# Geology and Geophysics of the Southern Raft River Valley Geothermal Area, Idaho, USA

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## ABSTRACT

The Raft River valley, near the boundary of the Snake River plain with the Basin and Range province, is a north-trending late Cenozoic downwarp bounded by faults on the west, south, and east. Pleistocene alluvium and Miocene-Pliocene tuffaceous sediments, conglomerate, and felsic volcanic rocks aggregate 2 km in thickness. Large gravity, magnetic, and total field resistivity highs probably indicate a buried igneous mass that is too old to serve as a heat source. Differing seismic velocities relate to known or inferred structures and to a suspected shallow zone of warm water. Resistivity anomalies reflect differences of both composition and degree of alteration of Cenozoic rocks. Resistivity soundings show a 2 to 5 ohm·m unit with a thickness of 1 km beneath a large part of the valley, and the unit may indicate partly hot water and partly clayey sediments. Observed self-potential anomalies are believed to indicate zones where warm water rises toward the surface.

Boiling wells at Bridge, Idaho are near the intersection of north-northeast normal faults which have moved as recently as the late (?) Pleistocene, and an east-northeast structure, probably a right-lateral fault. Deep circulation of ground water in this region of relatively high heat flow and upwelling along faults is the probable cause of the thermal anomaly.

## INTRODUCTION

A flow of about 2000 l/min of water at bottomhole temperatures of 147°C has been produced from a 1526-m-deep well completed in the Raft River valley, southern Idaho, early in 1975. The well was drilled after an integrated geologic, geophysical, and hydrologic exploration program begun a year and a half earlier by the U.S. Geological Survey (USGS) in cooperation with the Energy Research and Development Administration (ERDA). Drilling of additional wells is now (May 1975) in progress.

The southern Raft River valley near Bridge, Idaho (Fig. 1), was designated a Known Geothermal Resource Area (KGRA) in 1971 by the USGS (Godwin et al., 1971) on the basis of two shallow wells—Bridge and Crank—that flow boiling water (Fig. 2). The boiling wells and geochemical thermometry suggesting temperatures of about 150°C at depth had sparked ERDA's interest in the area as a potential site for an experimental binary-fluid geothermal power plant. The USGS studies were undertaken to provide a scientific framework for evaluation of the resource and to test the applicability of various geophysical and geologic techniques to the study of geothermal resources, and to aid in siting test wells.

The Raft River valley is part of an area mapped geologically

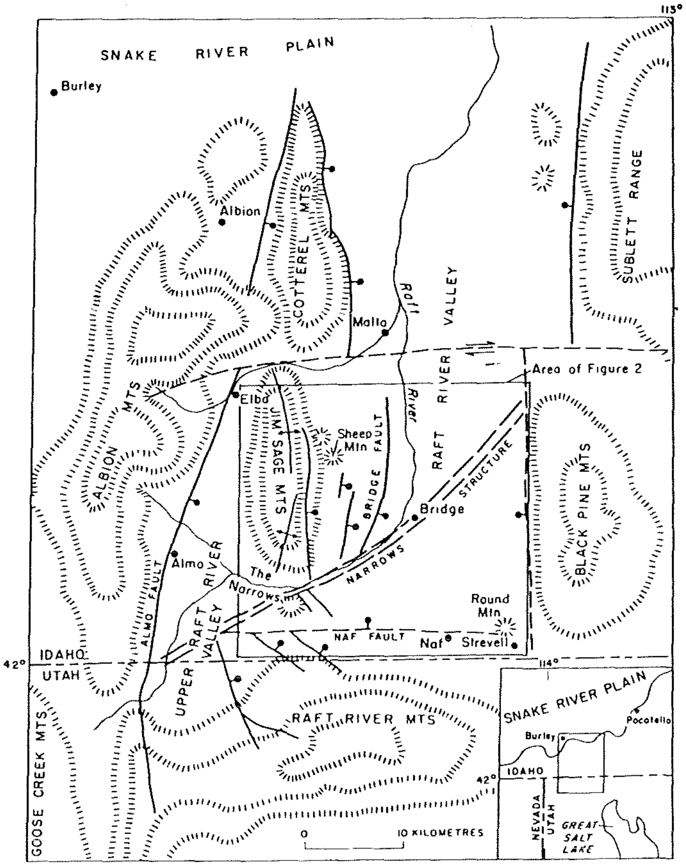


Figure 1. Map of the Raft River valley region, Idaho and Utah, showing major faults (bar and ball on downthrown side; arrows indicate relative direction of movement) and anitclines (Jim Sage Mountains only).

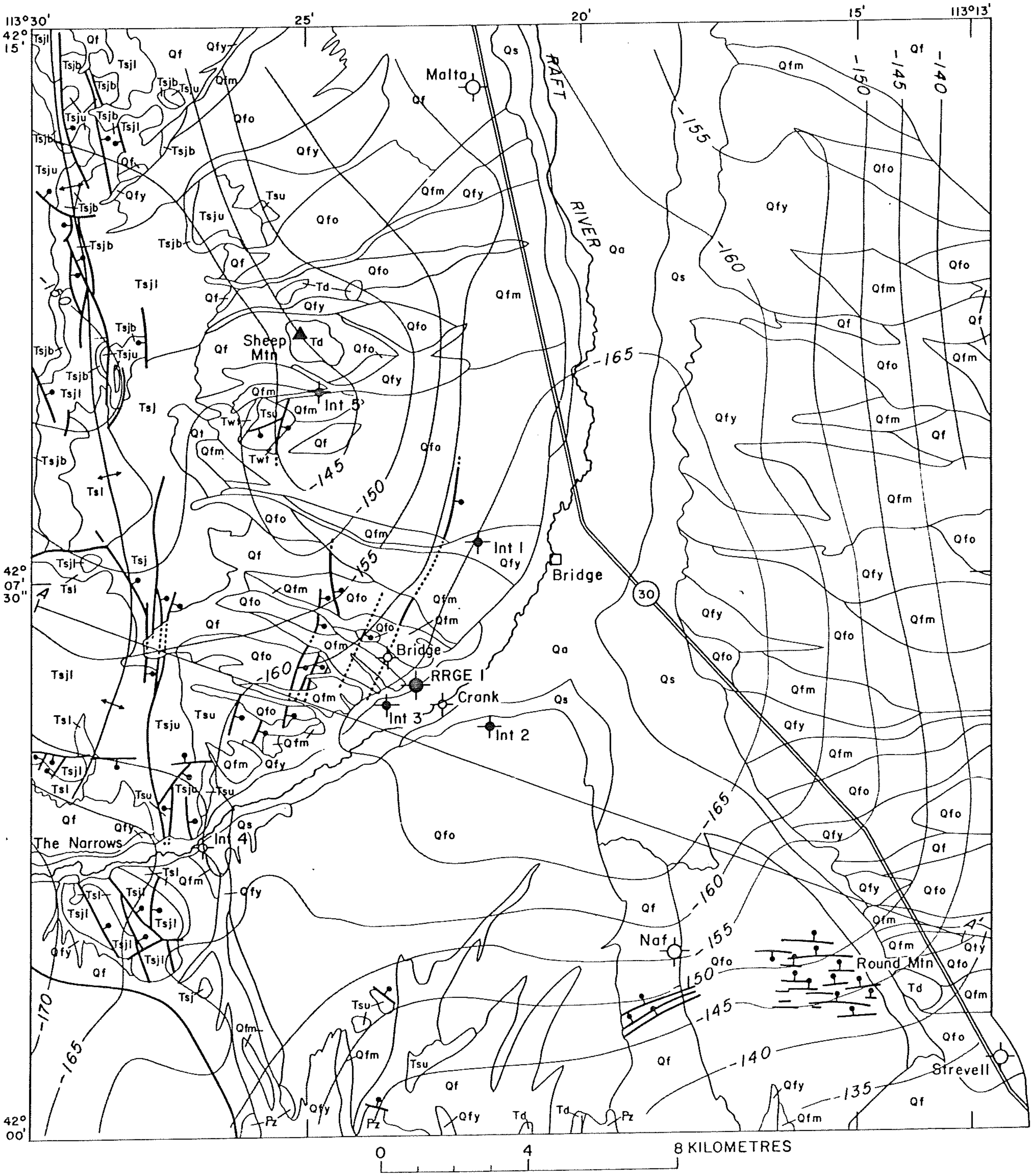
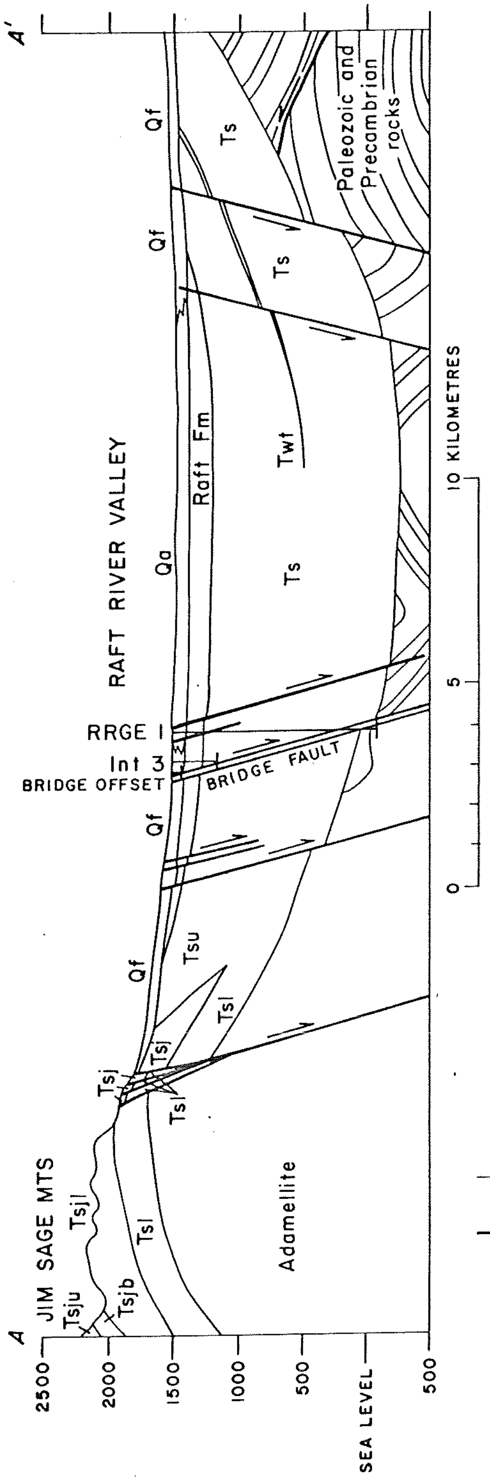
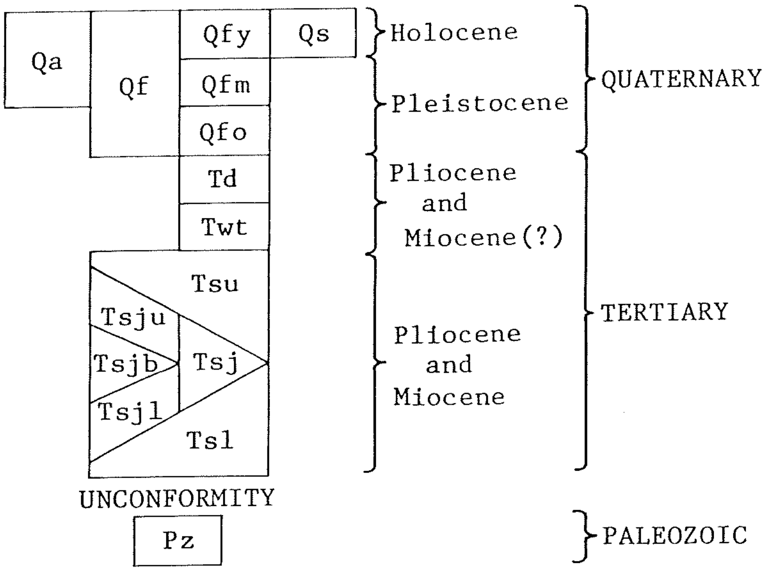


Figure 2. Geologic and gravitational features of the southern Raft River valley. *Left,* area map showing Bouguer gravity units in the area map and the cross section and a key to



CORRELATION OF MAP UNITS



LIST OF MAP UNITS

| | |
|---|---|
| | SURFICIAL |
| Qa | Alluvium |
| Qf | Fan gravels |
| Qfy | Young |
| Qfm | Middle |
| Qfo | Old |
| Qs | Silt |
| Td | VOLCANIC DOME |
| Twt | WELDED TUFF |
| Ts | SALT LAKE FORMATION |
| Tsu | Upper member |
| Tsj | Volcanic member at Jim Sage Mountain |
| Tsju | Upper flow unit |
| Tsjb | Vitrophyre breccia unit |
| Tsjl | Lower flow unit |
| Tsl | Lower member |
| Pz | PALEOZOIC ROCKS |

| | |
|---|---|
| ——— | CONTACT |
| ——┸—— | FAULT--Bar and ball on downthrown side. Dotted where concealed |
| | WELLS |
| ● | Raft River Geothermal Exploration (RRGE) |
| • | Intermediate depth (Int) |
| ○ | Deep oil test |
| ——165—— | BOUGUER GRAVITY CONTOUR--Interval 5 milligals |

contours, wells and geology. *Right,* cross section through AA' on the area map. *Far right,* correlation and list of geologic map symbols. Geology based on Williams et. al. (1974).

in reconnaissance by A. L. Anderson (1931). Ground-water studies by the USGS have been carried out over a period of four decades (Stearns, Crandall, and Steward, 1938; Nace et al., 1961; Mundorff and Sisco, 1963; and also Walker et al., 1970, in cooperation with the Idaho Department of Water Administration). Geochemistry of the water from the Bridge and Crank wells is described by Young and Mitchell (1973).

## SURFACE MANIFESTATIONS AND EXPLORATION

The presence of a geothermal reservoir in the southern Raft River valley is evident in only a few places. There is a warm seep (38°C) near Intermediate depth well (Int) in The Narrows (Fig. 2), and altered alluvium around the Bridge well marks the site of a former hot spring. Total dissolved solids in water from the Bridge and Crank wells are 1720 and 3360 ppm, respectively; aquifer temperatures inferred from the silica and Na-K-Ca geothermometers (Young and Mitchell, 1973) are nearly the same as the maximum temperature (147°C) measured in the first deep exploration well, RRGE 1. There are no tufa or sinter mounds. Gray Tertiary tuffaceous sediments are altered to light green and locally weather to yellow; accumulations of chalcedony locally are present. Lava and flow breccia exposed in The Narrows are altered from black and brown to yellow along faults and fractures, but plagioclase feldspars remain fresh. The green and yellow colors probably indicate formation of montmorillonitic clays, proving definite but weak and nonpervasive hydrothermal alteration (C. R. Nichols, oral commun., 1974).

The limits of the geothermal reservoir remain undefined. Warm water flows from several irrigation wells throughout the Raft River valley, and temperatures of 70°C were measured on the surface in water leaking from a completed but nonproductive oil test drilled near Malta (Fig. 1). Water temperatures of 60 and 38°C, respectively, were measured in wells northeast of Albion and near Almo (Fig. 1); (Young and Mitchell, 1973).

Initial shallow drilling was begun by the USGS cooperatively with ERDA in 1974 to determine temperatures and flow in the shallow aquifer. A total of 32 auger holes were drilled to depths of about 30 m in and near the Raft River flood plain between Bridge and The Narrows. An offset to the Bridge well was drilled to a depth of 123 m. In 1974 and early 1975, five core holes were drilled in cooperation with Idaho Department of Water Administration to intermediate depths of 76 to 434 m to test hydrological, geophysical, and geologic models; the deepest of these, No. 3, encountered water at 90°C near the bottom. The first deep hole, Raft River Geothermal Exploration (RRGE) 1, was drilled by a commercial contractor for ERDA, and was completed early in April 1975 to a depth of 1526 m. The Bridge fault zone was intersected between 1240 and 1300 m, and yielded a flow of about 40 l/sec at subsurface temperatures of 140 to 147°C. Cuttings from oil tests near Malta, Naf, and Strevell (Fig. 1) also yielded valuable information on the geology of the basin.

## GEOLOGIC SETTING

The lower Raft River valley in southern Idaho lies in a north-trending basin both warped and downfaulted in late Cenozoic time. The basin is in the northern part of the Basin and Range province near its boundary with the Snake River plain. About 60 km long and 20 to 24 km wide, with an average surface elevation of 1400 m, the basin is filled with Cenozoic sediments to an inferred depth of 1800 to 2000 m. The Raft River flows northward through the basin, which opens onto the Snake River plain. North of the Raft River basin is the prominent Great Rift system of open fractures in very young basalt flows that extends northward 50 km to Craters of the Moon National Monument. The basin is flanked on the west, east, and south by mountain ranges made up of Tertiary, Paleozoic, and Precambrian rocks, respectively. On the east are the Sublett Range (higher elevations about 2000 m) and the Black Pine Mountains (2900 m) consisting mainly of faulted Pennsylvanian and Permian sedimentary rocks (R. L. Armstrong and J. F. Smith, Jr., oral commun., 1974). On the west, the Cotterel and Jim Sage Mountains (2500 m), formerly grouped as the Malta Range, are made up of Tertiary rhyolites and tuffaceous sediments, which in the Jim Sage Mountains define a broken antiform structure, as first noted by Martin Pruatt (oral commun., 1973). Directly to the west of the Cotterel and Jim Sage Mountains, and separated from them by a narrow fault valley, lie the Albion Mountains (3000 m). Rising southward from the basin are the Raft River Mountains (3000 m), one of the few east-trending mountain ranges in the North American Cordillera. The Albion and Raft River Mountains expose gneiss-dome complexes of Precambrian (2.4 billion years) adamellite (quartz monzonite) mantled by Precambrian and lower Paleozoic metasedimentary rocks and by allochthonous upper Paleozoic sedimentary rocks (Felix, 1956; Armstrong, 1968; Compton, 1972). Drill data are demonstrating that the metamorphic complex directly underlies extensive parts of the Cenozoic fill of the Raft River basin. Borehole cuttings from the Malta and Strevell oil tests indicate the presence of metamorphic units resembling those in the Raft River Mountains, and not a thick succession of unmetamorphosed Paleozoic rocks that would have been inferred from outcrops.

Rock units and surficial deposits recognized in the southern Raft River basin and adjacent ranges are summarized in Table 1. Pre-Tertiary units are those described by Compton (1972); most of these units do not crop out in the mapped area (Fig. 2).

## GEOPHYSICAL STUDIES

### Gravity Measurements

Gravity stations were established at 330 points in the area of Figure 2. The data were reduced to the complete Bouguer anomaly assuming a density of 2.45 g/cm$^3$. The procedures used were designed to produce Bouguer anomaly values accurate to 0.2 mgal (milligal) except in areas of high local topographic relief where the uncertainty in the terrain correction may be as large as 0.4 mgal. The gravity map of the region (Mabey and Wilson, 1973) shows a series of lows along the entire course of the Raft River; the low in the southern Raft River basin is one of these. Bouguer anomalies rise toward highs over the Black Pine and Raft River Mountains and a high centered over the alluvium south of Sheep Mountain in the eastern Jim Sage Mountains. The gravity low is produced mostly by the density contrast between the Cenozoic sedimentary and volcanic rocks, calculated from the data to be about 2 km thick, and the

Table 1. Rock units and surficial deposits of the southern Raft River basin and adjacent ranges. Letter symbols refer to map units in Figure 2.

| Age | Description |
|---|---|
| Quaternary | |
| Holocene and Pleistocene | Alluvial and eolian silt (Qs). Alluvium of major drainage (Qa) |
| | Fan alluvium: Coarse to fine, moderately well-sorted subangular gravel on piedmont slopes. Young gravels (Qfy) deposited during last pluvial episode; middle gravels (Qfm) deposited during last 2 or 3 pluvial episodes; old gravels (Qfo) older than third oldest pluvial episode; age of undivided gravels (Qf) was not determined. |
| Pleistocene | *Raft Formation: Sand, gravel, silt and clay beneath Raft River Valley (Fig. 2) |
| Tertiary | |
| Pliocene and Miocene (?) | Volcanic domes (Td). Extrusive and shallow intrusive glassy and lithoidal rhyolite domes containing plagioclase phenocrysts at and north of Sheep Mountain, at Round Mountain, and along south edge of map area. Radiometric ages are: Sheep Mountain dome, 7.8 ± 1.1 m.y. (zircon fission-track, C. W. Naeser, U.S.G.S.) and 8.42 ± 0.20 m.y. (K-Ar feldspar, J. D. Obradovich, U.S.G.S.); Round Mountain dome, 8.3 ± 1.7 m.y. (zircon fission-track, C. W. Naeser). |
| | Welded tuff (Twt). Thin glassy rhyolite ash-flow tuff on Cedar Knoll, and in Malta and Naf wells. Radiometric age, 7.0 ± 2.0 m.y. (zircon fission-track, C. W. Naeser). Intercalated in upper member of Salt Lake Formation. |
| Pliocene and Miocene | Salt Lake Formation. Total thickness, about 1800 m. In western part of basin, divided by volcanic member at Jim Sage Mountain into upper and lower members. Tuffaceous sandstone, siltstone and conglomerate. In RRGE 1, the upper 670 m is light-green and gray tuffaceous sandstone and siltstone and coarse-grained sandstone and conglomerate; the lower 570 m is light-green bedded tuff, tuffaceous siltstone and sandstone, and tan calcareous siltstone and laminated shale. In the Naf well, the upper 1000 m is dominantly gray and tan tuffaceous sandstone and siltstone; the lower 260 m is mostly conglomerate and sandstone. |
| | Upper member (Tsu); Gray and light-green tuff, tuffaceous sandstone and siltstone, and buff and gray conglomerate. |
| | Volcanic member at Jim Sage Mountain: Consists of rhyolite flows (Tsj), divided into upper (Tsju) and lower (Tsjl) units where separated by a vitrophyre breccia unit (Tsjb). Flows 1 to 50 m thick of black glassy and red-brown porphyritic-aphanitic calc-alkali rhyolite containing phenocrysts of oligoclase-andesine and pigeonite; upper unit has normal magnetic polarity; most flows in lower unit are magnetically reversed. Vitrophyre breccia unit consists of black glass clasts a few centimeters to 2 m in diameter in a yellow and orange matrix of hydrated glass; rare tongues of glassy lava have reversed magnetic polarity; unit replaced laterally by bedded tuff in southern Jim Sage Mountains. Radiometric dates on upper flow unit: 9.2 ± 0.5 m.y. (K-Ar whole rock, Armstrong, Leeman, and Malde, 1975); 9.4 ± 1.6 m.y. (zircon fission-track, C. W. Naeser). |
| | Lower member (Tsl): Gray and white, thin-bedded to massive, tuff and tuffaceous sandstone, white to light-green shale and siltstone, and sparse beds of fine-grained conglomerate. |
| Permian and Pennsylvanian | Oquirrh Formation: Dark-gray sandy limestone and calcareous sandstone |
| Pennsylvanian and Mississippian | *Manning Canyon (?) Shale: Dark-gray phyllite |
| Ordovician | *Fish Haven (?) Dolomite: Gray and cream-colored metamorphosed dolomite |
| | *Eureka (?) Quartzite: White metaquartzite |
| | Pogonip (?) Group, Undivided: Tan-weathering impure marble |
| Cambrian (?) | *Schist of Mahogany Peaks: Dark-brown biotite-muscovite schist |
| | *Quartzite of Clarks Basin: Quartzite with thin muscovite-biotite schist interbeds |
| Precambrian (?) | *Schist of Stevens Springs: Fine-grained muscovite-quartz schist and graphite phyllite |
| | *Quartzite of Yost: White, locally green, muscovitic and hematitic quartzite |
| | *Schist of upper Narrows: Dark-brown biotite quartzofeldspathic schist and gneiss; occurs in RRGE 1 from 1390 to 1433 m |
| | *Elba Quartzite: White to pale-tan muscovitic quartzite. Occurs in RRGE 1 at 1433 to 1518 m |
| Precambrian | *Older schist: Brown mica schist |
| | *Adamellite: Bodies of massive and gneissic porphyritic adamellite; in part intrusive into Precambrian (?) metamorphic rocks and in part older than those rocks. Forms gneiss domes in western Raft River Range and Albion Range. Occurs in RRGE 1 below 1518 m |

*Unit does not crop out in map area, but is present in nearby area and/or in subsurface.

more dense pre-Cenozoic "basement" rocks. Relatively small variations in the gravity field superimposed on the large low may reflect mass anomalies within the Cenozoic rocks or within the basement rocks.

## Aeromagnetic Data

An aeromagnetic survey of part of the area was flown with north-south flight lines 800 m apart and 1800 m above sea level. The magnetic data are shown as a residual map in Figure 3. On the east side of the Jim Sage Mountains the magnetic anomalies correlate with the mapped distribution of volcanic rocks. Major highs and lows are associated with normally and reversely magnetized units. A general correlation between magnetic intensity and the gravity high south of Sheep Mountain suggests that the basement rock is slightly magnetic. The absence of large magnetic anomalies within the area of the major gravity low suggests that volcanic rock is not a major part of the basin fill. Two elongate magnetic highs south and east of Sheep Mountain may be produced either by volcanic rocks or by magnetic units within the basement rocks.

## Seismic Refraction Measurements

Seismic refraction spreads were obtained in an area extending from the large gravity low in the central part of the Raft River valley (Fig. 4) southwestward into The Narrows and westward from the low, across alluvial fans east of the Jim Sage Mountains. All spreads were shot from both directions, but complete reverse basement coverage was obtained on only part of the spreads.

Three major velocity units were mapped: 5.2 to 6.7 km/sec for the pre-Tertiary basement rocks, about 4 km/sec for Tertiary volcanic rocks, and less than 4 km/sec for Tertiary sedimentary rocks.

Three areas of different seismic velocities that correlate well with geologic and topographic features were defined in the Cenozoic rocks. One area is confined largely to the central part of the valley, but it also extends lower parts of the alluvial fans. In most places the velocity sections are typical of those expected from a basin containing a thick succession of poorly consolidated sediments. The second area is confined to the alluvial fans. Velocities in the range expected for lava flows (higher than those encountered at comparable depth in the first area) occur at depths

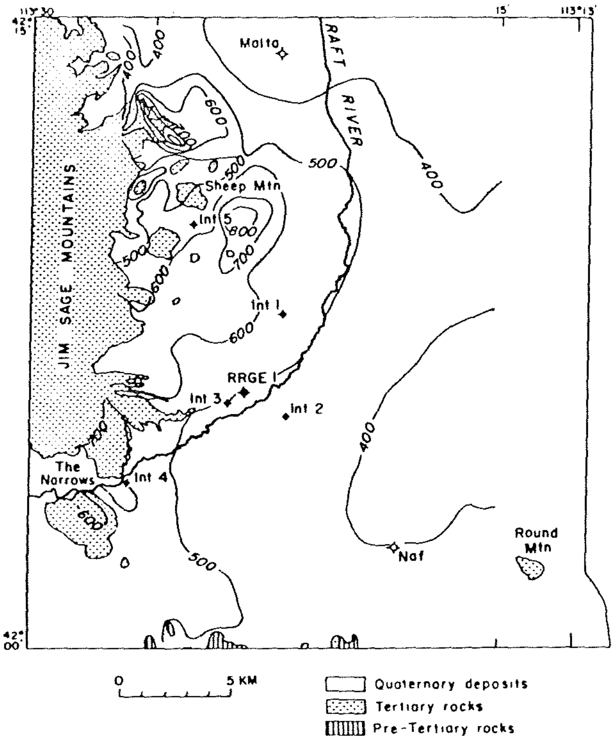


Figure 3. Aeromagnetic map of the southern Raft River valley. Contour interval 100 gammas.

less than 400 m. The third area is in and near The Narrows where high-velocity rocks (volcanics) are near the surface.

A typical velocity regime for water-saturated unconsolidated or partly consolidated basin fill is a gradual velocity increase with depth from about 1.5 to 2.5 km/sec. Much of the valley area is underlain by rocks of these velocities; nowhere do interpreted velocities exceed 3.0 km/sec. From the Bridge fault to The Narrows in a strip about 1.5 km wide, layers with 2.5 km/sec velocities are within a few tens of meters below the surface, suggesting hydrothermal induration of the sediments.

Basement velocities vary between approximately 5.2 and 6.7 km/sec, probably indicating lithologic differences or local fracturing.

## Audiomagnetotelluric Soundings

Sixty-eight audiomagnetotelluric (AMT) sounding stations were occupied in the southern Raft River valley. At each station two soundings were made, one for a north-south and the other for an east-west orientation of the telluric line. Scalar resistivities were calculated at each of 10 frequencies in the range 8 to 18 600 Hz to define the sounding curves, and maps were prepared for several of the frequencies to delineate areas of anomalous conductivity. The station spacing of 2 to 3 km defines only the gross conductivity variations in the area.

Figure 5 shows two AMT apparent-resistivity maps made at 26 Hz for each orientation of the telluric line. Differences in the maps reflect the presence of lateral resistivity variations near the sounding site. The range in apparent resistivity values is from about 2 to 200 ohm·m at 26 Hz. The skin depths (which are the approximate exploration depth) for these resistivities at 26 Hz are 140 to 1400 m.

Examination of the two AMT maps shows that the most prominent resistivity high is just east of The Narrows. This correlates with a north-trending structural high seen on the gravity map and a correlative high in the total field data. The differences in apparent resistivity between the two orientations indicate that the edge of the body was close to the station, and together with the gravity anomaly imply a narrow body. Fair correlation is evident between the AMT high and the gravity high near Sheep Mountain. The largest AMT low, in the vicinity of the hot wells, is defined by the 14-ohm·m contour.

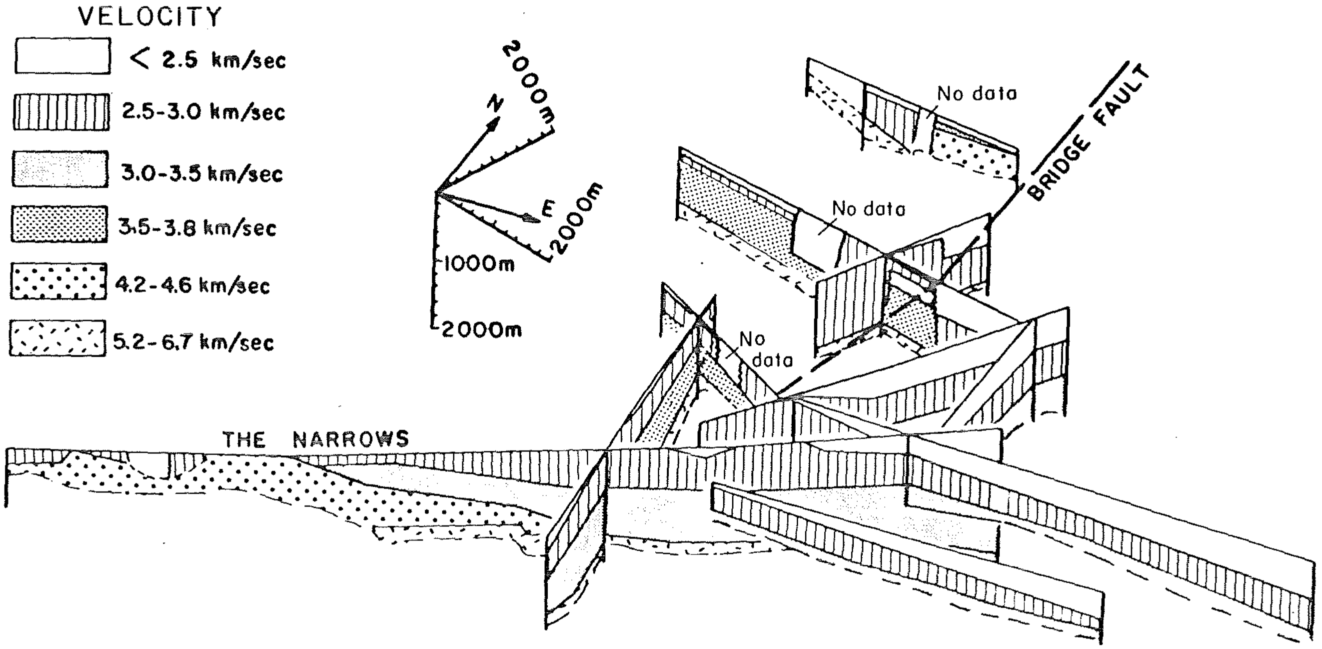


Figure 4. Seismic profiles of the southern Raft River valley.

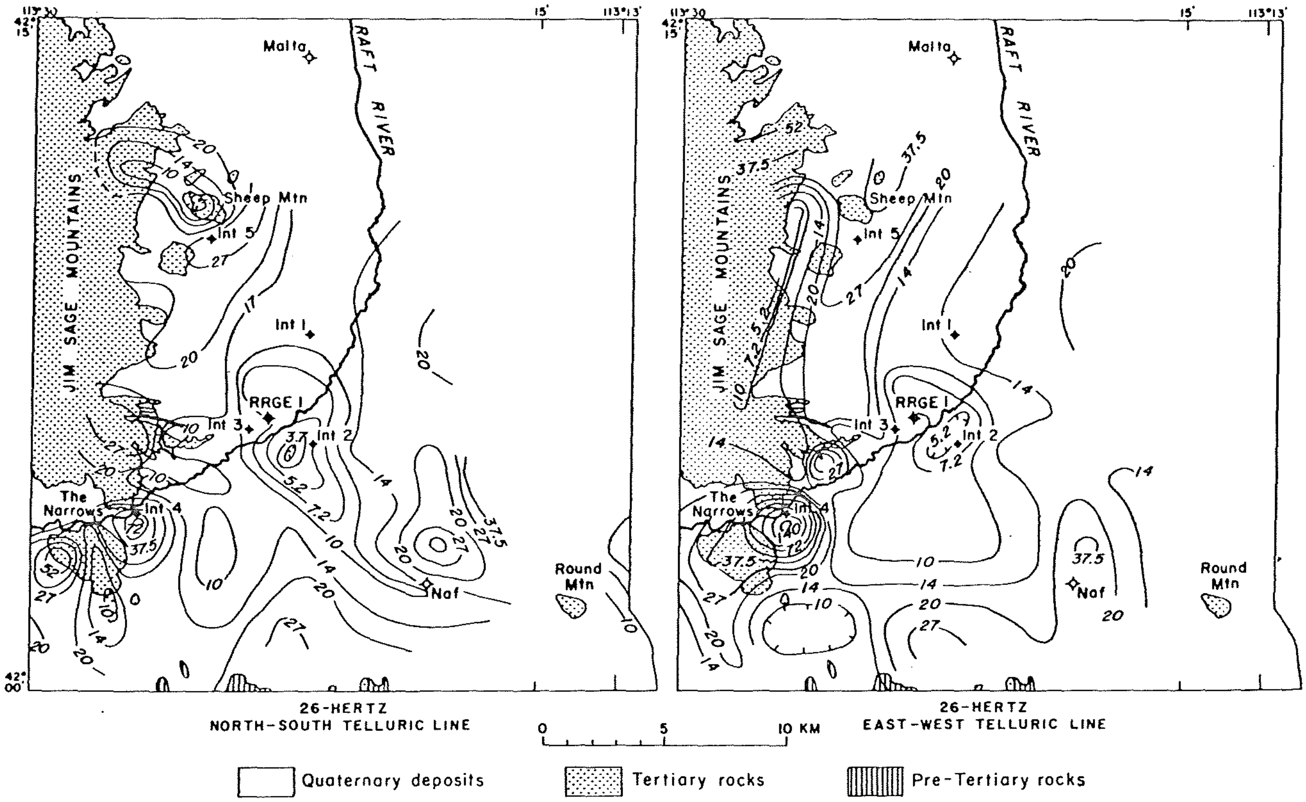


Figure 5. Audiomagnetotelluric apparent-resistivity maps of the southern Raft River valley. Resistivity contours shown are a logarithmic interval in ohm·meters.

## Direct-Current Resistivity Survey

A bipole-dipole total field resistivity survey consisting of 269 total field stations occupied about a current bipole 3.22 km long. At each station the potential differences were recorded between three potential electrodes (M, N, and N′) placed at the corners of a triangle and the electric field components were calculated from the approximations.

$$E_{MN} = \frac{V_{MN}}{MN}, \; E_{MN'} = \frac{V_{MN'}}{MN'}, \; E_{NN'} = \frac{V_{NN'}}{NN'}$$

These three components were added vectorially, using polar plots, to obtain the direction and the magnitude of the total electric field $E_T$. The lengths of the sides of the measured triangle ranged roughly from 30 to 100 m. Electric currents in the range of 40 to 60 A were provided from a 40-kVA truck-mounted generator, and the differences in potential at the field stations were measured on potentiometric chart recorders.

Figure 6 shows the normalized (or reduced) apparent-resistivity map which is obtained by calculating the ratio between the observed and theoretical apparent resistivities for horizontal layering beneath the center of the current bipole (Zohdy, 1973; Zohdy and Stanley, 1974). In general, areas outlined by values greater than unity indicate that the section contains more resistive materials or that basement rocks are shallower than at a sounding made at the current bipole, or both. Conversely, areas outlined by contour values less than unity designate the opposite. It should be noted, however, that false lows and highs may be caused by the

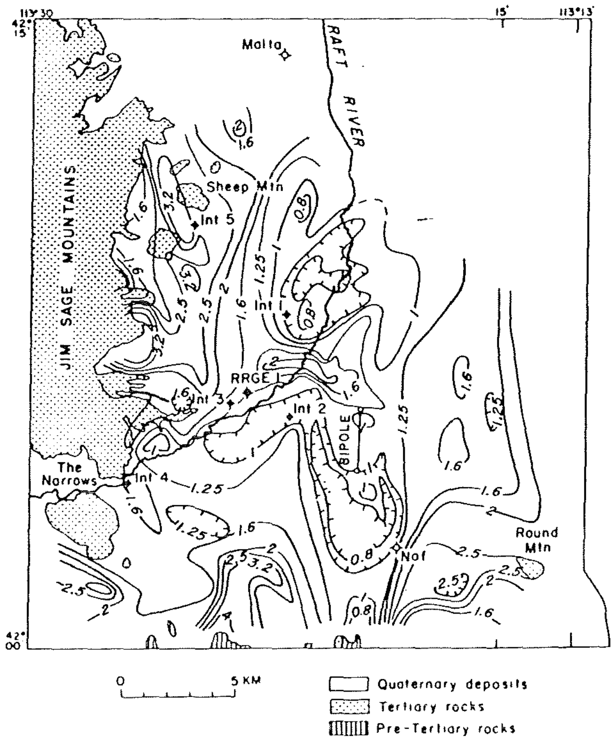


Figure 6. Normalized bipole-dipole resistivity map of the southern Raft River valley. Resistivity contours shown are a logarithmic interval in ohm·meters.

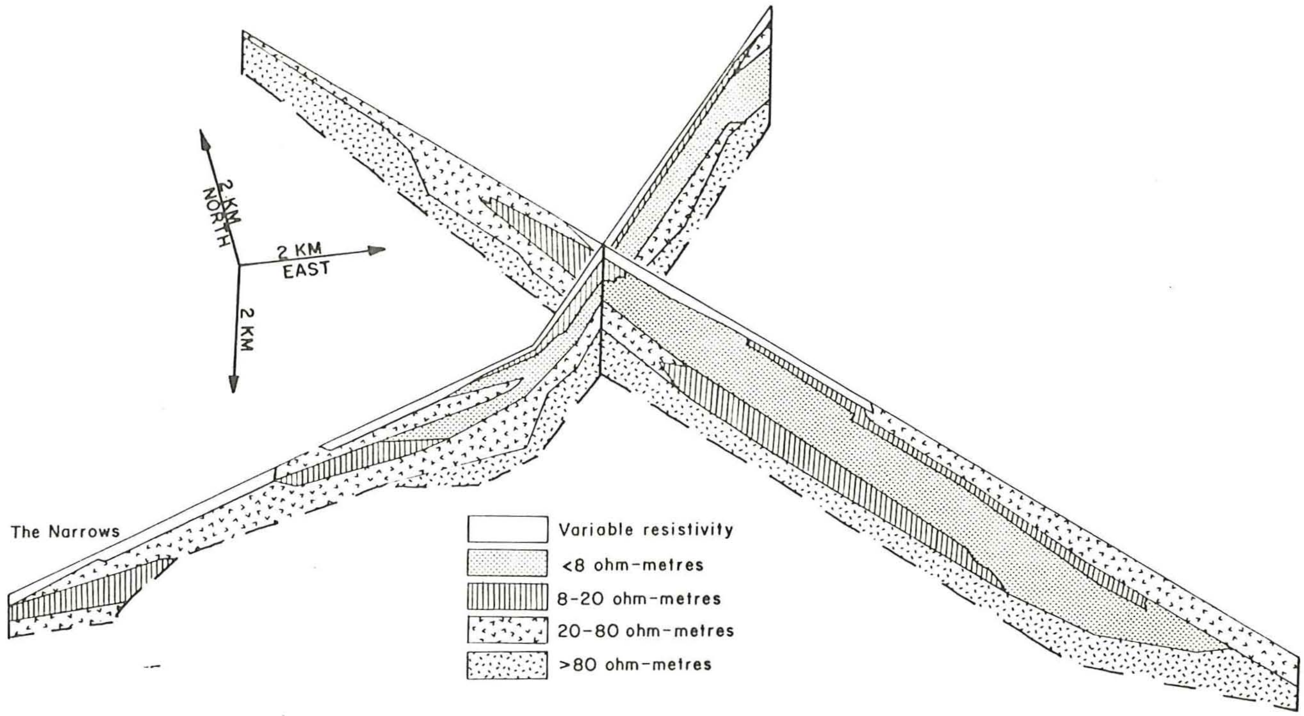


Figure 7. Resistivity profiles of the southern Raft River valley.

presence of steeply dipping faults separating media of large differences in resistivity.

Seventy-nine symmetric Schlumberger soundings were made. The maximum electrode spacing ($AB/2$) for most soundings ranged from $AB/2 = 914$ m (3000 ft) to $AB/2 =$ 3660 m (12000 ft). All the soundings were automatically processed and interpreted (Zohdy, 1974a, 1975; Zohdy, Jackson, and Bisdorf, 1975) using a DEC-10 digital computer and a Hewlett Packard 7203A graphic plotter. Equivalent solutions to the automatically obtained ones were derived by adjusting the corresponding D. Z. (Dar Zarrouk) curves (Zohdy, 1974b).

Figure 7 shows two resistivity sections based on some of these soundings. The high-resistivity material (>80 ohm·m) underlying most of the section is pre-Cenozoic basement rock. Resistivities between 20 and 80 ohm·m probably reflect volcanic rock or coarse clastic sediments. Resistivities below 20 ohm·m are probably finer-grained sediments. In the middle part of both sections is a low-resistivity layer (3 to 8 ohm·m) in the Salt Lake formation with an average thickness of about 1 km. Drilling data indicate that this layer is fine grained, consisting of silt and clay, and is weakly hydrothermally altered.

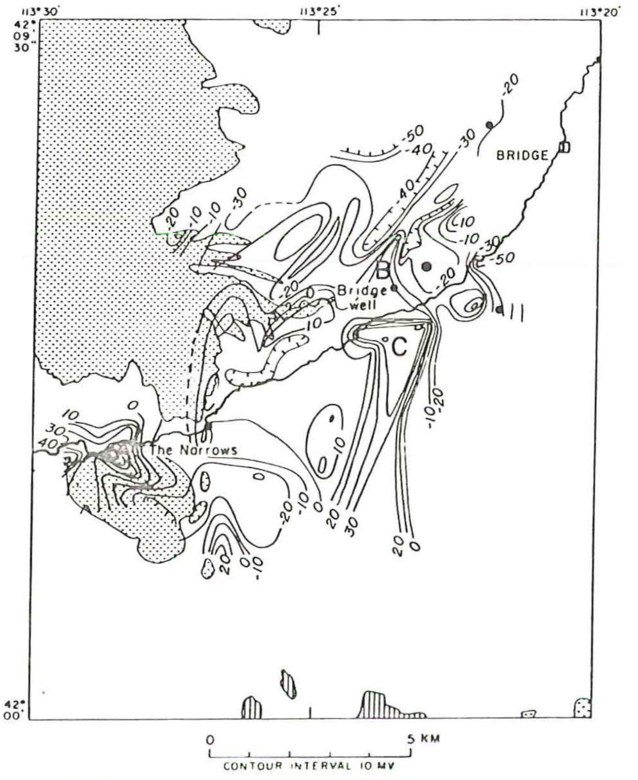


Figure 8. Self-potential map of part of the southern Raft River valley.

## Self-Potential Measurements

A self-potential (SP) survey was made in the area of known hot wells and warm seeps, from The Narrows to the vicinity of Bridge. The SP map (Fig. 8) was made with an electrode spacing of 500 m and so does not define short-wavelength anomalies. No large-amplitude anomalies were found; the maximum observed was about 60 mV, and anomalies are in part masked by topographic effects seen as more negative potentials as one goes higher up the pediment slopes.

Two regions show positive SP anomalies in areas of known near-surface hot water. One is a narrow north-trending zone just east of The Narrows (A). The other (B) extends through the Bridge well and trends north-northeast; it is flanked for about 2 km of its length by associated negative zones which presumably are due to the deeper negative source pole. This anomaly correlates with the Bridge fault which is assumed to be a major conduit for the near-surface hot water in the area.

A large positive anomaly (C) found just south of the area of hot wells on the south side of the Raft River does not appear to correlate with other geophysical data. However, it is coincident with a depositional segment of an alluvial fan and is at the junction of lineaments seen on aerial photographs. The significance of this anomaly is not yet clear.

### Geophysical Summary

In summary, the gravity data show accurately the gross structure of the basin, and yield an approximate thickness of the Cenozoic basin fill. Magnetic anomalies are related primarily to the volcanic rocks and are useful in inferring their distribution and structure. The AMT survey provided a preliminary indication of the resistivity anomalies related to lithology and structure. The seismic refraction and direct-current resistivity surveys provide information about the thickness and lithology of basin fill and the location of major faults. The significance of the self-potential survey results has not been determined, but anomalies may be related to near-surface circulation of hot water along faults.

An evaluation of the geothermal resources of the southern Raft River valley and similar areas requires an understanding of the geology in three dimensions. This can be obtained only through knowledge of the regional geology and geophysics, detailed geologic mapping in the immediate area of interest, intensive geophysical surveys, and test drilling. We have not discovered any geophysical technique for the direct detection of thermal waters.

## STRUCTURE

The geometry of the Raft River basin is well-defined by the gravity survey. Thicknesses of the Cenozoic basin fill predicted from gravity, resistivity, and seismic data are in close agreement and are confirmed by drilling at RRGE 1, where Precambrian rocks were encountered at a depth of 1390 m. The concealed basement high east of Sheep Mountain (Mabey and Wilson, 1973) trends northwest across the northern Jim Sage Mountains and apparently is an extension of the Big Bertha gneiss dome of the Albion Mountains (Armstrong, 1968). Intermediate drill-hole No. 5 encountered Precambrian (?) adamellite at 210 m, a depth predicted from the gravity study.

The Cenozoic rocks, including Pleistocene fan gravels, are cut by numerous faults that in a general way parallel the east, west, and south basin margins (Fig. 1). The faults with greatest displacement, as determined from steep gravity gradients and steep gradients of normalized total-field resistivity are (1) the north-trending Bridge fault; (2) a fault system along the west front of the Black Pine Mountains; and (3) a concealed east-west fault, the Naf fault, in the southern part of the basin at about the latitude of Round Mountain (Fig. 1). Generally, the faults show downward displacement toward the center of the basin; eastward dips in bedding of 15 to 30 degrees on the east flank of the Jim Sage Mountains anticline augment basinward stratigraphic throw on the faults. Faults are inferred to dip 60 to 70 degrees based on measurement of fractures in the core from Intermediate drill hole No. 3, direct measurement of an exposed fault plane in the volcanic member of the Salt Lake formation at Jim Sage Mountain, gravity expression, and the geometry of intersection of the Bridge fault in RRGE 1.

Age of latest movement on the faults is inferred from study of loessal soils mantling the alluvial fans. The north-trending faults near Bridge cut "older" fan surfaces mantled by as much as 3 m of loess reflecting at least four depositional-weathering episodes, indicating an age older than the fourth pluvial interval before the present. The same faults do not cut, and are covered by, fans of "middle" age, which are mantled by 0.6 to 1.5 m of loess deposited in two or three pluvial episodes. If the fourth-from-youngest pluvial is middle Pleistocene, then the most recent movement on the faults was several hundred thousand years before present.

Known occurrences of thermal waters above 100°C in the southern Raft River basin are located near the intersection of the north-trending normal faults with the Narrows structure (Fig. 1), a northeast-trending linear feature with regional geophysical expression, probably a basement shear, that passes just south of the Jim Sage Mountains. Nearly coincident with this structure is a concealed northeast to east-northeast fault through The Narrows that separates widely different structural styles in the Salt Lake formation, and is expressed by gravity and resistivity. The Bridge fault and other north-trending fault sets do not cross this structure.

The drill site for RRGE 1 was selected near the intersection of the Narrows structure with the Bridge fault, and the well was predicted to intersect the Bridge fault and produce hot water at or below 1400 m; actually, the fault zone and flow of water was encountered between 1240 and 1320 m. Seismic and resistivity studies predicted penetration of basement rocks in the well at a depth of about 1600 and 1400 m respectively; actual depth to basement is 1390 m. The seismic study had showed low-velocity basement under the well site, due probably to fractured rock, and this proved to be so.

## GEOTHERMAL MODEL

Geochemical and other data suggest that the Raft River geothermal system is typical of low-temperature hot water systems as described by White, Muffler, and Truesdell (1971). The system apparently is self-sealing. Masses of secondary silica and calcite do not occur at the surface, but a silica caprock was encountered at a depth of 1370 to 1373 m in RRGE 1; many fractures in cores from the intermediate-depth wells are filled with chalcedony and calcite. The high chloride content of the waters (1000 ppm and more) and aquifer temperatures lower than 150°C clearly indicate a hot-water rather than vapor-dominated system.

The southern Raft River valley geothermal system is probably the result of deep circulation of meteoric water along major faults. The most recent igneous activity in the southern part of the basin apparently took place between 7 and 10 million years ago, and any related intrusive masses are too old to be an important heat source. We propose a model in which meteoric water from the Albion, Goose Creek, and Raft River Mountains, which have relatively high precipitation of about 800 m/yr, collects in deep Cenozoic fill in the upper Raft River basin west of The Narrows and in the southernmost Raft River valley, perhaps with minor contributions from ranges east of the basin. Some of this water descends along faults to depths sufficient to heat it to 145°C. Heat-flow values of 2 to 3 $\mu$cal/cm$^2$/sec occur in the southern flank of the Snake River plain (Urban and Diment, 1975), which permits heating to 145°C at depths of 3 to 5 km. Heated water then migrates upward along The Narrows structure and north-trending faults, and is tapped by wells intersecting these structures. Faults are doubtless only parts of a conduit system that includes permeable aquifers in the Salt Lake formation, fractured zones in the Precambrian rocks, and perhaps, gently dipping thrust faults in Paleozoic and Precambrian rocks.

## ACKNOWLEDGMENTS

We thank the following Geological Survey colleagues: L. J. P. Muffler gave varied and generous support throughout the study; E. G. Crosthwaite, Eugene Shuter, and W. Scott Keys made drill core and hydrological data immediately available to us; H. R. Covington, D. H. McIntyre, and P. W. Schmidt contributed to surface mapping and subsurface studies; D. B. Jackson and J. E. O'Donnell did part of the resistivity study and a telluric current survey, respectively.

Others who contributed valuable information, data and assistance are C. R. Nichols, Boise State University; John Griffith, ERDA; J. F. Kunze, Lowell Miller, and Roger Stoker, Aerojet Nuclear Company; and Jack A. Barnett, Sherl L. Chapman, and Edward Schlender, Raft River Rural Electrical Co-operative. The sustained informal support of ERDA's Idaho Operations, Idaho Falls, is gratefully acknowledged.

This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards.

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