ABSTRACT

Although the regional surface geology of the Snake River Plain in Idaho is well known and many shallow and a few deep holes have been drilled on the plain, major uncertainties remain concerning the structure of the plain. Seismic refraction profiles have revealed that under the plain a thin upper crust overlies a lower crust which is thicker than that under the Basin and Range province to the south. The large Bouguer gravity high over the plain reflects this thin upper crust, but in the central and western plain it also indicates a dense layer at intermediate depth. Superimposed on the gravity high is a low produced by low-density sedimentary and volcanic rocks that partly fill the depression of the plain, which is in approximate isostatic equilibrium with the adjoining highlands. The regional magnetic anomaly over the central and western plain reflects a layer of strongly magnetized rock that is probably volcanic and, in the east, an upper crust made up of a complex of magnetized bodies. Near-surface heat flow is lower over the axis of the plain than along the margins, but this may or may not reflect the deep heat flow. A large negative P-wave delay anomaly lies along the northwest edge of the eastern plain.

INTRODUCTION

The Snake River Plain, which extends in a 600-kilometer arc across southern Idaho, is the most prominent Cenozoic feature in the state (Figure 1). The plain is distinguished from the surrounding terrain by lower elevation and lower surface relief and by a complete cover of Cenozoic sedimentary and volcanic rocks. Well-defined topographic features form the boundary of the Snake River Plain throughout most of its length except in the southern part of the arc of the plain, where the moderately dissected surface of the plain rises to merge with the mountains to the south. This segment of the boundary has commonly been drawn as an arc connecting the well-defined segments to the northwest and east. However, the gravity and magnetic data suggest that the subsurface structure of the plain extends farther south, and the boundary suggested by the geophysical data will be used in this report.

The western and central segments of the Snake River Plain appear to be a fault-bounded depression containing a layer of dense, strongly magnetized rock that may be Miocene basalt overlain by silicic volcanic rocks and interbedded basalt flows and sediments. Rocks typical of the upper crust of continents may not occur under the axis of this part of the plain. The eastern Snake River Plain is more likely a downwarp containing a complex of calderas with a great thickness of silicic volcanic rocks overlain by interbedded basalt flows and sediments. Fissures, along which the younger basalts have been erupted, parallel trends of the basin and range structures to the north and south of the eastern plain and may be extensions of these structures. Although typical upper crustal rocks may underlie the eastern plain, the geologic structure in these rocks appears to be different from the adjoining regions. The evolution of the eastern Snake River Plain appears to have consisted of a northeastward-moving center of volcanism that is now at Yellowstone National Park and of an increase in the density of the crust by a corresponding thinning of the upper crust and the resulting subsidence. Current deformation of the eastern plain is a southwest extension, parallel to the plain.
The western Snake River Plain is 50 to 70 kilometers wide, trends northwest, and is generally considered to be a faultbounded depression with normal faults forming major segments of both edges of the plain (Malde, 1965). Much of the northwestern part of the western Snake River Plain is covered by Quaternary alluvium. To the southeast, the surface rocks are primarily Tertiary and Quaternary lacustrine sediments and basalt flows, and the land surface and the rocks generally dip gently toward the axis of the plain. Southwest of the plain are the Owyhee Mountains with a core of metamorphic rocks and Cretaceous granitic rock overlain by Tertiary volcanic rock. To the northeast are the Cretaceous granitic rocks of the Idaho batholith locally overlain by Tertiary volcanic rock.

Several oil and geothermal test wells have been...
drilled on the western Snake River Plain to depths as great as 4,300 meters. These wells have revealed lacustrine sediments several hundred meters thick underlain by 1,000 to 2,000 meters of basalt flows with some interbedded sediments. The two deepest holes, Chevron Highland No. 1 and Halbouty James No. 1, had reportedly bottomed in interbedded silicic volcanic rocks, lacustrine sediments, and basalt. To the southeast, one deep drill hole, 22 kilometers southeast of Mountain Home, Bostic No. 1-A, penetrated about 2,300 meters of interbedded basalt and sediment and bottomed in silicic volcanic rock (Arney and others, 1980). A drill hole about 70 kilometers south of Boise, Anschutz Federal No. 1, penetrated basalt and sediment to a depth of 800 meters and then predominately silicic volcanic rock to 3,400 meters, where granite was found (McIntyre, 1979).

The major sets of geophysical data available in the western and central Snake River Plain are regional gravity and magnetic surveys (Mabey and others, 1974; Zietz and others, 1979), a seismic refraction profile (Hill and Pakiser, 1966), and numerous thermal-gradient and heat-flow measurements (Brott and others, 1976). More detailed geophysical studies have been made in local areas, particularly near some of the deep drill holes.

The Bouguer gravity high over the Snake River Plain, which was first reported by Bonini and Lavin (1957), has been studied by several investigators. The maximum amplitude of the high, which is about 100 milligals, is over the western Snake River Plain (Figure 2). Here the crest of the high trends a few degrees more westerly than the axis of the plain and has one major offset. Steep gradients associated with the gravity high show that at least part of the anomaly is produced by a positive mass anomaly within the upper crust, but part has a deeper source. The Bouguer gravity high is approximately coincident with the topographic high. Because the isostatic compensation for the plain is unusually local, the value of isostatic anomalies computed for gravity stations on or near the plain are highly dependent on the model assumed in computing the anomaly. The free-air and Faye anomalies over southwestern Idaho average slightly positive, and those over the axis of the gravity high on the plain are more positive than the average for southwestern Idaho (Figure 3). Although the plain in the area of the crest of the gravity high may not be in complete isostatic equilibrium, the western plain as a unit appears to be in approximate isostatic equilibrium with the adjoining regions, and the relative depression of the plain probably reflects an isostatic response to the large positive mass anomaly underlying the plain.

The gravity anomaly over the western Snake River Plain can be interpreted in several ways, but most interpretations involve a combination of dense basalt and a thinning of the upper crust that underlies the plain. At least three mass anomalies contribute in a major way to the gravity anomaly over the western Snake River Plain: a thin upper crust, low-density sediment with interbedded basalt, and massive dense basalt flows. The thinning of the upper crust, indicated by the refraction data, is a large positive mass anomaly and could produce most of the gravity high. Sedimentary rocks with some interbedded basalt cover much of the western plain and in some areas are over 1 kilometer thick. The average density of these rocks is low and their effect is to reduce the Bouguer anomaly over the plain. Three drill holes (Chevron Highland No. 1, Halbouty James No. 1, and Bostic No. 1-A) on the western Snake River Plain have penetrated 2 to 3 kilometers of basalt, but the bulk density of this basalt has not been determined. The dry bulk density of forty-nine samples of basalt flows of the Miocene Columbia River Basalt Group north of the plain averaged about 2.9 grams per cubic centimeter, and seven samples of basalt flows of the Miocene Columbia River Basalt Group north of the plain averaged about 2.55 grams per cubic centimeter. Two and one half kilometers of the denser basalt would produce a 25-milligal anomaly, about one-fourth of the measured high. Three of the deep holes (Halbouty James No. 1, Bostic No. 1-A, and Anschutz Federal No. 1) found thick sequences of other volcanic rocks that, on the average, are probably less dense than the average crustal rocks.

Residual magnetic intensity over the western Snake River Plain is generally higher than over the areas to the north and south, but no magnetic feature coincides...
with the axis of the plain or the gravity high (Figure 4). The most prominent feature of the total-intensity magnetic field is a high along the south side of the plain with a less conspicuous low along the north edge. Lower amplitude highs and lows, which generally do not correlate with surface geologic features, occur over the central part of the western plain. The magnetic field can be modeled in a variety of ways, but the high along the south edge of the plain and the low along the north edge, along with the extent of the associated gradients, strongly suggests that the plain is underlain, at a depth of a few kilometers, by a layer of rock strongly magnetized in the approximate present direction of the Earth's magnetic field. At one location on the southwest side of the plain, an appendage of the magnetic high extends beyond the plain. Underlying this appendage is the only extensive body of Eocene volcanic rock exposed south of the plain.

Shot points along the seismic-refraction profile that extends south across the plain from near Boise were at Lucky Peak Reservoir north of the plain, at C. J. Strike Reservoir near the axis of the plain, and at Mountain City south of the plain. In addition, underground nuclear tests on the Nevada Test Site were recorded. Several interpretations have been made of the data obtained, and although interpretations differ in detail, they agree that the total crust under the plain is over 40 kilometers thick, which is about 10 kilometers thicker than in central Nevada, and that the upper crust is thin under the axis of the plain (Hill and Pakiser, 1966).

Heat-flow measurements in southwestern Idaho have defined a heat-flow high along the margins of the plain and a relative heat-flow low over the plain (Figure 5). Brott and others (1978) conclude that a large heat source underlies the plain and that the heat-flow values measured in the near surface result from thermal refraction in the sedimentary and volcanic rocks underlying the plain and from the low heat generation of the rocks in the upper crust under the plain.

The gravity, magnetic, and seismic data have been combined to produce an interpreted profile across the
western Snake River Plain. The extent of the flanks of the gravity high beyond the plain require that a part of the positive mass either extends across the borders of the plain or lies at depths greater than 10 kilometers below the surface of the plain. Thus, the anomaly is not produced entirely by dense rock underlying the plain at depths of less than 10 kilometers. Very likely, the part of the anomaly with a deep source relates to the thinning of the upper crust as indicated by the refraction data. The steepest gravity gradients associated with the high, however, require a source above 10 kilometers. Some of these steep gradients can be attributed to variations in the thickness of the low-density sedimentary and silicic volcanic rocks, but a high-density mass above 10 kilometers is also indicated. If the magnetic anomaly over the plain is assumed to reflect a layer of dense, strongly magnetized rock, the magnetic data can be used with the gravity data to infer the depth and extent of this unit. The near-surface anomalies can be attributed to variations in the thickness and density of overlying low-density rocks and the remaining gravity anomaly attributed to the thinning in the upper crust. Such a model is shown in Figure 6. Large variations in this model are possible (for example, see Mabey, 1976), but good evidence exists for the approximate position and size of the major units.

Southwest of Boise, the crest of the gravity high along the axis of the plain is offset about 30 kilometers in a right-lateral sense (dashed line, Figure 2). This offset may reflect displacement upon a north-trending strike-slip fault. Such an offset is consistent with the magnetic data and the configuration of the southwest margin of the plain. North of the plain, the
trend of the offset projects along the linear western margin of the exposed part of the Idaho batholith. If the two highs reflect a geologic unit that has been offset, the offset probably occurred after most of the mass anomalies underlying the plain were emplaced but before part of the relative subsidence of the plain that produced the present topography occurred.

All of the geological and geophysical evidence is consistent with major segments of the western Snake River Plain being bounded by normal faults, although these faults may not have been the fundamental structure that formed the plain. A thick sequence of volcanic and sedimentary rock underlies the plain, but what, if any, pre-Cenozoic basement underlies the plain is not known. The large Bouguer gravity high and the approximate isostatic equilibrium of the plain relative to the adjoining highlands is in marked contrast to the basin and range structures to the south. With the basin and range structures, gravity highs do not occur over the basins; isostatic balance does not exist between the basins and the ranges; and the bounding faults do not appear to extend deep into the crust (Mabey, 1966). In contrast, the structure of the western Snake River Plain extends deep into and perhaps through the crust. If the term graben is used to describe the western Snake River Plain, a qualifying statement should be included noting that pre-Cenozoic rocks similar to those exposed north and south of the plain are not known to be downfaulted under the plain.

The western Snake River Plain has been described by Warner (1975) as a lateral rift, and by several others as a rift. Warner cites several lines of evidence to prove that 80 kilometers of left-lateral displacement has occurred along the Snake River Plain, mostly since early Pleistocene time. He also infers some separation across the western Snake River Plain. Yet, Warner's evidence for lateral movement does not appear to have been generally accepted by investigators of the plain. The trend of the western Snake River Plain is approximately parallel to the San Andreas and related faults southwest of the plain, but no evidence of the right-lateral movement of this system along the plain has been reported. Although the geophysical data do not establish that lateral movement has not occurred along the western Snake River Plain, lateral movement does not appear to be a likely cause of the major geophysical anomalies associated with the plain.

Several investigators have inferred a relationship
between the western Snake River Plain and a better exposed but narrower rift of parallel trend in northern Nevada (Christiansen and McKee, 1978; Zoback and Thompson, 1978; Mabey, 1976). The rift in Nevada, which is Miocene in age, consists of a swarm of basalt dikes overlain by a graben, filled with basalt flows and sediments. Christiansen and McKee suggest that the rift in Nevada and the western Snake River Plain developed as a continuous rift about 17 million years ago. They postulate that the two structures were offset in a right-lateral sense by a transform fault coincident with the eastern Snake River Plain and the Brothers fault zone and related fault zones in Oregon.

If a rift is defined as an elongate rupture of the entire thickness of the lithosphere under tension, such an origin of the western Snake River Plain appears consistent with most of the geological and geophysical evidence. The upper crust apparently was thinned or pulled apart as major extension began about 17 million years ago, and the resulting depression was filled with upwelling basalt and debris from the adjoining highlands. The only major inconsistencies are the cuttings of granitic rock reported from the bottom of the deep drill hole 70 kilometers south of Boise (McIntyre, 1979) and the suggestion given by the magnetic high over Eocene volcanic rocks south of the plain that the magnetic high under the plain may relate to Eocene volcanic rocks. The presence of granitic basement at the bottom of the drill hole overlain by a section of volcanic and sedimentary rocks that were not strongly magnetized is not consistent with the measured magnetic anomaly, which requires strongly magnetized rock at depth. Perhaps, the granite is a relatively thin slide block, a floored intrusive unit, or a narrow sliver. The possibility that a thick sequence of pre-Miocene volcanic rock may underlie the western Snake River Plain has not been evaluated.

The western Snake River Plain appears to be a rift. However, the western Snake River Plain differs significantly from typical modern continental rifts such as the Rio Grande rift in Colorado and New Mexico and the Dead Sea and east African rifts. One prominent difference is that the other rifts coincide with gravity lows produced by low-density sediments within the rift. Although the sediments underlying the western Snake River Plain produce a gravity low, the low is much smaller than the larger gravity highs with approximately the same extent produced by deeper mass anomalies. The gravity anomaly is similar to that in the Salton Trough or the mid-continent gravity high.

Two primary structures can explain the heat-flow pattern in the western Snake River Plain. Brott and others (1978) propose the emplacement of a large heat source under the plain about 20 million years ago and the development of an overlying crust with low thermal conductivity and low heat-generating capacity. The resulting model would account for the measured high heat flow along the margins of the plain and the low values on the plain. An alternate explanation would involve the continued extension concentrated along the margins of the plain and
continued subsidence as the plain seeks isostatic balance. Either thermal model is consistent with the formation of the western Snake River Plain in Miocene time as a tension rift.

CENTRAL SNAKE RIVER PLAIN

The boundary between the western and central Snake River Plain is here taken as an east-northeast line extending across the Snake River Plain from the south end of the Owyhee Mountains at Poison Creek to the southern flank of the Mount Bennett Hills (Figure 1). Southeast of this line the plain widens as the southwest margin of the plain loses topographic expression and bends to the south and as the northeast margin curves to the east and also becomes a less prominent topographic feature. The prominent magnetic high that lies along the southwest margin of the western plain bends to the south and continues to near the Idaho-Nevada border (Figure 4). Here, the high makes a bend of about 90 degrees to the east, and generally corresponds to the margin of the Bruneau-Jarbidge eruptive center (Bonnichsen, 1982 this volume). A less prominent gravity gradient is coincident with the magnetic anomaly. The margin of the Snake River Plain in this segment has no well-defined topographic or surface geologic expression and is here assumed to coincide with the south edge of the subsurface mass indicated by the magnetic high and the gravity gradient.

Silicic volcanic rocks extend southwest of the plain into northern Nevada and southeast Oregon. South of the plain silicic volcanic rocks lap onto a highland in northern Nevada with a core of pre-Tertiary sedimentary and intrusive igneous rocks and onto the Albion Mountains with a core of Precambrian gneiss domes. On the north are the Tertiary silicic volcanic rocks of the Mount Bennett Hills and further north, beyond the west-trending Camas Prairie, is the Idaho batholith.

The Tertiary sedimentary rocks that cover much of the surface of the western Snake River Plain extend into the northwest part of the central plain, but most of the central plain is covered by volcanic rocks. In the west and south, the volcanic rocks are Miocene and Pliocene rhyolite overlain by Pliocene and Quaternary basalt and, in the east, Quaternary basalt. Faults trending north to northwest are common in the older volcanic rocks. No data from deep holes are available from this part of the plain, but Bonnichsen (1982 this volume) has suggested that calderas are beneath this area, buried within the Bruneau-Jarbidge eruptive center.

Although the gravity and magnetic features along the north edge of the western Snake River Plain generally parallel its margin, the magnetic low is interrupted where this margin of the plain begins the eastward arc. Patterns in both the gravity and the magnetic data can be interpreted to indicate a structure across the plain on a projection of the linear northeast border of the western plain (Figures 2, 3, and 4). A northwest grain in the magnetic data is apparent to the east of this projection.

The amplitude of the gravity high over the central segment of the plain is about 75 milligals, contrasted with 100 milligals over the western plain. The crest of the gravity high lies near the north edge of the plain, and in two places to the south (Figure 2), closed gravity highs trend parallel to this main gravity crest. Although the amplitude of the gravity high over the central plain is lower than over the western plain, the plain and the total gravity high are broader and the cross-sectional area of the positive mass underlying the central plain is as large or larger than that under the western plain.

The magnetic pattern over the central Snake River Plain is similar to that over the western plain but the amplitude of the high along the south edge is greater. A northwest grain to the magnetic anomalies is also more prominent, particularly in the eastern part.

No deep seismic-refraction data are available across the central Snake River Plain, but the gravity anomaly suggests a thinning of the upper crust. The thinning, distributed over a greater width than under the western plain or shallower positive mass anomalies, may cause the greater width of the gravity high. As in the western plain, a layer of dense, strongly magnetized material appears to be overlain by less dense and less strongly magnetized rock.

The heat-flow pattern over the central plain is similar to the west except that high heat flow on the southwest is continuous with the large area of high heat flow in northern Nevada (Figure 5). The model of Brott and others (1981) for the western plain also applies to the western part of the central plain, but to the east an area of low heat flow related to the horizontal movement of ground water in volcanic aquifers extends into the central plain.

The similarity between the geophysical anomalies and the geology in the western and central Snake River Plain suggests that these two parts of the plain have a similar origin. One explanation is that they both developed during extension in response to regional tension approximately normal to the trend of the present western Snake River Plain. Southwest of the edge of the Idaho batholith, the extension and the resulting thinning of the upper crust and subsidence of the surface may have been concentrated in a narrow zone, thus producing the structure of the western Snake River Plain. Southeast of the batholith,
the extension may have been distributed over a wider zone producing the structure of the central Snake River Plain. If the crest of the gravity high reflects the zone of maximum thinning of the upper crust, the eastward arcing of the crest of the gravity high suggests a greater south component of movement of the block south of the Idaho batholith. Perhaps the block south of the plain was rotated clockwise.

**EASTERN SNAKE RIVER PLAIN**

The magnetic and gravity patterns change abruptly on the east at a zone that trends northwest across the plain from the northeast end of the Albion Mountains (dashed line, Figure 1). Southwest of this zone, a pronounced single or compound gravity high trends subparallel to the plain. Northeast of the zone, the Bouguer gravity anomaly is generally higher than over adjoining areas but consists of a complex pattern of highs and lows with the largest closed gravity high elongated approximately normal to the axis of the plain. No continuous magnetic high lies along the south edge of the eastern plain. Over the plain instead is a series of magnetic highs and lows with high amplitude and a grain normal to the plain. Thus, no evidence exists of a dense, strongly magnetized layer underlying the eastern Snake River Plain. The land surface along most of the axis of the eastern plain is higher than the margins, indicating greater recent subsidence of the margins.

Southeast of the eastern plain are basin and range structures trending approximately normal to the plain. The ranges are primarily folded pre-Tertiary sedimentary rock, and the valleys commonly are underlain by thick accumulations of Cenozoic sediments. Pliocene and Quaternary volcanic rock occur in several areas. Northwest of the eastern plain is a zone of basin and range structures flanked on the southwest by the Pioneer and White Knob Mountains and on the northeast by the east-trending Centennial Mountains. Folded pre-Tertiary sedimentary rocks are the most common rocks in the ranges north of the eastern plain, but Eocene extrusive and intrusive igneous rocks are abundant. Geologic mapping north and south of the plain has not revealed any evidence of lateral movement parallel to the axis of the plain (S. S. Oriel, oral communication, 1980).

Most of the eastern Snake River Plain is covered by Quaternary basalt flows. The younger flows appear to have erupted along fissures normal to the plain approximately parallel to and in some places along extensions of basin and range structures to the north and south. Rhyolite domes ranging in age from 0.3 to 1.5 million years rise above the surface of the basalt in the central part of the eastern plain (Kuntz and Dalrymple, 1979; Spear and King, 1982 this volume). Rhyolite ash flows are common around the margins of the plain, and rhyolite has been found in all of the deeper drill holes on the plain. Cenozoic sediments are abundant in the surface and shallow subsurface near the margins of the plain. Although cracks and fissures with trends generally normal to or parallel to the axis of the plain are common, evidence of displacement along them is rare.

The structure of segments of the margins of the eastern Snake River Plain appear to differ. The linearity and steep gravity gradient parallel to the margin of the plain east of Arco suggest a normal fault near the plain margin. Along the south edge of the plain west of Pocatello, the ranges appear to dip under the margins of the plain but the gravity data suggest they are terminated in the subsurface a few kilometers to the north. East of Idaho Falls, a segment of the margin of the plain is coincident with the edge of the Rexburg caldera complex (Embree and others, 1982 this volume).

Although the eastern Snake River Plain extends into the Intermountain seismic belt, there are few earthquakes under the plain. Apparently, whatever deformation is occurring does not involve large-scale brittle failure of rocks underlying the plain.

Northeast of the eastern Snake River Plain lie the large Island Park and Yellowstone caldera complexes. Another large caldera complex, the Rexburg caldera complex, has been identified on the eastern Snake River Plain, and the existence of several others has been inferred (Embree and others, 1982 this volume). A northeast decrease in age of the silicic volcanic rocks in and adjacent to the plain has been noted from southwestern Idaho to Yellowstone National Park (Armstrong and others, 1975). This large-scale progression has been interpreted as indicating that the central and eastern Snake River Plain coincides with the track of a northeastward-moving center of silicic volcanism (Christiansen and McKee, 1978).

Only one deep hole has been drilled on the eastern Snake River Plain. This hole, which is on the Idaho National Engineering Laboratory about 30 kilometers east of Arco, was 3,155 meters deep and was bottomed in a hydodacite porphyry. The rock in the lower part of the hole, which has been dated at 11.2 million years (McBroome, 1981), may be an ash-flow tuff or a high-level intrusive rock. Doherty and others (1979) suggest that this hole was drilled into a caldera. Drilling and resistivity soundings (Zobey and Bisdorf, 1980) suggest that Quaternary basalt is generally less than 1 kilometer thick on the eastern plain, although in part of the area it may be thicker.

Extensive seismic-refraction profiling has been done in the eastern Snake River Plain and Yellow-
stone National Park. Preliminary reports on the interpretation of these data suggest that the velocity structure of the crust under the eastern Snake River Plain is similar to that of the western plain with a thin upper crust and a thick lower crust and suggests that the total crust thickens northeastward toward Yellowstone National Park (Braile and Smith, 1979).

The regional gravity high centered over the eastern Snake River Plain extends well beyond the plain (Figure 7). This high apparently reflects the thinning of the upper crust toward the center of the plain indicated by the refraction data, and the thinning appears to extend well beyond the plain. Superimposed on this high are two gravity lows produced by the Cenozoic sedimentary and volcanic rocks underlying the margins of the plain. The maximum thickness of these Cenozoic rocks has not been determined, but it is likely to be several kilometers.

The source of most of the extensive magnetic highs on the eastern Snake River Plain is uncertain. The basalt flows in the near surface of the plain are strongly magnetized with both normal and reversely magnetized flows, but the more extensive magnetic highs have been interpreted as having a deeper source (Bhattacharyya and Mabey, 1980). Some of the highs on the plain near the south edge are over uplifted blocks of Cenozoic rock and can be inferred to relate to underlying Cenozoic intrusive rocks. Eaton and others (1975) and Mabey and others (1978) have pointed out that the eastern Snake River Plain is part of a northeast-trending magnetic zone: the Humboldt zone, that extends through Yellowstone National Park. To the northeast of Yellowstone, this zone is reflected in Precambrian rocks. Although the source of the deeper magnetic anomalies over the eastern Snake River Plain is uncertain, the crust under the plain is composed of more strongly magnetized units than adjoining areas.

Deep conductivity data are available in the eastern Snake River Plain from magnetotelluric (Stanley and others, 1977) and magnetic variometer soundings (Fitterman, 1979; Wier, 1979). Published interpretations of the magnetotelluric data indicate a conductive layer in the crust at depths of from 12 to 22 kilometers, but neither technique reveals a deep conductive anomaly coincident with the plain.

A delay of up to 1.5 seconds in teleseismic P-wave arrivals suggests that a low-velocity zone extends to depths of over 200 kilometers under the northwest edge of the eastern Snake River Plain (Evans, 1981). This anomaly is a westward continuation of the P-wave delay anomaly underlying Yellowstone National Park. Thus, the Snake River Plain appears to be offset from the low-velocity zone in the mantle. Shear wave velocities of the crust and upper mantle are lower under the eastern Snake River Plain than in the Basin and Range province to the south (Greensfelder and Kovach, 1980). Both low-velocity anomalies might reflect high-temperature zones.

Although the surface relief across the eastern Snake River Plain is about equal to that of the plain farther west, the gravity and magnetic anomalies suggest a somewhat different crustal anomaly. Rather than an abrupt thinning or perhaps complete parting of the upper crust, as appears to have occurred in the western plain with an outpouring of large volumes of basalt, the thinning of the crust under the eastern plain is a broader feature; no evidence of large early eruption of basalt is apparent. Instead, a complex of silicic volcanic rocks and related intrusive bodies appear to underlie most of the eastern plain.

The heat-flow pattern over the eastern plain is also similar to that in the west. Over most of the eastern plain, the near-surface heat flow is disturbed by the southwestward movement of ground water down the plain in the volcanic aquifer that underlies most of the eastern plain. Brott and others (1981) believe that this movement of water is the cause of the low heat flow measured over the interior of the plain and that the heat flow under the aquifer is very high. However, the thermal data from the three holes drilled through the aquifer in the INEL area of the plain do not confirm that the thermal gradients below the aquifer are higher than those along the margins of the plain.

The free-air gravity anomaly indicates that the eastern part of the Snake River Plain, like its central and western segments, is in approximate isostatic equilibrium with the adjoining highlands. The thinning of the upper crust under the plain represents a positive mass anomaly that is the compensation for the low surface elevation of the plain. The relative thinning of the upper crust could result from extension normal to the plain, from lateral mass transfer.
related to igneous activity, or a combination of the two. Extension normal to the plain would account for the thinned upper crust, and the concentration of the thinning near the margins could explain the apparent subsidence and high heat flow there. However, the evidence of northwest regional extension in this part of the western United States in late Tertiary and Quaternary time is unconvincing. The average density of the crust can also be increased by the ejection of lower density material in volcanic eruptions; however, there is no evidence of the very large eruptions that would be required to remove the volume of upper crustal material necessary to produce the density decrease indicated by the gravity anomaly.

In its simplest form, the thermal model suggests a heat source propagating northeast relative to the surface from southwest Idaho to a current position under Yellowstone National Park. Brott and others (1981) propose a quantitative model with a 120-kilometer-wide heat source plane normal to the Snake River Plain moved through a 42-kilometer-thick slab of lithosphere at a velocity of 35 millimeters a year. The model combines the heating and cooling in this thermal event with a density increase under the plain, which they believe could be caused by extension, dispersion of granitic material, extrusion of ash flows, or erosion. In this model, the major subsidence of the plain is caused by isostatic adjustment of the density increase. In their model, the continued subsidence is caused by contraction due to cooling, as is the development of rifts and the elevation decrease of the plain toward the southwest. Morgan (1972) had earlier suggested that the Snake River Plain is the track of a mantle plume over which the continent moved in Cenozoic time, whereas Smith and Christiansen (1980) suggest a mantle hot spot. Blackwell (1978) has suggested that the heat source is related to magma developed over a subducted slab. Others have suggested that the Snake River Plain is a zone of extension or a propagating fracture (Hamilton and Myers, 1966; Lachenbruch and Sass, 1978; Smith, 1977, 1978; Furlong, 1979). In these models, a mechanical process is the primary cause of the structure and the thermal events. Numerous combinations of thermal and mechanical processes are possible. A further complication is that the low-velocity zone in the mantel indicated by the P-wave delay anomaly, which is probably related to a deep heat source, lies north of the plain.

Numerous fractures extend inward from the margins of the eastern Snake River Plain. From segments of these fractures, large volumes of basalt have erupted; other are open fissures in basalt flows (Kuntz and others, 1982 this volume; King, 1982 this volume). These fractures must be tensional features related to extension parallel to the axis of the plain; the fact that basalt is erupted through them suggests that they extend to great depth. The model of Brott and others (1981) suggests that cooling and related contraction at depth could account for the opening of the rifts normal to the axis of the plain. However, these rifts may reflect a more regional extension suggested by the basin and range structures to the north and south.

The most prominent volcanic rift on the eastern Snake River Plain is the Great Rift along which the Craters of the Moon lava field occurs. On the north, this rift is coincident with an aeromagnetic anomaly that extends across the edge of the plain and for 100 kilometers north of the plain. To the north this anomaly is coincident with a zone which contains several Cenozoic plutons. On the plain, the rift arcs to the south to parallel basin and range structures south of the plain. Thus, the rift appears to be related to structures that extend beyond the plain.

The apparent relationship between the rifts on the eastern Snake River Plain and the basin and range faults to the north and south suggests they represent different responses to extension of the crust approximately parallel to the axis of the plain. Normal faults south of the plain, and presumably those north of the plain, appear to be controlled by old structures, many related to overthrusting; many of the normal faults flatten at depth to merge with major thrust faults. Movement along these faults results in a thinning of a surface layer that appears to generally correspond to the allochthonous unit involved in the thrusting. The underlying layer appears to extend by ductile flow without the development of major normal faults. Although the belt of overthrusting probably initially extended across the area of the Snake River Plain, subsequent igneous activity along the plain and perhaps extension normal to the plain have disrupted the thrust faults. Current extension of the upper layer on the plain is not accommodated along preexisting thrust faults but rather occurs by the opening of vertical fractures to the depth at which extension is by ductile flow. The greater subsidence of the margins of the plain could occur under tension parallel to the margins, if the ductile layer is thicker there, or it may reflect the development of more local isostatic balance.

Although the entire Snake River Plain appears to be in approximate isostatic equilibrium with the area to the north and south, a more regional isostatic anomaly is apparent on the Faye or average free-air anomaly map of southern Idaho (Figure 3). Over most of southern Idaho, the average free-air anomaly values are positive, as contrasted with near-zero values in Nevada (Mabey, 1966). However, the southeastern Idaho values are even more positive with most of the area higher than +20 milligals. The isostatic equilibrium of the plain relative to adjacent areas superimposed on a more regional isostatic
disequilibrium suggests that the compensation of the plain occurs at relatively shallow depths but that a much larger region apparently centered northeast of the Snake River Plain is undercompensated. Perhaps, deep dynamic forces account for a part of the high elevation of this large region.

CONCLUSIONS

Geophysical data and deep drilling have been used to obtain information on several aspects of the deep structure of the Snake River Plain. Major problems addressed are: (1) What regional anomalies in the crust and upper mantle are associated with the plain? (2) What is the nature of the stress fields and thermal events that have formed the plain? (3) What is the age of the plain? (4) What is the primary structure of the major segments of the plain? (5) What rocks underlie the plain at depths greater than the deeper drill holes? (6) Do structural patterns adjacent to the plain extend onto the plain?

The entire Snake River Plain appears to be underlain by a thicker crust than the Basin and Range province to the south. The Snake River Plain crust consists of a thin upper crust and thick lower crust. P-wave delays and shear-wave velocities indicate that the mantle underlying the region of at least the eastern Snake River Plain is also anomalous. The velocity structure of the eastern Snake River Plain has been studied intensely in recent years, and an analysis of the data obtained will provide a velocity model of this part of the plain. More refraction data are needed to define the velocity structure of the central and western plains. The anomalous crust and upper mantle very likely are directly related to the formation of the plain and probably preceded or accompanied the formation of the plain. The thin upper crust can be explained by extension, but the cause of thick lower crust is not obvious. Brott and others (1981) postulate that magma above a subducting slab coalesced under the Snake River Plain in the manner that salt flows laterally into an initial perturbation. A mantle hot spot or plume may have thickened the lower crust as it moved under the plain. The Snake River Plain-Yellowstone crust and upper mantle appear to be a unique intraplate anomaly, and the events in its development are not yet understood. Regardless of how the crustal and upper mantle anomaly under the Snake River Plain formed, the structure of the upper crust underlying the plain appears to have developed in a regional stress pattern that is much more extensive than the plain.

The Snake River Plain is a major feature in the crust. Active volcanism, open fissures, and evidence of continued subsidence show that the plain is an active structure that continues to develop. A suggestion exists in the magnetic data that the eastern Snake River Plain may be part of a northeast trend reflected in Precambrian rocks to the northeast, but no evidence has been reported to suggest that the plain existed before Miocene time. Several lines of evidence do suggest that the development of the plain may coincide with the large-scale extension of the Basin and Range province to the south, which began about 17 million years ago.

The western and central Snake River Plain appears to be, at least in part, a down-faulted block. It may be termed a graben or a rift but differs from typical continental grabens and rifts. It probably developed in Miocene time in response to west-southwest regional extension, and perhaps clockwise rotation of the block south of the plain, which greatly thinned or completely parted the upper crust. The gravity and magnetic data suggest that a thick layer of dense strongly magnetized rocks formed within the resulting depression. The plain has continued to subside perhaps because of cooling, continued tension, loading of sediment, and isostatic adjustment due to the large positive mass under the plain.

The eastern Snake River Plain appears to have a more complex history than the western plain. The eastern plain is basically a downwarp containing numerous calderas. Extension normal to the plain is a possible explanation for the thinned upper crust under the plain and the high thermal flux indicated by the intense volcanic activity. Alternately, the plain may represent the track of a thermal anomaly now centered under Yellowstone National Park that moved northeastward across southern Idaho producing a complex of calderas that are now largely obscured by younger basalt flows on the Snake River Plain. Such a thermal event can be used to explain the formation of the eastern Snake River Plain only if some mechanism for the development of a large positive mass anomaly under the plain is also involved. The current tectonics of the eastern plain appear to be extension parallel to the axis of the plain.

The gross structure of the central Snake River Plain combines elements of both the western plain and the eastern plain. There is evidence of a downfaulted block filled with dense, strongly magnetized rock, but the current deformation appears to be downwarping. This segment of the plain probably formed with the western plain but has an overprint of the structure of the eastern plain.

What rocks and structures underlie the Snake River Plain at great depth remains unknown. One of the deep drill holes on the western Snake River Plain apparently bottomed in granite, which could be part
of an extensive Cretaceous mass of granite that makes up the Idaho batholith north of the plain and is present south of the plain in less extensive outcrops in southwestern Idaho and northern Nevada. However, the very large gravity and magnetic anomalies over the western plain suggest that the crust under the plain is drastically different from adjoining areas. Thus, it appears unlikely that the pre-Tertiary rocks north and south of the western plain make up the bulk of the crust under the plain. The magnetic anomaly and particularly the gravity anomaly over the eastern plain are not as profound as over the western plain. The upper crust under the eastern plain is composed of more magnetic units than are adjoining areas, indicating a greater abundance of igneous rocks in the crust under the plain. The response of the eastern plain to the regional stress is very different from areas to the north and south. This suggests that the structure and perhaps the lithology are different. The average density of the upper crust under the eastern plain is probably not greatly different from the adjoining areas, but intense igneous activity in Cenozoic time has probably produced major changes in the lithology and destroyed most of the older structures. The basin and range structures north and south of the eastern Snake River Plain either terminate at the margin of the plain or extend only a few kilometers onto the plain. However, the pattern of volcanic rifts on the plain suggests that they may be related to the basin and range structures.

Concealed beneath a complete cover of Cenozoic sediments and volcanic rocks, several fundamental aspects of the deep structure of the Snake River Plain remain uncertain despite the acquisition of considerable regional geophysical data and the drilling of several holes to depths of over 3 kilometers. More geophysical data and creatively combined interpretations of all of the available data will continue to add to our understanding of the area, but many critical data can be obtained only by drilling very deep holes and taking continuous core samples.

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