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TECTONIC IMPLICATIONS OF THE HEAT FLOW OF THE WESTERN SNAKE RIVER PLAIN, IDAHO

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ABSTRACT

Heat flow data within the western Snake River Plain show typical Cordilleran Thermal Anomaly Zone values (about 1.7 μcal/cm^{2}sec), but anomalously high heat flow values are measured in granitic rocks along the margins of the Snake River Plain (2.5 μcal/cm^{2}sec or higher). The heat flow distribution is interpreted to be related to combined effects of crustal thermal refraction and a large crustal transient heat source. A regional model consistent with the heat flow pattern and other geophysical and geological data is described which assumes the emplacement of a large heat source (mafic intrusion?) under the western Snake River Plain about 10 to 15 million years ago. An anomaly of about 0.3 μcal/cm^{2}sec over the center of the body is due to the heat source at the present time. The timing of the emplacement of the heat source corresponds with the age of voluminous silicic volcanism in the western Snake River Plain. A time progressive thermal model is presented for the eastern Snake River Plain which is consistent with the time progression of silicic volcanism. The model predicts regional heat flow values of 2.5-3.0 μcal/cm^{2}sec over the eastern third of the Snake River Plain. Confirmation of the high regional heat flow values is not possible in the shallow bore holes available (200 ± m deep) because of regional

circulation of cold ground water in the Snake Plain aquifer. However, a close correlation between predicted heat flow and observed elevation changes along the axis of the Snake River Plain is strong support for the heat flow model. The possibility of high heat flow in the eastern part of the Snake River Plain implies that the area may have significant geothermal potential in spite of the low surface heat flow. The regional aseismic warping observed in the eastern Snake River Plain can be interpreted as a thermal contraction phenomenon involving the crust and possibly the upper mantle.

INTRODUCTION

The Snake River Plain is one of the major volcano-tectonic features of western North America. The physiographic features of the Snake River Plain extend from easternmost Oregon through southern Idaho in a great arc to the Yellowstone Plateau at the northwestern tip of Wyoming. The Snake River Plain is distinguished from adjacent regions to the north and south by relatively lower elevation and surface relief. It is mainly covered by late Cenozoic volcanics and sediments. The western half of the Snake River Plain is a deep graben filled with sedimentary and volcanic rocks (Malde and Powers, 1962; Newton and Corcoran, 1963). The eastern part of the Snake River Plain may be a regional downwarp (Kirkham, 1931) that followed a time-transgression episode of volcanism which progressed from southwest Idaho to Yellowstone Park (Armstrong and others, 1975). In southwestern Idaho a second, primarily volcanic, trend extends from near the center of the Snake River Plain westward to the Brothers Fault Zone (in central Oregon) and the Newbery volcano (Walker and others, 1967 and Green and others, 1972).

The object of this paper is to discuss the tectonic significance of new heat flow data in the western Snake River Plain and to present a thermal model that is consistent with geological and geophysical data. The more southerly volcanic trend which connects to the Brothers Fault Zone will not be discussed.

Potassium-argon dating of the Cenozoic silicic volcanics (mostly rhyolitic ash flows) of the Snake River Plain shows that the ages vary from 9 to 13 million years in western Idaho, 8 to 10 million years in central Idaho and 4 to 5 million years in eastern Idaho (Armstrong and others, 1975). Rhyolitic ash flows on the extreme eastern end of the plain (Island Park-Yellowstone area) vary in age from 2.6 to .56 million years. The basalt volcanic activity begins at about the same time as the silicic volcanism, but continues in each area for a much longer time span. For example, young basaltic extrusions (10,000 yrs. B.P. or younger) occur all along the Snake River Plain. Similarly, a westward time progression of silicic volcanism (rhyolites to rhyodacite domes and related ash flows) is observed in eastern Oregon along the Brothers fault zone to the Cascade Range (Walker, 1974; MacLeod and others, 1976; and Bowen and others, 1976).

The northern border of the western Snake River Plain consists mainly of Cretaceous plutonic rocks of the Idaho batholith. Southwest of Boise, the southern border of the Snake River Plain is the Owyhee Mountains, which have a core of pre-Cenozoic sediments and granitic intrusive rocks overlain by Miocene basalt (McIntyre, 1972). Southeast of the Owyhee Mountains the southern border becomes the Late Cenozoic silicic volcanics and sediments of the Jarbidge Mountains which overlie older Cenozoic volcanics and sediments and Mesozoic granitic rocks.

The origin of the Snake River Plain is not certain but several possibilities have been suggested. Hamilton and Myer (1966) suggest the formation of the Snake River Plain as a tensional rift. They use the seismic refraction data of Hill and Pakiser (1963, 1966) as evidence for the lack of continental crust below the western portion of the Snake River Plain. In contrast, Taubeneck (1971) argued that the gravity and seismic data, considered in terms of surface geology and the distribution of granitic rocks, are consistent with the interpretation that includes a granitic layer in the crust of southwestern Idaho. Taubeneck considered dike intrusions and lateral faulting as the mechanism of the origin.

Smith and Sbar (1974) suggest an origin caused by westward relative motion of the North American plate over a hot spot in the mantle. Warner (1976) proposed that a large left-lateral rift is the origin and used 12 offset geologic features, each with a displacement of approximately 80 km, as evidence for his model. Prostka and Oriel (1975) point out the possibility of the Snake River Plain being a quadruple junction centered at Twin Falls with linear segments consisting of the east and west arms of the Snake River plain, the Oregon rhyolite belts, and the center core of the Basin and Range province.

Geophysical data relating to the Snake River Plain and its environs are scanty in spite of the prominence of the feature in western United States geology. Hill and Pakiser (1966) interpreted a seismic refraction profile across the western part of the Snake River Plain. Microearthquake studies have been carried out by Pennington and others (1974). Several publications deal with the gravity field (Hill, 1963; Bonini, 1963; and Mabey and others, 1974) and magnetic field (U.S. Geological Survey, 1971) of southern Idaho. An electrical resistivity profile across the eastern Snake River Plain was carried out by Zohdy and Stanley (1973).

Relevant heat flow data include studies of Roy and others 1968a,b, 1972), Blackwell (1969, 1974), Sass and others (1971), Blackwell and Robertson (1973), Bowen and Blackwell (1975), Urban and Diment (1975) and Morgan and others (1976). The basis for this paper, however, is the report by Brott and others (1976). Brott and others (1976) reported on a heat flow study and presented a generalized heat flow map of the Snake River Plain region. Roy and others (1968a)investigated the mantle heat flow under the Basin and Range province.

GEOPHYSICAL DATA

Measured heat flow values in southwest Idaho (Brott and others, 1976; Urban and Diment, 1975; and Blackwell and Brott, work in progress) are listed in Table 1 and plotted on a map of southwestern Idaho in Figure 1. The heat flow values will be referred to in this paper in units of HFU (1 HFU = 1 microcalorie/cm^2-sec). Brott and others (1976) presented data from 136 wells in southern and central Idaho and the data shown in Table 1 represent those wells in southwestern Idaho for which reasonable estimates of heat flow can be made. Of the 35 heat flow values listed 18 are from pre-existing holes in the depth range 60-590 m, mostly water wells, and 17 are from holes drilled specifically for heat flow determinations. Eight of the 17 wells were drilled in granitic rocks on either margin of the Snake River Plain and range in depth from 60-250 m. The remaining 7 wells were drilled to a depth of 30 m in the Cenozoic rocks of the Snake River Plain.

Deeper holes near the 30 m holes corroborate in general the results of the shallow holes. In general the heat flow values in these shallow wells are considered more reliable than values from the deeper water wells because samples (core and cuttings) were available for thermal conductivity measurements. Heat flow values in the western Snake River Plain range from 0.5 to 2.0 HFU excepting one high value of 3.0 HFU. On the northern margin of the plain the values range from 2.3 to 4.0 HFU, generally decreasing to the north to values ranging from 1.6 to 2.0 HFU. The heat flow values on the southern margin range from 2.2 to 4.1 HFU.

Even though many of the heat flow values in the western Snake River Plain were obtained from water wells, the reported heat flow values are not believed to be significantly affected by lateral movements of ground water since no discharge system for a major aquifer can be found in the western portion of the Snake River Plain. Also the current recharge to aquifers in the western part is not sufficient to replace ground water extracted by wells (Ralson and Chapman, 1970 and Rightmore and others, 1975). In addition, Rightmore and others (1975) studied hydrogen and oxygen isotopes in waters obtained along the southern margin and suggested that the water in the artesian aquifer system there accumulated over a long period of time. Hence the aquifer systems in the western part of the Snake River Plain act as large reservoirs in which little lateral movement of ground water appears to occur.

Mantle heat flow for the Cordilleran Thermal Anomaly Zone (CTAZ, Blackwell, 1969) which includes the Basin and Range, Columbia Plateaus (which include the Snake River Plain), and the Northern Rocky Mountains is estimated to be about 1.4 HFU (Roy and others, 1968; Blackwell and Robertson, 1973; Blackwell, 1974). Swanberg and Blackwell (1973) showed that the average heat production for the granitic rocks of the Idaho batholith is 3.3 HGU (1 HGU = 10^{-13} calories/cm^3-sec) with a range along the southern margin of 2-5.5 HGU. Thus the expected heat flow for the margins of the western Snake River Plain would be about 1.7 ± 0.2 HFU. The observed values (2.5 HFU or greater) are therefore anomalous and suggest an anomaly in reduced heat flow.

A reversed seismic-refraction profile which extends north from Eureka, Nevada across the western Snake River Plain to Boise, Idaho was interpreted by Hill and Pakiser (1966) to suggest that the crust of the Basin and Range province has a 6.0 km/sec (P-wave) layer 19 to 24 km thick over a 6.7 km/sec layer 10 to 12 km thick. At the boundary of the Basin and Range province and the western Snake River Plain the crust thickens abruptly, and the 6.0 km/sec layer becomes very thin or disappears completely. The crust under the western Snake River Plain consists of an upper 5.2 km/sec layer 8 to 10 km thick and a lower 6.7 km/sec layer 33 to 38 km thick. The velocity of the mantle (P_n) below the Basin and Range province and western Snake River Plain is approximately 7.9 km/sec.

A microearthquake survey in parts of the Snake River Plain was carried out by Pennington and others (1974) and in three weeks of recording at various locations no earthquakes were observed. They suggested two probable reasons: (1) the source that produced the recent basaltic lava has either become inactive or migrated; or (2) that temperatures are high enough under the Snake River Plain to allow aseismic creep.

Bouguer gravity maps of the western Snake River Plain (Mabey and others, 1974; Bonini, 1963; and Hill, 1963) show gravity highs in the center with relative lows along the margins. Thus the gravity data seem to indicate an inverse relationship to the heat flow data. The gravity data suggest the presence of lower density rocks on the edges than in the center of the Snake River Plain. Greater sediment thickness may cause lower values of gravity on the margins, whereas the center of the Snake River Plain may have relatively more basalt. Two-dimensional models which fit the gravity profiles across the western Snake River Plain were constructed by Mabey (1976) and Hill (1963).

A residual aeromagnetic map shows a trend of magnetic highs on the southern margin and a trend of magnetic lows on the northern margin of the western Snake River Plain (U.S. Geological Survey aeromagnetic map, 1971; see also Mabey, 1976). The magnetic highs and lows seems to bound the lower values of heat flow characteristic of the center of the Snake River Plain, but the magnetic map does not show any distinct feature at the center. Mabey (1976) suggested that the relative positive magnetic anomaly on the southern margin and relative negative magnetic anomaly on the northern margin probably mark the south and north edges of a magnetic layer (basalt) which underlies the western Snake River Plain.

An electrical resistivity profile across the eastern Snake River Plain (from Arco to Blackfoot, Idaho) has been discussed by Zohdy and Stanley (1973). Under the center of the eastern Snake River Plain they interpreted four geoelectrical units: an upper 300 to 500 meter thick unit of dry basalt, a 1 to 2 km thick unit of saturated basalt, a 2 to 4 km thick unit of basalt intercalated with clayey sedimentary rocks, and a lower unit of Paleozoic (?) rocks. Near Arco they encountered a fifth geoelectrical unit that they interpreted as sedimentary rock and/or rhyolitic ash-flow tuff.

INTERPRETATION OF THE HEAT FLOW DATA

The heat flow pattern (Figure 1) is basically symmetrical about the axis of the western Snake River Plain. Heat flow values of about 1.7 HFU are found in the center and heat flows of 2.5 HFU or greater are characteristic of the margins. At a distance of 35 km from the northern margin heat flow drops to about 2.0 HFU. There are no heat flow measurements further than 30 km from the southern margin except values in north-central Nevada 100-150 km away. These values are generally high and are part of the Battle Mountain zone of high heat flow (Sass and others, 1971).

Crustal Thermal Model. A two-dimensional crustal model of the western Snake River Plain consistent with geophysical and geological data is shown in Figure 2. It is based on the following data. The Cenozoic rock units i the Snake River Plain are mainly sediments, vesicular basalts, and silicic ash flows (Malde and Powers, 1962).

The porosities of most rock units are high and mineral thermal conductivities are low to moderate so that the observed values are 4 ± 1, 3 ± 1, and 4.5 ± 0.3 mcal/cmsec°C for the basalts, sediments and silicic volcanics respectively. The basalts and sedimentary units are represented by a generalized 6 km thick layer of low thermal conductivity (3.0 TCU, 1 TCU = 1 millicalorie/cm-sec-°C) which is 60 km wide. Welded tuffs, non-vesicular basalt and/or the thin remaining granitic crust are interpreted as a 4 km layer of higher thermal conductivity. The thermal conductivity measurements of the granitic cores from the Idaho batholith range between 6 and 7 TCU (Brott and others, 1976) so the assumed thermal conductivity for the rest of the model is 7 TCU. Swanberg and Blackwell (1973) determined the average heat production of the Idaho batholith to be 3.3 HGU. The two 10 km thick layers with heat production of 3.3 HGU on each side of the layer of low thermal conductivity are interpreted as normal crust on the borders of the western Snake River Plain. The heat production of the Cenozoic rocks in the Snake River Plain is probably less than 1 HGU and is ignored in this model.

A regional thermal anomaly is postulated to be related to disruption of the continental crust during formation of the rift structure. The thermal anomaly is modeled as a large mafic intrusion emplaced during the late Cenozoic. The size of the mafic intrusion was determined from seismic and geological data. Hill and Pakiser (1966) interpreted seismic data to indicate that the lower crustal unit under the Snake River Plain is 21 to 28 km thicker than the lower crust under the Basin and Range province and that the top of the lower crust is about 10 km deep below the western Snake River Plain. This additional thickness of 28 km is assumed to be the thickness of the mafic mass which begins at a depth of 10 km. The southern end of the intrusion was determined to be 66 km from the center of the Snake River Plain from seismic data. The northern edge of the intrusion was determined from a geological map (Ross and Forrester, 1947) which shows surface outcrops of late Cenozoic basaltic lava flows approximately 20 km north of the northern margin of the Snake River Plain. These basaltic lava flows are assumed to mark the northern edge of the intrusion (50 km from the center of the Snake River Plain). The size of the intrusion is very large, but the intrusion probably occurred as several smaller intrusions over a short period of time, and the "intrusion" is probably a mixture of refractory crustal material and injected material of basaltic composition. The mafic intrusion is represented as an instantaneous heat source (10 km below the surface, 28 km thick, and 116 km wide) with an initial temperature of 1350°C. The initial temperature of the heat source is based on a 1050°C melting temperature for a molten mafic intrusion plus an additional 300°C to allow for the latent heat of melting (see Jaeger, 1965). The actual *in situ* initial temperature of the body is the difference between the temperature at some point from the steady-state model and 1350°C. The mantle heat flow is represented as a constant heat flow of 1.4 HFU into the base of the model.

Heat Flow Solution. The solution of the model was accomplished in two parts. First, a steady-state solution for the model shown in Figure 2 without the mafic intrusion was calculated. The heat flow profile of the steady-state solution is shown in Figure 2 and Figure 4 (1SS). Second, the instantaneous heat source was placed in the steady-state solution (the initial condition). Time transient solutions were obtained for 5, 10, 15 and 20 million years after emplacement of the mafic intrusion and the heat flow profiles for these solutions are shown in Figure 2. A finite difference program was used to obtain the solutions. Symmetry was assumed about the center of the Snake Riv Plain so the model was divided into two parts and the northern and southern halves of the model were calculated separately.

The calculated heat flow profiles (Figure 2) which are most consistent with the observed heat flow data (Figure 1) are the 10 and 15 million year profiles. These profiles show that the heat flow ranges from 1.3 to 2.0 HFU in the Snake River Plain and 2.8 to 3.3 HFU on the margins. These two ages approximately bracket the age range of the silicic volcanics in the western Snake River Plain (9 to 13 million years, Armstrong and others, 1975).

A diagrammatic cross section across the western Snake River Plain based on the thermal model (Figure 2) is shown in Figure 3. Figure 3 is an attempt to put geological flesh on the bones of the thermal model in Figure 2. The 250, 500, 750, and 1000°C isotherms obtained from the 12.5 million year solution are shown on the cross section. Indicated on the cross section is the thickening of the lower crust and the thinning of the upper crust below the western Snake River Plain. The additional thickness of the lower crust under the Snake River Plain is assumed to be part of the large mafic intrusion. The Cenozoic volcanic and sedimentary rocks are shown to be about 6 km thick in the Snake River Plain. The 4 km thick layer under the Cenozoic rocks may be pre-Cenozoic upper crust or Cenozoic igneous units. The granitic rocks of the Idaho batholith along the northern margin and granitic rock on the southern margins of the Snake River Plain are identified with the upper 10 km of the"upper crust."

The 6 km depth to the bottom of volcanic and sedimentary rocks is based on the seismic refraction data. The upper 3 km of rocks is known from the results of deep drilling. Near the center of the western Snake River Plain along the Idaho-Oregon border a well was drilled to a depth in excess of 3.5 km and remained in Cenozoic rocks to the bottom (Bowen and Blackwell, 1975). Only about 600 m of Columbia River (Owyhee) basalt was encountered in the well (beginning at a depth of 2 km below the surface). The well included about 1 km total thickness of basalt with the remainder of the section composed of sedimentary and silicic-volcanic rocks. Thus "Cenozoic Volcanic rocks" of Figure 3 include an unknown proportion of basalt to silicic volcanic rocks.

Observed geothermal gradients and heat flow values are plotted in Figure 3 with curves showing the surface gradient and heat flow profiles from the 12.5 million year model solution. In general the correspondance between the calculated and observed gradients and heat flow is good. The heat flow curve shows less scatter because the thermal conductivity in the different wells is not as uniform as assumed i the model of Figure 2, however, the gradient curve is shown to illustrate that although there is a discontinuity in heat flow of the Snake River Plain margins due to the thermal conductivity contrast, the geothermal gradient is continuous across the boundary.

<u>Other Heat Flow Models</u>. The observed heat flow pattern is somewhat unexpected because the Snake River Plain, the major tectonic and volcanic feature, has lower heat flow than its margins. In this section we will consider some alternative explanations of the heat flow data to the model discussed above. The low (relative) values of heat flow in the center of the Snake River Plain cannot be caused by heat transfer in a major aquifer system because, as mentioned above, there is no such system. Local circulation effects are probably responsible for some of the scatter in heat flow values, but no regional effect is present.

The western Snake River Plain is underlain by a thick sequence of sedimentary and volcanic rocks and it might be supposed that the heat flow at the surface is artificially low because of the sedimentation effect. However, it is doubtful that the classical models of the thermal effect of sedimentation (Benfield, 1949) apply to the western Snake River Plain. The extensive volcanism and probable intrusive activity with induced extensive hydrothermal convection and the extensive upward flow of water expelled during compaction of the sediments have an unknown effect on the history of thermal regime in the basin. Because of the uncertainty of the boundary conditions, thermal effects of the many possible assumptions, etc., no sedimentation correction has been applied to the data.

A more serious uncertainty in the thermal model is the radioactive heat generation of the upper crust beneath the Snake River Plain. If a granitic crust similar to the Idaho batholith underlies the rift then the predicted steady-state heat flow would be about 1.7 HFU (1.4 HFU mantle heat flow plus about 0.3 HFU from crustal radioactive heat generation) and no anomaly except a marginal refraction anomaly would be present. This model is shown in Figure 4, an expanded version of the heat flow curve from Figure 3. Model 1 is the 12.5 million year curve from the model shown in Figure 2 and Model 1 - SS is the steady-state heat flow from the model in Figure 2, excluding the heat flow from the mafic body and assuming that the graben has been present for a long time. Model 2 - SS shows the effect of adding a block of material 10 km thick with a heat generation of 3.3 HGU below the low thermal conductivity unit extending to a depth of 6 km in the Snake River Plain. As illustrated this model does not fit the observed heat flow data as well as Model 1. The hardest data to fit with this sort of model are those indicating a systematic decrease in heat flow over a distance of 30 km or more away from the margin, in the granitic rocks.

We believe that the geological and geophysical data support a model similar to Model 1 as opposed to a model such as Model 2. It is hard to imagine the formation of the Snake

River Plain, extensive silicic volcanism, and the complete modification of the lower crust without a significant thermal event of the type suggested here. The effect of some amount of crustal radioactivity would modify the observed surface heat flow in the opposite direction from the sedimentation effect. Thus these two effects may cancel each other to first order and this possibility is an additional justification for exclusion of both effects in Model 1.

DISCUSSION

Western Snake River Plain Model. The model presented in Figures 2 and 3 is a very simplified one, but is consistent with most pertinent data. The western Snake River Plain is modeled as a sediment and volcanic filled rift in the continental crust which originated 10-15 million years ago associated with a crustal scale thermal event. The age of the thermal event as determined from the models is in very good agreement with the age of the silicic volcanism in the western Snake River Plain. If the silicic volcanics are related to large-scale partial melting of the lower crust during formation of the rift and/or emplacement and differentiation of the thermal source (possibly a large mafic intrusion) the thermal model is in remarkable agreement with the geological data.

In this model the highest heat flow values are due to the modification of the anomaly from the thermal source by the inhomogeneous crustal conductivity and the refraction of heat into the higher conductivity margins. This effect is clearly illustrated by the two anomaly curves plotted in Figure 3 (see also the enlarged version in Figure 4). The highest gradients are in the center of the Snake River Plain, but the highest heat flow values are at the margins in the granitic rocks. The highest heat flow values predicted by this regional model are about 3.0 HFU in the granite where it contacts the low conductivity rift sediments and volcanics. The heat flow distribution along the margins of the Snake River Plain is similar in magnitude and width to the strip anomaly identified by Reiter and others (1975) along the western margin of the Rio Grande Rift. It is possible that the regional anomaly there is also primarily due to the combined effect of a heat source and to refraction on a crustal scale rather than presence of many local heat sources.

Several values much in excess of the predicted heat flow are found along the southern (2) and northern (1) margins and one value of 3.0 HFU is found in the center of the Snake River Plain. The regional model presented predicts temperatures in excess of 250°C within the sediments and volcanics at depth in the rift and it is reasonable to suggest that where suitable structures exist hydrothermal convection will occur with resulting very high local heat flow values. Ross (1971) describes many thermal wells and springs in southern Idaho and many of these are concentrated along the margins of the Snake River Plain where major faults occur. Specific examples of this type of feature are the Cow Hollow anomaly near Vale, Oregon (Bowen and Blackwell, 1975) and the Boise Front geothermal system (Applegate and others, 1975). Although at any one point along the Snake River Plain silicic volcanism has been limited in time, basaltic volcanism has continued over a much longer period of time. So some local shallow heat sources may also be present associated with the very young basalts which are common in the Snake River Plain. The model presented is a regional one and does not attempt to include these local, but geothermally significant, anomalies.

Eastern Snake River Plain. If the major thermal event in the western Snake River Plain is dated by the age of the silicic volcanics, then this thermal event may be present in successively earlier stages in the eastern Snake River Plain. In this case the heat flow curves of different ages in Figure 2 can be related geographically with portions of the eastern Snake River Plain.

Brott and others (1976) reported low heat flow values in the center of the eastern Snake River Plain (less than 1.0 HFU) and high heat flow values on the southern margin of the eastern Snake River Plain (4.0 HFU or higher near Rexburg, Idaho and 3.0 HFU or higher near Burley, Idaho). The low heat flow values in the eastern Snake River Plain were obtained from shallow wells located in and over the Snake River Plain Aquifer. The discharge of the Snake River Plain aquifer (with a coefficient of transmissibility of 1-173 million liters per day per meter) is 185 kiloliters per second and occurs primarily at Thousand Springs located near Hagerman, Idaho (Mundorff and others, 1964). The low values of surface heat flow in the eastern Snake River Plain are caused by transport of heat laterally through the aquifer by rapid water flow. Deep wells which penetrate through the aquifer are needed to obtain a reliable heat flow value for the eastern Snake River Plain.

Although the heat flow data are lacking in the eastern part of the Snake River Plain for reasons described above, there is a systematic trend in topography that is consistent with an eastward time progressive thermal model. A plot of elevation versus distance from the western end of the Snake River Plain is shown in Figure 5. Elevation points are plotted at every 150 m of height difference in the western two-thirds, and every 300 m of height difference in the eastern one-third, of the Snake River Plain. The data indicate a gradual increase from about 750 m at the west end of the profile near the Oregon-Idaho border to just over 1500 m near Idaho Falls, a distance of about 500 km. Over the last 130 km the elevation rises more rapidly to an average elevation of almost 2500 m in Yellowstone National Park. The heavy line drawn through the points is a sixth order polynomial fitted to the elevation points. In general the points below the line are areas where the Snake River has cut an unusually broad canyon and the areas above the line are areas where there are thicker sections of young basalt volcanics.

Superimposed on the same plot are the heat flow values as a function of distance from the model discussed above (Figure 2) based on two different assumptions. The heat flow data have been scaled so that the heat flow and elevation curves can be directly compared. The first heat flow-distance model is shown as the heavy horizontal barred lines connected by a dotted line which is a fourth order polynomial fitted to the barred lines. The horizontal location of any particular heat flow was determined from the time of onset of silicic volcanism at any position along the Snake River Plains as discussed by Armstrong and others (1975). The approximate location of the various ages of volcanism are shown along the bottom part of Figure 5 by heavy horizontal barred lines connected by a dotted line which is a fourth order polynomial fitted to the observed ages. The heat flow values at the various times from the dates of silicic volcanism were obtained from the solution shown in Figure 2 and are plotted over the same range of lateral distance as the exposure of a particular dated volcanic unit (see Armstrong and others, 1975, Figure 2). The dashed line in the upper graph is heat flow as a function of distance assuming that the thermal event moved eastward at a constant speed beginning at 18 M.Y. ago in Oregon and arriving at the eastern edge of Yellowstone 2 M.Y. ago. Ages corresponding to the dashed heat flow curve are also shown at the bottom of the Figure 5 as a dashed line and the location of several towns along the section are shown below the figure. We assume throughout this discussion that the elevation differences are related to thermal expansion and phase changes associated with the heating up of the crust and upper mantle beneath the Snake River Plain.

The heat flow curve based on the ages of silicic volcanism rises less steeply than the elevation at first, but at approximately the position of Idaho Falls it begins to rise more steeply than the elevation. Both the elevation and heat flow curves show an inflection point near the position of Idaho Falls.

This type of use of the age data is perhaps too literal, however. The sources of most of the dated tuffs are not known because the source areas are buried beneath the younger sediments and basalts in the center of the Snake River Plain. Furthermore older or younger silicic units may once have been present at any place along the system, but may not be exposed because of younger cover or because they have been eroded away.

As an alternative to a literal interpretation of the volcanic age data a second heat flow model is also presented. This second model is based on the assumption that the eastward progress of the thermal event was more uniform than indicated by the age data. The heat flow in this model increases smoothly from west to east (dashed curve in Figure 5). This heat flow curve could be used to predict the elevation at any point along the Snake River Plain within 200 m over an elevation range of 1700 m. It does not, however, show the inflection in the vicinity of Idaho Falls that both the elevation and volcanic age heat flow models show.

The correlation of the predicted heat flow and elevation is so close that we can conclude with some certainty that a time progressive thermal model, as well as a time progressive volcanic episode is applicable to the evolution of the Snake River Plain. Based on the correlations discussed here we would predict a doubling of the regional heat flow in the Snake River Plain from west to east and a regional heat flow of the area from Idaho Falls to the Idaho-Wyoming border of from 2.5 to 3.0 HFU (the corresponding gradients would range from 85 to 100°C/km).

The thermal model described in this paper for the Snake River Plains is of course far from unique and other models could be devised to fit the data. Especially in the application of very young times it cannot be taken literally. The initial conditions assume that the graben has been in existence for a long time before the emplacement of the thermal event. In the actual situation, if the Yellowstone system is the model for the first few million years of the model, there must be a significant period of time (several millions of years) before the graben developes, and the thermal effect of the rhyolitic volcanics, and the probable underlying granite batholith are insignificant.

Correlations between elevation and heat flow have been well established for ocean spreading systems (Sclater and Francheteau, 1970; Sclater and others, 1971, and subsequent papers). While correlations between heat flow and elevation for continents are probable their illucidation has proved difficult and the data presented here probably represent the clearest example of the relationship so far described. In the Snake River Plain a surface elevation difference of about 1700 m is observed to correlate with a heat flow variation from about 1.7 HFU to 3 + HFU. However, it is clear that an empirical relationship between elevation and heat flow derived for the Snake River Plain cannot be directly used for the western United States as areas of much higher elevation than the western Snake River Plain have lower surface heat flow (the Colorado Plateau, for example).

Furthermore, although the surface elevation changes by 1700 m, the elevation change of a given geologic horizon may not be the same. For example, the top of the silicic volcanic sequence is exposed in Yellowstone and is buried over 2 km below the surface in the western Snake River Plain (Bowen and Blackwell, 1975) implying a total elevation change of up to 3.7 km. This elevation difference is too much to be associated solely with thermal expansion and phase changes in a 50 km or so thick section of the earth's outer surface. Obviously as the surface subsides, deposition of sedimentary and additional volcanic rocks into the depression causes additional subsidence. In view of the simplicity of the thermal model it does not seem profitable to attempt to draw quantitative crustal structure heat flow, and elevation relationships at this time as has been done for the oceans. As further geophysical and geothermal data are obtained the further implications of the elevation-heat flow model can be discussed.

Implications of Heat Flow Model. The regional thermal anomaly of the western Snake River Plain verifies that its origin was a major crustal tectonic and thermal event. Similar heat flow anomalies due to major crustal heat flow refraction and emplacement of high temperatures in the lower and middle crust may exist in the western United States, but the western Snake River Plain heat flow pattern is the best documented. Other places where similar anomalies might exist are in the Imperial Valley area of southern California (Combs, 1971) and in the Rio Grande Rift of New Mexico (Reiter and others, 1975). Similar, but smaller scale, thermal refraction and thermal emplacement anomalies may also occur associated with many Basin and Range graben-horst structures.

It is probable that the regional heat flow is much higher in the eastern Snake River Plain than in the western area described in this paper. The high heat flow values predicted have important tectonic and geothermal implications. A very interesting regional elevation versus heat flow relation for the Snake River Plain is implied by the thermal model and observed elevation differences from east to west along the Snake River Plain. The existence of the time sequence will allow a study of all stages of the formation and evolution of the Snake River Plain from its very inception (possibly now represented by the Yellowstone Plateau) to a time of 10-18 M.Y. since its inception (at the western margin).

Based on the data and models discussed in this paper we can describe a time progressive sequence of events for the history of the development of the Snake River Plain at any one point along their length. Consider for example the Oregon-Idaho border area. Beginning about 18 M.Y. ago a large outpouring of rhyolitic ash flows, associated with regional uplift of several hundred meters above the surrounding terrain, caldera formation at the source of the extrusives, large scale hydrothermal activity, etc. occurred. After a few million years the scene of the rhyolitic volcanism was located a few tens of kilometers to the east, the site of original activity has subsided 500 m or so in elevation, and the caldera system has been flooded by basalts.

Over the next few million years the eastward movement of the volcanic centers and the subsidence of the older centers continued. The original center is a continuing locus of basaltic volcanism and focus of thick sediment accumulation because the area is now lower in elevation than the surrounding terrain. The proportion of crustal rifting in the development of the system is unknown, but is probably large.

The identification of the mechanism for large changes in elevation, once the thermal and volcanic event has passed, as thermal contraction has important and testable consequences. For example the regional warping which is so widely described (Kirkham, 1931; McIntyre, 1972) yet which appears not to be associated with seismic activity (Pennington and others, 1974) is easily explained.

The very high heat flow values predicted for the younger part of the Snake River Plain have important geothermal consequences. It is unlikely that conductive heat flow on a regional scale will reach values much in excess of 2.5-3.0 HFU before hydrothermal convection becomes an important or even dominant heat transfer mechanism. Hence, a consequence of the thermal model presented here is that there should be many active geothermal systems in the eastern Snake River Plain where the age of inception ofsilicic volcanism ranges from 5 to 0.6 million years. The area must thus represent an important geothermal resource area.

Because of the crustal heat flow anomalies which dominate the surface heat flow pattern, any mantle heat flow anomaly from a mantle hot spot (Smith and Shar, 1974) or other deep seated mantle effect which might underlie the Snake River Plain cannot be identified. North of the Snake River Plain in the Idaho batholith, there is at the present time no conclusive evidence of mantle heat flow in excess of the normal CTAZ value of 1.4 HFU. South of the Snake River Plain there is a large gap in the heat flow data. About 100-150 km to the south typical heat flow values are 2.5-3.5 HFU in the Battle Mountain region of northern Nevada (Sass and others, 1971). Ages of volcanic rocks in the area of the Battle Mountain "high" are generally in excess of 10 M.Y. and there are extensive exposures of pre-Cenozoic basement in the ranges. Thus the profound crustal disruption which occurred in the Snake River Plain has apparently not occurred in north central Nevada and application of a model similar to that shown in Figure 2 does not seem appropriate for any less extreme model. In spite of this, howev the two most likely possibilities are that a model similar to Figure 2 may be applicable, or the presently observed heat flow data may be strongly biased by proximity to hydrothermal convection systems. Only more data in the area of the Battle Mountain "high" and between the Battle Mountain "high" and the Snake River Plain can resolve the nature of the regional heat flow in these large areas. Such data is crucial to understanding the regional setting of the Snake River Plain and the geothermal potential of the northern Basin and Range Province.

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TABLE 1. HEAT FLOW DATA IN SOUTHWEST IDAHO

North Latitude	West Longitude	Interval of Gradient (meters)	Geothermal Gradient (°C/km)	Thermal Conductivity millicalories/cm-sec-°C	Heat Flow microcalories/cm²-sec		Reference
					uncorr.	corr.	
43°50'	116°15'	5-150	60.2±0.2	6.57±.09	4.1	4.0	A
43°47'	115°51'	120-590	26.0±0.0	7.23±.51	1.9	2.0	A
43°42'	115°41'	190-245	21.0±1.1	8.71	1.7	1.9	A
43°39.4'	115°17.0'	10-88	25.7±2.3	7.23±.25	1.7	1.7	C
43°33.5'	116°21.8'	63[a]	49.0(40.0-51.0)[b]	3.47	1.7(1.4-1.8)		A
43°32.8'	116°17.9'	20-30	11.0±1.0	4.73±0.08	0.5		A
43°32.8'	115°26.6'	10-122	29.3±2.1	8.31±.18	2.3	2.0	C
43°23.3'	116°14.1'	12-30	32.6±4.3	3.40	1.1		A
43°23.1'	115°42.9'	10-117	28.1±2.1	8.56±.07	2.2	2.3	C
43°19.2'	115°20.6'	95-150	46.7±0.5	6.30±.05	3.0	2.9	A
43°17.8'	115°49.8'	58[a]	55.0(55.0-73.0)[b]	3.45	1.9(1.9-2.5)		A
43°15.6'	115°58.6'	160[a]	42.0(37.0-42.0)[b]	4.62	1.9(1.7-1.9)		A
43°16.2'	115°57.2'	145[a]	40.0(36.0-42.0)[b]	4.62	1.8(1.7-1.9)		A
43°14.8'	116°35.3'	45-125	51.0±2.9	3.96	2.0		A
43°14.5'	116°18.6'	15-30	62.7±3.5	4.76	3.0		A
43°15.5'	115°42.2'	520[a]	49.0(43.0-86.0)	3.49	1.7(1.5-3.0)		A
43°15.2'	115°32.7'	10-30	24.7±2.0	5.47	1.4		A
43°12.8'	116°31.3'	100[a]	43.0(33.0-53.0)[b]	3.48	1.5(1.1-1.8)		A
43°13.1'	115°54.3'	90[a]	38.0(38.0-60.0)[b]	4.58	1.7(1.7-2.7)		A
43°12.3'	116°31.8'	358[a]	43.0(34.0-60.0)[b]	3.48	1.5(1.2-2.0)		A
43°12.0'	115°31.6'	83[a]	38.0(31.0-44.0)[b]	4.58	1.7(1.4-2.0)		A
43°11.3'	116°41.1'	252[a]	47	6.60	3.1		B
43°10.9'	115°54.5'	80[a]	51.0(51.0-113.0)[b]	3.29	1.7(1.7-3.7)		A
43°07.8'	115°49.8'	190[a]	66.0(66.0-91.0)[b]	2.68	1.8(1.8-2.4)		A

TABLE 1. CONTINUED

North Latitude	West Longitude	Interval of Gradient (meters)	Geothermal Gradient (°C/km)	Thermal Conductivity millicalories / cm-sec-°C	Heat Flow microcalories / cm^2-sec uncorr.	corr.	Reference
43°05.0'	115°42.0'	15-30	43.7±4.1	4.46±.13	1.5		A
43°04.7'	115°39.7'	119[a]	62.0(44.0-81.0)[b]	2.72	1.7(1.2-2.2)		A
43°04.5'	115°39.2'	79[a]	63.0(63.0-82.0)[b]	2.69	1.7(1.7-2.2)		A
43°62.4'	116°17.2'	18-30	45.6±1.26	3.65±.21	1.7		A
43°01.1'	116°47.8'	130-390	52.3±0.9	5.16±.21	2.5	2.6	A
42°57.6'	116°16.1'	8-15	174.7±11.6	2.29	4.0		
		18-32	124.6±3.8	3.33	4.1		A
42°54.2'	116°04.6'	60[a]	54.0(46.0-90.0)[b]	2.96	1.6(1.4-2.7)		A
42°54.1'	116°04.6'	55[a]	57.0(44.0-112.0)[b]	2.96	1.7(1.3-3.3)		A
42°49.5'	115°59.5'	13-30	110.7±11.8	3.01±.01	3.3		A
42°48.3'	116°24.3'	252[a]	31	7.0	2.2		B
42°44.3'	116°19.9'	13-20	153.9±7.3	2.30	3.6	3.5	
		23-32	77.3±1.1	4.32	3.5	3.3	A

(a) The depth of the well measured instead of the depth interval.

(b) The best value and the lower and upper limits on gradient in cases where the gradient had large disturbances.

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B. Urban and Diment (1975).
C. Blackwell and Brott (unpublished heat flow values).

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Figure 1: Generalized heat flow map of southwest Idaho. The heat flow values with the superscript (^{a}) are preliminary values from Blackwell and Brott (work in progress) and the values with the superscript (^{b}) are from Urban and Diment (1975). Other values are from Brott and others (1976). The geology is after Ross and Forrester, (1947). The inset map shows the location of the study area with respect to the state of Idaho. The location of the heat flow site is at the decimal point of the appropriate number.

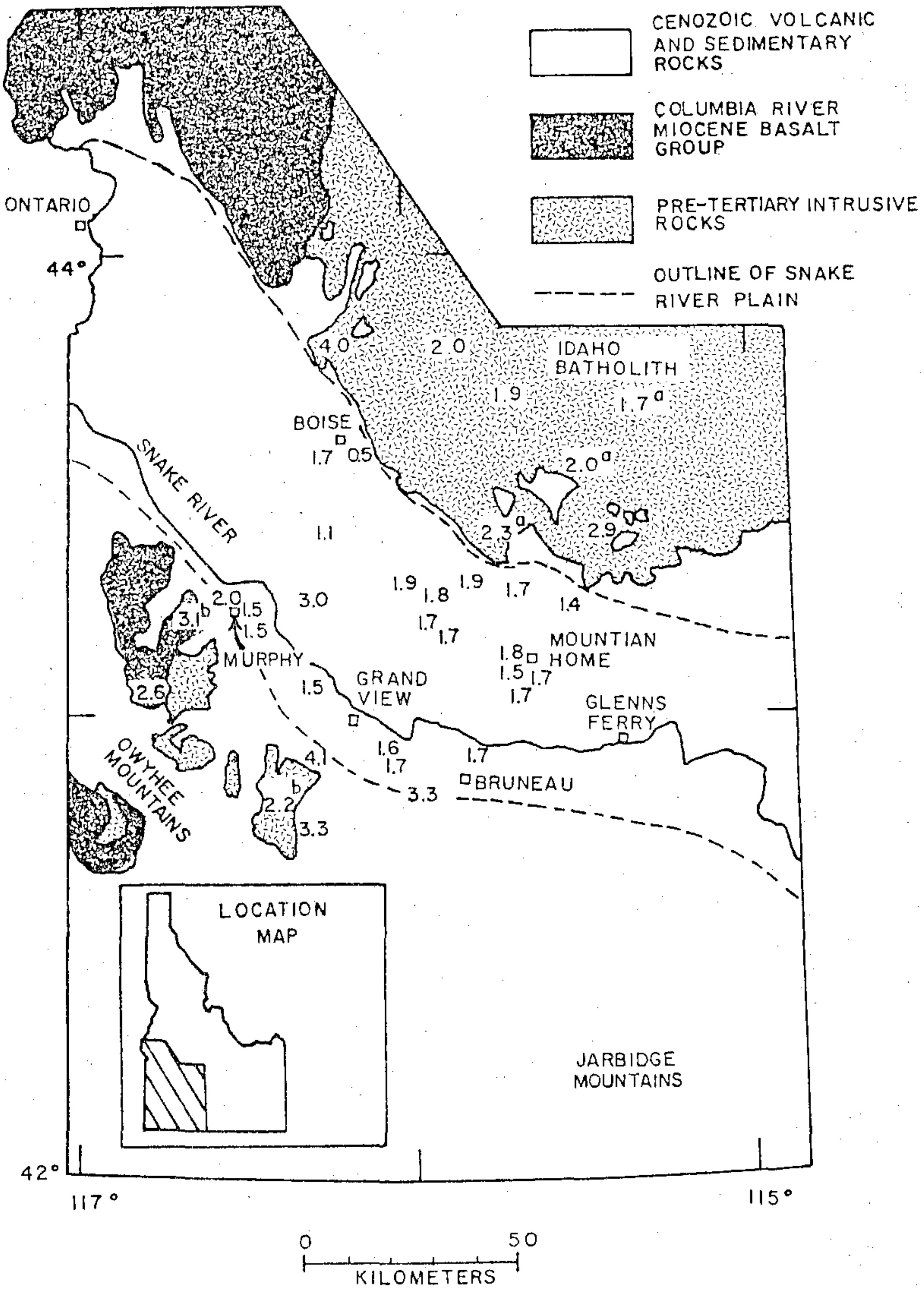

CENOZOIC VOLCANIC AND SEDIMENTARY ROCKS
COLUMBIA RIVER MIOCENE BASALT GROUP
PRE-TERTIARY INTRUSIVE ROCKS
OUTLINE OF SNAKE RIVER PLAIN
ONTARIO
44°
IDAHO BATHOLITH
4.0
2.0
1.9
1.7 a
BOISE
1.7
0.5
2.0 a
SNAKE RIVER
1.1
2.3 a
2.9
1.9
1.8
1.9
1.7
1.4
3.0
2.0
3.1 b
1.5
1.5
1.7
1.7
MOUNTIAN HOME
MURPHY
1.8
1.5
1.7
1.7
2.6
1.5
GRAND VIEW
GLENNS FERRY
OWYHEE MOUNTAINS
4.1
1.6
1.7
1.7
BRUNEAU
b
2.2
3.3
3.3
LOCATION MAP
JARBIDGE MOUNTAINS
42°
117°
115°
0
50
KILOMETERS

Figure 2: Heat flow model and calculated heat flow profiles for the western Snake River Plain. The low thermal conductivity layer (3.0 TCU) is interpreted as Cenozoic volcanics and sediments. The heat production layers (3.3 HGU) are interpreted as upper crustal granitic rocks on the margins of the Snake River Plain. The large block with initial temperature of 1350°C is interpreted as a large thermal event, possibly a large mafic intrusion. The "thermal event" is probably the result of a complex sequence of intrusions which were intruded within a short period of time. The constant heat flow (1.4 HFU) at the lower boundary of the model is the assumed mantle heat flow. Heat flow profiles at 5, 10, 15, and 20 million years after the emplacement of the thermal source and a steady-state profile of the heat flow produced by the heat production layer and constant heat flow at the lower boundary are shown above the model.

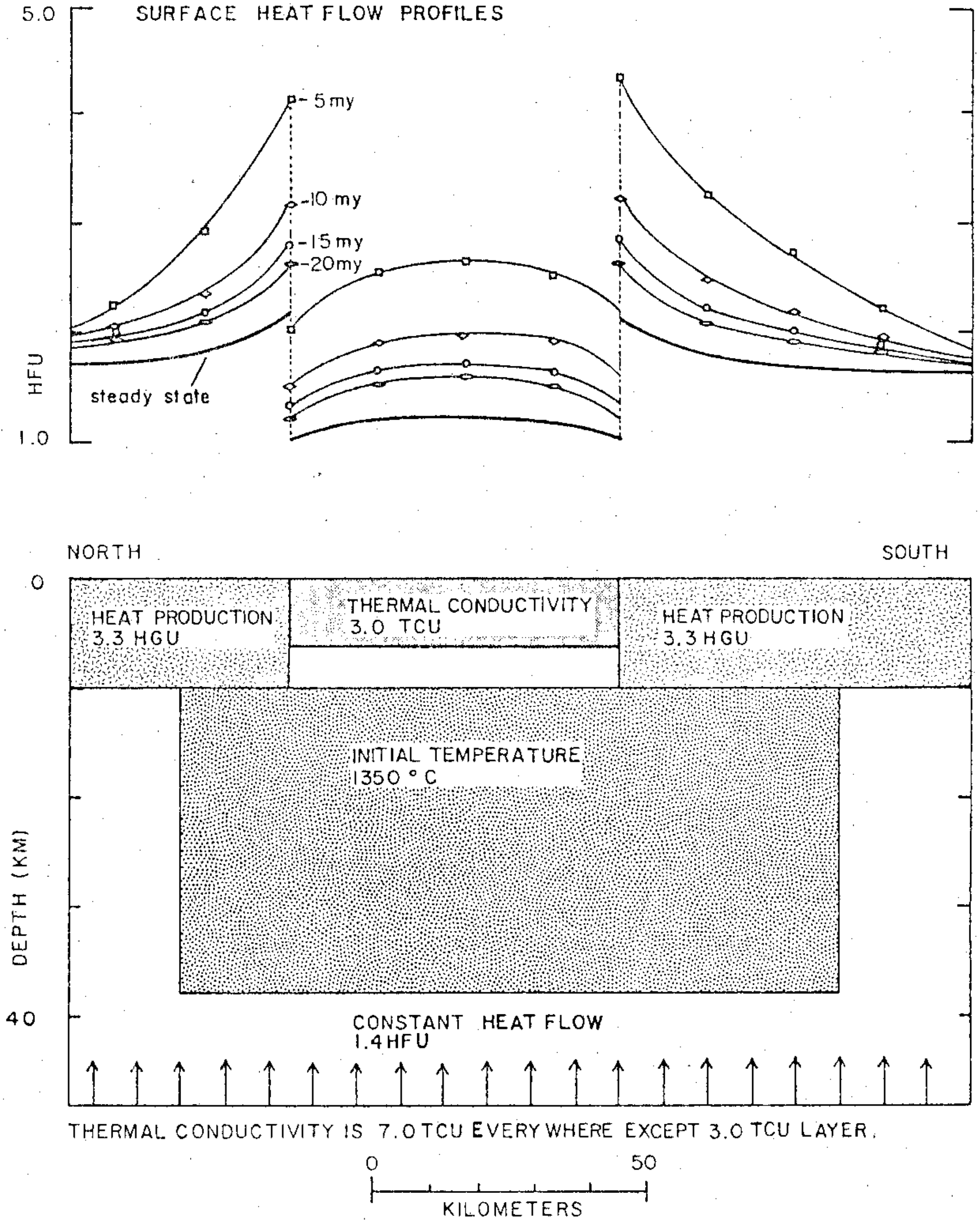

SURFACE HEAT FLOW PROFILES
5.0
1.0
HFU
-5 my
-10 my
-15 my
-20my
steady state
NORTH
SOUTH
0
40
DEPTH (KM)
HEAT PRODUCTION 3.3 HGU
THERMAL CONDUCTIVITY 3.0 TCU
HEAT PRODUCTION 3.3 HGU
INITIAL TEMPERATURE 1350 ° C
CONSTANT HEAT FLOW 1.4 HFU
THERMAL CONDUCTIVITY IS 7.0 TCU EVERYWHERE EXCEPT 3.0 TCU LAYER.
0
50
KILOMETERS

Figure 3: Diagrammatic cross-section of the western Snake River Plain including geothermal gradient and heat flow profiles. The observed values for the gradient and heat flow are circles and the solid lines on the profiles are from the 12.5 million year solution of the model in Figure 2. 250, 500, 750, and 1000°C isotherms are shown on the cross-section (obtained from the 12.5 million year solution). The Cenozoic volcanic rocks shown in the section include an unspecified proportion of basalt versus silicic ash flow units. The open circles are measured in volcanic and sedimentary rocks and the solid circles are measured in granitic rocks.

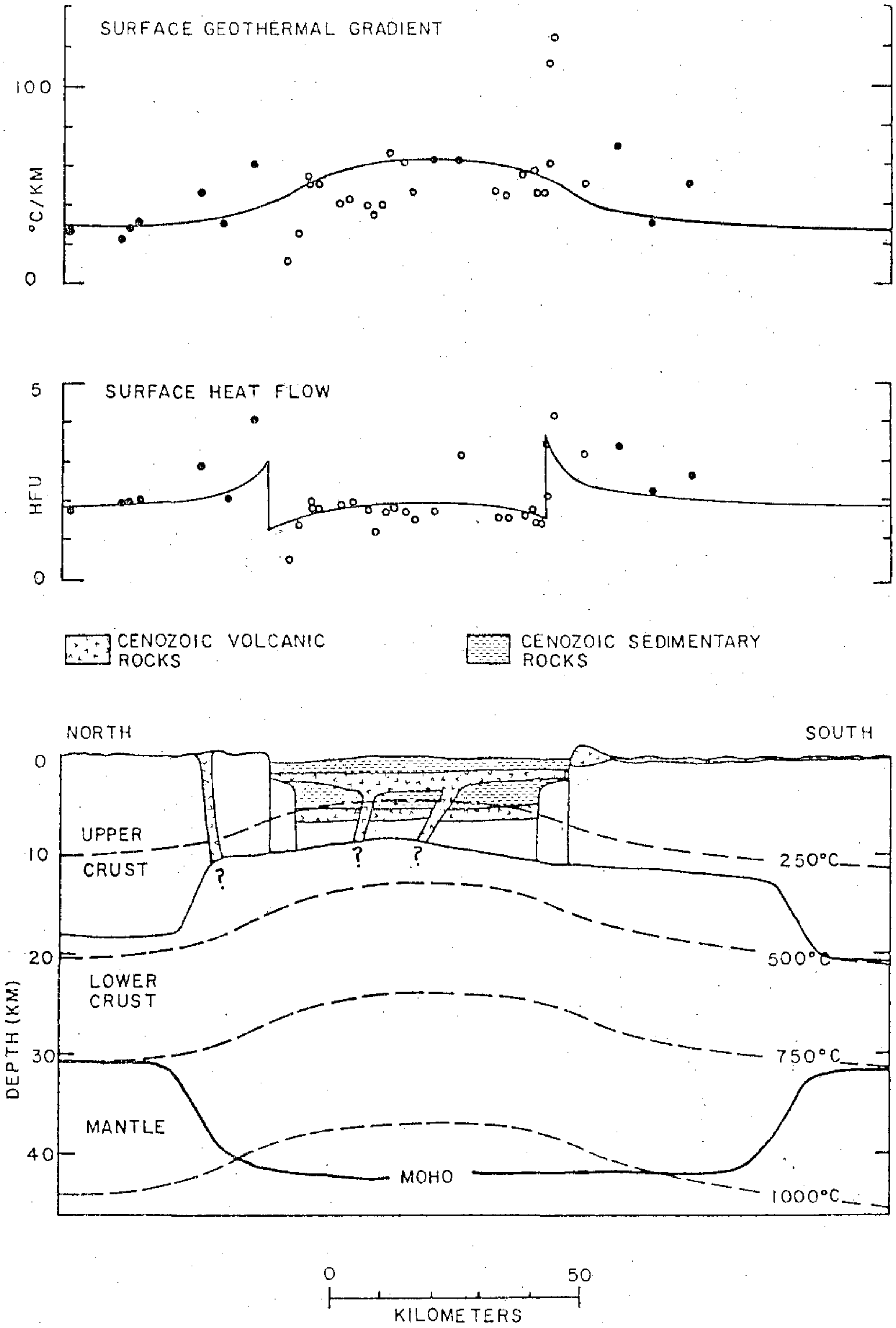

SURFACE GEOTHERMAL GRADIENT
100
°C/KM
0
5
SURFACE HEAT FLOW
HFU
0
CENOZOIC VOLCANIC ROCKS
CENOZOIC SEDIMENTARY ROCKS
NORTH
SOUTH
0
10
20
30
40
DEPTH (KM)
UPPER CRUST
LOWER CRUST
MANTLE
MOHO
?
?
?
250°C
500°C
750°C
1000°C
0
50
KILOMETERS

Figure 4: Three thermal models for the western Snake River Plain. Model 1 is the 12.5 M.Y. solution for the model shown in Figure 2. Model 1 SS is the steady-state solution from Figure 2. Model 2 SS does not include the mafic intrusion but does include a 10 km thick 3.3 HGU layer below the graben. The observed heat flow data are also shown. The circles are observed heat flow values and the solid circles are heat flow data from granitic rocks.

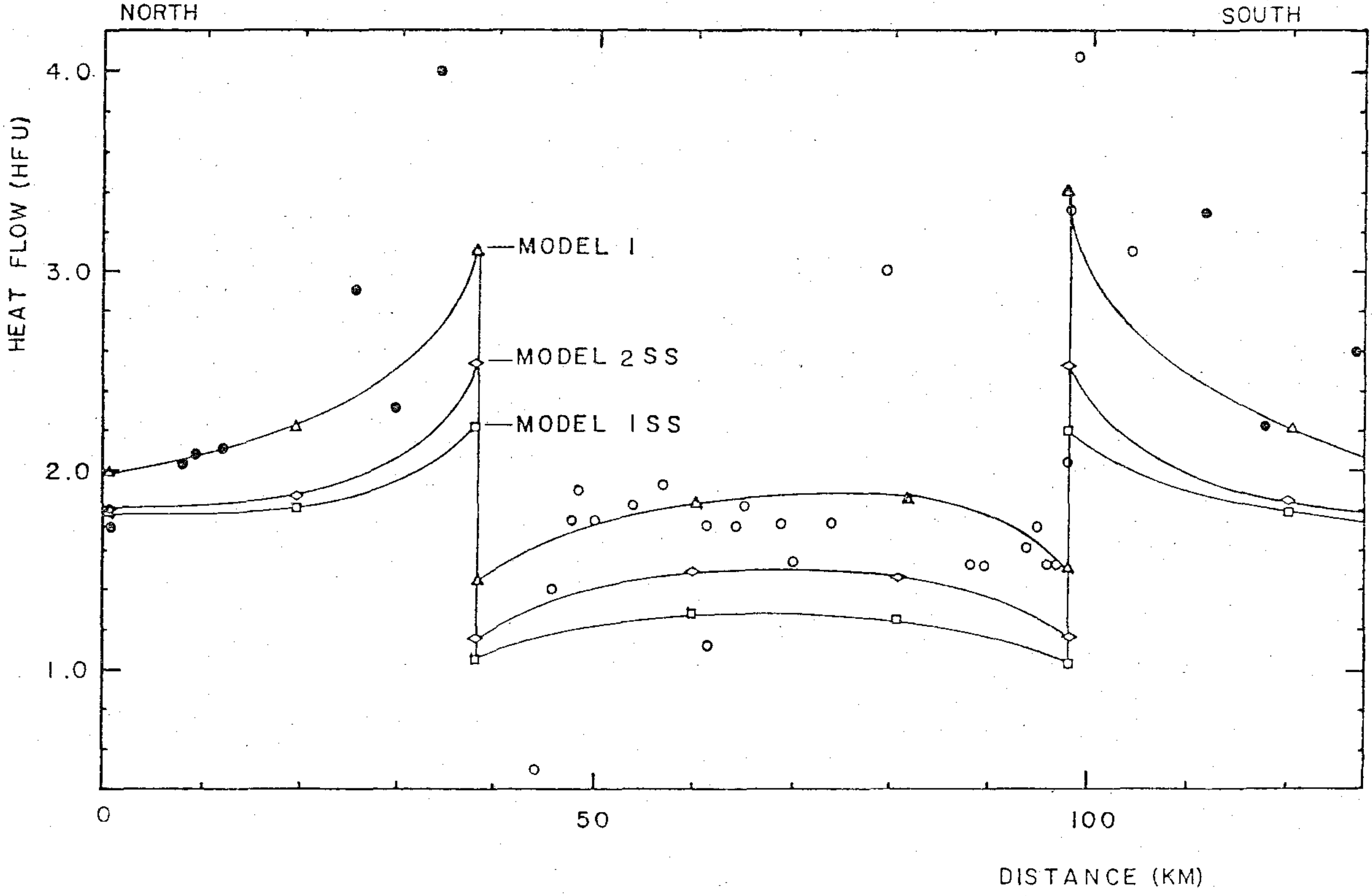
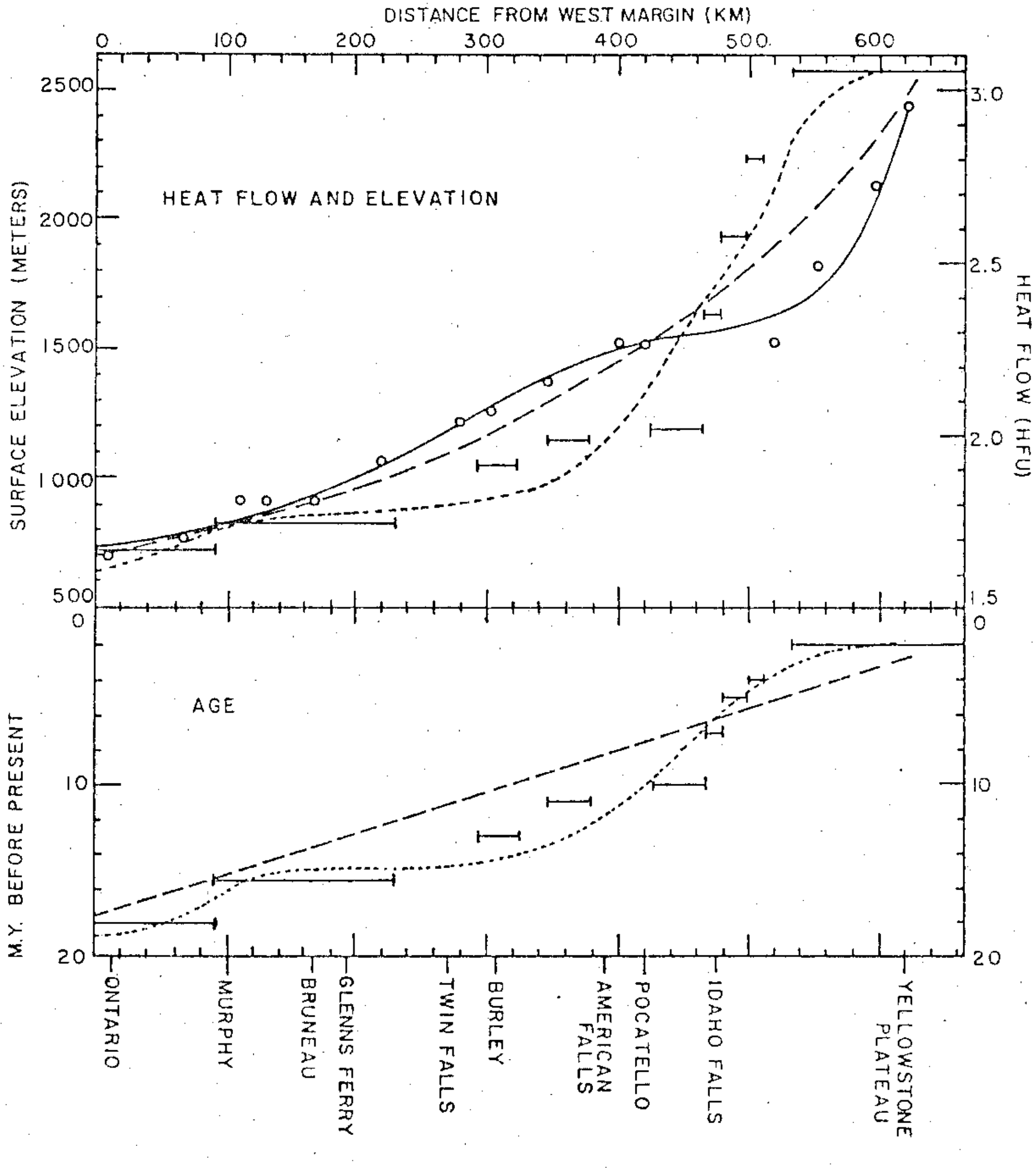

NORTH
SOUTH
HEAT FLOW (HFU)
4.0
3.0
2.0
1.0
0
50
100
DISTANCE (KM)
MODEL I
MODEL 2 SS
MODEL I SS

Figure 5: Elevation, predicted heat flow, and age for the Snake River Plain. A sixth order polynomial fit to the observed elevations (circles) is shown as the solid line. The heat flow model with ages given by silicic volcanics is shown as the horizontal lines connected by dotted curve (a fourth polynomial fit). The heat flow model assuming constant velocity of the thermal event is shown by the dashed curve. The corresponding ages for the two heat flow models are shown in the lower graph and the position of some of the towns and Yellowstone are shown across the bottom. The dashed line is the ages assuming constant velocity and the dotted line is a fourth order polynomial fitted to the observed ages of silicic volcanics.


DISTANCE FROM WEST MARGIN (KM)
0
100
200
300
400
500
600
SURFACE ELEVATION (METERS)
2500
2000
1500
1 000
500
HEAT FLOW (HFU)
3.0
2.5
2.0
1.5
HEAT FLOW AND ELEVATION
AGE
M.Y. BEFORE PRESENT
0
10
20
ONTARIO
MURPHY
BRUNEAU
GLENNS FERRY
TWIN FALLS
BURLEY
AMERICAN FALLS
POCATELLO
IDAHO FALLS
YELLOWSTONE PLATEAU