Regional implications of heat flow of the Snake River Plain, Northwestern United States

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(Received March 24, 1988; revised version accepted October 24, 1988)

Abstract


The Snake River Plain is a major topographic feature of the Northwestern United States. It marks the track of an upper mantle and crustal melting event that propagated across the area from southwest to northeast at a velocity of about 3.5 cm/yr. The melting event has the same energetics as a large oceanic hotspot or plume and so the area is the continental analog of an oceanic hotspot track such as the Hawaiian Island–Emperor Seamount chain. Thus, the unique features of the area reflect the response of a continental lithosphere to a very energetic hotspot. The crust is extensively modified by basalt magma emplacement into the crust and by the resulting massive rhyolite volcanism from melted crustal material, presently occurring at Yellowstone National Park. The volcanism is associated with little crustal extension. Heat flow values are high along the margins of the Eastern and Western Snake River Plains and there is abundant evidence for low-grade geothermal resources associated with regional groundwater systems. The regional heat flow pattern in the Western Snake River Plains reflects the influence of crustal-scale thermal refraction associated with the large sedimentary basin that has formed there. Heat flow values in shallow holes in the Eastern Snake River Plains are low due to the Snake River Plains aquifer, an extensive basalt aquifer where water flow rates approach 1 km/yr. Below the aquifer, conductive heat flow values are about 100 mW m⁻². Deep holes in the region suggest a systematic eastward increase in heat flow in the Snake River Plains from about 75–90 mW m⁻² to 90–110 mW m⁻². Temperatures in the upper crust do not behave similarly because the thermal conductivity of the Plio-Pleistocene sedimentary rocks in the west is lower than that in the volcanic rocks characteristic of the Eastern Snake River Plains. Extremely high heat loss values (averaging 2500 mW m⁻²) and upper crustal temperatures are characteristic of the Yellowstone caldera.

Introduction

The Snake River Plain (Fig. 1) has been a focus of an extensive series of heat flow studies (Brott et al., 1976, 1978, 1981). The purpose of this report is to discuss new temperature gradient and heat flow data for the Western Snake River Plain, representing a continuation of these studies, to summarize all heat flow data, to discuss new thermal data from deep holes, and to discuss the regional implications of the thermal character. The detailed data are presented together with extensive information for other areas of Idaho, especially the southern part of the Idaho batholith, by Blackwell (1989). These data allow a detailed analysis of the heat flow, the geothermal gradient distribution, and the regional geothermal potential of the various physiographic provinces in Idaho.

The only other published heat flow studies dealing with the area have been local in nature (Sass et al., 1971a; Urban and Diment, 1975; Morgan et al., 1977; Nathenson et al., 1980; Urban...
Fig. 1. Regional setting of the Yellowstone Plateau, Snake River Plain and Owyhee Plateau areas. The stipple indicates primarily alluvium-filled Basin and Range-type valleys intersecting the Snake River Plain and those associated with it (Red Rock Valley, Camas Prairie and Mahagony Mountains). Location of ages of major silicic volcanic centers associated with the proposed hotspot as summarized by Malde (1989) are shown.

et al., 1986). An exception was an extensive study of the Western Snake River Plain by Smith (1980, 1981), the results of which are summarized in this paper.

The Snake River Plain trends across Idaho in a broad arc (Fig. 1). At the eastern end is the currently active silicic volcanic center of the Yellowstone region, while at the western end is a deep late Cenozoic sedimentary basin, the Western Snake River Basin. The Owyhee Plateau along the southwestern margin, a site of voluminous silicic volcanism between 15 and 10 m.y. ago is sometimes considered part of the feature (Leeman, 1982a; Malde, 1989). The province is north of the Basin and Range province and south of the Northern Rocky Mountain province (Ross and Forrester, 1958). The Columbia Plateau province forms the northwestern border of the Western Snake River Basin.

The broad geologic features of the various provinces are well known. The Columbia Plateau province within Idaho is an area covered by the mid-Miocene Columbia Plateau flood basalts. These basalts are recognized as far south as the noteworthying Shift. The sedimentary basements in the northern Rocky Mountain province which in this area is characterized by late Paleozoic sedimentary rock, is the Central Plateau. The Northern Rocky Mountains area is characterized by an orogen and structurally complex alluvial plains. The Snake River Plain, which in this area is characterized by fresh fault scarps, the Borah Plateau and the Blaine Basin, are parts of the range front. The Paleozoiccover of the Owyhee Plateau, which is the Mississippi Plateau, is part of the Basin and Range province, and is characterized by N-S-trending lineaments at right angles to the Snake River Plains.

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The northern border of the Western Snake River Plain. These Miocene basalts overlie an older basement about which little is known. In the northern part of Idaho the Northern Rocky Mountains includes a large Mesozoic batholith which intrudes Precambrian belt series sedimentary rocks. A major portion of the Northern Rocky Mountain province in Idaho is identified as the Central Idaho Basin and Range subprovince. This area is composed of Basin and Range topography and structure with high-relief ranges separated by alluvial valleys. The general trend of the topography is NW–SE (almost at right angles to the Snake River Plain). The youthfulness of the ranges in this area is clearly indicated by the numerous fresh fault scarps and the occurrence of the M 7.3 Borah Peak earthquake beneath the Lost River Valley near Mackey on October 28, 1983 (Doser and Smith, 1985; Scott et al., 1985). The bedrock of the ranges consists of folded and thrust-faulted Paleozoic and Precambrian sedimentary rocks of the Mesozoic Cordilleran thrust belt. The northern part of the Basin and Range province consists of N–S-trending ranges and valleys in an area characterized by late Cenozoic extension more-or-less at right angles to the trend of the Snake River Plains.

The Snake River Plain–Yellowstone feature represents a hotspot in the same energetic sense as Hawaii because the thermal output of the Yellowstone geothermal system and the Hawaiian volcanoes is similar. Using the Cl balance technique, Fournier et al. (1976) measured a heat loss rate at Yellowstone of 2 x 10^{9} cal/s. If a magma temperature changes by 600 °C (or loses 120 cal/g, including latent heat), a volume of 0.02 km^3/yr would be required assuming no losses. Thus, an intrusive rate in the order of 10^{-1}–10^{-2} km^3/yr seems reasonable. This rate of magma emplacement compares to that of Kilauea and Mauna Loa in the order of 10^{-1} km^3/yr, and to Iceland where the eruption rate (over a 400-km long zone) is 5 x 10^{-2} km^3/yr. However, whether this hotspot is mechanistically similar to those operating beneath the ocean plates is still the subject of discussion. Study of the Snake River Plain allows detailed investigation of the behavior of the continental lithosphere when acted on by a massive thermal event. The setting is relatively unusual and still not widely appreciated as an example of massive continental volcanism of the bimodal type which is not associated with significant extension (in fact, the crust is thickened).

Summary of physiography and geologic history

Brott et al. (1978) emphasized that the three main physiographic regions associated with the Yellowstone–Snake River Plain feature represent time snap-shots of the response of the continental lithosphere to the passage of a massive thermal event. A suite of huge rhyolite calderas from which large volume ash flows (100's–1000's of cubic kilometers) have been extruded during the past 2 m.y. (Hildreth et al., 1984) occurs at high elevation (approximately 2500 m) in Yellowstone Park. To the west of this caldera system, west of the oldest clearly exposed caldera (in Island Park: Christiansen, 1982), the Eastern Snake River Plain has been described as a regional downwarp (Kirkham, 1931). Surface rocks are basalts, some younger than 10,000 yrs. The geologic section encountered in a 3150-m deep test well at the Idaho National Engineering Laboratory near Arco is probably typical for this area of the Snake River Plain. A total of 600 m of Snake River basalt is encountered in the hole, followed by 50 m of sedimentary rocks, followed in turn by 2500 m of rhyolite ash, ashflow tuff and possible hypabyssal intrusive rocks (Doherty et al., 1979: Morgan et al., 1984). Although the structure of the Eastern Snake River Plain appears to be a downwarp, along the northwestern edge the surface rocks cover a large-scale normal fault or caldera rim (Braile et al., 1982). Based on geophysical and geologic investigations, several large calderas (Fig. 1) are inferred to be buried beneath the surface cover of basalts (Embree et al., 1982: Morgan et al., 1984).

The Western Snake River Plain consists of a deep sedimentary basin with a thickness of Pleistocene–Pliocene rocks in excess of 2–2.5 km. Interbedded with and beneath the sedimentary rocks are a series of basalt flows. The main sedi-
mentary basin (the Western Snake River Basin) (Newton and Corcoran, 1963) appears to be a fault-bounded graben and the internal structure of the basin is now becoming clear (Wood et al., 1980; Wood and Anderson, 1981; Wood, 1984). The locus of silicic volcanic activity 10–20 m.y. ago was at the extreme western edge of Idaho south of the sedimentary basin. Most of the calderas that were the sources of the ashflows during this period appear to be located beneath basalt flows and silicic volcanics in the Owyhee Plateau south of the Western Snake River Plain sedimentary basin (see Malde, 1989) for a discussion, and Fig. 1). Evidence of the divergence of the trend is the fact that deep wells in the Western Snake River Plain (e.g., Ore-Ida 1 (3100 m) and J.N. James 1 (4267 m), just west of Boise) do not encounter significant thicknesses of rhyolitic rocks.

These seemingly disparate physiographic regions are related to each other by their unusual crustal structure. The crustal section, based on seismic refraction experiments (Hill and Pakiser, 1965; Braile et al., 1982) consists of an unusually thick lower crust and an unusually thin upper crust. Three cross sections are shown in Fig. 2 (the locations are shown in Fig. 1). Because of the inherent ambiguities, earlier gravity studies were often interpreted as indicating a thinner than normal crust (Hill, 1963; Mabey, 1976). A unique feature of the crust which underlies the Eastern Snake River Plain, Western Snake River Plain and the Owyhee Plateau, and which may be evolving under the Yellowstone region, is that it is unusually thick, even though the Snake River Plain has been interpreted as an extensional feature (rift valley). The crust is thicker because during passage of the continent over the hotspot a large intrusive body (probably of gabbroic composition) has been emplaced in the mid–lower crust. This mafic intrusive body has differentiated and has also partially melted the lower and upper crust. As a result, extensive silicic ashflow sequences and calderas have formed in the upper crust (Brott et al., 1978, 1981; Leeman, 1982a). Significant density changes were associated with loss of the light granitic component of the crust due to erosion and ashflow expulsion (Brott et al., 1981). There may also have been a small amount of extension. As the crust (and underlying mantle) cooled following the passage of the hotspot, thermal contraction is responsible for as much as 2–2.5 km of subsidence. The actual observed topographic surface west of Yellowstone is approximately proportional to the square root of time (Brott et al., 1978, 1981) and decreases about 1.5 km (Fig. 3), although simple analysis is complicated in the west by the formation of the sedimentary basin.

The propagating volcanic episode was described by Christiansen and Lipman (1972) and the sequence of volcanism illustrated by a generalized stratigraphic section was presented by Armstrong et al. (1975). This section, as modified...
Fig. 3. Stratigraphic chart of the Snake River Plains–Yellowstone region (Leeman, 1982a) and mean elevation–distance curve from Brott et al. (1978). SRG—Snake River Group volcanics; CRB—Columbia River basalt.

Thus, each point along the Yellowstone–Snake River Plain system marks a point in the evolutionary sequence following passage of the hotspot beneath the continental lithosphere. Rhyolite volcanism and granite emplacement at shallow depths above a large mafic batholith forming in the lower crust predominate over the top of the hotspot. Subsequently, as the hotspot moves eastward, cooling, contraction and subsidence begin. At some point, basalt magma is able to penetrate to the surface and is extruded over the subsiding surface of rhyolitic ashflows. With the passage of time, cooling continues and additional subsidence occurs. If the area is topographically closed, sediment will be deposited in the basin, and if the orientation is suitable, a partially extensional rift basin may form. Filling of the Western Snake River Plain Basin continued until the western end of the Snake River was captured by the Columbia River drainage about 4 m.y. ago (Wheeler and Cook, 1954; see discussion in Malde, 1989).

**Thermal character**

The provinces north of the Snake River Plain have a similar thermal character (Blackwell, 1978, 1989). The average heat flow is $75 \pm 5 \text{ mW m}^{-2}$.

by Leeman (1982a), is shown in Fig. 3. The eastward younging of the silicic volcanic rocks, the basaltic volcanic activity that follows the silicic volcanism at each location, and the sedimentation in the Western Snake River Basin are shown. The diagram is based on radiometric dating of exposed lavas and tuffs. Also shown in the figure is the progressive westward decrease in the elevation of the Snake River Plain. As pointed out by Brott et al. (1978), this change in elevation is similar to that observed as ocean lithosphere ages away from a ridge crest. In the case of the oceans the decrease in elevation is associated with cooling and thermal contraction of the lithosphere (Parsons and Sclater, 1977).

Leeman (1982a) has calculated the volumes of material added to the crust and the energetics of the modification of the crust. He postulated a lower crustal thickening rate of about 1 km/m.y. based on the presumed initial crustal section and that observed in the Western Snake River Plain (Fig. 2). With the active zone 600 km long and 100 km wide he calculated an addition of basaltic magma to the crust of about 0.035 km$^3$/yr. Based solely on the energetics of Yellowstone, a similar figure can be deduced as described in the introduction.
and the heat flow–heat generation relationship is similar to that proposed for the Basin and Range province by Roy et al. (1968). This zone of higher than normal heat flow continues north into Canada (Davis and Lewis, 1984). The heat flow in the northern part of the Basin and Range province south of the Owyhee Plateau–Snake River Plain is not well known. Lachenbruch and Sass (1977) suggest that the area is part of the Battle Mountain Heat Flow High where average heat flow values are in the order of 100 mW m⁻². Blackwell (1983) also discusses the nature of the heat flow distribution in northern Nevada. In fact, there are few data in the adjacent part of the Basin and Range province and the heat flow there is not well established.

Techniques of heat flow measurement

The heat flow dataset is quite voluminous and is described in detail by Blackwell (1989); thus, only summary results are given in this paper. The field and laboratory equipment and techniques have already been described (Blackwell and Spafford, 1987). Most measurements were made in holes drilled by rotary techniques and thermal conductivity measurements were made on cuttings as described by Sass et al. (1971b). Terrain corrections were made where necessary. The special difficulties of thermal studies in the Eastern Snake River Plain due to the extensive aquifer there have been described in detail by Brott et al. (1981).

Almost all of the holes in the Snake River Plain for which data have been collected were drilled for the purpose of water development and no core or cuttings were saved for thermal conductivity measurements. Thus, only a single value of thermal conductivity measured on a sample collected from the surface cuttings piles may be available. In a few cases there are multiple samples available from the same hole. Therefore, in general, it has been necessary to estimate mean conductivity values for holes or sections of holes based on lithology from cuttings piles and well logs. This procedure is relatively unreliable and may miss significant depth variations in thermal conductivity. Thus, the deeper holes are likely to yield more reliable heat flow estimates because they are more likely to sample the predominant lithology in the area. Also, because there is a large number of measurements in many areas, gradient averages can be used to increase the reliability of a heat flow value determined for a single well that is part of a larger group. There are over twenty holes in the depth range 300–500 m. The heat flow in the deep and shallow holes is generally consistent.

Western Snake River Plain

The thermal character of the Western Snake River Plain was first studied in detail by Brott et al. (1976, 1978). Subsequent studies were described by Smith (1980, 1981) and by Mitchell (1981). Detailed aspects of subareas have also been discussed; e.g., the extensive low-temperature geothermal systems along the northern and southern margins, the Weiser, Boise, and the Bruneau–Grand View–Oreana areas have been the object of several studies (e.g., Young and Lewis, 1982). New data and reinterpretation of some of the data contained in the papers by Brott et al. (1976, 1978) and by Smith (1980, 1981) are included in the report by Blackwell (1989) and are shown in Fig. 4. Included on the map are heat flow values in the Idaho batholith close to the Snake River Plain and in the Owyhee Plateau along the southern margin of the Snake River Plain. The contours near the Oregon border are based on data from the Western Snake River Plain in Oregon (Blackwell et al., 1978). In spite of the extensive database, some details of heat flow and the geothermal gradient pattern remain uncertain because of the complexity. The broad outlines of the distribution are quite clear at this point however. The various areas of contrasting heat flow and geothermal gradient are shown in Fig. 4 and identified by name for ease of reference in this discussion.

The data within the Western Snake River Plain fall into two general categories. These categories correspond to areas of relatively high gradient and heat flow (in the order of 100°C/km and 120–150 mW m⁻²), and areas of moderate gradients (about 40°C/km) and average heat flow values (60–80 mW m⁻²). Most of the gradients range between 45 and 85°C/km, with an average of 69 ±
Snake River Plain, and certain lines of 3°C/km (Table 1). Heat flow values show more variation, ranging from 50–150 mW m⁻² with an average of 99 ± 4 mW m⁻² (Table 1). The lithology in most of the holes is lacustrine sediment, with the exception of a few of the holes which were drilled in basalt. The areas of high heat flow are distributed in two bands along the northwestern and southern margins of the Snake River Plain (Boise and Camas Prairie in the north, and Bruneau-Grand View and Western Snake River anomalies in the south). The low gradients and heat flow are found along the axis of the Snake River Plain between Caldwell and Mountain Home (WSRPL in Fig. 4).

**TABLE 1**

<table>
<thead>
<tr>
<th>Province</th>
<th>Geothermal gradient (°C/km)</th>
<th>Heat flow number (mW m⁻²)</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Idaho Batholith</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(excluding the Snake River</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plain margin and geothermal systems)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western Snake River Plain</td>
<td>27 ± 3</td>
<td>77 ± 4</td>
<td>12</td>
</tr>
<tr>
<td>Owyhee Plateau</td>
<td>51 ± 4</td>
<td>98 ± 7</td>
<td>23</td>
</tr>
<tr>
<td>Eastern Snake River Plain *</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern margin</td>
<td>55 ± 9</td>
<td>93 ± 13</td>
<td>23</td>
</tr>
<tr>
<td>Southern margin</td>
<td>71 ± 7</td>
<td>113 ± 11</td>
<td>80</td>
</tr>
<tr>
<td>Above Snake River aquifer</td>
<td>18 ± 2</td>
<td>27 ± 4</td>
<td>125</td>
</tr>
</tbody>
</table>

* Brott et al. (1981).
A heat flow cross section is shown in Fig. 5. The line of the section is shown in Fig. 4. The origin of the main features of the observed pattern was discussed in detail by Brott et al. (1978) on the basis of a substantially smaller amount of data. With additional data, the origin of some parts of the pattern are now clearer. Deep drilling in the Boise front area and in the Bruneau-Grand View region had demonstrated that the high heat flow values there are related to intermediate temperature (40°-80°C) geothermal systems and relatively local geothermal anomalies. The shallow heat flow pattern is indicated by the dash-dot line in Fig. 5. Holes in these systems show isothermal or low-gradient sections starting between 80 and 280 m with maximum temperatures in the depth range 200–500 m varying from 40° to 80°C. This pattern of heat flow and gradient is probably due to systematic regional flow of groundwater toward the margins of the Snake River Plain from higher regions to the north and south (Young and Lewis, 1982). The flow is driven by elevation differences on the water table. Very low heat flow also possibly representing part of the shallow regional flow pattern occurs south of the Bruneau-Grand View area (Fig. 4).

Thus, hydrologic boundaries at the edge of the Snake River Plains cause upflow which gives rise to the geothermal systems at the various locations. The effects on the heat flow are generally modest, however. The average heat flow values observed are in the order of 50–100% above the regional background values. Outside the areas of most active fluid flow, temperature-depth curves are linear to depths of at least 400–500 m, and in the case of well Bostic 1-A (Arney et al., 1982; Arney, 1982) to a depth of 2500 m (see below).

Lower, but still high, gradients and heat flow values are found in holes drilled in granitic rocks on both margins of the Snake River Plain (Urban and Diment, 1975; Brott et al., 1978; Blackwell, 1989). The high heat flow in these rocks (presumably not major participants in the regional groundwater flow systems) is related to the large-scale nature of crustal disruption associated with the Snake River Plain (Brott et al., 1978). These
holes are shown by a special symbol in Fig. 5 and the pattern of regional heat flow is shown by the dashed and solid curves in the figure. This pattern is based on data from the deepest holes and from holes drilled in granite along the margins. The regional heat flow is about 100 mW m$^{-2}$ south.
and about 75 mW m$^{-2}$ north of the Snake River Plain. In the center of the Snake River Plain, the heat flow is about 60–75 mW m$^{-3}$, while on the margins it is 25–50% higher than in the provinces to the north or south.

The two-dimensional thermal model of the Western Snake River Plain presented by Brott et al. (1978, fig. 3) is shown in Fig. 6. The major features of this model are a low-thermal conductivity basin about 6 km thick and 60 km wide filled with basalt and sedimentary rocks. The major heat source was thermally modeled as an instantaneous intrusion 28 km thick and 116 km wide at a depth of 10 km below the surface, with an initial temperature of 1350°C. The size of the intrusion is based on seismic evidence on the size of the anomalous lower crust beneath the Snake River Plain. Solutions for various times were obtained and shown by Brott et al. (1978, fig. 4). The 12.5-Ma solution is shown in Fig. 6, as this time is appropriate for this area (see Figs. 1 and 3).

The theoretical pattern predicted by the solution is that the average heat flow is lower in the center of the Snake River Plain (and the gradient higher) than in the surrounding terrain. At the edge of the basin, higher heat flow values in the basement rocks are predicted because of the refraction effect. The exact type of anomaly found at the edge depends on the geometry of the contact (see Lachenbruch and Marshall (1966) and Blackwell (1983)), but the heat flow will be enhanced by a factor of 2–3. This enhancement is not sufficient to explain some of the heat flow values in the rhyolites, which must be due to fluid circulation. However, the high heat flow values in the granites around the margin of the Snake River Plain are caused by the refraction effect. Similarly, lower (relative) heat flow values in the basin are consistent with the model predictions.

**Camas Prairie**

The Camas Prairie is an E–W fault-bounded basin, and thus has a strike at odds with the generally high-angle intersection of most Basin and Range-type structures to the Snake River Plain. Although this trend is anomalous, the currently active Hebgen Lake earthquake zone and the young Red Rock Valley–Centennial Mountains at the northeastern edge of the Eastern Snake River Plain (Fig. 1) may be an analogous feature. The geothermal features in the Camas Prairie have been discussed by Mitchell (1976) and Mitchell et al. (1980). The existence of high geothermal gradients was pointed out by Walton (1962) based on the increase in flowing temperature with well depth in the artesian wells in the valley. He calculated an average gradient of 92°C/km in the low-thermal conductivity clays of the valley fill. Heat flow values in granite rocks adjacent to the Camas Prairie, included in Fig. 4, are also anomalously high compared to the Northern Rocky Mountain background. Furthermore, silicic volcanic centers younger than would be expected are present in the area, based on the hotspot model (Fig. 3) (see Leeman, 1982b). Thus, the Camas Prairie area is clearly part of the Snake River Plain regional thermal anomaly.

**Thermal regime in the Eastern Snake River Plain**

Geothermal data in the Eastern Snake River Plain and Island Park area are shown in Fig. 7. This map includes data that postdate those presented by Brott et al. (1981). Many of the holes have temperatures that are controlled by groundwater flow in the Snake River Plain aquifer (the aquifer has been described by Mundorff et al. (1964) and Lindholm (1985)). The data from holes in the Snake River Plain aquifer do not represent heat flow measurements in the conventional sense and details of their interpretation are discussed by Brott et al. (1981). The data shown in Fig. 7 include average heat flow values above the Snake River Plain aquifer (small symbols) and conventional corrected heat flow values for holes outside, or that penetrate below, the aquifer (for locations where two or more wells are too close to be resolved, a representative value is shown). Most of the wells in the study were drilled for water, but eight of them, averaging 100 m in depth, were drilled specifically for heat flow, and four, over 500 m in depth, were drilled in the Snake Plain aquifer for geothermal studies. In addition, a dataset from a geothermal exploration project was made available by Oxy Geothermal Incorporated.
Heat flow map of Southeastern Idaho. The heat flow values are coded as shown. The Snake River Plain aquifer outline is shown in generalized form. Small heat flow symbols are plotted for heat flow values above the aquifer. Large symbols are heat flow values outside or below the aquifer. Deep wells are identified by abbreviations.

This data includes holes drilled for geothermal and gradient studies to depths of up to 300 m. Several holes within the Island Park caldera are included in this dataset.

The lithology encountered in most of the wells outside the aquifer consists of rhyolite ashflows (welded and unwelded). In some holes, basalt and Cenozoic sedimentary rocks were also encountered. Typical thermal conductivity values of the rhyolites are approximately 1.9–2.4 W m\(^{-1}\) K\(^{-1}\). The predominant lithology of the holes within the aquifer is basalt.

As was the case for the Western Snake River Plain, the data show generally high heat flow values (many over 100 mW m\(^{-2}\)) on the margins and low values (mostly in the range of 0–40 mW m\(^{-2}\)) in the Snake River Plain aquifer. Although a qualitatively similar heat flow distribution is observed in the Western Snake River Plain, i.e., low heat flow in the Western Snake River Plain and high heat flow on the margins, the causes of the pattern there are somewhat different. The low heat flow in the Western Snake River Plain results from large-scale refraction of heat due to crustal thermal conductivity contrasts, with regional aquifer motion affecting only the margins. In contrast, the low heat flow in the central part of the Eastern Snake River Plain is caused by regional cold groundwater circulation in the major aquifer system. The thermal refraction effect in the Eastern Snake River Plain is minor because there is no large, deep sedimentary basin.
The statistics of the heat flow values are shown in Table 1. The division of the northern and southern margins of the Eastern Snake River Plain into eastern and western parts is along a line which passes approximately through Arco and Pocatello. The values east of this line are associated with silicic volcanics which are 5 m.y. old or younger. The low heat flow values on the northern margin near Arco are due to lateral movement of groundwater into the Snake River Plain aquifer, and these values are not included in the averages. The average values for the northern margins are poorly constrained due to the paucity of accessible wells. Most of the wells along the northern margin, eight out of eleven, were drilled specifically for heat flow. The large variation in values within each of the areas suggests that geothermal systems have a major effect on the distribution of surface heat flow along the margins of the Snake River Plain aquifer. In spite of these complexities, the average surface heat flow values are clearly anomalously high on the margins and anomalously low in the Snake River Plain aquifer.

**Temperature in deep wells in the Snake River Plain**

Most of the thermal data discussed in previous sections have been obtained from shallow wells drilled for water or for heat flow and geothermal gradient exploration. Typical hole depths are 150–300 m. In this depth range the results that have been discussed have clearly shown that much of this thermal data is affected by groundwater flow. Temperature and heat flow data from deep holes are obviously necessary to evaluate the deep thermal conditions. In this section, data from several wells over 500 m deep are discussed.

The locations of holes over 300 m deep are shown in Fig. 8. The holes deeper than 1 km are listed in Table 2. Accurate equilibrium temperature–depth information is available for the Ore-Ida...
1, Bostic 1-A, INEL-GT 1 and the Anderson Camp wells. Logs of unknown quality measured shortly following completion of drilling are available for the Sturm 1, Madison County 1, Federal 60-13 1 and Mountain Home Air Force Base wells. Only bottom hole temperature information was available for the James 1 well so this well is not shown in Table 2. The lithologies encountered in the wells are volcanic rocks of rhyolitic and basaltic composition and lacustrine sedimentary rocks. An exception is the Federal 60-13 1 well which bottoms in the Idaho batholith granite.

Figure 9A shows a diagrammatic longitudinal section along the Snake River Plain based on well log and lithologic information from the Sturm 1, INEL-GT 1, Bostic 1-A and Ore-Ida 1 wells. The well section in Fig. 9A illustrates the eastward transgressive sequence of continental lacustrine rocks onlapping basalt, in turn onlapping rhyolite along the Snake River Plain (this is also shown diagrammatically in Fig. 3). Whitehead (1986) has presented a detailed set of geophysical maps, including numerous cross sections based on well data, of the Snake River Plain. The sections presented in Fig. 9 are more generalized and extend to greater depths than those of Whitehead (1986).

A cross section across the Snake River Plain at any location may show significant variation from this highly generalized longitudinal section. Figure 9B shows a transverse section across the Western Snake River Plain from the Federal 60-13 1 well through a recently drilled well at Mountain Home Air Force Base (Lewis and Stone, 1988) to the Bostic 1-A well. This section shows a thicker sedimentary package on both margins with the thickest basaltic section in the middle, and the second thickest basaltic section on the east side. This type of relationship is not likely to extend to all parts of the Snake River Plain, but the types of lateral variations that might occur are illustrated. The westernmost wells, James 1 and Ore-Ida 1 wells cut a predominantly sedimentary and basaltic section with few, if any, rhyolitic volcanic rocks present.

Temperature–depth curves for the wells are shown in Fig. 10. Equilibrium and nonequilibrium logs are identified. The temperature–depth curves for most of these holes are quite complicated and require some interpretation. The temperature measurements for the Sturm 1 well, at the edge of, but outside the Island Park caldera, are not equilibrium measurements and have the characteristic pattern of thermal drilling disturbance, i.e., high temperatures at shallow depths and a hook at the bottom as the temperature–depth curve approaches equilibrium. This well was drilled entirely in silicic volcanic rocks even though it is on the flanks of, and not inside, the Island Park caldera. Based on data from a shallow-gradient test well nearby, the high temperatures (30°-
Fig. 9. A. Diagrammatic longitudinal geologic section of the Snake River Plain based on the Sturm 1, INEL-GT 1, Bostic 1-A and Ore-Ida 1 wells. The caret pattern depicts granite (YNP), Yellowstone National Park. This section and the one in Fig. 9B illustrate the general geologic section to about 3 km. B. East-west transverse section across the Western Snake River Plain based on the Bostic 1-A, Mountain Home Air Force Base and Anschutz Federal 60-13 1 wells.
35°C) at shallow depth may be real rather than an effect of the drilling. This high temperature is consistent with the presence of a geothermal heat input as most groundwater temperatures within and adjacent to the Island Park caldera are barely in excess of the mean annual temperature of 5°–7°C (Whitehead, 1978).

The temperatures are anomalously low at the site of the Madison County 1 well (Kunze and Marlor, 1982). The drilling history of this hole was complicated. Lost circulation and caving were extensive and well logs were not obtained for much of the well. Thus, the temperature data quality is poor. Nevertheless, temperatures in this well appear to be extremely low at depth as is characteristic of shallower holes in this vicinity (Brott et al., 1976). In the Eastern Snake River Plain, the highest quality data are from the INEL-GT 1 well (Brott et al., 1981). The upper part of the INEL-GT 1 well has very low gradients and near-isothermal conditions characteristic of the Snake Plain aquifer. The temperature gradient below approximately 200 m averages 40°C/km with variations associated with local water movement.

There is a large distance between the INEL-GT 1 and Madison County wells and the next deep
hole to the west. One hole in this gap was drilled near the southern margin (Anderson Camp) and detailed temperature data are available as shown in Fig. 10. These data indicate typical gradients of 60°C/km or more for this section of the Snake River Plain. The basalt thickness at the site of the hole is about 240 m.

Lithologic and alteration data from the 2.9-km deep Bostic 1-A well have been discussed in detail by Arney et al. (1982) and Arney (1982). Arney (1982) published the temperature-depth curve shown in Fig. 10. This curve is from a commercial well log, but it shows the characteristics that might be expected of a good temperature-depth log with higher gradients at shallower depths associated with the lower thermal conductivity sedimentary rocks and lower gradients at depth associated with the higher thermal conductivity basaltic and silicic volcanic rocks. There is no evidence of fluid flow effects on the temperatures. Temperatures are also shown from a nonequilibrium log measured a few days after drilling was completed in a well at Mountain Home Air Force Base. The temperatures in the well are very close to those in the upper part of the Bostic 1-A well about 20 km to the southwest.

Temperature-depth data from the Federal 60-131 well also show characteristics of a recently drilled well (the log was made 2 days following completion of the well) with high shallow temperatures and near-isothermal conditions. The gradient between 1500 and 3390 m averages over 32°C/km. The bottom hole temperature (nonequilibrium) is 145°C at 3390 m. As is the case with the Sturm 1 well, the upper part of this hole may in fact not be as disturbed as it appears. Drillholes in the depth range 300-500 m in the immediate vicinity are part of the Bruneau-Grand View geothermal anomaly and temperatures of 40°-60°C occur at depths of 200-400 m. This system appears to be quite shallow as deeper temperatures are not anomalously high for the Snake River Plain. Even in this irregular log, gradients below 1400 m can be correlated with thermal conductivity variations associated with different lithologies (McIntyre, 1979).

The highest reliably documented temperature is observed in the Ore-Ida 1 well at the extreme western end of the Snake River Plain. This hole penetrated an extraordinarily thick sedimentary package; almost the total depth of the hole is composed of sedimentary rocks, and only the bottom few hundred meters has interbedded basalts, sedimentary units and tuffs. The measured bottom hole temperature at a depth of 3.2 km is approximately 195°C. When measured, the hole was flowing artesian water (2-4 l/min) from perforations in the casing at a depth of 1800 m; thus, the upper part of the curve is affected by this artesian flow (observed temperatures are about 10°C above in-situ temperatures due to the flow). Nevertheless, the gradient averages approximately 90°C/km between the surface and 1 km and 55°C/km between 1 and 3 km.

Thus, all the holes, with the exception of the Bostic 1-A well, show possible evidence of intraborehole fluid flow disturbance. In spite of the evidence for some fluid flow, except for the depth interval 0-250 m in INEL-GT 1, 0-1400 m in Federal 60-13 1, in Madison County 1 and in Sturm 1, the gradients are dominated by thermal conducition. Even in the very irregular log of Federal 60-13 1, made 2 days following completion of drilling, gradients below 1400 m can be correlated with thermal conductivity.

Thermal conductivity measurements are available on cuttings (Ore-Ida 1 and Federal 60-13 1) and in cores (INEL-GT 1 and MHAFB 1) from four holes. The measurements available for three of the holes are shown in Fig. 11. Because the stratigraphic section encountered in all the holes is similar, and because many additional measurements are available for samples from shallow holes, it is possible to establish reasonable estimates of thermal conductivity versus depth for all the holes. In addition to estimating values based on lithology alone, a correlation was constructed between sonic travel times as measured by well logs, and thermal conductivity for the basalts and rhyolites (Williams, 1981). This correlation was used to assist the determination of thermal conductivity values for several of the wells.

The temperature-depth curves show the curious fact that the temperatures are higher in the west (Ore-Ida 1, Bostic 1-A and MHAFB 1) and lowest in the east where the silicic volcanism is
The objective of this paper is to summarize the regional geology, thermal conditions and geologic history of the Snake River Plain. The heat flow in the Yellowstone area has been discussed by Fournier et al. (1976), Morgan et al. (1977) and Blackwell et al. (1989). The geologic, geophysical and thermal data presented here are consistent with the origin of the feature as a propagating hotspot beneath the North American lithosphere. The area is characterized by a sequence of events associated with a massive thermal event including thermal expansion and uplift, crustal melting of silicic rocks by a large mafic intrusive mass generating silicic volcanism, and caldera formation. Very high heat flow and massive geothermal systems are associated with this period. As the hotspot moved eastward and cooling began in the crust and lithosphere, contraction was dominant. At this time some mafic magma was able to penetrate the upper crust and basaltic volcanism became prominent. The present-day example of this part of the system is of course the Eastern Snake River Plain. A third part of the evolutionary pattern may be the formation of a large sedimentary basin. Formation of a basin, however, requires a trapping mechanism. The Western Snake River basin may owe its origin to the fact that the Snake River drained westward at a higher grade level prior to about 4 m.y. ago (see Malde, 1989). At that time, it was captured by the Columbia River system and could then rapidly cut lower into the basin instead of allowing the basin to continue to fill. Alternatively, the orientation and depth of fill of the basin may be controlled by modest extension along directions sympathetic with Basin and Range trends. Evidence for the extension model may be the different response of the Owyhee Plateau and the Western Snake River Plain, both of which probably participated in a similar thermal disturbance.

Temperatures at a depth of about 3 km vary by 50°C from place to place and may be higher in the Western Snake River Plain than in the Eastern Snake River Plain. This effect is related to the very low thermal conductivity of the sedimentary rocks in the western holes.

Discussion

Fig. 11. Thermal conductivity versus depth for three deep wells in the Snake River Plain. The shape of the symbol is keyed to the hole name and the condition (open, filled or crossed) is keyed to the lithology of the sample. Samples from Ore-Ida 1 and Federal 60-13 1 are cuttings measurements with porosity corrections applied. The values have not been corrected for the in-situ temperatures.

Temperatures at a depth of about 3 km vary by 50°C from place to place and may be higher in the Western Snake River Plain than in the Eastern Snake River Plain. This effect is related to the very low thermal conductivity of the sedimentary rocks in the western holes.
In a general way, there is a decrease in heat flow to the west, as might be expected (Brott et al., 1981, fig. 11). However, because of the complicating effects of structural setting and thermal perturbations such as the effect of sedimentation, which cannot be evaluated with the information presently available, rigorous comparison of model to observed results is not possible. Given a reasonable modification of the heat flow in the west by the effects of sedimentation and crustal-scale thermal refraction, there may not be much difference in deep crustal and mantle heat flow along the length of the Snake River Plain. As is the case in the oceans, the best evidence for regional thermal conditions at depth is probably the systematic elevation effects because these depend on the integrated lithosphere temperature and the lithosphere thickness and are less perturbed by upper crustal effects. The heat flow data from the deep holes are broadly consistent with the model, however.

One question that has not been addressed by study of the thermal data is the width of the heat source effect on the continental lithosphere. The width of the anomalous crust in the Western Snake River Plain is at least 100 km, whereas it is only about 80 km in the oceans. Given the model for the source, a clear indication of a source with its center 50 km south of the Basin Range is an excellent divide, and it appears that the occurrence of a center 50 km can be discerned in the data (Fig. 12). This conclusion agrees with former seismological studies of the area (Fig. 12). The occurrence of a center 50 km should not be confused with the conclusion of Smith et al. (1985) that the Eastern Snake River Plain should be divided into two zones of the convection cell. Overall, the mantle heat flow is not anomalous.

Acknowledgments

Our knowledge of the well-documented geothermal regime through the Yellowstone-Snake River Plain is based upon many data sets, including from large geophysical surveys conducted by the Department of Energy and the U.S. Geological Survey. For more information on the geothermal regime, see the references not shown.

References

Armstrong, B. E., 1983.
about 60 km wide in the Eastern Snake River Plain. Brott et al. (1978) used a 116-km wide model for the west and Brott et al. (1981) used a source width of 120 km for the east. In the east, clear evidence for thermal contraction associated with recovery following hotspot passage extends 50 km north of the Snake River Plain where three Basin and Range valleys show internal drainage divides (Ruppel, 1967). A similar phenomenon occurs on the south side of the area. The seismicity of the Intermountain Seismic Belt appears to be deflected around the Eastern Snake River Plain. This deflection is illustrated in Fig. 12 (from Smith et al., 1985). Smith et al. (1985) referred to the aseismic area between the Snake River Plain and the seismically active area as the “thermal shoulder”. Thus, the seismic and topographic evidence suggest thermal effects over a region 200–250 km wide in the Eastern Snake River Plain. This width may be a more realistic estimate of the width of the disturbance in the upper mantle and lower crust than is the width of the topographic feature.

Acknowledgements

Collection and analysis of data from the deep wells in the Snake River Plain was supported by funds from the National Science Foundation through NSF grant No. EAR-8213156 to the Southern Methodist University. Malcolm Mossman, of the Anchutz Corporation made samples from well Federal 60-131 available for thermal conductivity measurement. Leah Street logged the Anderson Camp well and made the log available. Roger Jenson logged the Mountain Home Air Force Base well and Robert Lewis gave permission to use the data and make thermal conductivity measurements on several core samples. Without the cooperation of these people this paper would not have been possible.

References


