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Seismic refraction study of the Raft River geothermal area, Idaho

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The Raft River geothermal system in southeastern Idaho is a convective hot water system, presently developed to demonstrate the production of electricity from low-temperature (≈150°C) water. Interpre of seismic refraction recordings in the area yielded compressional velocities from near the surface t crystalline basement at a maximum depth of approximately 1600 m. The results show a complex seque sediments and volcanic flows overlying basement. Velocities in the sedimentary section vary laterally. C lation with well data suggests that zones of higher velocities may correspond to zones where sedimen hydrothermally altered. Flowing hot wells occur near the boundary between inferred shallow altered an altered rocks. The basement surface does not appear to be displaced by large faults, although there is surface evidence of faulting. The deep circulation of hot water necessary for a convective system m through many small faults and fractures. Fracturing is suggested on the basis of lateral velocity vari within the basement complex.

INTRODUCTION

In 1973, the U.S. Geological Survey undertook a multidisciplined (hydrologic, geologic, geophysical) exploration study of the Raft River geothermal area in southeastern Idaho (Williams et al, 1976). This geothermal system is a low-temperature, convective, hot-water system (White et al, 1971) charged by meteoric water probably derived from nearby mountains. Circulation probably proceeds down to 3–5 km along major faults bounding the Raft River Valley, and then upward into a large aquifer through fractures (Williams et al, 1976).

This seismic survey was part of the overall exploration efforts, which were culminated by the drilling of five intermediate depth (IM) core holes between 41 and 434 m deep. The locations of these holes were selected to best test the working hypotheses and conclusions of the various studies.

Three deep wells, Raft River Geothermal Exploration (RR) 1, 2, and 3 have been drilled in the area for the Energy Research and Development Administration, now the Department of Energy. All three wells intersected crystalline basement rocks at depths between 1395 (RR 1) and 1610 (RR 3) m. Flow tests (Mabey et al, 1978) have revealed that large quantities of hot water (149°C) can be produced from an aquifer about 140 m thick immediately overlying base and lesser amounts from fracture zones withi basement.

The seismic refraction interpretations do not large basement faults within the valley. How 50-m or smaller vertical displacements of the ment surface might not have been detected. O other hand, the interpretations do reveal many logic changes in the form of lateral velocity vari from near-surface depths down into the base

This paper will attempt to reconcile the se refraction interpretations with the drill findings i of the known geology and then extend these throughout the survey area.

GEOLOGIC SETTING

The Raft River geothermal area (Figure within the Raft River Valley, a north-tre Cenozoic depression bounded on three sid mountains. Volcanic activity in the area is evid in the Jim Sage Mountains, west of the valley, consist principally of uplifted and deformed, bedded Miocene and Pliocene rhyolite flows tuffaceous sediments of the Salt Lake form The sediments underlying the valley are princ tuffaceous sandstones, siltstones, and conglom

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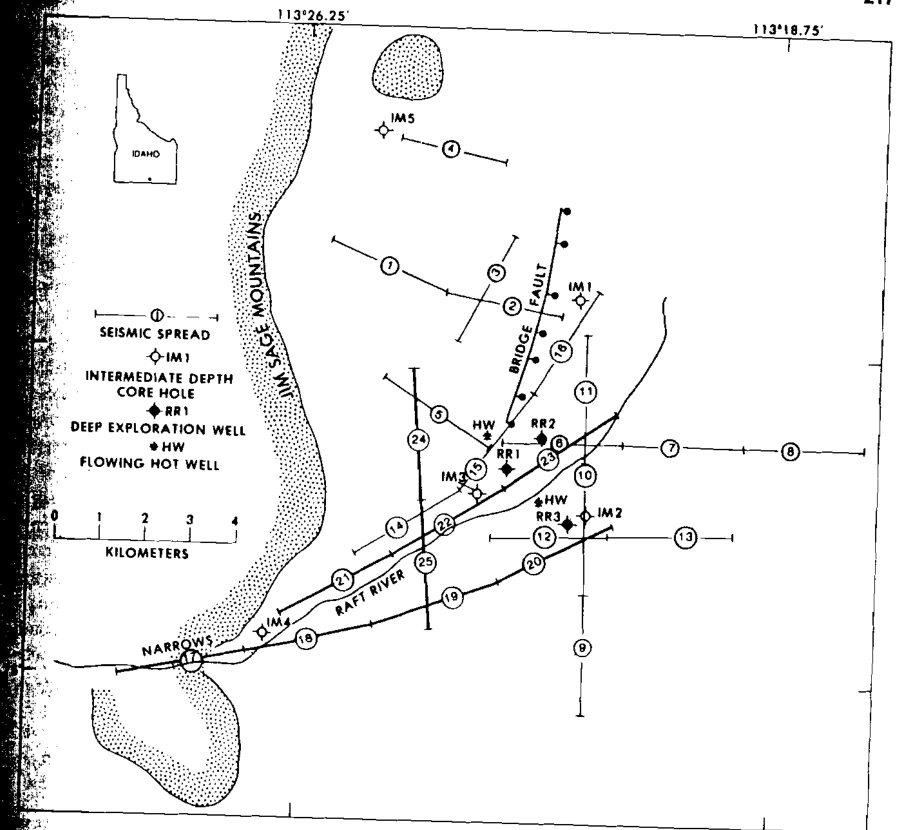

Location of seismic spreads, exploration wells, and flowing hot wells in the Raft River geothermal area. Spreads with complete reverse coverage of the basement horizon are shown with heavy lines.

lt Lake formation, overlain by a layer, up to hundred meters thick, of Pleistocene age sediments named the Raft formation, and ternary alluvium.

ting in the valley occurred as late as several thousand years ago, determined from disents within the alluvial fans. One of these named the Bridge fault, is shown in Figure 1. Raft River cuts through the southern end of the Mountains in a geologically complex place The Narrows (Figure 1). Geologic and geoal evidence (Mabey et al, 1978) suggests that a feature, possibly a basement shear, trends into rrows from the northeast. RR 1 was drilled intersection point of this inferred Narrows zone and the southward projection of the Bridge fault. This location is also within 1.5 km of the two shallow wells in the valley which produce boiling water (Figure 1).

THE SURVEY

Seismograms from 25 seismic refraction spreads, each approximately 2760 m long, were recorded in analog form. Spreads consisted of 24 single-seismometer stations. Recordings were made with fixed amplifier gain which was calibrated periodically by oscillator recordings.

Most spreads were recorded with from 7 to 11 in-line shotpoints, both internal and offset to the spreads. The purpose of the numerous shotpoints

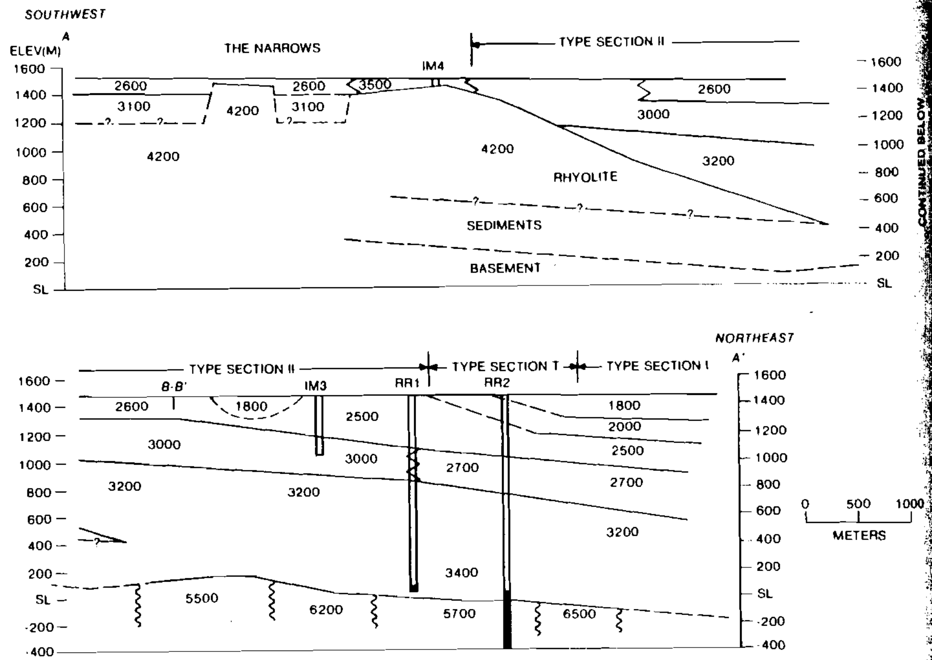

FIG. 2. Velocity section A-A′ interpreted from spreads along the Raft River. Velocities are in m/sec. Vertical exaggeration is 1.3 times. Location of A-A′ is shown in Figure 3.

was to obtain complete reversed coverage of as many refracting horizons as possible.

During the early stages of the survey, maximum in-line offset distance was only one spread length. This provided subsurface coverage to depths of roughly 1000 m. During the later stages, offsets were increased up to three spread lengths (8280 m). This procedure provided complete reversed coverage of the basement surface at a maximum depth of about 1600 m. In addition, close-in shots were continued for shallower coverage.

Shots consisted of from 5 to 100 lbs of dynamite at depths between 3 and 4 m. Shot holes were either drilled with a power auger or dug by back-hoe. Multiple shot holes were used for the larger charges to prevent surface cratering.

Spread locations and their identification numbers are given in Figure 1. The spreads for which complete reversed basement coverage was obtained are shown by heavier lines.

Seismogram quality was generally good, and first arrivals could be read with confidence. Record quality tended to deteriorate in some of the areas underlain by volcanic rocks.

INTERPRETATION METHODS AND PRESENTATION

Interpretations were made using interactive computer programs written by the author. These programs calculate the subsurface as discrete layers whose velocity can vary both vertically and horizontally. Methods and algorithms used are principally adaptations of both ray-tracing techniques (Slotnick, 1950) and, where complete reversed coverage on a given layer is available, wavefront methods (Thornburgh, 1930; Rockwell, 1967; Schenck, 1967). In the case of complete reversed coverage, computer output consists not only of depths at selected intervals beneath the spreads but also lateral velocity variations for the layer being determined. By calculating both depth and velocity changes simultaneously, models can be determined which satisfy the data to within their limits of accuracy. In this work, basement depths and the depth to a rhyolite flow predicted from the seismic data agree with later drilling results to within five percent.

The wealth of recorded data resulted in some redundancy which was helpful in providing internal checks on refraction data accuracy and computations. It also permitted calculation of more detailed models than is usual for spreads recorded from only two or three shot locations.

The interpretations are presented as velocity cross-sections in Figures 2, 4, 5, and 6. It should be kept in mind that the true geologic section is quite complex and certainly not layered with precisely defined boundaries as shown. Velocities may vary gradually both vertically and horizontally. The depth to which lateral velocity changes extend usually cannot be determined from refraction data. Therefore, the vertical jagged lines representing lateral velocity changes, in many cases, are left "hanging". Nevertheless, the cross-sections shown are thought to be a good representation of a quite complex velocity distribution.

Basement velocities exceed 5400 m/sec. The velocity cross-sections show the basement, in places, compartmented into discrete zones of constant velocity. Once again, the lateral extent of these zones is not rigorously defined, and the velocity in any zone may vary. The values shown were actually obtained by time-averaging numerous incremental velocities obtained from the computer process. In places, the basement is shown as a dashed line. Dashed lines are used wherever velocity information is insufficient to make a unique interpretation.

INTERPRETATIONS

The seismic velocity cross-sections reveal a basement of varying velocity with an overlying sequence of sediments and volcanic flows having a complex velocity distribution. An important contributing factor to this complexity may be the effects of hydrothermal fluids having interacted with the sediments. Preliminary examination of the cores from the intermediate depth holes (H. Covington, USGS, oral communication) indicates that some show such interaction through the emplacement of pyrite and other sulfides, fracture filling by secondary calcites, replacement of primary calcite by silica, a green coloration of some mudstones and claystones due to clay mineral alteration, and the possible emplacement of biotite and muscovite.

The interpreted velocity section (A-A′), obtained from spreads located from The Narrows, northeast parallel to the Raft River Valley is shown in Figure 2. The location of A-A′ is given in Figure 3. The spreads used in compiling this section are numbers 17, 18, 21, 22, and 23 of Figure 1.

The line of section A-A′ passes near two of the intermediate depth holes (IM 3 and 4) and two of the deep exploration wells (RR 1 and 2). These well locations and their depths, projected onto the line of the section, are shown as vertical bars in Figure 2. The depth at which the wells penetrated basement is shown by the change in shading of the bars.

The lower right-hand (northeast) edge of velocity section A-A′ (Figure 2) is representative of much of the sedimentary section within the study area. This type section has near-surface velocities of about 1.8 km/sec which gradually increase with depth, reaching values of about 3.0 km/sec at depths of roughly 900 m. For a basin filled with clastic sediments, this type of velocity function indicates unconsolidated or very weakly consolidated near-surface beds which gradually become indurated with depth. A velocity of 3.0 km/sec represents a well indurated though possibly porous rock (Watkins et al, 1972; Lindseth, 1976). The portion of the study area for which the interpretations reveal this type of sedimentary section will be called "type section I" (Figure 3).

Moving left (southwestward) on section A-A′, the velocity distribution suggests that the sediments become denser and less porous. Near-surface velocities, for instance, change laterally from about 1.8 to 2.6 km/sec over a distance of just a few kilometers. Much of this change is seen to occur in a transition zone roughly 1.5 km wide. This transition has similarly been noted in the interpretations of other spreads and the zone in which it occurs will be called "type section T" (Figure 3).

The portion of section A-A′ between type section T and The Narrows has near-surface velocities between 2.5 and 3.0 km/sec, which gradually increase with depth until either basement or a 4.2-km/sec layer identified as rhyolite is encountered. This type of velocity distribution has been similarly interpreted for other spreads and the included area has been designated as "type section II" (Figure 3). A fourth area, extending northwestward toward the Jim Sage Mountains, and having a somewhat similar velocity distribution has been designated as "type section IIA" (Figure 3). This type section will be discussed later.

Rapid lateral velocity changes of the magnitude shown in Figure 2 normally do not occur in intermontane basins (Eaton and Watkins, 1967; R. H. Godson, USGS, oral communciation). Thus, facies change due to sorting, though possibly a contributing

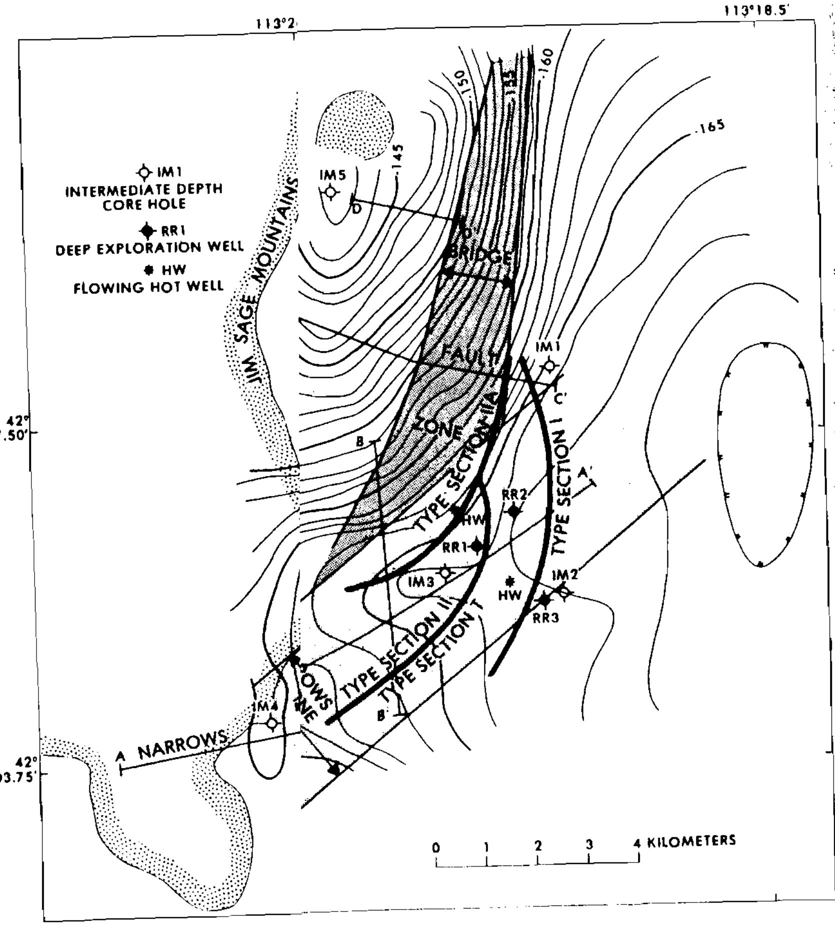

FIG. 3. Map showing locations of v(sections A-A', B-B', C-C', and D-D', the boundaries of type sections I, T, II and IIA, the exploratic flowing hot wells, the Bridge fault zone, and the inferred Narrows zone and Bouguer gravity anomaly c's (Mabey et al, 1978).

factor, can hardly be the major cause:se lateral velocity variations. Instead, they m due to a lateral change in the degree of in›n of the materials comprising the basin. S possible causes have been considered, such a: basement structures having displaced upward indurated beds, or the presence of shallow lava (However, the drilling and seismic results sh'idence of neither. There is evidence suggestinmajor low angle gravity faults have displaced ›cks overlying basement (Mabey et al, 1978) ırthermore that these rocks are highly deforKeys and Sullivan, 1979). Unfortunately, the effect of thi possible faulting and deformation on the distributio of velocities of the basin fill cannot be assessed from the present data.

On the other hand, comparing the intermedia depth drilling results with the seismic interpretation suggests that the observed lateral velocity change may be due in large part to the action of hydrotherma fluids having indurated and altered the sedimen within the convective system.

Intermediate depth core holes, IM 1 and 2, we drilled near the boundary between type section I an

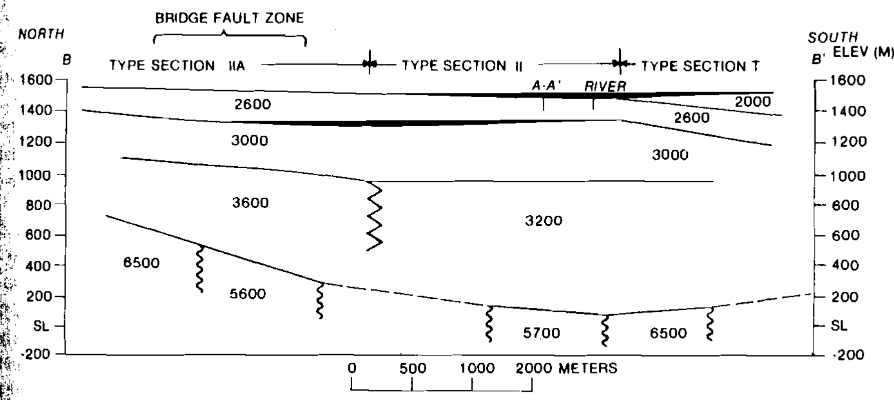

FIG. 4. Velocity sections B-B'. Velocities are in m/sec and the vertical exaggeration is 1.3 times.

type section T (Figure 3). The Raft formation penetrated by these holes is unaltered. IM 2 bottomed in the Raft formation at 232 m depth. IM 1 penetrated the Salt Lake formation at 267 m depth and bottomed in this formation at 336 m. The Salt Lake formation showed some evidence of alteration.

IM 3 was drilled to a depth of 434 m in type section II, at a location where near-surface velocities are approximately 2.5 km/sec (Figure 2). The cores revealed extensive hydrothermal alteration in both the Raft and Salt Lake formations in the form of abundant pyrite and biotite, silica- and calcite-cemented fractures, and green claystone. Furthermore, 90°C water was encountered near the bottom of the hole and numerous small high-angle faults are present.

Assuming that the rocks encountered in IM 1, 2, and 3 are representative of the type velocity sections in which they occur suggests that the shallower sediments in type section I are generally unaltered, and that the amount of alteration increases in type section T and is most intense in type section II.

There are two types of evidence suggesting that the sediments comprising type section II are quite heterogeneous. First, the near-surface interpretations have revealed several zones roughly 200 m deep whose velocity is only about 1.8 km/sec. One of these is shown in Figure 2 near IM 3. Others were detected beneath spreads 15 and 18 (Figure 1). Additional zones of low-velocity material, apparently imbedded within higher velocity rocks, were also located within type section IIA (Figure 5). Secondly, deeper within type section II, heterogeneity is implied by the rapid attenuation of first arrivals in places. (A systematic study of attenuations was not made.) Large

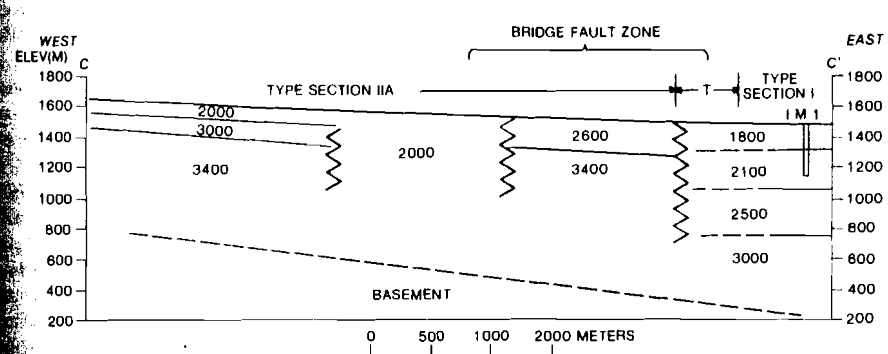

FIG. 5. Velocity section C-C'. Velocities are in m/sec and the vertical exaggeration is 1.3 times.

attenuation coefficients for seismic waves within other geothermal areas have been measured previously by Hill (1976) and Hochstein and Hunt (1970). Rapid attenuation of refracted seismic arrivals is commonly due either to thin high-velocity beds imbedded in lower-velocity strata, scattering caused by numerous random reflecting surfaces, lateral change in rock properties, or a tortuous travelpath for refracted initial arrivals. It is suggested that a nonuniform alteration process more or less randomly affecting different zones within the subsurface could be an important factor contributing to the heterogeneity noted above.

The southwest end of section A-A′ (Figure 2) is in The Narrows where the Raft River cuts through the rhyolite flows of the Jim Sage Mountains. Within The Narrows, the interpretations show the rhyolite as a very irregular layer, of 4.2 km/sec velocity, close to the surface in places and several hundred meters deep in others (Figure 2). Northeast of The Narrows, the rhyolite forms a rather steeply dipping layer projecting out into the valley. IM 4 was drilled at the mouth of The Narrows near the line of section A-A′. This hole bottomed in rhyolite at 41 m depth.

Seismic interpretations of the basement horizon along section A-A′ show it to be a slightly undulating layer dipping to the northeast, with velocities which vary between 5.5 and 6.5 km/sec.

The three deep exploration wells, RR 1, 2, and 3 were each drilled into or very near the edge of type section T. RR 1 and 2 are about 370 m north of section A-A′. They encountered crystalline basement (mostly quartz monzonite) at depths of 1395 and 1420 m, respectively. Projected onto the line of the section, these depths are about 70 m shallower than calculated from the seismic data. RR 3, drilled about 380 m north of spread 22, encountered basement at a depth of 1610 m, about 40 m deeper than calculated at the point projected onto spread 22.

The basement depths shown on section A-A′ are probably reliable where basement is not shown to be overlain by the 4.2 km/sec rhyolite layer. Where rhyolite occurs the calculated basement depth depends on the thickness assumed for the rhyolite. Therefore, basement depth was calculated using two extremes; one, assuming that the 4.2-km/sec layer continues uninterrupted to basement; and two, assuming that the rhyolite is very thin and is underlain by 3.2 km/sec sediments. In case one, basement would be near sea level beneath The Narrows. In the latter, basement would flex upwards beneath the rhyolite to an elevation of about 600 m beneath The Narrows.

RR 2 penetrated 407 m of basement, which compares with the wavelength transmitted through that layer. A representative velocity for this section calculated from the sonic log is between 5.8 and 5.9 km/sec. This agrees approximately with the 5.7 km/sec calculated near that location from the seismic data. This single point provided the only check of the basement velocity calculations. RR 1 and 3 did not penetrate sufficient basement to allow a similar comparison.

The calculation of lateral velocity variations within basement hinges on the correct calculation of raypaths of head waves emerging from basement. Because of the complexity of the overlying section, it is doubtful that ray-tracing computations are entirely accurate. Therefore, basement velocities are not given on portions of the velocity sections where the overlying velocity distribution is in serious doubt, such as beneath the rhyolite on section A-A′, and near some large lateral velocity changes on sections B-B′ and C-C′ in Figures 4 and 5.

A laterally varying basement velocity implies some degree of heterogeneity of the basement rocks themselves. The velocity of crystalline rocks is governed to a large extent by the amount of fracturing and the manner and extent to which these fractures are closed. The zones of lower basement velocity may represent fractured zones, allowing deep circulation of water, necessary for a convective system. The high-velocity zones are relatively impermeable.

The left-hand (northern) half of velocity section B-B′ (spreads 24 and 25) and all of section C-C′ (spreads 1, 2, 11, and 16), located in Figure 3, lie on fan gravels east of the Jim Sage Mountains. Both sections cross the Bridge fault zone, defined on the basis of geologic mapping of surficial deposits (Williams et al, 1976) and gravity interpretations (Mabey et al, 1978). Section B-B′ (Figure 4) crosses the southern terminus of the fault zone where gravity interpretations suggest a widening of the zone with displacements distributed between a series of faults. At this location the seismic data interpretations show a steeply dipping basement horizon with velocities which vary between 5.6 and 6.5 km/sec. A series of small faults distributed across this zone would not be inconsistent with the seismic interpretations.

Section C-C′ (Figure 5) crosses the Bridge fault zone slightly north of its inferred intersection with The Narrows zone (Figure 3). Seismic data interpretations of the basement horizon here are based on unreversed and partially reversed profiles obtained from spreads 1, 2, and 16. These interpretations were further complicated by an extremely complex velocity distribution overlying basement as seen in Figure 5. The interpretations show an east-dipping undulating basement horizon with no indication of a single large fault. Because of uncertainties introduced by the shallow velocity distribution, the basement in section C-C′ is not shown as undulating, but simply as a straight dashed line. Once again a series of small faults superimposed on this dashed line would not be inconsistent with the seismic interpretations.

Velocity sections B-B′ and C-C′ show a 3.4 to 3.6-km/sec layer at a depth of 400–600 m. Velocities in this range were not interpreted in type sections I, T, or II, although sonic logs from the deep wells do show that in the 300 m interval immediately overlying basement, a considerable portion of the Salt Lake formation sediments do have velocities in the 3.4–3.8 km/sec range. The portion of the study area having velocities in the 3.4–3.6 km/sec range at depths of roughly 600 m or less is designated as type section IIA (Figure 3).

The rocks in type section IIA overlying the 3.4 to 3.6-km/sec layer have a velocity distribution generally similar to that in type section II. This is particularly evident on velocity section B-B′ where there is little if any change in the shallow sediments in passing from type section II to type section IIA. Velocity section C-C′, on the other hand, is different from B-B′ because it shows the transition from the unaltered sediments of type section I to type section IIA. Here the change is more dramatic than in section B-B′, owing to the fact that the entire section changes velocity at once, rather than occurring only at depths between 400–600 m. We note that the transition occurs very near the eastern edge of the Bridge fault zone.

Similar to type section II, an additional property of type section IIA is that its continuity of layering is broken by long deep zones of low-velocity material, over 1 km wide, which extend deep into the 3.4 to 3.6 km/sec layer. One of these is shown as the 2-km/sec zone near the center of section C-C′. Spread 3 which is over 2.5 km long and approximately parallels the Bridge fault zone (Figure 1) lies entirely in this zone. Another such low-velocity zone was detected beneath spread 5 (Figure 1).

The 3.4 to 3.6-km/sec layers of type section IIA have not been drilled and therefore their composition can only be inferred. They may be rhyolite flows, similar to those in the Jim Sage Mountains. This possibility was initially discounted because the 3.4- to 3.6-km/sec velocity, although acceptable for rhyolite flows, is considerably less than the 4.2- to 4.5-km/sec velocity clearly identified with these rocks both in The Narrows and the east end of spread 4. However, recent interpretations (Mabey et al, 1978) suggest that low angle faults due to sliding have displaced rhyolite flows up to 3 km eastward from the Jim Sage Mountains. Thus, the 3.4- to 3.6-km/sec layer may represent rhyolite flows, the reduced velocity being due to extensive fracturing related to sliding. The large zones of low-velocity material interpreted at several places within type section IIA may be due to rupturing also caused by sliding.

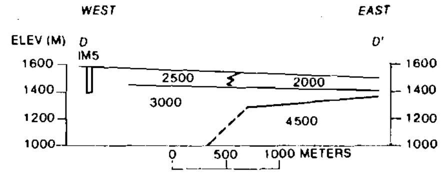

FIG. 6. Velocity section D-D′. Velocities are in m/sec and the vertical exaggeration is 1.3 times.

An alternate hypothesis is that the 3.4 to 3.6-km/sec layers are not rhyolite flows, but instead, well indurated sediments of the Salt Lake formation similar to those identified from the sonic logs within 300 m of basement. The problem then, as seen in section C-C′, is to explain the juxtaposition of 3.4-km/sec Salt Lake formation sediments against 2.1 to 3.0-km/sec sediments of the same formation; and similarly 3.6-km/sec sediments against 3.2-km/sec sediments in section B-B′. High-angle faulting, at first glance, seems a likely mechanism because the eastern boundary of type section IIA in section C-C′, coincides with the geologically mapped Bridge fault zone (Figure 3). However, faulting as the sole mechanism must be discounted because it would require roughly 700 m of vertical displacement to produce the effect seen in section C-C′, and the seismic data interpretations do not permit large basement displacements. Hence, it is suggested once again that a contributing factor to the increased velocity may be hydrothermal alteration; specifically, that the processes which have cemented, solidified, and altered the rocks at depths of over 1100 m in the deepest portion of the Raft River basin, have operated at significantly shallower depths in the area of type section IIA.

Figure 6 shows velocity section D-D′, interpreted from spread 4 recorded at the far northwestern edge of the study area. Magnetic data indicate that the east end of this section is underlain by shallow volcanic flows. The initial gravity interpretations suggested shallow pre-Tertiary basement rocks.

Because a shallow basement was assumed, this spread was recorded without offset shotpoints. The interpretation shows that the eastern half of section D-D′ is underlain at about 120 m depth by 4.5-km/sec rocks which terminate westward. They are assumed to be rhyolite because of their magnetic signature. Basement velocities were not interpreted from these data. Nevertheless, considering the high velocities of the rhyolite and the other near-surface sediments, basement could be as shallow as 600 m and not have been detected.

DISCUSSION

Three deep exploration wells in the Raft River geothermal area have penetrated a large productive reservoir containing 149°C water within the sediments of the Salt Lake formation immediately overlying basement. The initial deep well was drilled at the intersection of two inferred structures; one a north-trending normal fault and the other a northeast-trending lineament thought to be a shear zone.

Interpretations of the seismic refraction data do not reveal large basement faults. Faults with 50 m or less of vertical displacement could have been missed because of scatter in the data and a complex velocity distribution.

The interpretations do show a basement whose velocity varies laterally between 5.5 and 6.5 km/sec. The lower velocities in this range may reflect zones with fracture porosity and associated small faults. It is suggested that the necessary deep convection is through zones of this type rather than along any single major fault.

Interpretation of the data from above basement reveals a sedimentary section with a systematic lateral variation in velocity. Thus the sediments of the entire study area can be conveniently divided into four sub-areas which have been labeled type sections I, T, II, and IIA (Figure 3). The geology producing these velocity variations is not clear. Correlation with drill holes suggest that zones of higher velocity are the result of induration caused by interaction of sediments with hydrothermal fluids. Such a simple relationship is certainly complicated by factors suggested by others, such as low-angle gravity faults with associated rupturing and deformation of sedimentary beds, and by high-angle normal faults.

The velocities of the sediments within type section I are relatively low (Figure 2), and indicate unconsolidated near-surface sediments which gradually become indurated with depth. At roughly 800 m depth, velocities reach 3.0 km/sec, suggesting indurated rock which may be porous.

Type section T marks a transition zone between type section I and type sections II and IIA. Type section II has near-surface velocities generally varying between 2.5 and 3.0 km/sec which also increase with depth (Figure 2). Velocities in this range are not encountered in type section I until depths of 400 to 800 m. Intermediate depth drilling suggests that sediments with these velocities are hydrothermally altered. Deep pockets of lower velocity sediments and highly attenuated first arrivals in places suggest that the rock properties in this type section may be highly variable. A contributing factor to this variability could be a nonuniform alteration process.

The distinguishing difference between type section II and IIA occurs at a 400–600 m depth, where the rocks in type section IIA undergo a rapid increase in velocity to about 3.5 km/sec. Above this depth the velocity distributions are similar. The entire section is broken in several places by kilometer-wide zones of low velocity (approximately 2 km/sec) material which extend far into the 3.5-km/sec layer. The 3.5-km/sec layer has not been identified by drilling. It may be a fractured rhyolite flow, displaced several kilometers from near the Jim Sage Mountains by gravity sliding. In this case, the low-velocity materials may represent ruptured zones related to sliding. On the other hand, the 3.5-km/sec layer may represent well indurated, sedimentary beds of the Salt Lake formation, of about the same density as are found just above basement in the deep exploration wells. The low velocity zones then would represent gross lateral variations in density, possibly related to nonuniform hydrothermal alteration.

Assuming that hydrothermal alteration is an important contributing factor to the higher velocities of the sediments within type section II and IIA, the areal extent of these type sections (Figure 3) infers that the sediments within a large part of the study area have been hydrothermally altered. This suggests widespread near-surface geothermal activities in the geologic past. Today this shallow activity is manifested principally through two shallow wells, less than 2 km apart, which produce boiling water. They are not located deep within the area of inferred altered sediments, but instead near its edge, along the boundary between the type section T and type sections II and IIA.

The presence of shallow hot wells near the edge of an altered zone, rather than in its interior, might be expected. Geothermal activity in the Raft River area may have increased the seismic velocity of a large mass of sedimentary rocks, implying an overall increase in their density and a decrease in their porosity.

This mass of relatively impermeable rocks should tend to form a seal, forcing the further escape of hot water to the surface out along its perimeter. One thus envisions a deep source of hot water, overlain by an ever-expanding altered zone which directs the escape of hot water to its outer edge.

Using, as a working hypothesis, a model of an expanding impermeable cover over a more or less central source of hot water should direct exploration away from the perimeter and towards the center of an altered zone. The three deep exploration wells in the Raft River geothermal area were located in or near the transition zone and are within 1.5 km of the shallow flowing hot wells. Tests show that production is principally from an aquifer overlying basement, not from within the basement itself. If the above hypothesis is correct, the deep hot water source may lie to the west of the location of the three deep wells.

It has been pointed out several times in this paper that the seismic refraction interpretations show no positive evidence of faults on the basement horizon. However, Figure 10 in the Mabey et al (1978) paper shows a basement displacement, based principally on gravity interpretations, of almost 400 m at the Bridge fault zone. This displacement is too large to be reconciled with the seismic interpretations. On the other hand, we note on section C-C′ (Figure 5) that the boundary between type section IIA with type section T nearly coincides with the eastern boundary of the Bridge fault zone. These boundaries are marked by a drastic lateral change in velocity in the upper 1000 m of the section, inferring a corresponding lateral change in density. This author therefore suggests that a portion of the Bridge fault zone gravity anomaly is due to lateral density changes in the rocks overlying basement and that actual basement displacement in the fault zone is less severe than indicated.

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