and Empire Creek do not have significant anomalies. A model of the Marysville stock was developed from the data using the numerical technique of Talwani (Ref. 17). Two contours plus the outcrop trace of the stock are shown in Fig. 2.

B. Electrical Surveys

A roving dipole resistivity survey was done by the U. S. Geological Survey in 1972. The results of that survey indicate rather high resistivities of 150-1000 Ω-meters associated with the geothermal anomaly. Similarly, a magneto-telluric survey (Ref. 18) carried out during 1974 found high apparent resistivities associated with the heat flow anomaly. In contrast, relatively low values of electrical resistivities are usually associated with geothermal areas (see Ref. 6 for example).

C. Seismic Ground Noise

High levels of ambient background noise are associated with some geothermal areas (Refs. 19 and 20). Such a survey of the Marysville area had negative results with the lowest values of ground noise associated with the highest heat flow.

D. Microearthquake Survey

Microearthquakes, earthquakes so small that they are not usually detected on the permanent seismic networks, may be causally associated with geothermal areas (Ref. 21). A microearthquake survey of the general area (Ref. 22) indicates activity along a fault or faults extending from northwest of Helena to the southeastern margin of the geothermal area. However, no microearthquakes were located in the geothermal anomaly itself. The fault mechanisms determined include both normal and strike slip motion, but with a consistent northeast-southwest orientation of tension axes.

E. Infrared Survey

An airborne infrared survey was conducted (Ref. 23) in order to test the ability of this technique to detect the geothermal anomaly. The estimated anomaly amplitude required for detection was between 20-100 $\mu cal/cm^2$-s and, indeed, the geothermal anomaly was not detected. Data processing is continuing, however, with a goal of reducing the noise level of the observations by careful corrections.

F. Gravity Survey

A gravity survey of the geothermal area has been in progress for three years. The relatively rugged topography and lack of elevation control have made gravity work difficult. The results of the survey to date are shown in Fig. 3. The data contoured are terrain-corrected Bouguer gravity values from which the regional gravity values (fitted by a cylindrical surface with values decreasing to the west) have been removed. The gravity effect of the Marysville stock has also been removed from the data utilizing the shape determined from interpretation of the magnetic data. A negative residual gravity anomaly is associated with the geothermal anomaly, but the lowest values of gravity (up to -12 mgal from the regional) are south of the geothermal anomaly.

G. Heat Flow Survey

Before the present study began 15 heat flow values, in four different geographic areas, were available (Ref. 2). During the course of this study 17 holes have been drilled. The depth of these holes has ranged from 50 to 130 m with an average depth of about 100 m. The published data plus the results from 11 of the holes drilled for the project are shown in Fig. 3. The thermal conductivity of the rocks does not vary greatly from locality to locality, so the geothermal gradients, shown in Fig. 3 beside each hole or group of holes, can be compared directly. The values shown have been corrected for topography, and the regional geothermal gradient of about 30°C/km has been removed. Heat flow values in holes drilled during 1974 (not plotted) require the geothermal anomaly be bounded in the southern direction as indicated by the model shape in Figs. 2 and 3.

V. DISCUSSION

A. Models

The preliminary results of the geological and geophysical studies are summarized in Fig. 2. The subsurface shape of the Marysville stock is based on interpretation of the magnetic data, the shape of the heat source body is based on interpretations of the heat flow data, and the contact metamorphic zones are based on petrographic and x-ray analysis. The Marysville stock extends about 2 km southwest and northwest of its surface exposure, while its contacts on the northeast and southeast are steep and nearly coincident with surface exposures. A large vertical dike extends upward from the body near its center and might have been a feeder for volcanics above the stock. The contact metamorphic data indicate that extensive portions of the geothermal anomaly are underlain at shallow depth (less than 300 m) by Cenozoic intrusive rocks.

The resistivity study indicates that the rocks to depths of hundreds of meters have relatively high resistivities and thus low porosity. The seismic ground noise in the area is extremely low, but microearthquake activity is located immediately to the southwest of the geothermal anomaly. A negative residual gravity anomaly is associated with and south of the geothermal anomaly. The gravity anomaly has values up to -12 mgal relative to the regional values.

B. Deep Drilling

A deep exploration drill hole was drilled to a depth of 2.4 km during 1974 at the site indicated on Fig. 1. The geologic section encountered in the drill hole consisted of argillite to a depth of 297 m (Empire and possibly Spokane Formations) and the Empire stock below 297 m. The rocks of the Empire stock increased in grain size with depth, and the rock could be called at different depths a quartz-feldspar porphyry, quartz monzonite, and monzonite. Below a depth of 500 m, several discrete sets of fracture zones with extensive fluid movement were encountered. Final logging and analysis have yet to be completed, but preliminary interpretation of the results imply that the source of the high heat flow values, in the northern part of the geothermal area at least, is hydrothermal fluid circulating through the Empire stock. In this hole, the maximum temperature of approximately 95°C was reached at a depth of about

500 m. From 500 m to total depth, the temperature remained essentially constant. The preliminary geochemical temperatures based on the silica and Na-Ca-K geothermometers (Refs. 24 and 25) are about 115 and 170°C, respectively.

C. Conclusions

On the basis of the information available at the present time, preliminary conclusion is that the immediate source of the geothermal anomaly is a hot water circulating in the Empire stock. Thus, the coincidence of the negative gravity anomaly with the geothermal anomaly appears to be a secondary one in that the negative gravity anomaly is due to the presence of the Empire stock and the heat flow is due to geothermal fluids using the Empire stock as a conduit to shallower depths. It is rather unusual that in this case one granitic stock acts as a reservoir while a second granitic stock, the Marysville, apparently acts as a boundary of the geothermal area. The high resistivity values observed are apparently due to the high resistivity of the Empire stock (except in localized fracture zones in which the geothermal fluids are circulating). The Empire stock must have very low magnetic susceptibility to explain the lack of a significant magnetic anomaly. The end of a zone of microearthquake activity in the immediate vicinity of the geothermal anomaly remains puzzling, as does the significance of the maximum gravity values south of the area of the geothermal area. The highest negative values of gravity, therefore, might either be caused by a deep (3 km or more) source of heat or by a deeply buried southern extension of the Empire stock.

The source of the high-temperature water circulating through the Empire stock remains an enigma and neither of two hypotheses originally suggested as a source of heat in the area can be ruled out, i.e., deep circulation of fluids along a formation or horizon (such as a thrust fault) or interaction of fluids with a deep seated magma chamber (Ref. 2). However, if the source is a magma chamber, then it is deeper than the direct conductive model would suggest because the heat near the surface is being transferred by hydrothermal convection. These results are useful as a test case of a geothermal area in which there are conflicting indications from geophysical studies. These results reiterate the fact that basement rocks can act as reservoirs and that drilling in basement rocks is certainly not precluded for the development of presently economic geothermal resources. The results further indicate that the likelihood of finding shallow (>3 km) magma chambers cooling by conduction alone is probably small and that the direct cause of most geothermal anomalies is convecting ground water. Whether or not in general this convection of ground water is driven by heat from magma chambers will probably have to be proved by indirect evidence in most cases. The implications of these results for the exploration for dry hot rocks are that even in basement rocks, it will be very difficult to distinguish between high gradients due to convection and high gradients due to conduction on the basis of surface geophysical exploration.

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Table 1. Major igneous units in the Marysville, Montana area

Locality	Rock type	Age
Upper Part of Empire Shale	Microdiorite sills	Precambrian (?)
Marysville	Granodiorite stock	Cretaceous (79 MY)
Bald Butte	Quartz porphyry plug	Eocene (49 MY)
Empire Creek	Quartz feldspar porphyry stock	Oligocene (40 MY)
Southwest of Marysville stock	Quartz porphyry dikes and sills	Oligocene (37 MY)
Hope Creek	Rhyolite flows	Oligocene (37 MY)
Geothermal Anomaly	Heat source (?)	Quaternary or recent

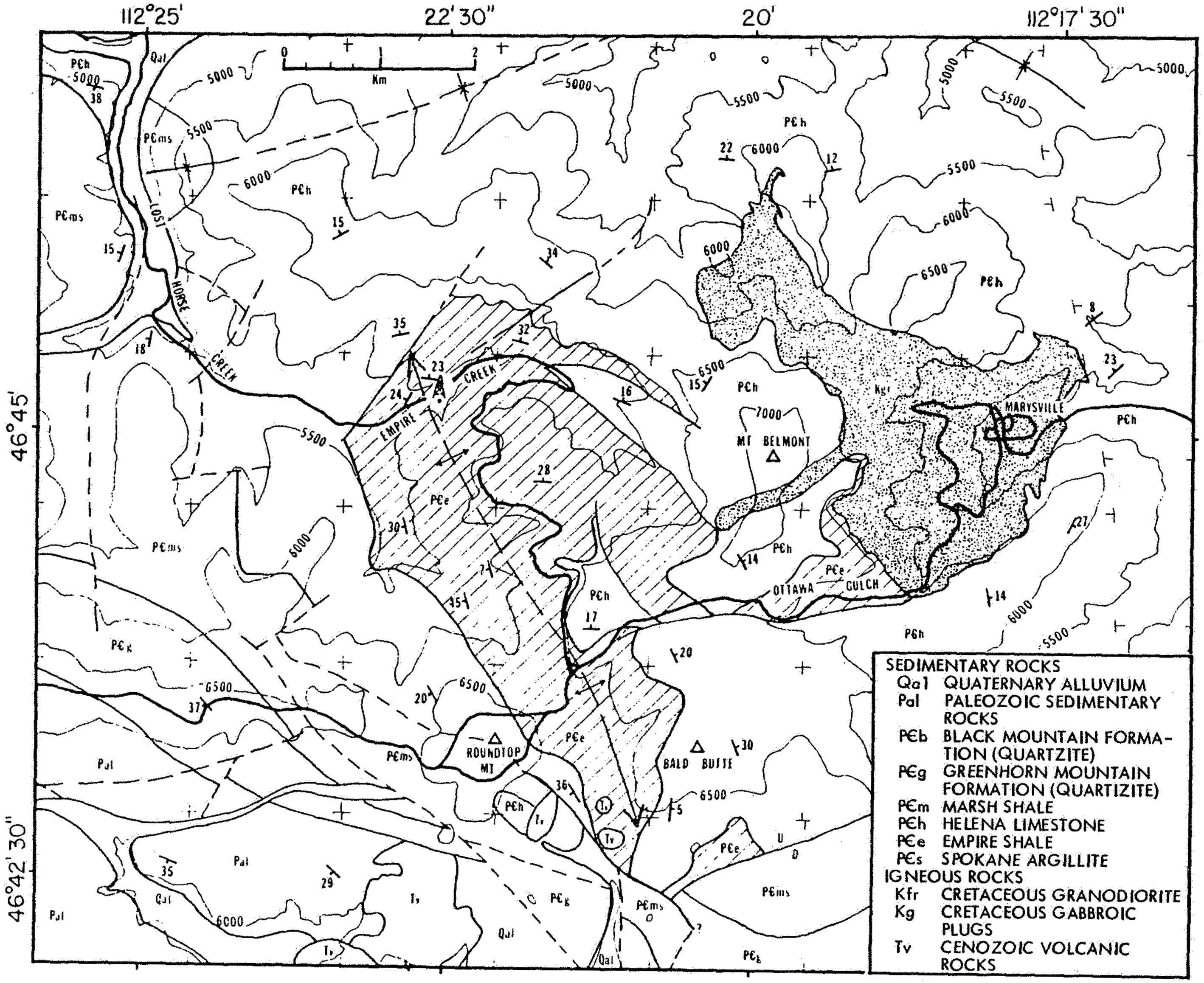

Fig. 1. Topography and geologic map of Marysville geothermal area: contour interval = 500 ft (152 m); location of deep drill hole indicated by derrick symbol; many Cenozoic dikes and sills omitted from map

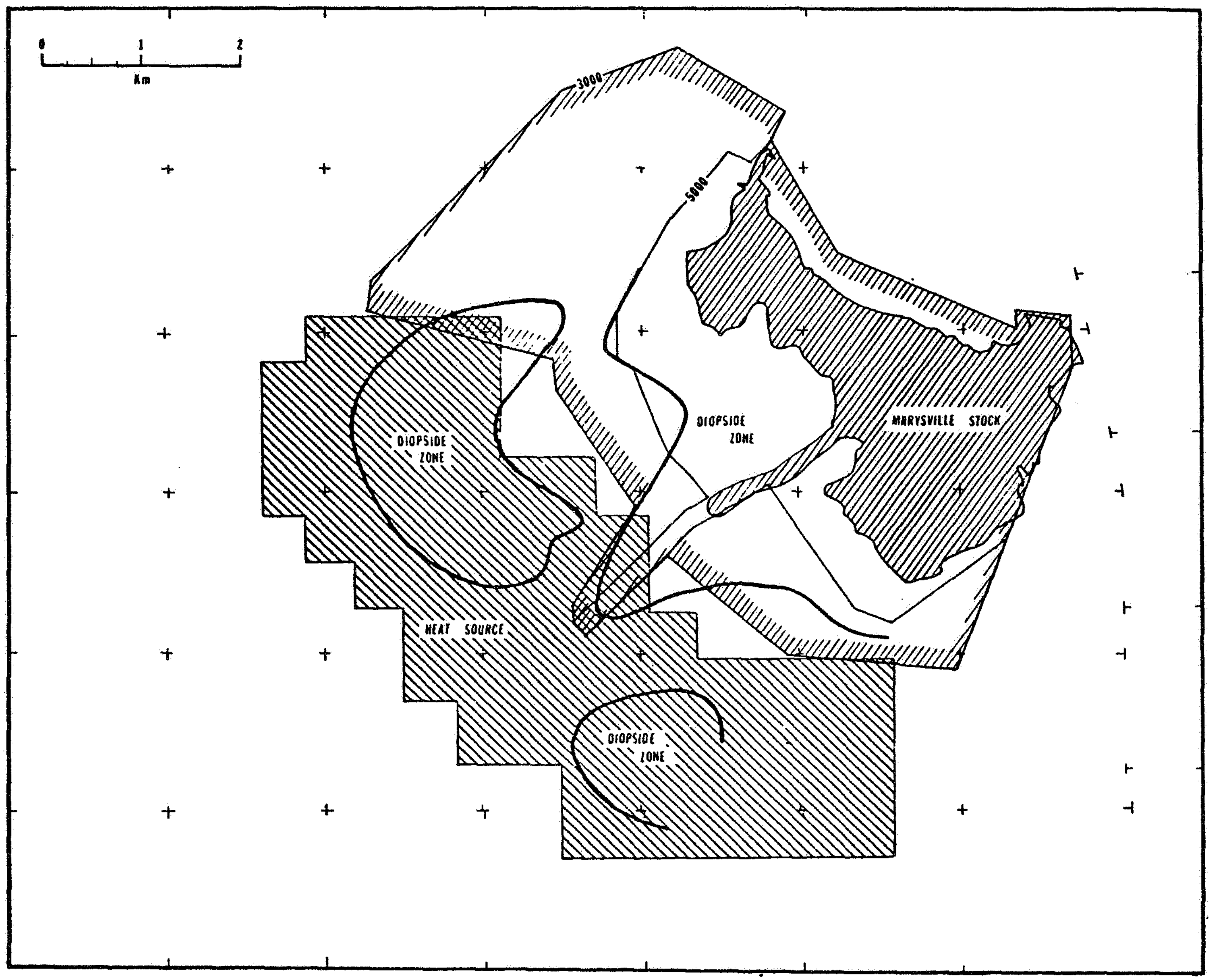

Fig. 2. Contact Metamorphism (heavy lines) and geophysical models of Marysville stock and heat source: contours of Marysville stock in feet above sea level

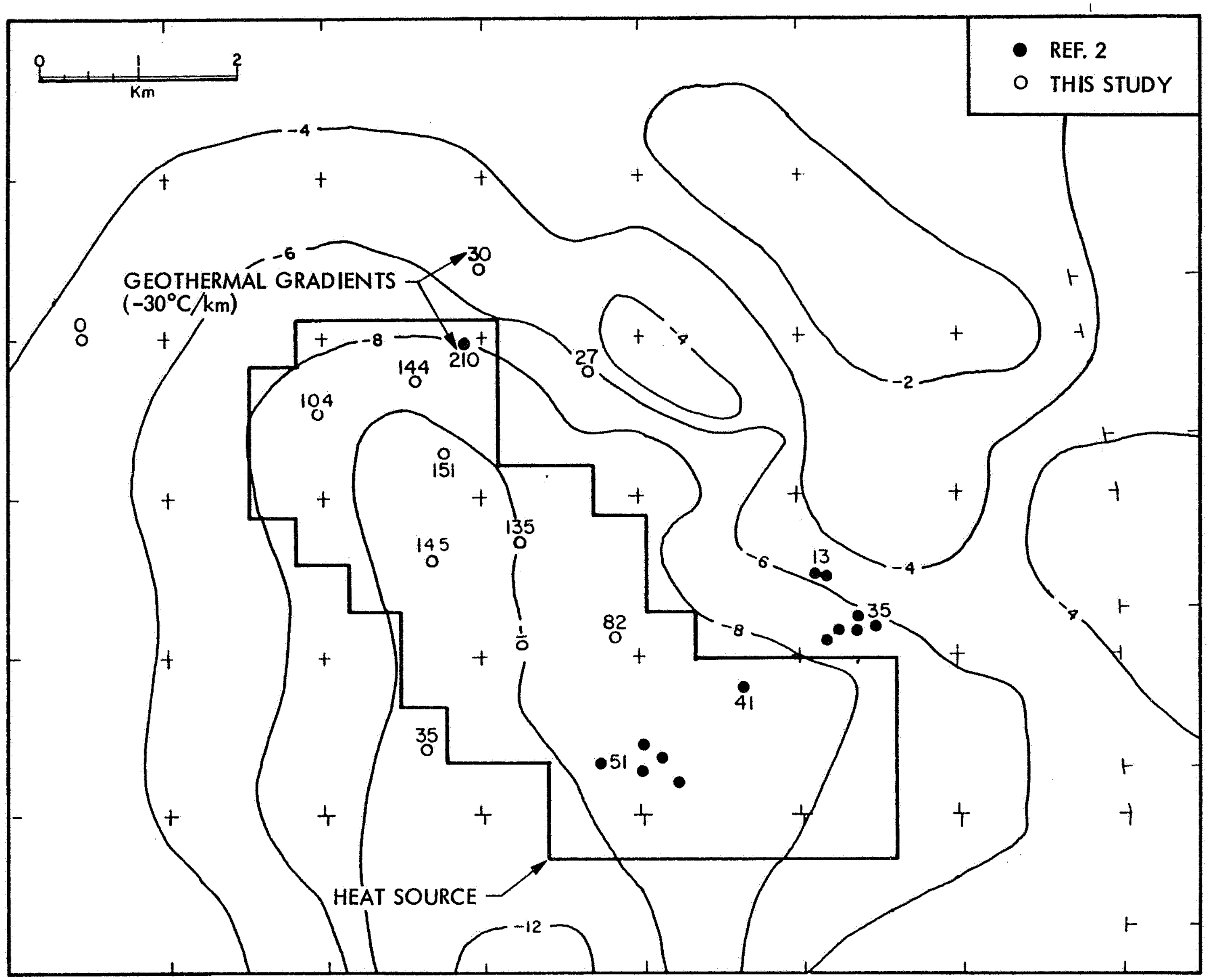

Fig. 3. Heat flow and gravity, Marysville geothermal area: contours of gravity in mgal relative to regional values