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Reconnaissance geophysical studies of the geothermal system in southern Raft River Valley, Idaho

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Gravity, aeromagnetic, and telluric current surveys in the southern Raft River have been used to infer the structure and the general lithology underlying the valley. The gravity data indicate the approximate thickness of the Cenozoic rocks and location of the larger normal faults, and the aeromagnetic data indicate the extent of the major Cenozoic volcanic units. The relative ellipse area contour map compiled from the telluric current survey generally conforms to the gravity map except for lower values in the area of the geothermal system. An area of low apparent resistivity values defined by the audiomagnetotelluric (AMT) survey appears to outline the extent of the geothermal reservoir even though the reservoir is deeper than the penetration of the survey. Self-potential anomalies relate to near surface hydrology. The Raft River Valley is underlain by about 2 km of Cenozoic rock, most of which is Tertiary sediments of the Salt Lake formation. On the west side of the valley the Tertiary rocks appear to be separated from the underlying Precambrian basement by a low angle fault along which the Tertiary rocks have slid off a buried basement dome. Subsequent normal faults displace both the basement surface and the Tertiary beds. The geothermal system occurs where these north-trending faults intersect a poorly understood northeast-trending zone that may be a basement shear zone. Apparently deep circulating water at a temperature of about 150°C rises in the area of this intersection and then spreads laterally in porous zones near the base of the Tertiary rocks to form the geothermal reservoir. Upward leakage from the reservoir produces shallower effects that were measured by the AMT survey.

INTRODUCTION

The Raft River Valley (Figure 1) is a north-trending Basin and Range valley in southern Idaho immediately south of the Snake River plain. In the southwestern part of the valley, warm water seeps along the Raft River and an area of altered alluvium around a warm spring, which is now a flowing hot well, are the surface evidence that a geothermal system underlies this part of the valley. A well at the hot spring and another about 1 km to the southeast were drilled to depths of about 150 m and encountered hot water that flowed to the surface at temperatures of 90° and 93°C. The water from one well has been developed to provide space heat for a greenhouse. Aquifer temperatures of these waters inferred from the silica and sodium-potassium-calcium geothermometers ranged from 135°–145°C (Young and Mitchell, 1973).

The Energy Research and Development Administration (ERDA) identified the southern Raft River Valley as a potential site for a plant to demonstrate the production of electricity from medium temperature (about 150°C) water, and in 1973, the U.S. Geological Survey and ERDA began a cooperative program to determine if a geothermal resource adequate to support the proposed demonstration plant existed in the area. The USGS made a series of geological, hydrological, and geophysical studies supported by shallow and intermediate depth drilling (up to 450 m). Subsequently, ERDA drilled three production wells and is proceeding with the plans to construct a demonstration plant.

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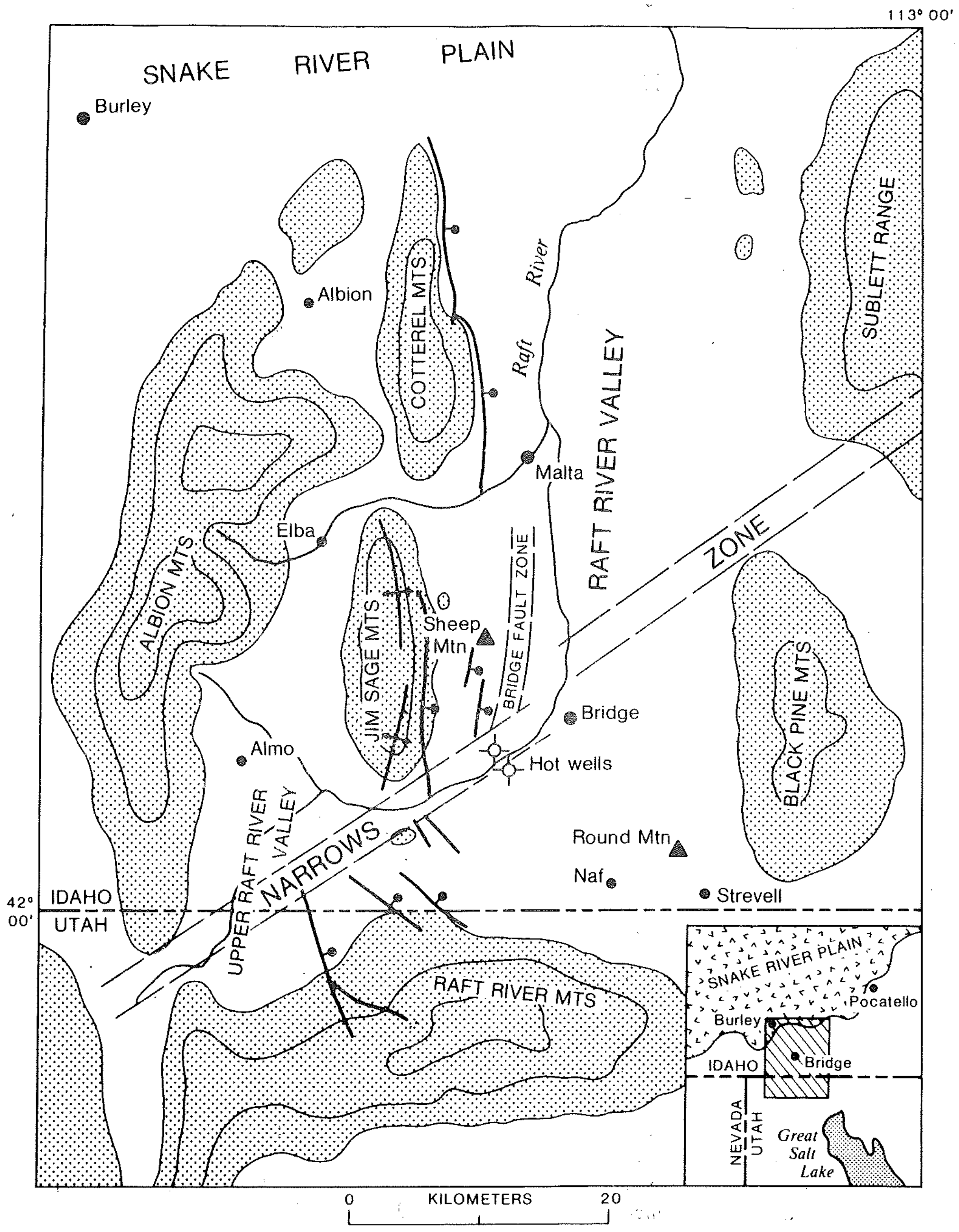
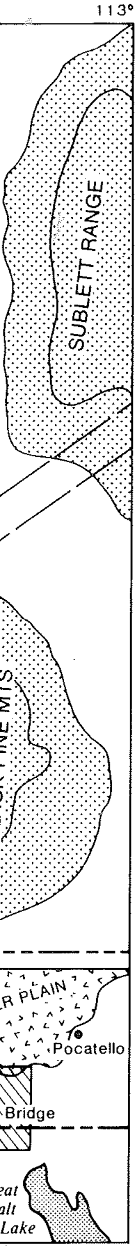


FIG. 1. Map of the Raft River Valley region, Utah and Idaho, showing major topographic features and faults.



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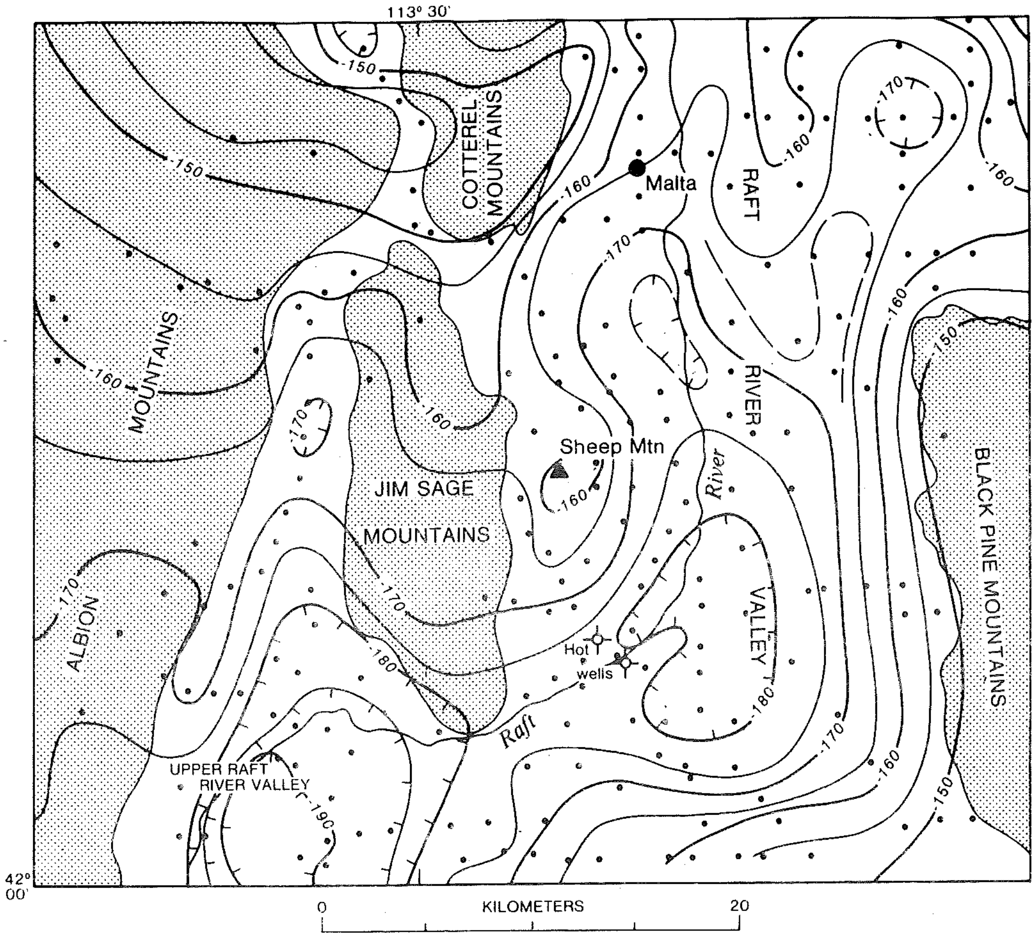

FIG. 2. Bouguer gravity anomaly map of the southern Raft River Valley and adjoining areas, Idaho. Contour interval is 5 mgals. Dots are gravimeter stations.

Although the water sought—and found—was lower in temperature than has been the objective in most geothermal exploration programs in the U.S., this program is an example of the use of a variety of geophysical methods, along with geologic and hydrological studies in the investigation of a geothermal system. A summary report at an earlier stage of the project has been published (Williams et al, 1976). Most of the data were released to the public shortly after they were obtained and are available in the following open file reports: Ackermann (1975); Crosthwaite (1974); Hoover (1974); Lofgren (1975); Mabey (1973); Mabey and Wilson (1973, 1974); U.S. Geological Survey (1974); Williams et al (1974); Wilson and Mabey (1974); and Zohdy et al (1975).

GENERAL GEOLOGY

Raft River Valley (Figure 1) is about 60 km long and 25 km wide. East of the valley, the Sublett range and Black Pine Mountains rise to 1400 m above the valley floor and are composed primarily of Paleozoic sedimentary rocks. The Jim Sage and Cotterel Mountains to the west of the valley are interbedded Miocene and Pliocene volcanic flows and tuffaceous sediments mostly of the Salt Lake formation. Maximum elevations in these mountains are about 1000 m higher than the valley floor. The Raft River Mountains south of the valley and the Albion Mountains west of the Jim Sage Mountains contain cores of gneiss-dome complexes of Precambrian age overlain by Precambrian and allochthonous Paleozoic metamorphic rocks. These mountains are the highest in the region, reaching elevations 1800 m above the floor of Raft River Valley. To the north, the Raft River Valley opens onto the Snake River plain.

The floor of Raft River Valley is covered with Quaternary alluvium. Underlying the alluvium and overlying the Salt Lake formation is the Pleistocene Raft formation, a lacustrine deposit that does not crop out in the southern part of the valley. Round Mountain, Sheep Mountain, and other smaller hills near Sheep Mountain are domes of rhyolite about 8 m.y. old.

GEOPHYSICAL STUDIES

Reconnaissance gravity and aeromagnetic surveys were made over the Raft River Valley and the results published before the geothermal investigations were started (Mabey and Wilson, 1973). As part of the geothermal program, more detailed gravity and aeromagnetic surveys were made and reconnaissance resistivity data were obtained from telluric current (TC) and audiomagnetotelluric (AMT) surveys. Later one magnetotelluric (MT) sounding was made in the area of the geothermal system. The above data are the subject of this report.

Regional gravity and aeromagnetic surveys

The regional gravity and magnetic maps prepared from the reconnaissance survey are illustrated in Figures 2 and 3. These maps have not been upgraded with the more detailed data now available; therefore, they illustrate the actual data available before the start

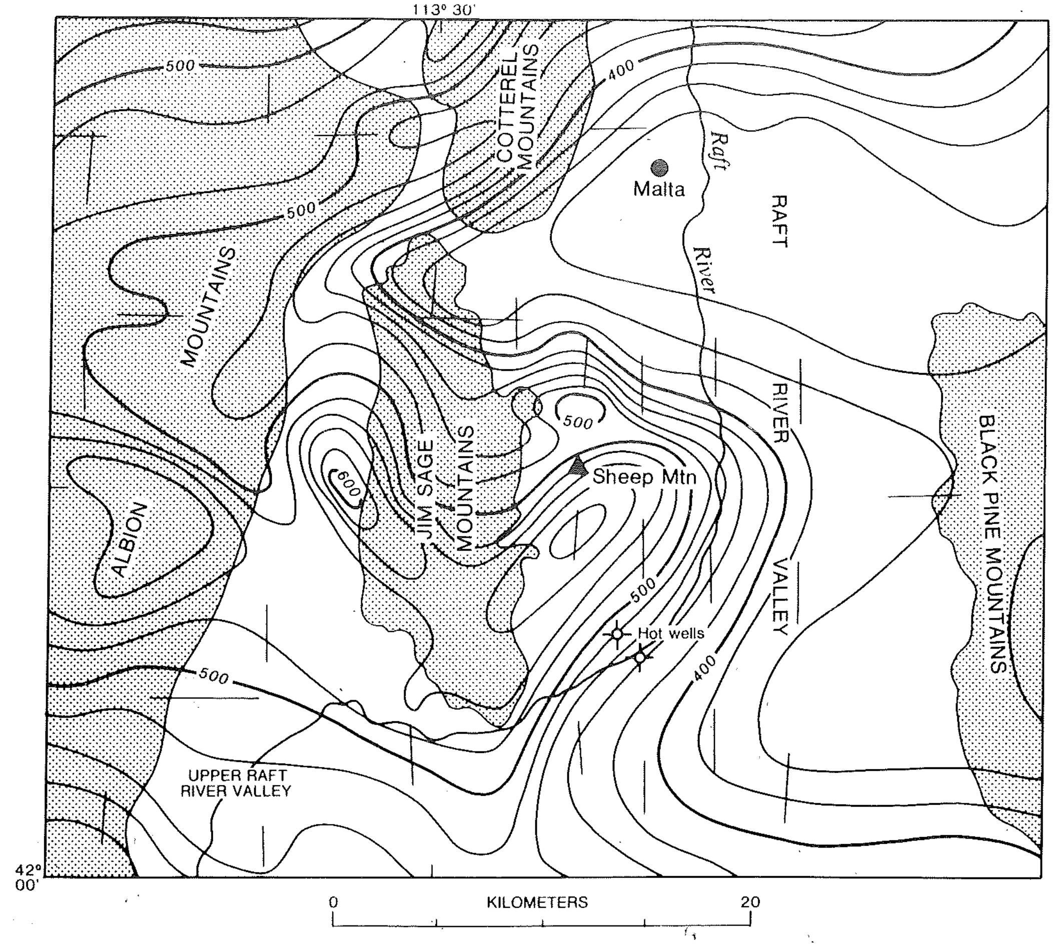

FIG. 3. Residual intensity aeromagnetic map of the southern Raft River Valley and adjoining areas, Idaho. Flight lines are 3700 m above sea level and shown as widely dashed lines. Contour interval is 20 gammas.

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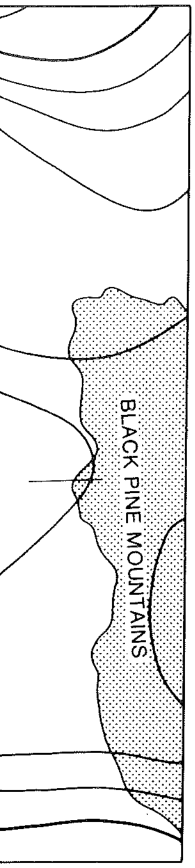

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of more detailed geophysical studies. The gravity data were reduced to the Bouguer anomaly with an assumed density of 2.67 g/cm^3. Corrections for terrain effect in excess of 2 mgals were applied. The aeromagnetic map is based primarily on east-west flight lines 5 minutes apart (9 km) and 3700 m above sea level (approximately 2200 m above the floor of Raft River Valley). Six additional north-south flight lines at the same elevation about 3 km apart were flown to provide additional detail on the anomaly on the west side of the southern Raft River Valley.

The gravity survey defines large lows in the Raft River and upper Raft River Valleys. These lows are produced primarily by the low density Cenozoic rocks underlying the valleys. The low in the Raft River Valley is more complex than in the normal Basin and Range valley. A gravity high in the north-central part of the valley indicates a completely buried ridge of pre-Cenozoic rock. Of particular interest to the geothermal investigation is the gravity high in the area of Sheep Mountain and the east- to northeast-striking gravity contours in the area of the hot wells.

The regional magnetic map defines an arcuate magnetic high extending from the western part of the Raft River Valley across the Jim Sage Mountains. Little correlation with the Jim Sage Mountains is apparent in the magnetic data even though strongly magnetized volcanic rocks are elevated several hundred meters in the range. A magnetic closure south of Sheep Mountain is centered about 5 km north of the hot wells in an area covered with Quaternary alluvium.

The interpretation of the regional gravity and magnetic anomalies in the Bridge area (Mabey and Wilson, 1973) published before any of the deep drilling stated the following:

> In the southern part of the Raft River Valley is another extensive gravity low. The low is interpreted as reflecting a basin, here called the Bridge basin, filled with low density Cenozoic rocks. The low is partly open to the southwest toward the upper Raft River basin and north toward the Idahome basin. On the northwest, east, and south the basin is bounded by steep gravity gradients, which are interpreted as indicating faults. The fill in the Bridge basin is about 6000 ft thick with the greatest thickness east of the topographic low area in the valley. The magnetic data do not suggest any magnetic material underlying the main part of the Bridge basin.

Since this was written, more intensive geophysical surveys have been made and several deep wells drilled. The new information has confirmed the interpretation made of the regional gravity and magnetic data relative to the Bridge basin.

Concerning the gravity and magnetic highs northwest of the hot wells, the report concluded:

> West of the Bridge basin but within the Raft River Valley are approximately coincident gravity and magnetic highs, which are here called the Bridge anomalies. No similar coincident anomalies were mapped in the area, and no evidence at the surface suggests a cause of the anomalies. . . .
>
> Two possible explanations are proposed for the Bridge anomalies: (1) a local accumulation of basalt, or (2) a concealed intrusive possibly combined with relief on the base of the low density Tertiary rocks. . . . A tentative interpretation of the anomaly is that an intrusive body that is moderately magnetic underlies the area, and this mass is either more dense than the normal pre-Tertiary rock or is part of or underlies a buried ridge that is enclosed by low density Tertiary rocks. . . . Perhaps the Bridge anomalies reflect a relatively young intrusive that is still cooling and providing heat to ground water that is circulating in normal faults that bound the Bridge basin. If this interpretation is correct, a rather large area lying generally north of the two wells might be underlain by significant amounts of hot water or steam.

Several lines of new evidence indicate that the anomalies are not related to a near surface heat source. The anomalies now appear to be related to a buried basement dome and related low angle faults. The experience in the use of the regional gravity and magnetic data in the Raft River Valley is typical of the Basin and Range province. The regional data are generally reliable indicators of the gross structure of the basins and sometimes indicate the presence of volcanic rocks in the basin fill, but detailed interpretations of the regional data are hazardous.

The regional gravity map is based on observations made at bench marks and spot elevations determined in preparing the topographic maps of the area. No additional surveying was required, and the cost of the survey was low. Because only the larger terrain corrections were made, the cost of reducing the data and preparing the contour map was also low. The basic regional magnetic data were available from a more extensive survey but were also a low cost item. Thus, for a very modest investment, the regional gravity and magnetic data were obtained and, when used with existing reconnaissance geology, provide an accurate indication of the regional setting of the geothermal system.

Detailed gravity and magnetic surveys

When interest focused on the southern Raft River Valley, more detailed gravity and magnetic surveys were made. Surveying was required to obtain hori-

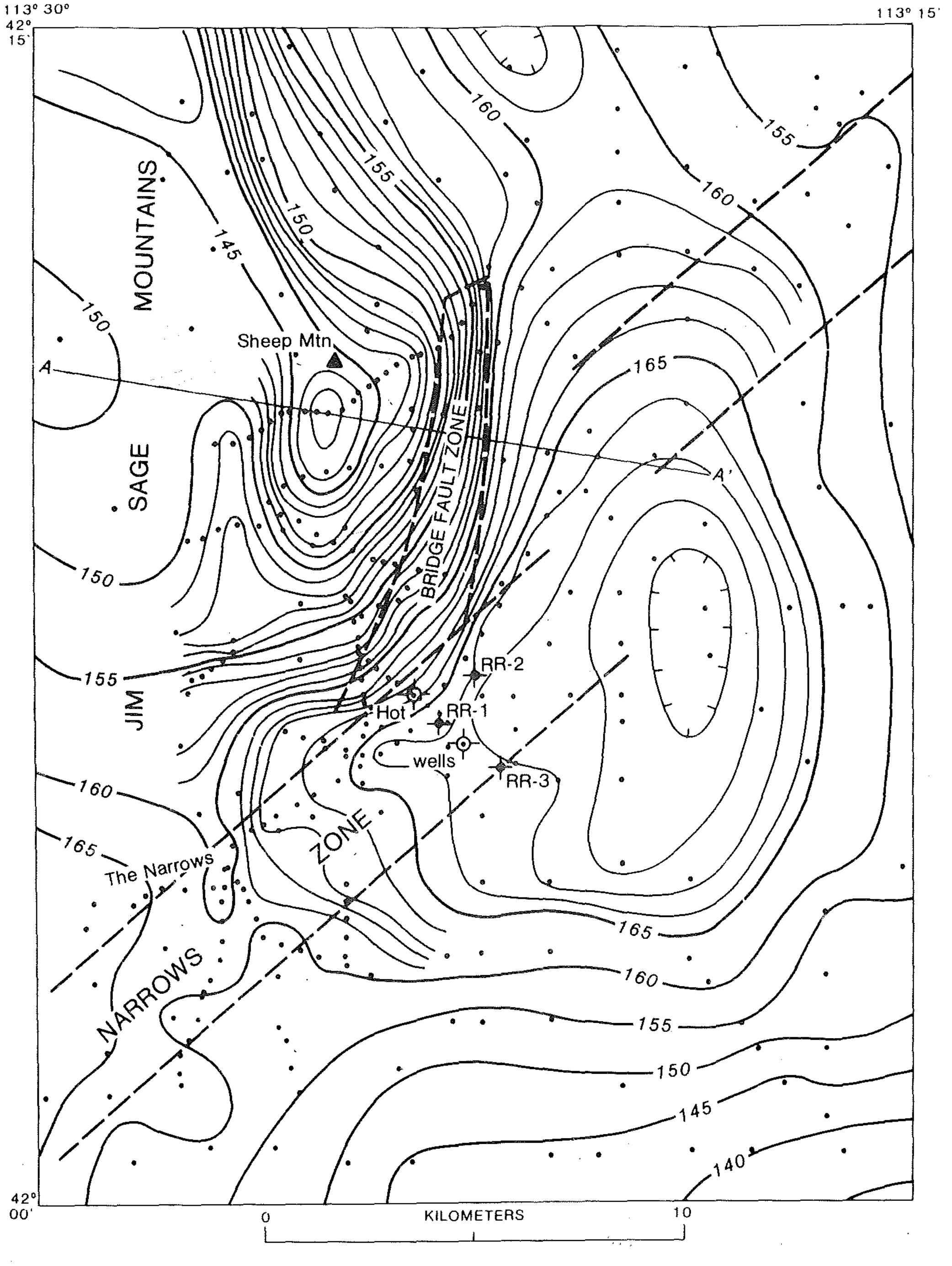
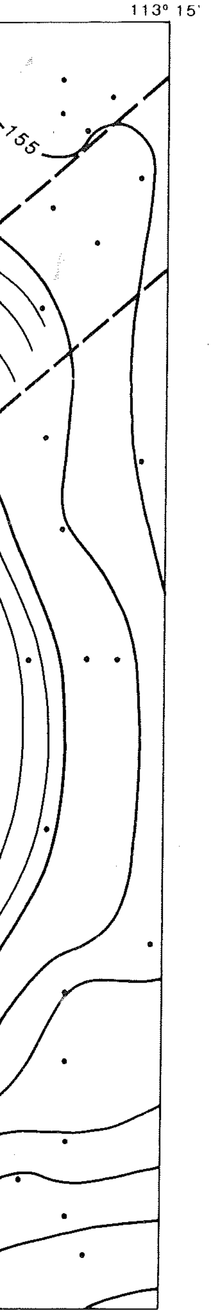


FIG. 4. Complete Bouguer gravity anomaly map of the southern Raft River Valley. Contour interval is 1 and 5 mgals. Deep drill holes are shown and numbered. Dots are gravimeter stations.



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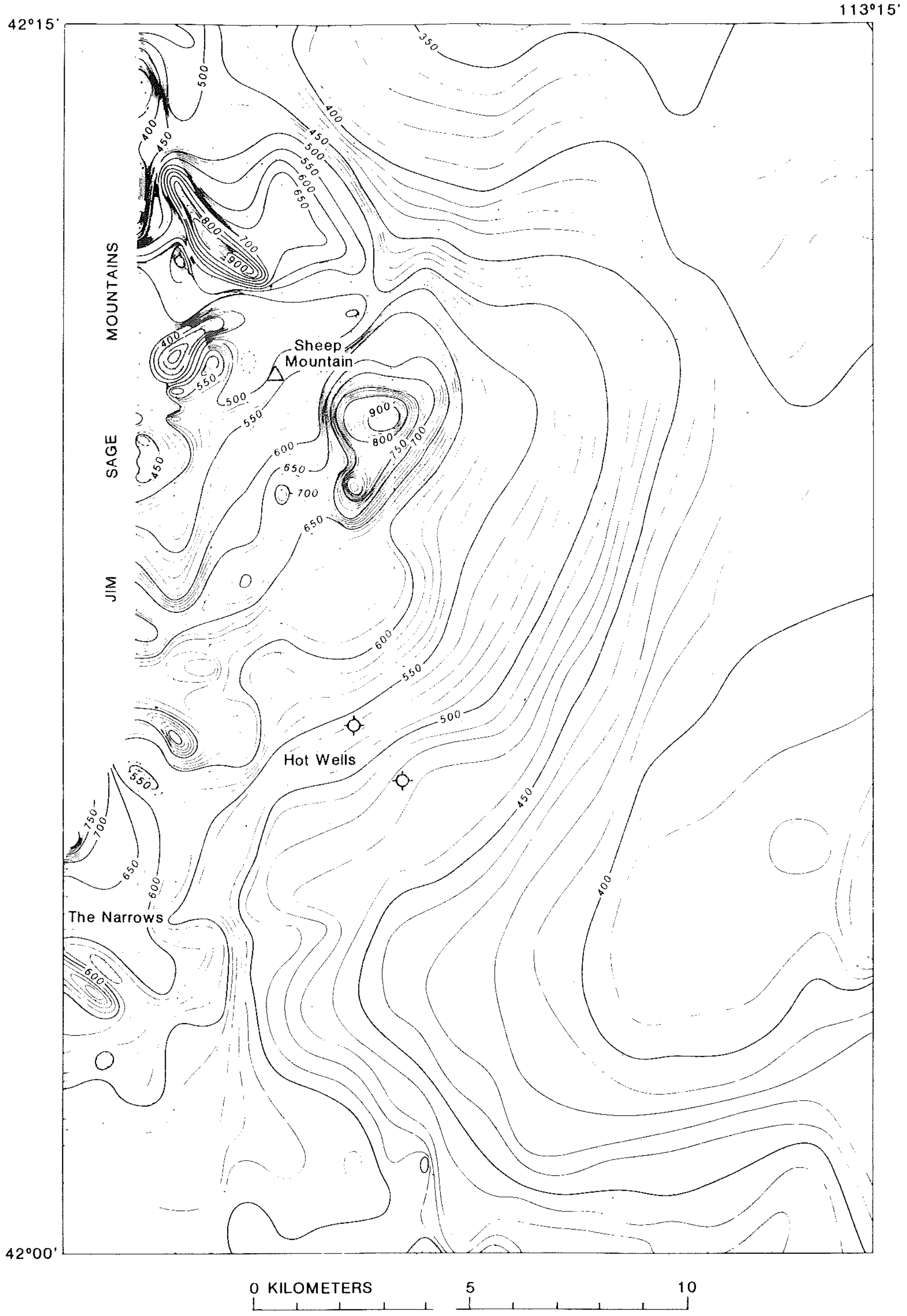


FIG. 5. Residual intensity aeromagnetic map of the southern Raft River Valley. Flight lines are 2800 m above sea level and 0.8 km apart. Contour interval is 10 gammas.

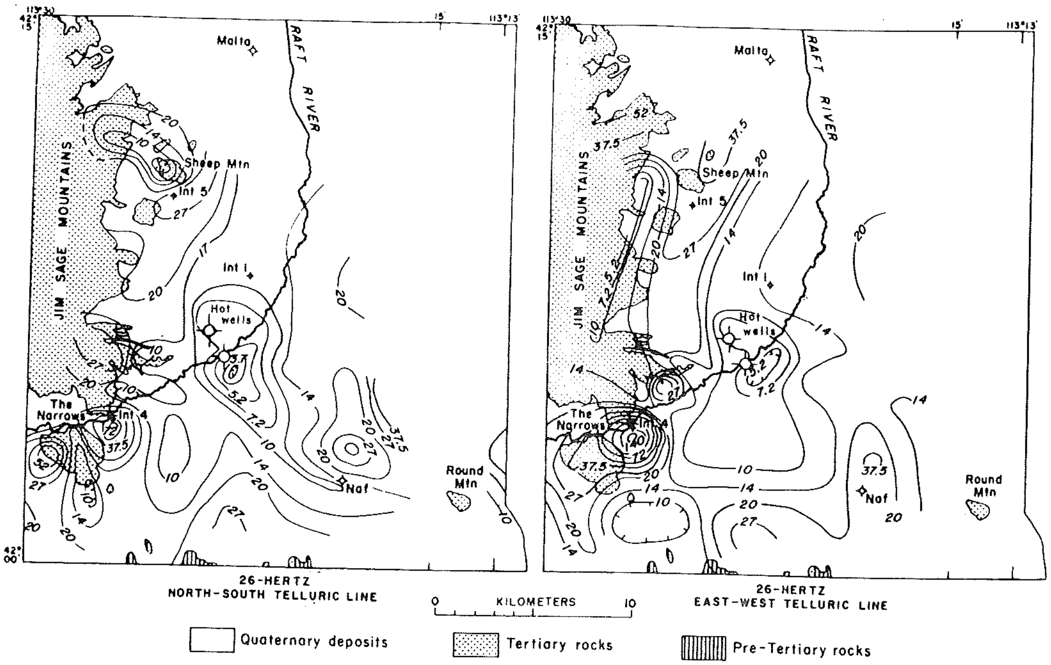


FIG. 6. AMT apparent resistivity maps of the southern Raft River Valley. Contours are a logarithmic interval in ohm-meters.

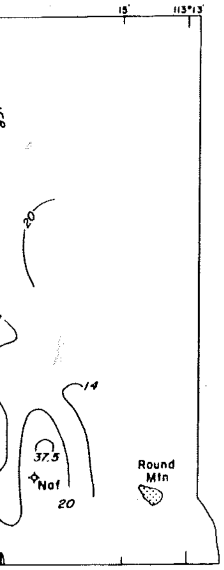
zontal and vertical control for many of the additional gravity stations. More accurate terrain corrections were required, so the topography for a large area was digitized. An aeromagnetic survey was flown at a lower elevation with appreciably reduced flight line spacing.

The data for the more detailed gravity survey were used to prepare a complete Bouguer anomaly map (Figure 4) computed with a density of 2.45 g/cm^3, which is the approximate average density of the alluvium and volcanic rock that constitute much of the surface relief in the area of particular interest. The more detailed gravity survey reveals complexities not apparent from the regional survey. In particular, the better definition of the gravity field on the west side of the valley suggests a more complex underlying structure than was inferred from the regional survey.

The lower level aeromagnetic survey (Figure 5), which was flown with flight lines 800 m apart and 1800 m above sea level, or about 350 m above the surface in the area of the hot wells, defines much greater detail of the magnetic field. The broad magnetic high, that was relatively simple on the regional map, at this level is a highly complex feature. Elements of the anomaly within the Jim Sage Mountains correlate with volcanic rocks, with highs and lows generally reflecting normal and reversed remanent magnetization. The large high within the valley south of Sheep Mountain has multiple closures with a possibility that the anomaly may reflect a linear northeast-trending feature offset in an apparent right lateral sense by a north-trending structure. Clearly, at least a part of the anomaly is produced by a near-surface source. The local magnetic anomaly south of Sheep Mountain is offset from the gravity high in a manner that indicates they may not be directly related as was assumed in interpreting the regional surveys. The absence of anomalies over the central part of the valley similar to those produced by the volcanic rocks in the Jim Sage Mountains indicates that these rocks are not abundant there.

Audiomagnetotelluric survey

AMT soundings were made in the southwestern part of the Raft River Valley as the first phase of the resistivity investigations in the area. Scalar resistivities were calculated for a north and east orientation of the telluric line for each of 10 frequencies in the range 8 to 18,600 Hz (Hoover and Long, 1976). Contour maps of the apparent resistivity values mea-



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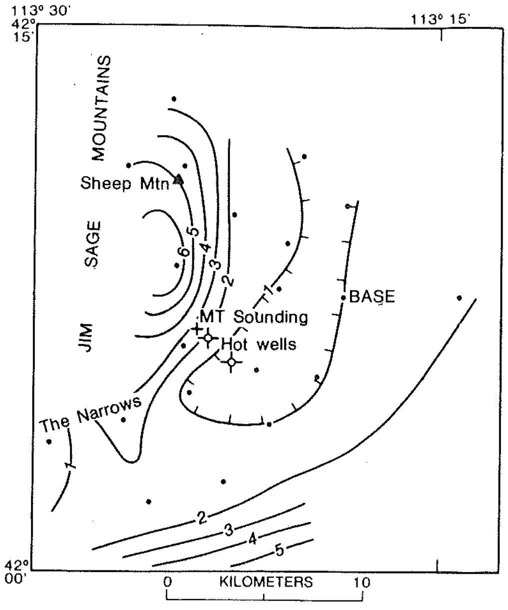

FIG. 7. Telluric current map of the southern Raft River Valley. Contours are J values relative to the base station. Dots are station locations.

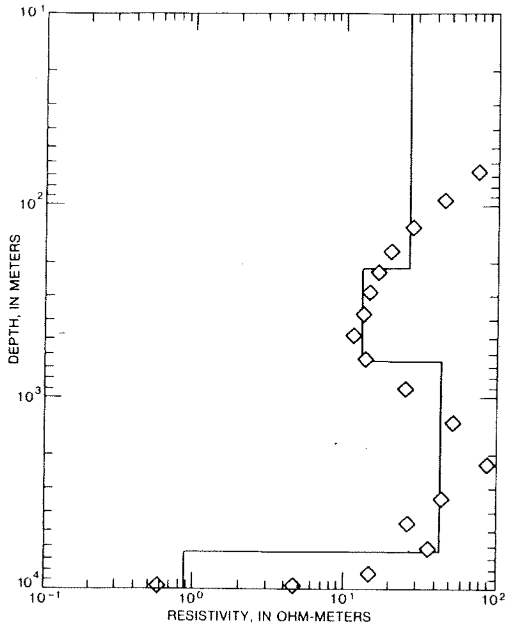

FIG. 8. Resistivity interpretation of an MT sounding in the southern Raft River Valley (from Stanley, 1977). Location of MT station is shown in Figure 7.

sured at 26 Hz are shown in Figure 6. Three features are apparent on these maps and maps of apparent resistivity determined at other low frequencies: (1) high values south of Sheep Mountain, (2) a complex pattern but generally high values in the area east of The Narrows, and (3) low values in the area of the hot wells. The probable depth of penetration at 26 Hz indicates that the low in the bridge area, outlined by the 10 Ω-m contours, reflects resistivities to depths of less than 310 m (one apparent skin depth).

Differences in the two 26 Hz maps are due to lateral variations of resistivity within about one skin depth of the stations. Evidence of lateral variations in the AMT soundings are abundant, indicating a complex, shallow resistivity structure. This is seen in the case of the resistivity high associated with the gravity and magnetic highs south of Sheep Mountain. Here the north-trending flanks of the structure are well defined, as would be predicted for the east-west orientation of the telluric line. The orthogonal orientation provides much poorer definition of these boundaries. The station density is insufficient to give good definition of the resistive body but it is probably related to either (or both) the gravity or magnetic anomalies. The body can be interpreted as plunging to the south beneath more conductive overburden, which also is in accord with the gravity data.

The principal resistivity low seen in Figure 6 is in the vicinity of the hot wells and does not correlate with the principal Bouguer gravity low. It suggests that in this region the AMT data are reflecting the influence of the shallow hydrothermal system rather than variations in the thickness of basin fill.

Telluric current survey and magnetotelluric survey

Twenty-two telluric current (TC) stations were established in the southern Raft River Valley. The technique used measures relative ellipse areas (J values) between vectograms recorded simultaneously at a roving field station and a base station (Yungul, 1968). The TC systems' band-pass filters had a range from 10 to 70 sec and the predominant period recorded was 20 sec. An estimate of the depth of penetration for the TC survey, based on the apparent resistivity of 30 Ω-m obtained from the magnetotelluric (MT) sounding at the period of 20 sec (Stanley et al, 1977), is 8.7 km where the J values are 2, which is the J contour value where the MT sounding was located. In geothermal areas, the J value has been shown (Hermance et al, 1976) to agree quite well with the sum of the spectra energy ratio, that is, the sum of both telluric measuring axes, which were north and east in this survey. Consequently, the *J* value can be interpreted as an estimate of the apparent resistivity sum ratio for the two measuring axes. The *J* values, relative to a base in the central part of the valley, ranged from 0.5 to 6.0 (Figure 7). The TC survey defines a relative resistivity high in the area of Sheep Mountain and a low in the valley which includes the area of the hot wells.

The one MT sounding established in the area was part of an extensive MT survey of southern Idaho by Stanley et al (1977). Their resistivity versus depth interpretation (Figure 8) gives a low resistivity layer of 12 Ω-m at a depth of 220 to 660 m, and a more conductive layer of 0.9 Ω-m starting at 6.3 km. The TC survey indicates the apparent resistivity is a factor of 4 less in the central valley than at the MT station. Thus, the central valley area has an electrical structure such that the deep conductive layer (0.9 Ω-m) is closer to the surface or the low resistivity (12 Ω-m) layer is much thicker or has an even lower resistivity. Other combinations of structures could combine to lower the apparent resistivity.

Self-potential survey

A reconnaissance self-potential (SP) survey was also conducted during the first phase of the electrical work to determine the applicability of the method to exploration for geothermal systems. The rising thermal waters, if moving through a heterogeneous medium, (Nourbehecht, 1963) could be expected to give self potentials due to electrokinetic, thermal, and chemical effects, although probably not of large magnitude. The method thus offers promise of providing a direct indication of the presence of thermal waters.

A station spacing of 500 m was used and, because of the large area to be covered, a ''leap-frog'' technique of progressing was employed. Care was used in tying as many profiles as possible to minimize errors. The survey covered the region of known thermal water discharge from The Narrows to the hot wells.

The SP map (Figure 9) shows a pattern of elongate north- to northeast-trending narrow anomalies north of the Raft River that appear to terminate along a northeast-trending zone. The effect of topography is evident in the data as indicated by the increasingly negative potentials measured up slope to the north. On the east side of The Narrows, three small positive closures define a north-trending zone about 3 km long. This zone correlates with a gravity gradient, and warm springs occur at the southern end. Near the Bridge well and hot spring, a narrow positive zone is flanked by two narrow negative zones. In both of these areas the positive potential values appear to define zones along faults in which thermal waters are rising to, or near, the surface. The short wavelengths of these anomalies indicate a near surface source.

The largest anomaly, +60mV, occurs on the south side of the Raft River about 2 km south of the Bridge well. It is not associated with any known thermal discharge nor directly with other geophysical anomalies. It is coincident with a recent alluvial fan and bounded on the north and east by very steep gradients at the fan edges, but the significance of this anomaly is unknown.

The self-potential data show that some information about the near surface hydrothermal system can be obtained from this method. The anomalies, however, are small and can be easily masked or confused with other effects. At least in this area, SP surveying is not an effective reconnaissance tool, but may be useful as a supplement to detailed hydrologic studies.

INTERPRETATION

The two major features of the gravity field in the southern Raft River Valley are a low in the central and southwestern parts of the valley and a high centered just south of Sheep Mountain. These anomalies are produced in large part by variations in the thickness of the low-density Cenozoic sedimentary and volcanic rocks, but the effect of mass anomalies within the Cenozoic rocks and within the older rocks and regional mass anomalies related to features at great depth must be considered in attempting any quantitative analysis. The southern Raft River Valley lies across the axis of a regional gravity low related to the regional topographic high between the Snake River plain and the Lake Bonneville basin. This regional gravity variation over pre-Tertiary bedrock in the Albion Mountains 25 km to the west is a northward increase averaging 1 mgal/km for a distance of 50 km. The regional gradient in the Black Pine Mountains to the east is smaller with anomaly values increasing southward.

In the earlier analysis of the regional gravity survey in the southern Raft River Valley (Mabey and Wilson, 1973), a regional gravity field was computed assuming a simple inverse relationship between the regional topography and the regional Bouguer anomaly values (Mabey, 1966). A quantitative analysis of the resulting residual anomaly yielded fill thicknesses in the central part of the valley that were later confirmed by seismic refraction and resistivity sound-

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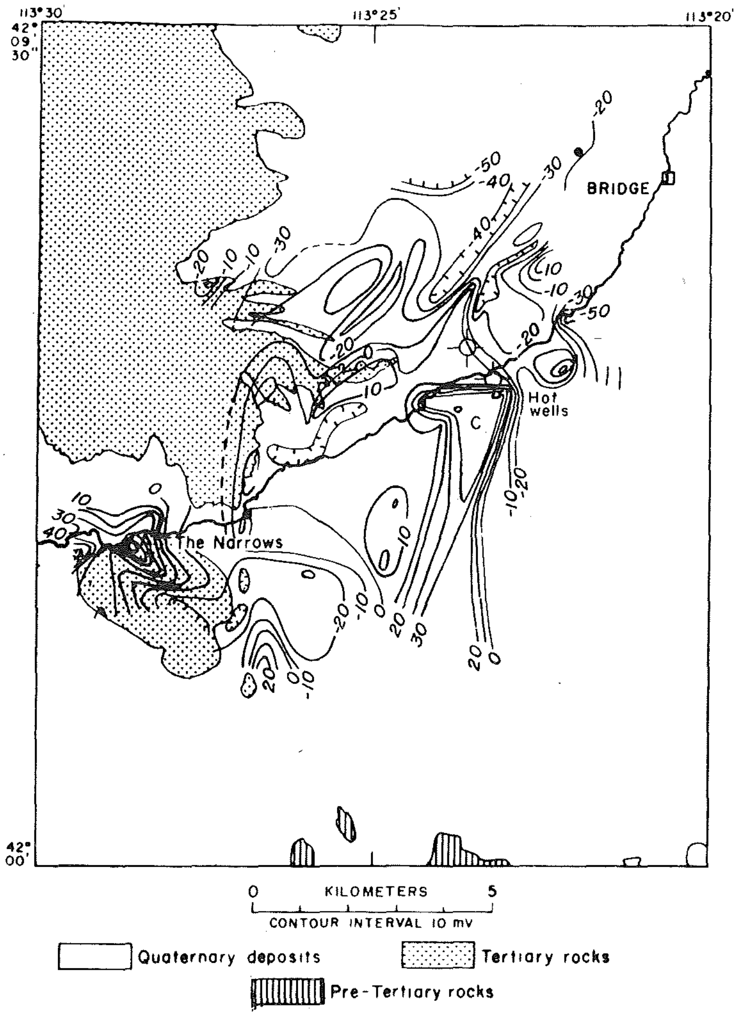

FIG. 9. SP map of part of the southern Raft River Valley.

ings and drilling. The same analysis, however, indicated that the fill was about 200 m thick in the area immediately south of Sheep Mountain. Subsequent resistivity and seismic surveys and drilling established that the fill is much thicker here, probably about 500 m. The underestimate of thickness of Cenozoic rocks in the area south of Sheep Mountain may have resulted from one or all of the following: (1) incorrect regional gravity anomaly assumed, (2) too large a density contrast assumed, or (3) density variations within the Cenozoic rocks or with the older rocks. A match between the measured and computed anomaly using existing control on the thickness of Cenozoic rocks can be obtained assuming an average density contrast of 0.35 g/cm^3 with the underlying basement. Due to the lack of control, effects of variations in the density within the basement rock and Tertiary rocks, and effects of variations in the thickness of the Tertiary rocks cannot be evaluated; thus, detailed quantitative interpretation is not justified.

Although the large, and as yet not fully understood, lateral variations in density limit the extent to which gravity data can be used to infer the thickness of the Cenozoic rocks, the gravity anomaly can be used to identify the faults with large vertical movement. The zone of high-gravity gradients lying between the Sheep Mountain high and the gravity low in the central part of the valley indicates faulting. On the basis of surface and subsurface geology, Williams et al (1976) concluded that one of the north-trending faults in the area north of the hot wells is particularly significant to the geothermal system and named it the Bridge fault. The geophysical expression of this particular fault is not clear so the name Bridge fault zone, which includes the Bridge fault, will be used here to refer to a system of north-trending faults, to the east and southeast of Sheep Mountain.

The steepest gravity gradient lies east of Sheep Mountain and suggests that the Bridge fault zone here has the largest vertical displacement. To the south, the gravity contours begin to swing westward but not in a manner that indicates a westward bend of a fault. Rather, the data suggest that the fault zone widens to the south with vertical displacement distributed between a series of faults trending slightly east of north. All gravity expression of the north-trending faults terminates north of the Raft River. Apparently the southern limit of the Bridge fault zone is controlled by structure approximately parallel to the east-northeast-trending segment of the Raft River. West of the Bridge fault zone, the gravity data indicate a north-trending fault that also terminates north of the Raft River. On the south side of the Sheep Mountain gravity high is an east-trending zone of steeper gravity gradients. No correlation between this gradient and surface geology is apparent. This gradient may reflect an east-trending step in the surface of the pre-Tertiary basement. Elsewhere the gravity data indicate that the structural high reflected by the Sheep Mountain gravity high plunges rather gently to the south.

In the area of known hot water, small local variations in the Bouguer gravity anomaly were defined that do not appear to be related to the thickness of the Cenozoic rocks. These gravity features may reflect local density changes relating to induration of Cenozoic sediments by thermal water; however, this has not been confirmed. Near the east end of The Narrows is a north-trending zone of high gravity, AMT resistivities, TC J values, and magnetic intensity values. All of these could be produced by a zone of more abundant volcanic rock in the Salt Lake formation.

Within the Jim Sage Mountains, the magnetic anomalies correlate with the surface geology with positive anomalies produced by the normally magnetized volcanic rocks and negative anomalies by the reversely magnetized volcanic rocks. East of the Jim Sage Mountains is an area of generally high magnetic intensity that is approximately coextensive with the Sheep Mountain gravity and resistivity highs. The easternmost magnetic anomaly has the highest intensity on the magnetic map—larger than the anomalies measured over outcropping volcanic rock in the Jim Sage Mountains to the west. The approximate coincidence of these highs suggests that they might have a common source; however, the magnetic anomaly is more complex than the gravity anomaly with a part of the anomaly having a shallower source than the source of the gravity high. The magnetic anomaly may be a composite feature produced in part by the elevated basement rock and near surface strongly magnetic units, probably volcanic rock.

The most prominent magnetic feature in this complex high is a northeast-trending high with two offset areas of high closure. The major features of the northeast-trending anomalies can be modeled in several ways. The two anomalies could be produced by a slab with an irregular boundary and magnetized toward the northwest. With this model the band of low magnetic intensity northwest of Sheep Mountain is the polarization low marking the edge of the slab-like magnetic mass. However, a hole drilled to a depth of about 450 m, 1 km south of Sheep Mountain, did not encounter volcanic rock or other rock that would contribute to the magnetic anomaly. Thus, the strongly magnetized rock that underlies the zone of highest intensity at shallow depths does not extend at the same depth to the northwest. At least part of the anomaly is produced by a near surface material in an area where the pre-Tertiary basement is apparently about 1000 m below the surface. An interpretation that is consistent with all present information is that the anomaly represents a thick unit of strongly magnetized Tertiary volcanic rocks with restricted areal extent.

A section across the west side of the southern Raft River Valley that is consistent with all existing data is shown in Figure 10. This section is based on the assumption that the Salt Lake formation underlying the valley has moved eastward a maximum of 3 km along a low angle fault that parallels the basement (adamellite) surface west of the basement high. In this section, the eastern part of the thick wedge of volcanic rocks in the Jim Sage Mountains now lies under the alluvium east of Sheep Mountain. Subsequent movement along the Bridge fault zone has displaced this low angle fault surface and the eastern end of the wedge of volcanic rocks. Drill holes that have penetrated the base of the Salt Lake formation in the geothermal area reveal that the beds are dipping more steeply than the basement surface and that the base of the formation is fractured. Both these facts are consistent with the existence of a low angle fault

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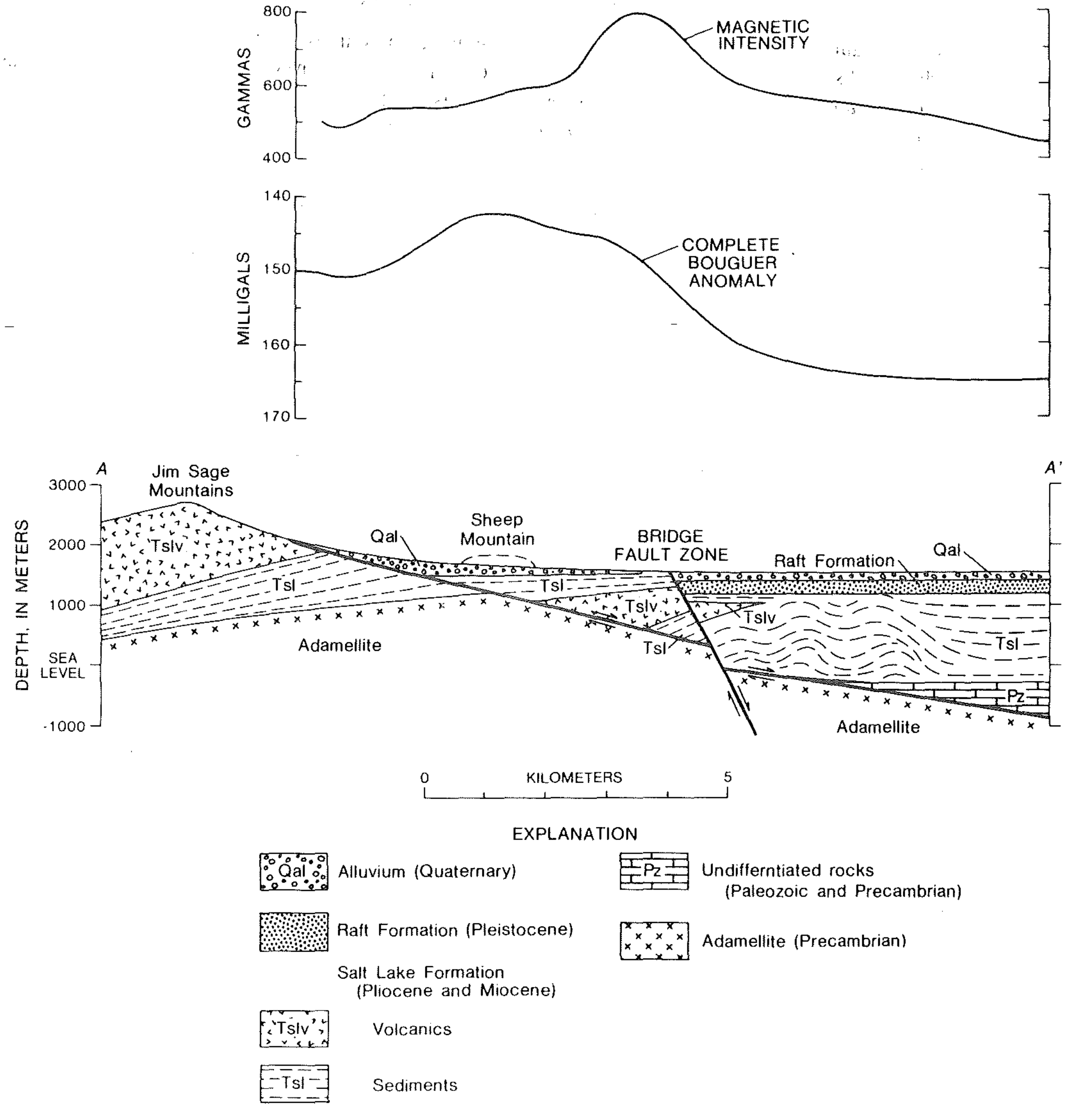

FIG. 10. Interpreted section across the west side of the southern Raft River Valley. Location of section is shown in Figure 4.

between the Salt Lake formation and the basement. Tertiary gravity glide faults are known to occur around other gneiss dome complexes in the western U.S. (for an example, see Davis, 1976).

The southern limit of the gravity and magnetic highs on the west side of the southern Raft River Valley is a general, northeast-trending zone parallel to a segment of the Raft River. If this zone is projected to the southwest, it passes south of the main mass of the Jim Sage Mountains and across the upper Raft River Valley (Figure 1). To the northeast the zone, slightly offset, forms the south edge of a completely buried ridge indicated by the gravity data and the north end of the Black Pine Mountains. On the west side of the Raft River Valley, north-trending faults all lie north of this zone. In The Narrows at the south end of the Jim Sage Mountains, Williams et al (1974) have inferred the existence of a right-lateral strike slip fault trending approximately east. The few surface faults apparent in the alluvium in the area of the zone trend east to northeast. Both the refraction seismic and dc resistivity surveys reveal northeast-trending anomalies in the Tertiary rocks east of The Narrows. The geophysical data have not defined a discrete structure in this area, but they strongly suggest that major changes are occurring in a northeast-trending zone. We have named the northeast-trending zone of geophysical anomalies The Narrows zone (Figures 1 and 4).

Although we do not have sufficient definition of the geology in The Narrows zone to determine what kind of geologic feature it is, a few characteristics are apparent. Because the zone appears to control the southern limit of Basin and Range structures on the west side of the Raft River Valley, it probably predates them and may be an old basement feature. The trend of The Narrows zone is approximately parallel to the southeastern edge of the eastern Snake River plain. A northeast-trending zone extending from western Nevada to the U.S.–Canada border, and including the eastern Snake River plain and the Yellowstone caldera, has been named the Humboldt zone (Mabey et al, 1978). The Narrows zone appears to be a part of this more extensive feature.

Geothermal system

The geothermal system in the southern Raft River Valley occurs where the Bridge fault zone intersects The Narrows zone (Figure 1). Large flows of water at a temperature of about 150°C are produced from permeable zones near the base of the Tertiary Salt Lake formation. Lesser flows are produced from fractures in the underlying pre-Tertiary basement. Regional heat flow in the area is estimated to be 2.5–3.0 HFU (Brott et al, 1976) and no evidence of a local heat source is apparent. The hot water has probably circulated to depths of 3 to 6 km in basement fractures where it is heated to 150°C. The water may enter the ground 35 km to the southwest in the area of the headwaters of the Raft River where precipitation is relatively high and migrate down and to the northeast through The Narrows zone to rise where The Narrows zone intersects the Bridge fault zone. When the ascending water encounters permeable zones near the base of the Salt Lake formation, it spreads laterally to form the reservoir that is the principal geothermal resource in the southern Raft River Valley. Upward leakage through the Salt Lake formation, probably along faults, supplies the water to the shallower hot water aquifers. In the Basin and Range province, deep circulation hydrothermal systems commonly occur at the intersection of Basin and Range fault zones with cross-structure or at flexures of generally straight Basin and Range faults.

The above-normal temperatures measured in shallow wells and the area of low resistivity that does not conform with the center of the Cenozoic basin suggested the location and extent of the geothermal system in the southern Raft River Valley. Assuming that the system was fault controlled, the first deep drill hole, RR-1 (Figure 4), was located to intersect the pre-Tertiary basement where geology and geophysical data indicated the structure to be most complex. The hole penetrated the pre-Tertiary basement at 1433 m, very close to the depth predicted from the dc resistivity soundings and the seismic refraction profiles, and was bottomed at 1520 m in Precambrian adamellite. A flow of water of the desired temperature and quality was produced from permeable zones in the lower part of the Tertiary Salt Lake formation and lesser amounts from fractures in the pre-Tertiary basement. Bottom temperature was 146°C and "hot" shut-in pressure about 11 atm. Two wells drilled subsequently produced water at slightly higher temperatures from what appears to be the same aquifer. Although the testing of the wells is not complete, it appears that the aquifer may be, at least in part, fractured zones in the Salt Lake formation, perhaps related to a low angle fault.

CONCLUSIONS

In the southern Raft River Valley, as elsewhere in the Basin and Range province, regional magnetic and gravity surveys are useful in determining the structural setting of geothermal systems and estimating the thickness and gross lithology of the Cenozoic rocks. However, care must be exercised not to overinterpret the regional data. The low cost and ease with which these data can be obtained over large areas make them very attractive reconnaissance methods.

Detailed gravity surveys were useful in determining details of the structure, particularly of normal faults. In the southern Raft River Valley, complications relating to as yet poorly understood lateral density variations in both the Cenozoic rock and pre-Cenozoic basement, and a complex regional gravity field, limited the extent to which quantitative interpretations could be made of the gravity data. The detailed magnetic survey was useful in investigating the regional structure and inferring the extent of major volcanic units.

AMT and TC surveys defined a resistivity anomaly that appears to be coincident with the location of the

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geothermal reservoir, although the low resistivity zone reflected in the AMT anomaly is much shallower than the geothermal reservoir. A single MT sounding reveals a conductive material about 6 km below the surface. The significance of this material is not known.

The information obtained on the aquifer from the three drill holes and preliminary production testing is consistent with that inferred by the AMT and TC surveys. The SP survey defined anomalies related to the near surface hydrology.

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