

Thermal and Tectonic Implications of Heat Flow in the Eastern Snake River Plain, Idaho

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Geothermal data from 248 wells and drill holes, a thermal model for the effects of the Snake Plain aquifer on observed heat flow, an estimate of the regional heat flow in the eastern Snake River Plain, a detailed moving source, regional thermal model, and a discussion of the origin and the relationship of the eastern and western halves of the Snake River Plain are included in this paper. In order to determine the thermal structure of the eastern Snake River Plain, an extensive geothermal gradient and heat flow survey was carried out. Data from 248 holes show high heat flow values along the margins but low values along the center because of effects of the extensive Snake Plain aquifer. Based on a thermal model of the aquifer, a heat budget was derived from which a mean heat flow for the eastern Snake River Plain of 190 mW m^{-2} was calculated. This value can be compared to observed values along the margins of 120 mW m^{-2} and two values in deep holes along the northeastern margin of 110 and 109 mW m^{-2} . The areas of highest expected values, in the Island Park caldera region, have not been sampled by heat flow measurements, however. Based on the heat flow results from the eastern and the western Snake River Plain and other geophysical and geological data, a finite-width moving-source-plane thermal model is developed for the Snake River Plain. Even though the geological and geophysical characteristics of the eastern and western Snake River Plain are somewhat different, they are attributed to the same moving heat source, and the spatial geological and geophysical differences are explained by different stages in a time-related sequence of thermally driven geological and tectonic events. The Snake River Plain is due to a strong thermal source interacting with the crust with the resulting complete chemical reorganization of the crust. The major immediate driving mechanism is a thick mafic intrusive emplaced in the midlevels of the crust. Associated with this thermal event are regional uplift of a kilometer or so as the heating occurs, associated melting of the upper crust, and subsequent rapid subsidence of approximately $1/2$ to 1 km because of the change in density of the crust and upper mantle section associated with the emplacement of the basic intrusive and the disruption of the granitic upper crust. After the heat source moves eastward, continued subsidence occurs due to cooling of the lithospheric section (similar to that seen for oceanic regions). Along with the subsidence and soon after completion of the extensive silicic volcanism, basalts began to be extruded. Thermal contraction also generates faulting on the sides and perhaps in the center of the hot spot track. The subsidence causes reversal of the dips of the silicic ash flows from their initial away-from-the-source configuration, to the toward-the-source configuration observed in the Snake River Plain. Continued subsidence and cooling cause the formation of the basin which is then filled by sediments, causing additional subsidence due to isostatic adjustment (the western Snake River basin). Thus all aspects of the Snake River Plain–Yellowstone region are consequences of a single thermal event, and all stages in the future history of the Yellowstone region and the past history of the western Snake River basin are represented by westward or eastward traverses (respectively) along the Snake River Plain.

INTRODUCTION

The Snake River Plain is a major volcanic-tectonic feature of the North American continent. It extends in a large arc approximately 550 km long and 100 km wide across southern Idaho. The Snake River Plain differs physiographically from adjacent regions because of its relatively lower elevation and relief. The surficial rocks are all late Cenozoic volcanic and sedimentary rocks, but a geologic and tectonic distinction has been made between the western and eastern parts. The western half is described as a rift or graben [Malde and Powers, 1962; Newton and Corcoran, 1963], whereas the eastern part is described as a regional downwarp [Kirkham, 1931]. The northern and southern borders consist mainly of older rocks: Cretaceous plutonic rocks of the Idaho batholith make up the west half, and Paleozoic to Mesozoic sedimentary rocks of the Rocky Mountain Foreland province make up the east half of the margins. Pre-Snake River Plain silicic volcanic and sedimentary rocks of the Basin and Range

province commonly cover the older rocks along the southern margin.

Christiansen and Lipman [1972] discussed a systematic eastward decrease in age of silicic volcanism along the Snake River Plain. Subsequent potassium-argon dating of the Cenozoic silicic volcanics (mainly rhyolitic ash flows) along the margins of the western, central, and eastern parts of the Snake River Plain shows that the ages vary from 9 to 13 m.y. , 8 to 10 m.y. , and 4 to 5 m.y. , respectively [Armstrong *et al.*, 1975]. Armstrong *et al.* [1975] suggested that the eastward progressive episode of silicic volcanism propagated with a velocity of about 35 mm yr^{-1} . The rhyolitic ash flows at the far eastward end (in the Island Park–Yellowstone area) range in age from 2.6 to 0.56 m.y. and appear to be the youngest members of this volcanic progression [Smith and Christiansen, 1980; Eaton *et al.*, 1975]. The basaltic activity for each of the locations began at approximately the same time as the silicic volcanism but has continued intermittently to the Pleistocene–Holocene.

Several thermal-mechanical models consistent with the eastward progression of younger volcanics were proposed by Brott *et al.* [1978]. The thermal constraints for these models were based on a heat flow study of the western

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Snake River Plain [Brott *et al.*, 1976]. Brott *et al.* [1976] observed heat flow values of about 70 mW m^{-2} along the center and values of 100 mW m^{-2} and greater on the margins. Brott *et al.* [1978] related this heat flow pattern to the combined effects of high mantle heat flow, crustal thermal refraction, and cooling of a large crustal intrusion. A two-dimensional model was constructed, and it was concluded that calculated heat flow profiles for cooling ages between 10 and 15 m.y. best fit the observed heat flow distribution. Because of the correspondence of this time period with the 9–13 m.y. potassium-argon dates of the Cenozoic silicic volcanism in the western Snake River Plain, a moving source model, consistent with the age progression of the silicic volcanics for the entire Snake River Plain, was proposed. This model, which consisted of a constant temperature plane source moving through a slab, is similar to McKenzie's [1967] model for oceanic ridges. The parameters of this model were chosen to be consistent with known geophysical and geological data: the slab thickness of 42 km was based on the crustal thickness derived from a reversed seismic refraction profile [Hill and Pakiser, 1966]; the uniform velocity of 35 mm yr^{-1} was consistent with the progression of ages of the silicic volcanism [Armstrong *et al.*, 1975]; and the background temperature distribution of the slab was calculated using a Basin and Range mantle heat flow of 60 mW m^{-2} [Blackwell, 1978]. On the basis of the moving source model, Brott *et al.* [1978] suggested that mean crustal temperatures should systematically increase from west to east, peaking beneath the currently active Yellowstone caldera. Only a few heat flow data were available for the eastern Snake River Plain at that time, and the predicted eastward increase in heat flow could not be confirmed. However, it was pointed out that a systematic increase in elevation along the axis of the Snake River Plain from west to east could be caused by thermal expansion of the lithosphere. The similarity to correlations between elevation, age, and heat flow that are well established for the oceanic lithosphere [Parsons and Sclater, 1977] is obvious.

Following the 1978 study, an extensive heat flow program was carried out in the eastern Snake River Plain. A major problem in determining the regional heat flow is that low surface heat flow is observed in the eastern Snake River Plain because of widespread circulation of cold groundwater in the Snake Plain aquifer, a major regional aquifer system [Brott *et al.*, 1976]. The approach to the difficulty in making conventional heat flow measurements was to make many measurements in the aquifer and to calculate thermal models for, and a heat budget of, the aquifer. A few deep holes supplement the heat budget approach, as do measurements along the margins of the Snake River Plain, outside the aquifer.

The purpose of this paper is to present the new heat flow data in the eastern Snake River Plain, to develop a thermal model for the effects of the Snake Plain aquifer on the observed heat flow, to estimate the heat flow in the eastern Snake River Plain, to refine the moving-source regional thermal model presented by Brott *et al.* [1978], and to use this refined model in a discussion of the origin, and the relationship of the eastern and western halves, of the Snake River Plain.

PREVIOUS GEOPHYSICAL STUDIES

Most of the published geophysical studies discuss the eastern and western parts of the Snake River Plain separate-

ly. This separation, in part, is due to the fact that pertinent data, such as extensive detailed geological mapping [Malde and Powers, 1962; Malde *et al.*, 1963] and a seismic refraction profile [Hill and Pakiser, 1966], were published for the western half in the mid-1960's, whereas the same type of data were not available for the eastern half until recently. Another reason for the separation is the structural differences of the eastern and western Snake River Plain. The various studies are summarized in the following section.

Seismic Data

A seismic refraction-reflection profile along the axis of the Yellowstone-eastern Snake River Plain region was interpreted by Braile *et al.* [1979] and Schilly [1979]. The crustal section derived from these data consists of four different crustal layers: an upper sediment layer about 1 km thick with P wave velocities of 2 to 3.4 km s^{-1} , a 3- to 4-km-thick volcanic layer with an average velocity of about 5.4 km s^{-1} , a thin layer of 'normal' or 'granitic' crust about 4 km thick with a velocity of around 6.0 km s^{-1} , and a 32-km-thick layer with a seismic velocity of 6.7 to 6.8 km s^{-1} . The Moho was interpreted to be approximately 40 km below the surface.

A seismic profile across the eastern Snake River Plain was interpreted by Olsen *et al.* [1979], Sparlin *et al.* [1979], and Sparlin [1981]. They proposed an abrupt northward thinning of the upper crust, coincident with thickening of the total crustal section at the southern margin. The total crustal thickness increases from 25 to 35 km under the Basin and Range province (the adjacent region to the south) to about 40 km under the eastern Snake River Plain (a seismic section is shown below as part of Figure 11). Thus the interpreted crustal section is almost identical to the one across southwestern Idaho. Hill and Pakiser [1966] interpreted a total crustal thickness in the western Snake River Plain of about 43 km with a thin layer of upper crust (about 10 km thick) above a 33-km-thick lower crust. This unusual crustal structure and its similarity in the eastern and western Snake River Plain are strong evidence that the two halves developed in the same manner.

A microearthquake survey at various locations in the Snake River Plain was conducted by Pennington *et al.* [1974], and during a 3-week recording period, no earthquakes were observed. The reasons they proposed for the aseismicity were that the source that produced the recent basaltic volcanics is presently inactive or has migrated and/or the temperatures under the Snake River Plain are high enough to allow aseismic creep throughout most of the crust.

Gravity and Magnetic Data

Studies of the Bouguer gravity in Idaho [Mabey *et al.*, 1974; Bonini, 1963] show that the eastern Snake River Plain is composed of a complex pattern of subsidiary highs and lows superimposed on a general gravity high. Since the overall high is related to the lower elevation in the plain with respect to its borders, the entire region is in approximate isostatic equilibrium [Mabey, 1978]. Mabey [1978] and LaFehr and Pakiser [1962] explain the broad regional gravity high by thinning of the upper crust beneath the Snake River Plain and outward to several tens of kilometers beyond the physiographic margins. The interpretation of the local highs and lows is not yet clear.

In the western Snake River Plain, in addition to the regional gravity high, a clear local Bouguer gravity high is

observed in the center, and gravity lows are observed along the margins [Mabey, 1976; Bonini, 1963; Hill, 1963]. Several two-dimensional models which satisfy gravity profiles across the western Snake River Plain require a very thin or completely missing 'granitic' upper crust [Mabey, 1976; Hill, 1963]. The margins of the western Snake River Plain probably have a greater thickness of sedimentary rock, which results in lower gravity values, whereas in the center there is a thicker sequence of basalt.

A residual aeromagnetic map shows a very complex pattern of magnetic highs and lows in the eastern Snake River Plain [U.S. Geological Survey, 1971; also see Mabey, 1976, 1978]. The magnetic highs appear to correspond with gravity lows and vice versa. Mabey [1978] suggested that the origins for the gravity highs are structural highs covered by a thinner layer of Cenozoic rocks and the magnetic highs are structural lows covered with a thick sequence of Cenozoic rocks. In general, topographic and gravity highs and magnetic lows coincide with the axis of the eastern Snake River Plain. If these topographic highs along the axis were due to basalt, a magnetic high would be expected. Mabey [1978] suggested that one possibility for this combination of topographical, gravity, and magnetic observations is that greater subsidence has occurred along the margins than in the center of the eastern Snake River Plain.

The magnetic pattern observed in the western Snake River Plain is generally characterized by magnetic lows along the northern margin and magnetic highs along the southern margin. Mabey [1976] suggested that these magnetic trends are related to the north and south edges of a magnetic layer (basalt) which underlies the western Snake River Plain.

Geoelectrical Data

An electrical resistivity profile across the eastern Snake River Plain (from Arco to Blackfoot) was completed by Zohdy and Stanley [1973]. Under the center of the profile they interpreted four resistive layers: an upper layer of 300 to 500 m of dry basalt, a 2- to 4-km-thick layer of wet basalt intercalated with clay-rich sediments, a unit of Paleozoic (?) rocks, and basement. Near Arco they encountered a fifth unit that they interpreted as sedimentary rock and/or rhyolitic ash flows.

Magnetotelluric soundings along a profile extending from the Raft River geothermal area in southern Idaho to Yellowstone National Park, Wyoming, have been discussed by Stanley *et al.* [1977]. Along the portion of the profile which approximately parallels the axis of the eastern Snake River Plain, they interpreted a resistive layer 18–24 km thick to be older sedimentary and metamorphic rocks along with the granitic crust. Under Yellowstone Park, this layer abruptly thins to about 5 km. This resistive layer ranges in depth from 2 to 3 km below the surface and generally thickens from Pocatello to Island Park. The boundary between the upper resistive layer and the deeper low resistivity layer does not correlate with any seismically determined layering. From these data, they proposed that given isotherms would rise to the west in the Snake River Plain and Island Park caldera with a very sharp thermal boundary between the Island Park caldera and Yellowstone Park. This interpretation is not consistent with the observed heat flow data, the elevation-distance relationship, or the regional model presented in this paper. However, the results do show that the resistivity in the resistive layer decreases systematically from west to

east; from a value of 310 Ω m northwest of Pocatello to 1.0 to 4.7 Ω in Yellowstone. This systematic resistivity variation may correspond to the systematic temperature variation from west to east.

Contemporary Deformation

Reilinger *et al.* [1977] presented results based on releveling studies of benchmarks in southern Idaho, southwestern Montana, and Yellowstone National Park. They found that the Snake River Plain is subsiding relative to points to the north and west of the province. Further, they found that the eastern part of the Snake River Plain is subsiding faster than the western part. On the other hand, uplift rates of up to 14 mm yr⁻¹ have been found for parts of the Yellowstone caldera [Pelton and Smith, 1979; Smith and Christiansen, 1980]. These results are compatible with the predicted behavior of these areas based on our thermal model.

HEAT FLOW DATA

Geothermal data from 248 holes in southeastern Idaho are listed in Table 1. Because of the nature of the control on surface heat flow, Table 1 has been divided into two parts. In the first part, Table 1a, 112 conventional heat flow measurements are presented. In Table 1b geothermal data for 136 wells in the Snake Plain aquifer are listed. The data in Table 1b do not represent heat flow measurements in the conventional sense. The data are summarized in Figure 1 where the 'corrected' heat flow values from Table 1a and the 'above' heat flow values from Table 1b are plotted (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 11 of the wells, averaging 100 m in depth, were drilled specifically for heat flow, and four wells over 500 m in depth were drilled in the Snake Plain aquifer for geothermal studies. More details of the heat flow data are given by Brott *et al.* [1981].

Data shown in Table 1a include the township/range-section location, the latitude-longitude location for each hole, a brief hole name and logging date, collar elevation, and the depth interval of the gradient calculation. Location within a section is given by the convention that A, B, C, and D represent NE, NW, SW, and SE subdivisions, respectively, and the sequence is from 1/4 to 1/4 1/4 to 1/4 1/4 1/4 section, respectively. Thus hole 2ABB is in the NW1/4 of the NW1/4 of the NE1/4 of section 2. Average thermal conductivity is shown as are the uncorrected and the corrected geothermal gradients. Terrain corrections were applied to the few holes for which such corrections were necessary. The topography is relatively subdued in most of the study area, and therefore terrain corrections were not necessary for many of the holes. The final column shows the heat flow quality with an approximate error indicated according to the convention that an A quality indicates an error of $\pm 5\%$, a B quality indicates an error of $\pm 10\%$, and a C quality indicates an error of $\pm 25\%$. Standard error of the least squares fit straight line to the temperature-depth data and the mean harmonic thermal conductivity is shown below the appropriate thermal conductivity and uncorrected gradient values. The lithology encountered in most of these wells consists of rhyolite ash flows (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 to 2.4 W m⁻¹ K⁻¹. Lower values in Table 1a

TABLE 1a. Geothermal Data for the Eastern Snake River Plain Outside the Snake Plain Aquifer

Twn/Rng- Section	N Lat. Deg.Min.	W Long. Deg.Min.	Hole ID Date Logged	Collar Elev. m	Depth Interval m	Avg. TC [†] No. Wm ⁻¹ K ⁻¹ TC	Uncorr. Gradient °C/km	Corr. Gradient °C/km	Corr. HF mWm ⁻²	HF [‡] Qual.	
13N/40E- 10CAC	44-27.82	111-43.93	SMU KS2 6/29/79	1987	27.5 65.0	1.88 .83	2	81.4 3.2	77.5	146	B
12N/36E- 34BCB	44-19.67	112-12.77	SMU SP3 6/29/79	1795	10.0 89.0	2.06 .23	5	54.5 1.1	51.4	105	B
12N/37E- 18CAR2	44-22.07	112- 8.58	SMU SP2 8/15/78	1859	25.0 70.2	1.67 .08	5	45.7 1.5	38.8	64	B
12N/38E- 2ABB	44-24.14	111-56.44	SMU KS1 9/29/79	1945	25.0 90.0	2.22 .10	7	10.2 .7	10.2 .7	23	C
11N/32E- 35DDC	44-13.85	112-39.50	SMU LHS2 8/15/78	1868	12.5 142.5	2.22 .18	18	17.8 .5	17.8 .5	39	A
10N/33E- 24ACD	44-10.85	112-31.28	SMU LHS1 6/29/79	1672	102.5 151.5	2.43 .06	8	57.6 1.2	59.2	143	B
10N/34E- 22B	44-11.09	112-26.94	WJ 8/19/77	1544	105.0 138.0	(2.43)		29.5 1.3	29.5 1.3	71	C
9N/29E- 1CAA	44- 8.33	112-56.68	WJ BLM 8/21/77	1951	100.0 183.0	(1.46)		33.7 1.3	33.7 1.3	49	B
9N/30E- 2CDD	44- 7.95	112-50.75	RDH-U-LC 7/29/78	1987	15.0 100.0	2.43	1	38.3 1.8	27.4	66	B
9N/32E- 30BCA	44- 4.92	112- 7.62	RDH-U-RG 7/31/78	1926	15.0 65.0	2.38	1	20.3 1.7	16.7	39	C
9N/42E- 6BDA1	44- 8.38	111-32.80	WJ NEVIL 7/27/77	1724	20.0 150.0	(1.51)		22.7 .6	22.7 .6	34	C
9N/42E- 20CCD1	44- 5.21	111-31.94	USGS 8/ 7/75	1582	20.0 53.5	(1.88)		40.0 2.6	40.0 2.6	75	C
9N/42E- 25CCB	44- 4.46	111-27.17	WJ CITY 10/16/77	1599	25.0 175.0	1.92	1	78.3 2.6	78.3 2.6	150	B
9N/42E- 25CDA	44- 4.71	111-26.79	WJ CITY2 6/13/78	1602	15.0 105.0	1.92	1	62.1 1.5	62.1 1.5	119	B
8N/29E- 32CCC1	43-58.46	113- 1.89	RDH-PB1 8/20/78	2121	17.5 59.0	3.22 .17	2	24.3 .2	33.3	107	C
8N/31E- 7AB	44- 2.57	112-48.02	WJ BALL 8/19/77	1672	70.0 130.0	1.46	1	36.9 1.0	36.9 1.0	54	B
8N/34E- 17CCC6	44- .97	112-29.61	USBR 7/11/77	1465	20.0 78.0	(1.46)		31.0 .8	31.0 .8	45	C
8N/39E- 14BDC	44- 1.35	111-49.76	SMU STR2 8/16/78	1602	7.5 123.5	1.84 .07	18	58.8 .9	61.6	113	B
8N/39E- 17DBD	44- 1.09	111-52.94	SMU STR1 8/16/78	1684	12.5 59.0	1.80 .09	6	46.7 .9	42.3	76	B
8N/43E- 26DDA	43-59.18	111-20.49	WJ 8/22/77	1740	90.0 190.0	(2.05)		53.6 1.2	53.6 1.2	110	B
8N/43E- 35AAA	43-57.56	111-20.49	WJ HRSGB 6/ 5/77	1740	80.0 180.0	(2.05)		58.2 .8	58.2 .8	119	B
8N/44E- 15CDB	44- .93	111-15.11	WJ KANDL 6/ 4/77	1768	120.0 230.0	(2.05)		36.7 .4	36.7 .4	75	B
7N/42E- 15AB	43-56.34	111-29.01	USBR 8/14/75	1646	10.0 65.0	1.92	1	24.0 1.1	32.6 1.5	62	B
7N/42E- 17AB									243	A	
7N/42E- 17BA									203	B	
7N/42E- 19AB	43-55.53	111-32.67	USBR C 8/ 2/74	1594	10.0 150.0	(2.05) .08	18	87.8 2.2	87.8 2.2	179	B
7N/42E- 19CD	43-54.81	111-32.68	USBR DH6 8/ 9/75	1628	95.0 130.0	(2.05) .08	18	57.0 2.5	57.0 2.5	116	B
7N/42E- 19DC	43-54.80	111-32.88	USBR 8/ 9/75	1629	170.0 195.0	.96	1	213.2 9.3	213.2 9.3	207	B

TABLE 1a. (continued)

Twn/Rng- Section	N Lat. Deg.Min.	W Long. Deg.Min.	Hole ID Date Logged	Collar Elev. m	Depth Interval m	Avg. TC Wm ⁻¹ K ⁻¹ TC	No. TC	Uncorr. Gradient °C/km	Corr. Gradient °C/km	Corr. HF mWm ⁻²	HF Qual.
7N/42E- 23DCB	43-54.84	111-28.06	WJ NEDR3 9/2/77	1678	110.0 253.0	1.55	1	36.7 9.0	32.0 7.9	49	B
7N/42E- 27DCB	43-53.99	111-29.21	WJ SCHAN 9/5/77	1735	85.0 225.0	(2.05) .08	18	74.2 1.6	74.2 1.6	152	B
7N/42E- 29BD 1	43-54.48	111-31.93	USBR 8/8/75	1634	60.0 100.0	1.76	1	133.9 2.2	133.9 2.2	234	A
7N/42E- 30AD 1	43-54.42	111-32.24	USBR 8/9/75	1536	20.0 105.0	(2.05) .08	18	131.3 1.1	114.5 1.0	235	A
7N/42E- 32BB	43-53.68	111-32.11	USBR D 7/31/74	1631	20.0 140.0	(2.05) .08	18	177.6 3.5	177.6 3.5	364	A
7N/42E- 33BD 1	43-53.49	111-30.98	USBR B 8/18/75	1649	10.0 130.0	(2.05) .08	18	107.9 5.7	107.9 5.7	220	A
7N/43E- 10ABB	43-57.27	111-22.09	WJ KERBS 6/28/78	1719	10.0 345.0	(2.05) .08	18	44.5 1.9	44.5 1.9	91	C
7N/43E- 12BCA	43-57.02	111-20.11	USBR 8/15/75	1743	50.0 110.0	(1.46)		14.7 .4	14.7 .4	21	C
7N/43E- 21AA	43-55.57	111-22.75	USBR 8/12/75	1727	45.0 215.0	(1.46)		19.7 .8	19.7 .8	28	C
7N/43E- 30CCC	43-53.87	111-26.27	WJ 8/14/75	1732	10.0 255.0	(2.05) .08	18	107.5 3.6	107.5 3.6	220	A
7N/43E- 32BC 1	43-53.45	111-24.95	WJ LINDM 8/21/73	1745	50.0 240.0	(1.51)		12.0 .5	12.0 .5	18	B
6N/41E- 11CDB2	43-51.47	111-35.57	USGS 8/15/74	1591	30.0 100.0	(2.05) .08	18	110.4 5.3	110.4 5.3	225	B
6N/41E- 25ABC	43-49.39	111-34.00	WJ NEDR2 7/10/77	1687	40.0 180.0	(1.51)		6.1 4.1	6.1 4.1	9	C
6N/41E- 25ADC	43-49.15	111-33.72	WJ NEDR1 7/7/77	1713	10.0 215.0	(1.51)		8.6 1.1	8.6 1.1	13	B
6N/43E- 18CCD	43-50.45	111-26.29	WJ NEELY 4/20/77	1771	20.0 100.0	(1.51)		17.4 .9	17.4 .9	26	B
6N/44E- 35DAD	43-48.01	111-13.26	COAL BKR 8/11/78	1812	10.0 135.0	1.92 .22	5	79.3 5.5	79.3 5.5	152	C
4N/40E- 10CAD	43-41.39	111-44.23	WJ 8/14/74	1554	10.0 80.0	(1.80)		94.9 10.4	94.9 10.4	170	B
4N/40E- 13CAB	43-40.54	111-41.88	WJ GROUR 6/27/77	1707	10.0 195.0	(1.80)		96.7 4.4	96.7	173	B
3N/18E- 26ABC	43-34.06	114-16.53	WJ RINGER 8/4/78	1829	7.5 65.0	1.80	1	33.8 1.2	28.7 1.0	51	C
3N/39E- 13DAD	43-35.27	111-48.53	A1 7/15/77	1561	10.0 45.0	1.80	1	63.3 2.3	63.3 2.3	113	C
3N/40E- 15CCB	43-35.11	111-44.61	P-41-X 6/28/77	1570	10.0 65.0	(1.80)		45.0 3.4	45.0 3.4	81	B
3N/40E- 15DA	43-35.32	111-43.64	WJ SIMON 6/16/77	1609	30.0 110.0	(1.80)		49.1 2.6	49.1 2.6	88	B
2N/40E- 20ABD	43-29.64	111-46.01	WJ BROWN 6/14/77	1669	20.0 95.0	1.80	1	41.8 7.4	41.8 7.4	75	C
2N/40E- 21CDB	43-29.16	111-45.56	WJ DYELL 7/12/77	1699	20.0 225.0	(1.80)		72.6 2.5	72.6 2.5	130	C
1S/12E- 13BAA1	43-20.33	114-58.78	USGS 7/19/74	1551	15.0 65.0	1.37 .05	3	89.1 2.3	89.1 2.3	122	B
1S/13E- 7DCA	43-20.72	114-57.28	WJ 7/26/77	1551	10.0 60.0	(1.38)		72.9 4.0	72.9 4.0	100	B
1S/14E- 20CDD	43-18.83	114-49.37	WJ T/S 8/6/78	1536	10.0 55.0	(2.51)	1	181.4 3.4	181.4 3.4	417	C
1S/15E- 21ABC	43-19.50	114-41.48	WJ FRSTS 8/6/78	1526	10.0 70.0	(2.51)		89.8 3.6	89.8 3.6	206	C

TABLE 1a. (continued)

Twn/Rng- Section	N Lat. Deg.Min.	W Long. Deg.Min.	Hole ID Date Logged	Collar Elev. m	Depth Interval m	Avg. TC Wm ⁻¹ K ⁻¹ TC	No. TC	Uncorr. Gradient °C/km	Corr. Gradient °C/km	Corr. HF mWm ⁻²	HF Qual.
1S/18E- 16DCC	43-19.93	114-19.49	SHU FF1 8/23/78	1524	20.0 78.0	2.43 .05	9	37.0 .6	37.0 .6	89	B
1S/18E- 32ACC	43-17.70	114-20.53	SHU FF2 6/30/79	1579	10.0 110.0	2.44 .07	17	65.7 .5	64.0 .5	156 5	B
2S/14E- 36DCC	43-11.96	114-44.35	SHU MBH1 7/ 7/79	1609	10.0 90.2	1.41 .05	10	51.4 2.0	51.4 2.0	69	B
2S/17E- 29ACC	43-16.77	114-24.11	WW CROFT 8/ 3/78	1474	5.0 100.0	(1.26)		136.2 13.6	136.2 13.6	171	C
2S/39E- 16DAA	43-14.67	112- .00	WW CDX 7/ 5/78	1585	117.5 280.0	1.88	1	38.0 .2	38.0 .2	71	B
5S/12E- 26CCB	42-57.35	115- .33	BL 1 8/26/75	1019	15.0 30.0	1.54	1	50.0 1.2	50.0 1.2	77	C
5S/15E- 68BC	43- 1.39	114-43.85	WW BSSM1 8/31/78	1109	105.0 220.0	1.55	1	94.9 2.8	94.9 2.8	146	B
6S/12E- 19CDD	42-52.84	115- 4.63	BL2 8/26/75	983	15.0 30.0	1.21	1	113.0 2.0	113.0 2.0	137	B
3S/12E- 23AAC	42-43.40	115- 1.28	WW BLGUL 6/25/74	1064	95.0 165.0	(2.05)	8	55.0 1.1	55.0 1.1	111	B
8S/30E- 23DCD	42-42.35	112-54.77	USGS 8/ 9/77	1375	40.0 84.0	1.63	1	42.6 1.2	42.6 1.2	69	B
8S/31E- 4CBB1	42-45.20	112-50.87	WW BRCKR 6/18/78	1392	10.0 70.0	1.55	1	140.6 4.1	140.6 4.1	217	B
8S/31E- 8CAC	42-44.24	112-52.05	WW 8/ 9/77	1386	20.0 230.0	1.42	1	60.5 2.2	60.5 2.2	85	B
9S/13E- 18CB	42-38.52	114-59.02	WW BLGUL 9/ 1/75	1157	20.0 300.0	2.03 .10	8	56.9 1.2	56.9 1.2	115	A
9S/13E- 20CCD1	42-37.40	114-57.91	USGS 7/ 7/74	1160	30.0 220.0	(2.05)	8	63.9 3.7	63.9 3.7	129	B
9S/13E- 32CDD	42-35.70	114-57.53	WW BLGUL 8/31/75	1170	90.0 210.0	(2.05) .10	8	72.5 2.6	72.5 2.6	147	B
9S/13E- 33CA	42-35.98	114-56.47	WW BLGUL 6/27/74	1170	35.0 175.0	(2.05)	8	60.7 1.6	60.7 1.6	123	B
9S/13E- 33CB	42-35.98	114-56.74	WW BLGUL 6/27/74	1169	50.0 146.0	(2.05)	8	71.4 9.5	71.4 9.5	144	B
9S/14E- 23ABA	42-38.20	114-47.98	WW 9/ 2/78	1012	20.0 61.5	1.59	1	45.1 2.1	45.1 2.1	71	B
9S/17E- 20BCC	42-37.85	114-30.00	WW AMERS 9/ 3/78	1100	35.0 95.0	1.63	1	39.4 3.0	39.4 3.0	57	C
9S/17E- 22BCB	42-37.99	114-27.68	WW LCKLY 9/ 3/78	1112	27.5 119.0	1.63	1	53.1 .5	53.1 .5	86	B
9S/25E- 23CDA	42-37.34	113-30.02	WW 8/ 4/77	1304	15.0 58.0	1.38	1	49.5 5.3	49.5 5.3	67	C
9S/26E- 7AAB	42-39.72	113-27.33	USBR 7/12/74	1280	10.0 236.0	1.42	1	93.1 4.4	93.1 4.4	132	B
9S/28E- 18BAD	42-38.56	113-13.75	BLM 6/16/79	1292	10.0 110.0	1.51	1	58.2 .5	58.2 .5	87	B
9S/30E- 15DDD	42-37.96	112-55.59	WW-NELSN 6/ 3/79	1371	.0 215.0	(1.51)		85.6	85.0	128	C
10S/26E- 25DCC	42-31.07	113-21.77	WW 8/ 4/77	1346	20.0 290.0	1.76	1	79.9 4.9	79.9 4.9	140	B
10S/30E- 24CDD	42-31.91	112-53.86	WW-WSTN1 6/ 3/79	1513	25.0 205.0	(1.51)		121.3 10.5	121.3 10.5	182	C
10S/31E- 19BCC1	42-32.37	112-53.14	WW-WSTN2 6/ 2/79	1478	10.0 240.0	(1.51)		81.4 3.8	81.4 3.8	122	B
11S/17E- 25DDD1	42-25.98	114-24.09	WW BLM 6/13/79	1261	10.0 105.0	1.46	1	54.1 3.5	54.1 3.5	79	B
11S/19E- 27CAD1	42-26.17	114-13.36	WW 7/31/76	1276	10.0 115.0	1.63	1	48.4 1.9	48.4 1.9	79	B

TABLE 14. (continued)

Twn/Rng- Section	N Lat. Deg./Min.	W Long. Deg./Min.	Hole ID Date Logged	Collar Elev. m	Depth Interval m	Avg. TC Wm ⁻¹ K ⁻¹ TC	No. TC	Uncorr. Gradient °C/km	Corr. Gradient °C/km	Corr. HF mWm ⁻²	HF Qual.
11S/20E- 33DAD1	42-25.30	114- 6.45	WJ 8/ 2/76	1293	10.0 120.0	(1.63)		88.0	88.0	129	C
11S/21E- 90DA	42-28.67	113-59.40	WJ 9/18/75	1318	75.0 145.0	(2.05)	8	48.7 3.3	48.7 3.3	98	B
11S/22E- 32CC	42-25.05	113-54.61	WJ 7/29/77	1313	10.0 140.0	1.88	1	43.7 4.3	43.7 4.3	82	B
11S/26E- 34ADC	42-25.37	113-23.87	WJ 8/ 3/77	1344	10.0 120.0	1.09	1	155.2 6.8	155.2 6.8	168	B
12S/15E- 26ADD	42-21.25	114-39.19	WJ 9/13/75	1380	30.0 230.0	(1.46)		39.2 .5	39.2 .5	57	B
12S/15E- 27BAA	42-21.58	114-40.98	WJ 9/13/75	1377	25.0 155.0	(2.01)	1	44.6 .4	44.6 .4	90	C
12S/19E- 2ADC	42-24.62	114-11.64	WJ 7/31/76	1304	30.0 100.0	(2.05)	8	66.4 2.3	66.4 2.3	134	B
12S/20E- 1ACC	42-24.61	114- 3.49	WJ 9/17/75	1309	20.0 190.0	2.03 .10	8	27.4 4.6	27.4 4.6	55	C
12S/20E- 3CBD	42-24.40	114- 6.21	WJ 8/ 1/76	1320	40.0 100.0	1.26	1	77.6 4.6	77.6 4.6	97	B
12S/20E- 25CBB	42-21.04	114- 4.01	WJ 9/18/75	1427	15.0 120.0	(2.05)	8	40.8 2.1	40.8 2.1	82	B
12S/21E- 2DAA	42-24.57	113-57.03	USBR 7/29/77	1329	60.0 200.0	2.03 .10	8	65.4 1.3	65.4 1.3	132	B
12S/21E- 31BDB	42-20.45	114- 2.63	WJ 8/ 1/76	1396	40.0 95.0	2.03 .10	8	68.6 2.9	68.6 2.9	139	B
12S/21E- 31BCC	42-20.29	114- 2.88	WJ 9/17/75	1417	20.0 100.0	2.03 .10	8	60.1 2.5	60.1 2.5	122	B
12S/25E- 7CC	42-23.21	113-35.26	WJ 8/ 3/77	1504	10.0 177.0	(1.30)		60.3 27.4	60.3 27.4	78	C
13S/15E- 11AAD	42-18.82	114-39.35	WJ 9/12/75	1395	10.0 95.0	1.34	1	68.2 3.4	68.2 3.4	90	B
13S/16E- 10DB1	42-18.64	114-33.94	WJ 9/ 9/75	1410	5.0 70.0	(1.34)		94.9 5.3	94.9 5.3	128	B
13S/21E- 5CCD	42-19.00	114- 1.45	WJ 9/17/75	1426	10.0 110.0	(2.05)	8	60.7 2.2	60.7 2.2	123	B
13S/21E- 20AD	42-16.92	114- .62	WJ 7/31/76	1695	30.0 115.0	(2.05)	8	59.6 4.1	66.2	135	B
14S/14E- 14BBB	42-12.73	114-47.31	WJ 7/15/77	1585	15.0 140.0	(1.38)		40.8 .9	40.8 .9	56	B
14S/15E- 23CD	42-11.35	114-39.88	WJ 7/12/74	1522	10.0 92.0	1.05	1	192.8 14.6	192.8 14.6	200	B
14S/15E- 26BB	42-11.04	114-40.34	WJ 7/12/74	1522	10.0 65.0	1.09	1	178.0 31.4	178.0 31.4	190	C
14S/15E- 25BAD2	42-10.95	114-42.18	USGS 7/12/74	1516	20.0 52.0	(1.09)		223.6 33.7	223.6 33.7	239	C
15S/16E- 20BC	42- 5.71	114-36.74	WJ 7/17/77	1787	25.0 330.0	1.80	1	53.7 1.9	53.7 1.9	96	B
15S/25E- 12ACC	42- 9.00	113-21.70	RR-1B 5/ 3/75	1478	.0	1.05	1	130.0	130.0	.25 *	E
15S/25E- 22FLL	42- 5.80	113-23.60	RR-3B 5/ 3/75	1485	.0	1.67		180.0	180.0	292 *	D
15S/25E- 23CAP	42- 6.20	113-23.00	RRGE-1B 5/ 3/75	1475	.0	(1.57)		200.0	200.0	334 *	D
15S/25E- 25APC	42- 5.60	113-21.70	RR-2B 5/ 3/75	1472	.0	1.26		200.0	200.0	251 *	B

The standard error of the thermal conductivity (TC) and uncorrected gradient are shown below the average value. Blanks within a particular column signify that measurements were not made or calculated.

† Brackets around the thermal conductivity value signify value is from surrounding well or wells.

§ Quality: A, 100-m linear gradient and several core conductivity values, estimated error $\pm 5\%$; B, linear gradient, estimated error $\pm 10\%$; and C, disturbed gradient, uncertain thermal conductivity, estimated error $\pm 25\%$.

* Heat flow data from *Urban and Diment* [1975].

TABLE 1b. Geothermal Data for the Eastern Snake River Plain Inside Boundaries of the Snake Plain Aquifer

Twn/Rng- Section	N Lat. Deg.Min.	W Long. Deg.Min.	Hole ID Date Logged	Collar Elev. m	Depth Interval m	Avg. TC $\text{Wm}^{-1}\text{K}^{-1}$	No. TC	Corr. Gradient $^{\circ}\text{C}/\text{km}$	Corr. HF mWm^{-2}	Aqu. Status	Aqu. Temp. $^{\circ}\text{C}$
15N/43E- 24AB8	44-37.00	111-19.04	WJ IP 8/5/75	2024	5.0 30.0 40.0 62.0	(1.13) (1.46)		53.3 5.5 4.0 5.3	-59 5	AB IN	7.67
12N/44E- 20ADB	44-21.21	111-16.57	WJ IP 8/5/75	1914	22.5 32.5	(1.46)		8.0	11	IN	5.07
11N/39E- 11CDA	44-17.57	111-49.38	WJ BLACK 5/13/77	1916	20.0 50.0	(1.46)		9.1 1.3	13	IN	6.44
11N/40E- 4ADA	44-18.86	111-44.25	WJ BLACK 5/15/77	2032	20.0 80.0	(1.46)		5.9 .1	8	IN	6.01
10N/39E- 5CCD	44-13.02	111-53.53	WJ LUSK 7/25/77	1827	20.0 60.0 60.0 200.0	(1.46) (1.46)		7.6 .6 14.5 .7	11 21	AB IN	7.67
10N/42E- 24ABR1	44-11.21	111-26.54	USGS 8/6/75	1887	20.0 50.0 50.0 65.5	(1.46) (1.46)		-25.2 3.1 20.8 1.5	-36 30	AB IN	3.98
9N/39E- 4AAC	44- 8.49	111-51.65	WJ BALL 5/19/77	1725	50.0 260.0	(1.46)		6.9 .2	10	AB	9.89
9N/40E- 5DDD	44- 7.85	111-46.51	WJ 5/22/77	1682	10.0 190.0 190.0 220.0	(1.46) (1.46)		7.3 .3 17.3 1.4	10 25	AB IN	10.27
9N/44E- 21CAD1	44- 5.80	111-15.22	WJ IP 8/5/75	1728	10.0 32.5	(1.51)		12.6 1.3	22	AB	5.56
9N/34E- 17CCC3	44- .97	112-29.61	USBR 8/13/77	1465	25.0 120.0 120.0 182.0	(1.46) (1.46)		30.2 .3 28.8 1.8	44 42	AB IN	13.97
9N/40E- 1CAD1	44- 2.78	111-41.36	USBR 7/12/77	1573	20.0 100.0 105.0 114.0	(1.46) (1.46)		28.8 3.4 21.4 4.4	42 31	AB IN	13.24
9N/40E- 21DDD3	44- .00	111-44.25	USBR 7/12/77	1513	20.0 50.0 50.0 114.0	(1.46) (1.46)		45.0 1.9 21.0 1.7	66 31	AB IN	13.11
7N/31E- 22BDD	43-55.37	112-44.71	NRTS AN7 6/27/77	1504	20.0 110.0	(1.46)		-10.8 .4	-15	AB	9.09
7N/31E- 23CAC	43-54.27	112-46.07	NRTS PW1 6/29/77	1493	20.0 105.0	(1.46)		-9.0 .5	-13	AB	9.26
7N/35E- 13AAD4	43-56.43	112-16.70	USBR 7/7/77	1460	15.0 80.0 80.0 225.0	(1.46) (1.46)		28.2 1.6 -.5 .1	41 -0	AB IN	11.73
7N/35E- 16BDD	43-56.16	112-20.79	WJ 7/15/77	1497	35.0 81.0	(1.46)		4.5 .4	6	IN	12.23
7N/38E- 23DBA6	43-55.10	111-56.52	USBR 7/12/77	1479	70.0 190.0	(1.46)		1.9 .2	2	IN	11.26
7N/39E- 34CCB1	43-53.21	111-51.41	USBR 8/14/74	1472	30.0 70.0	(1.46)		16.7 1.5	24	AB	10.84
7N/40E- 16BCC1	43-56.13	111-45.29	USBR 8/15/74	1489	.0 40.0					IN	11.33
7N/40E- 19AAD1	43-55.49	111-46.70	USBR 7/8/77	1480	.0 45.0					IN	11.53
7N/40E- 20CDC3	43-54.84	111-46.25	USBR 7/8/77	1484	45.0 120.0	(1.46)		-7.1 2.0	-10	IN	11.21
6N/31E- 27BAD1	43-49.43	112-44.70	NRTS 7 6/5/77	1460	70.0 105.0 105.0 260.0	(1.46) (1.46)		100.1 3.3 11.8 .5	146 17	AB IN	19.78

TABLE 1b. (continued)

Twn/Rng- Section	N Lat. Deg.Min.	W Long. Deg.Min.	Hole ID Date Logged	Collar Elev. m	Depth Interval m	Avg. TC $\text{Wm}^{-1}\text{K}^{-1}$	No. TC	Corr. Gradient $^{\circ}\text{C}/\text{km}$	Corr. HF mWm^{-2}	Aqu. Status	Aqu. Temp. $^{\circ}\text{C}$
GN/32E- 11ABA	43-52.20	112-39.57	NRTS 26 6/13/78	1460	65.0 88.0	(1.46)		15.0 2.3	21	IN	15.04
GN/32E- 26CAB2	43-49.12	112-40.07	NR ANP10 6/14/78	1459	65.0 220.0	(1.46)		2.1 .4	3	IN	15.35
GN/32E- 26CAC2	43-49.02	112-40.02	NR ANP 9 6/14/78	1459	20.0 70.0 70.0 100.0	(1.46) 1.46		41.3 7.9 -2 .4	60 -0	AB IN	 13.35
GN/33E- 26DDB1	43-48.82	112-32.30	NRTS 27 6/11/78	1458	20.0 70.0 70.0 90.0	(1.46) (1.46)		90.4 5.7 1.4 .4	132 2	AB IN	 15.55
GN/36E- 11ABR4	43-52.18	112-10.81	USBR 7/ 9/77	1468	105.0 215.0	(1.46)		-21.8 2.6	-31	IN	9.68
GN/36E- 23CCC	43-49.67	112-11.68	BLM 6/21/79	1488	20.0 40.0	(1.38)		7.0 1.6	9	IN	10.61
GN/37E- 29AC 1	43-49.31	112- 7.19	USBR 9 7/ 1/74	1480	30.0 110.0 110.0 160.0	(1.46) (1.46)		-21.3 1.3 .8 .2	-31 1	AB IN	 8.10
GN/38E- 25AC 1	43-49.31	111-55.54	USBR 8/ 1/74	1474	50.0 160.0	(1.46)		20.5 1.0	30	IN	8.50
GN/38E- 30BAD4	43-49.40	112- 1.64	USBR 7/ 9/77	1485	30.0 135.0 135.0 177.0	(1.46) (1.46)		-14.8 .5 8.0 .1	-21 11	AB IN	 8.14
GN/39E- 10BBB4	43-52.15	111-51.36	USBR 7/ 8/77	1473	40.0 80.0 80.0 178.0	(1.46) (1.46)		-4.1 1.1 45.3 5.0	-6 66	AB IN	 12.00
GN/39E- 29ACC3	43-49.18	111-53.16	USBR 7/ 8/77	1470	20.0 75.0	(1.51)		31.4 5.8	47	AB	12.28
GN/39E- 30ADC3	43-49.25	111-54.09	USBR 7/ 8/77	1468	10.0 85.0 85.0 132.0	(1.46) (1.46)		-19.3 1.9 18.8 .9	-28 27	AB IN	 9.51
GN/40E- 40CC	43-52.20	111-45.34	USGS 63 7/ 9/79	1489	425.0 687.5	1.79 .25	6	44.3 1.0	79	BL	10.22
SN/29E- 18BBB	43-47.87	112-57.30	WM SHPT2 8/ 8/78	1464	40.0 170.0	(1.46)		.1	0	IN	9.47
SN/29E- 23CDA1	43-44.50	112-57.98	NRTS 19 7/ 6/77	1463	20.0 85.0	(1.46)		97.6 2.0	143	AB	16.98
SN/30E- 48CC	43-47.50	112-53.61	WM SHPT1 8/ 1/78	1461	15.0 155.0 155.0 335.0	(1.46) (1.46)		33.5 1.6 .2	49 0	AB IN	 13.37
SN/31E- 14CAD1	43-45.47	112-43.60	NRTS 18 6/12/78	1496	85.0 102.0	(1.46)		1.7 1.4	2	IN	14.63
SN/31E- 26CCC1	43-43.57	112-46.52	NRTS S14 7/21/77	1461	30.0 90.0 90.0 215.0	(1.46) (1.46)		77.8 4.2 5.5 1.7	113 7	AB IN	 16.91
SN/32E- 15BAD	43-45.95	112-41.34	USGS 62A 7/ 2/79	1459	10.0 95.0 95.0 407.5 407.5 789.5	1.46 1.33 .13 1.84 .06	1 6	75.4 10.0 16.1 .4 59.8 1.0	109 21 110	AB IN BL	 20.01

TABLE 1b. (continued)

Twn/Rng- Section	N Lat. Deg.Min.	W Long. Deg.Min.	Hole ID Date Logged	Collar Elev. m	Depth Interval m	Avg. TC $^{\circ}\text{Wm}^{-1}\text{K}^{-1}$	No. TC	Corr. Gradient $^{\circ}\text{C/km}$	Corr. HF mWm^{-2}	Aqu. Status	Aqu. Temp. $^{\circ}\text{C}$
SN/33E- 10CDC1	43-46.42	112-34.33	NRTS 31 7/21/77	1453	20.0 80.0 90.0 90.0	(1.46) (1.34)		76.1 6.2	111	AB IN	15.50
SN/33E- 13BDC1	43-46.08	112-31.95	NRTS 30 6/24/77	1458	20.0 85.0 85.0 150.0 150.0 216.0	(1.46) (1.34) (1.84)		44.4 4.1 13.0 1.4 28.2 2.9	64 17 51	AB IN BL	15.82
SN/33E- 17ADD	43-45.48	112-36.48	NRTS 28 6/ 9/78	1455	20.0 73.0 20.0 73.0	(1.38) (1.38)		101.3 7.4	140	AB IN	14.64
SN/33E- 23DD1	43-44.73	112-32.35	NRTS 32 6/11/78	1468	80.0 120.0	(1.34)		22.9 7.9	30	IN	13.69
SN/34E- 9BDA1	43-46.94	112-28.35	NRTS 4 5/10/78	1461	20.0 85.0 85.0 128.0	(1.46) (1.34)		19.9 .8 .2 .4	8 0	AB IN	11.10
SN/34E- 29DAA1	43-44.12	112-28.85	NRTS 29 7/21/77	1486	20.0 100.0	(1.46)		22.0 1.0	32	AB	12.36
SN/36E- 2BDA3	43-47.00	112-11.60	USBR 7/ 9/77	1451	5.0 115.0 120.0 230.0	(1.46) (1.34)		.7 .2 8.1 .5	0 10	IN IN	9.95
SN/36E- 22BBA	43-45.35	112-13.02	HW 8/13/77	1452	5.0 95.0 100.0 180.0	(1.46) (1.34)		6.4 2.5 17.1 1.6	9 23	IN IN	9.75
SN/37E- 21DB	43-44.88	112- 6.65	USBR 8/13/75	1454	25.0 70.0 70.0 145.0	(1.46) (1.34)		-8.0 1.4 1.5 .3	-11 2	AB IN	9.06
SN/39E- 18CAC1	43-45.77	111-55.05	USBR 7/13/77	1470	40.0 80.0	(1.46)		-2.2 3.0	-3	IN	7.00
SN/40E- 8CBB	43-46.70	111-47.16	HW RICKS 5/11/78	1556	85.0 100.0	(1.34)		-1.6 1.0	-2	IN	20.40
SN/40E- 17ABA	43-46.27	111-46.23	USGS 8/14/74	1580	50.0 145.0	1.80	1	47.4 2.7	85	AB	
4N/26E- 21ABB1	43-40.07	113-22.02	USGS 9/19/75	1643	120.0 175.0	1.42	1	5.1 .2	7	IN	9.83
4N/29E- 9DCD1	43-40.93	113- .02	NRTS 23 7/ 6/77	1488	20.0 120.0 120.0 130.0	1.46 (1.34)	1	49.8 1.1 1.0 .5	72 1	AB IN	14.70
4N/29E- 14CAA	43-40.47	112-57.95	NRTS 517 6/14/78	1487	120.0 257.0	1.38	1	1.7 .4	2	IN	11.97
4N/30E- 6ABB1	43-42.58	112-55.28	NRTS 15 6/28/77	1467	100.0 160.0	(1.34)		.9 1.2	11	IN	11.43
4N/30E- 7ADB1	43-41.40	112-55.12	NRTS 12 6/10/78	1469	20.0 120.0 120.0 215.0	1.51 1.30	1 1	24.7 .8 .1 .1	37 0	AB IN	12.07
4N/30E- 22BDD1	43-39.63	112-52.00	NRTS 17 6/22/77	1473	30.0 100.0 100.0 150.0	1.42 (1.34)	1	24.0 1.2 58.1 1.8	34 43	AB IN	12.79
4N/30E- 26CCA1	43-38.47	112-51.13	NRTS 96 6/16/78	1337	110.0 125.0	(1.34)				IN	13.58

TABLE 1b. (continued)

Twn/Rng- Section	N Lat. Deg.Min.	W Long. Deg.Min.	Hole ID Date Logged	Collar Elev. m	Depth Interval m	Avg. TC $\text{Wm}^{-1}\text{K}^{-1}$	No. TC	Corr. Gradient $^{\circ}\text{C}/\text{km}$	Corr. HF mWm^{-2}	Aqu. Status	Aqu. Temp. $^{\circ}\text{C}$
4N/31E- 16ADD1	43-40.52	112-45.45	NRTS 6 6/29/77	1493	20.0 120.0	1.46	1	22.0 .8	32	AB	
					130.0 177.0	1.38	1	22.7 .3	31	IN	13.51
4N/35E- 14AAA1	43-41.03	112-18.12	USBR 15 8/18/71	1505	25.0 115.0	1.51	1	.7 .1	1	IN	
					130.0 230.0	(1.38)		7.5 .5	10	IN	9.75
4N/37E- 36CCC1	43-37.77	112- 9.93	USGS 6/21/79	1810	5.0 45.0	(1.38)		36.0 2.9	49	AB	
					45.0 60.0	(1.34)		3.4 1.0	4	IN	10.61
4N/38E- 12BBB5	43-41.88	111-56.54	USGS 7/ 8/77	1472	60.0 275.0	1.38	1	1.1 .5	1	IN	9.10
3N/26E- 22ABR1	43-34.75	113-20.57	USGS 7/31/77	1619	190.0 228.0	(1.34)				IN	13.29
3N/28E- 1BAR	43-37.41	113- 3.95	INEL-GT1 9/10/78	1561	87.5 230.0	(1.42)		15.5 .4	22	IN	14.55
					230.0 550.0			45.1 .3		BL	
					550.0 750.0			47.1 .3		BL	
					750.0 1000.0			49.9 1.6		BL	
					1000.0 3100.0	2.76	10	39.5	109	BL	
3N/29E- 19CBB1	43-34.38	113- 3.33	NRTS 22 6/25/77	1539	20.0 199.0	1.51	1	54.3 .3	81	AB	
					20.0 199.0	1.51				IN	17.77
3N/29E- 25CAA3	43-33.38	112-56.77	NRTS 37 6/21/78	1503	20.0 145.0	(1.51)		7.6 2.7	11	AB	12.56
3N/29E- 36BCB1	43-32.75	112-57.18	NRTS 85 6/21/78	1506	20.0 145.0	(1.51)		9.7 .3	14	AB	>11.54
3N/30E- 12CDD1	43-36.67	112-49.15	NRTS 5 6/14/78	1505	20.0 150.0	1.51	1	23.3 1.7	35	AB	>12.88
3N/30E- 31AAD1	43-32.88	112-55.00	NRTS 20 6/15/78	1498	20.0 141.0	(1.51)		9.1 1.0	13	AB	>11.56
3N/32E- 13DCB1	43-35.17	112-38.80	ARBOR A1 6/26/78	1574	20.0 205.0	(1.51)		19.7 .8	29	AB	
					205.0 237.0	1.38	1	.2 .1	0	IN	13.16
3N/32E- 29DDC1	43-33.33	112-43.38	NRTS 2 6/21/77	1562	40.0 205.0	(1.51)		23.5 .3	35	AB	13.15
3N/34E- 32BEC1	43-33.12	112-30.00	NRTS H42 6/20/77	1590	20.0 220.0	1.46	1	17.6 .2	25	AB	
					220.0 240.0	(1.38)				IN	12.53
3N/37E- 2CBD1	43-36.93	112- 4.65	USGS 7/16/77	1467	50.0 110.0	(1.38)		-1.9 .7	-2	IN	10.94
3N/37E- 12BDB	43-36.38	112- 3.30	USBR 6/20/79	1449	5.0 50.0	1.38	1	28.9 7.4	39	AB	
					50.0 95.0	(1.34)		-4.3 .9	-5	IN	9.23
2N/26E- 22DDA1	43-28.88	113-20.20	USGS 8/ 1/77	1634	10.0 310.0					IN	13.72
2N/27E- 2DDC1	43-31.37	113-12.05	NRTS 8 6/26/77	1583	20.0 230.0	(1.51)		9.5 .4	14	AB	
					230.0 245.0	(1.38)		3.4 1.0	4	IN	10.67

TABLE 1b. (continued)

Twn/Rng- Section	N Lat. Deg.Min.	W Long. Deg.Min.	Hole ID Date Logged	Collar Elev. m	Depth Interval m	Avg. TC Wm ⁻¹ K ⁻¹	No. TC	Corr. Gradient °C/cm	Corr. HF mWm ⁻²	Aqu. Status	Aqu. Temp. °C
2N/28E- 21BBB1	43-29.58	113- 8.02	NRTS 86 6/20/78	1547	20.0 197.0	(1.51)		7.8 .2	11	AB	9.44
2N/29E- 13AAA1	43-30.38	112-55.26	NRTS 83 6/18/77	1506	20.0 160.0 165.0 220.0	(1.51) (1.38)		16.1 .2 8.1 .3	24 11	AB IN	11.78
2N/29E- 36CC	43-27.09	112-57.15	NRTS 06 7/ 7/77	1530	30.0 170.0	1.46	1	25.0 .4	36	AB	13.74
2N/30E- 9AAA1	43-31.27	112-53.78	AEC OMRE 6/30/77	1505	170.0 205.0	(1.34)		1.1 .2	1	IN	13.14
2N/31E- 35DCC1	43-27.00	112-46.58	NRTS 1 7/ 1/77	1531	20.0 165.0	1.51	1	29.5 .4	44	AB	14.15
2N/32E- 22ABD	43-29.44	112-41.05	USGS G1 7/ 2/79	1637	20.0 300.0 300.0 455.0 455.0 537.5	2.34 .12 1.97 .13 1.58 .17	3 10 3	31.7 .3 5.3 41.7 1.0	74 10 65	AB IN BL	19.43
2N/35E- 28BC1	43-32.30	112-19.27	NRTS H41 6/15/77	1551	220.0 345.0	(1.34)		.1 .2	0	IN	10.01
2N/37E- 2AB	43-32.23	112- 4.23	BLM 6/19/79	1444	25.0	(1.34)		4.8 .5	6	IN	10.38
2N/38E- 16ADD	43-30.31	111-59.03	WJ 7/18/77	1444	20.0 70.0	1.51	1	-25.0 .9	-37	IN	<10.87
1N/29E- 21DCC	43-23.81	113- 3.79	SMU BSB1 8/25/78	1585	7.5 106.0	2.76 .06	16	9.3 .2	25	AB	
1N/29E- 30BBB1	43-23.65	113- 6.75	NRTS 11 6/30/77	1544	200.0 212.0	(1.34)		.8 .4	1	IN	11.64
1N/30E- 10BBB1	43-26.32	112-55.97	WJ BLM 6/25/78	1518	10.0 179.0	1.46	1	20.5 .8	30	AB	13.57
1N/36E- 1CCB1	43-26.55	112-10.88	USBR 6/11/78	1424	10.0 61.0	1.46	1	-9.1 9.8	-13	AB	11.00
1N/37E- 15BBB3	43-25.47	112- 5.95	USBR 6/10/78	1416	35.0 95.0	1.46	1	7.2 .9	10	IN	11.38
1S/21E- 13DB	43-19.98	113-54.00	WJ SLSW 8/ 7/78	1457	5.0 80.0					IN	11.05
1S/22E- 3AA	43-22.03	113-48.93	WJ 8/ 7/77	1493	.0 52.0					IN	17.33
1S/23E- 26CCC	43-18.15	113-41.64	USGS 5/25/79	1532	10.0 380.0	1.25	1	.5 .3	1	IN	9.86
1S/27E- 14DCC	43-19.80	113-16.30	USGS 8/ 1/77	1572	150.0 310.0	(1.46)				IN	13.33
1S/30E- 15BCA1	43-20.32	112-56.85	NRTS 14 6/29/77	1564	30.0 120.0 120.0 210.0	(1.46) (1.38)		34.8 1.0 10.9 .9	51 15	AB IN	13.67
1S/37E- 36DCB	43-17.08	112- 4.17	WJ FLDG1 6/13/78	1464	10.0 80.0	1.55	1	112.0 6.7	173	AB	18.60
2S/20E- 1ACC2	43-16.70	114- 1.50	USGS 7/27/74	1460	20.0 50.0	1.37 .06	3	54.3 1.5	74	AB	
3S/20E- 2DDA1	43-11.27	114- 2.15	USGS 8/ 2/78	1403	10.0 90.0	(1.46)		2.0 .3	7	AB	10.72
3S/27E- 24DDA	43- 8.67	113-14.55	USGS 5/28/79	1518	250.0 275.0	(1.38)		15.0 .5	20	IN	15.45
3S/33E- 2DC	43-11.09	112-33.87	USBR 6/29/79	1359	10.0 205.0	1.42	1	-7.3 .9	-10	IN	11.10
4S/17E- 24CDD	43- 3.36	114-23.05	WJ 8/23/77	1311	20.0 57.0	1.51	1	31.8 .8	47	AB	

TABLE 1b. (continued)

Twn/Rng- Section	N Lat. Deg.Min.	W Long. Deg.Min.	Hole ID Date Logged	Collar Elev. m	Depth Interval m	Avg. TC $\text{Wm}^{-1}\text{K}^{-1}$	No. TC	Corr. Gradient $^{\circ}\text{C}/\text{km}$	Corr. HF mWm^{-2}	Aqu. Status	Aqu. Temp. $^{\circ}\text{C}$
4S/17E- 35DA 1	43- 2.09	114-24.49	BLM R275 5/24/78	1341	20.0 70.0 70.0 110.0	1.51 (1.38)	1	30.2 2.2 .2 1.1	45 0	AB IN	12.70
4S/24E- 6BBC	43- 6.59	113-39.02	USGS 7/ 3/79	1377	10.0 105.0	(1.38)		5.4 .3	7	AB	11.41
4S/32E- 1CBAB	43- 6.11	112-40.07	USGS 8/10/78	1356	40.0 109.3	(1.51)		-6.7 .7	-9	IN	10.09
5S/15E- 17BCB	42-59.56	114-42.61	WJ 8/31/78	1103	37.5 62.5	(1.38)		16.0 2.7	22	IN	12.77
5S/15E- 34ACC	42-56.84	114-39.74	WJ MUFFY 8/28/78	1105	7.5 53.5	1.88	1	44.5 5.7	84	IN	14.14
5S/17E- 26ACA1	42-57.70	114-24.07	USBR 7/ 9/78	1210	10.0 62.5	1.51	1	35.0 2.6	52	AB	12.53
5S/18E- 6ACC	43- 1.15	114-21.74	WJ 7/26/77	1301	70.0 121.0	(1.51)		.1 .1	0	IN	13.19
5S/23E- 17CAA	42-59.20	113-44.63	USGS 7/ 3/79	1341	15.0 90.0	(1.38)		17.7 .3	24	AB	13.20
5S/25E- 22ADA1	42-58.18	113-27.27	USGS 5/31/79	1396	15.0 150.0 155.0 175.0	(1.42) (1.34)		23.7 .4 24.0 2.1	33 32	AB IN	14.78
5S/28E- 26BBD1	42-57.77	113- 9.65	USGS 7/28/78	1506	20.0 215.0 215.0 225.0	1.51 1.42	1 1	9.5 .9 -1.0 .3	14 -1	AB IN	12.32
6S/13E- 16AAD1	42-54.42	114-54.58	USGS 7/18/74	1000	10.0 50.0 50.0 100.0	(1.42) (1.38)		102.0 .9	146 1	AB IN	16.93
6S/14E- 23DDA	42-52.99	114-45.11	WJ 8/30/78	1070	67.5 77.5	1.46	1	3.6 .6	5	IN	14.30
6S/18E- 7BCB1	42-55.10	114-22.34	USBR 6/24/78	1213	20.0 70.0	1.55 .80	3	4.9 2.2	7	AB	14.45
6S/19E- 18BCD	42-54.11	114-14.83	WJ 7/27/77	1234	75.0 140.0	1.37 .88	2	9.8 2.3	13	IN	15.33
6S/32E- 31CAB	42-51.34	112-51.59	W YOUNG 8/ 6/78	1342	15.0 35.0 15.0 35.0	(1.46) (1.46)		.1 .4	-1	AB IN	9.74
7S/14E- 30DCC	42-46.99	114-51.39	WJ HSCUR 9/ 3/78	978	15.0 98.5					IN	14.47
7S/19E- 19AA 1	42-48.48	114-16.09	USGS 6/11/79	1237	5.0 75.0	1.34	1	3.2 .3	4	AB	15.09
7S/24E- 29ADD1	42-50.62	113-36.54	USBR 8/ 6/78	1306	10.0 72.0	(1.51)		48.8 4.2	73	AB	12.65
7S/26E- 14CCC1	42-48.45	113-23.55	USBR 7/14/78	1342	20.0 120.0	1.51	1	9.7 1.4	14	AB	12.21
7S/30E- 28BBC	42-47.25	112-57.66	WJ ALLEN 8/10/78	1381	10.0 70.0 70.0 89.0	(1.51) 1.42	 1	18.1 1.6 .6 .2	27 0	AB IN	10.42
8S/14E- 8AAA	42-45.22	114-49.81	WJ 9/ 2/78	976	10.0 36.5	(1.38)		26.5 1.6	36	IN	14.58
8S/14E- 16CBB1	42-43.88	114-49.78	USGS 9/ 1/78	967	.0 16.2					IN	14.30
8S/19E- 5DAB1	42-45.40	114-15.15	USBR 6/27/78	1242	10.0 95.0	(1.51)		18.4 2.9	27	AB	15.16

TABLE 1b. (continued)

Twn/Rng- Section	N Lat. Deg.Min.	W Long. Deg.Min.	Hole ID Date Logged	Collar Elev. m	Depth Interval m	Avg. TC $\text{Wm}^{-1}\text{K}^{-1}$	No. TC	Corr. Gradient $^{\circ}\text{C}/\text{km}$	Corr. HF mWm^{-2}	Aqu. Status	Aqu. Temp. $^{\circ}\text{C}$
8S/24E- 2ABB1			USBR 7/19/78	1303	10.0	(1.51)		31.0	46	AB	
					70.0			2.1			
					70.0 83.0	(1.38)		.9 .4	1	IN	12.48
8S/25E- 36DAA1	42-41.03	113-28.23	USBR 7/27/78	1282	10.0	(1.51)		29.6	44	AB	
					35.0			1.1			
					35.0 50.0	(1.38)		1.4 .3	2	IN	12.89
8S/26E- 3CDD1	42-44.90	113-24.27	USBR 7/16/78	1320	10.0	1.51	1	25.4	38	AB	
					110.0			2.3			
					110.0 145.0	1.38	1	12.4 3.7	17	IN	13.86
8S/29E- 34CBC3	42-40.78	113- 3.62	USBR 7/26/78	1337	20.0	(1.38)		10.1	13	IN	11.85
					60.0						
					60.0 119.8	1.59	1	53.4 1.3	84	BL	
9S/14E- 2ACC	42-40.46	114-46.79	THOUS SP 9/ 1/78	908	.0					IN	14.44
9S/14E- 3ABB1	42-40.88	114-48.05	USGS 9/ 1/78	976	22.5 28.0	(1.38)		19.0	26	IN	14.15
9S/17E- 19ABA1	42-38.20	114-30.45	USGS JCC 6/22/78	1091	45.0 52.0	(1.38)		1.3 .5	1	IN	13.61
9S/19E- 25BBC1	42-36.98	114-11.27	USBR 7/10/78	1198	10.0	1.51	1	68.3	102	AB	
					40.0			10.0			
					40.0 47.5	(1.38)				IN	15.23
10S/21E- 28BC	42-31.24	114- .40	USBR 7/28/77	1265	20.0 120.0	(1.55)		-8.7 2.3	-13	IN	13.80
10S/22E- 20CD	42-32.04	113-54.34	USBR 7/27/77	1266	25.0 129.0	(1.55)		-7.1 1.0	-10	IN	13.50

The abbreviations in the aquifer status column (Aqu. Status) are AB, gradient above Snake Plain aquifer; IN, gradient in Snake Plain aquifer; BL, gradient below Snake Plain aquifer. Aquifer temperatures (Aqu. Temp.) are the observed temperatures within the Snake Plain aquifer. Blanks in a particular column signify that measurements were not made or calculated. Brackets around the thermal conductivity values signify that the value is from surrounding well or wells.

indicate that the holes or intervals were in Cenozoic sedimentary rocks or basalts. Only a few of the holes encountered pre-Cenozoic rocks. These holes included 9N/30E-2CDD and 9N/32E-30BCA, which were drilled in Paleozoic limestone; hole 8N/28E-3CCC1, which was drilled in Paleozoic quartzite; and holes 1S/18E-16DCC and 1S/18E-32ACC, which were drilled in Mesozoic granite of the Idaho batholith. The last four holes shown in Table 1a were drilled in the Raft River geothermal area and published by *Urban and Diment* [1975].

The data shown in Table 1b are from wells drilled in areas occupied by the Snake Plain aquifer. The predominant lithology of all the holes in the Snake Plain aquifer is basalt. Occasional interbeds of sedimentary rocks are present, but volumetrically these are minor. Similar data for each hole are shown as in Table 1a except that no uncorrected heat flow values are shown and there is a gradient status column instead of a heat flow quality column. No terrain corrections are needed for any of the holes in the aquifer so no uncorrected gradient column is included in Table 1b. The interval gradient and heat flow data from wells located within the boundary of the Snake Plain aquifer as shown in Figure 1 are divided into as many as three heat flow regimes identified as 'above,' 'in,' and 'below' the aquifer system.

Abbreviations for these categories are shown in place of the heat flow quality shown in Table 1a. The 'above' regime appears to be generally conductive; the heat flow is controlled by the difference between the mean annual surface temperature and the local aquifer temperature and may be negative over large areas. In a significant fraction of the holes the 'above' temperatures are disturbed according to what has previously been described by *Brott et al.* [1976] as a 'vesicular' basalt effect. In these holes, which typically exhale or inhale air depending on atmospheric pressure and temperature conditions, air circulation completely disturbs the gradient above the water table and produces an exaggerated annual wave with amplitudes of several degrees centigrade to depths of 100 m or more. No 'above' values of gradient or heat flow are reported in Table 1b for holes which display this disturbance. Within the top tens of meters of the aquifer the heat flow regime is convective and the temperatures are approximately isothermal due to the mixing of circulating fluid. Thermal conductivities for these holes, which are generally in basalt, were estimated for measurements from samples all over the eastern Snake River Plain. Due to the nature of the heat flow, errors introduced in assuming thermal conductivity are probably insignificant. The significance of the aquifer data will be discussed in more

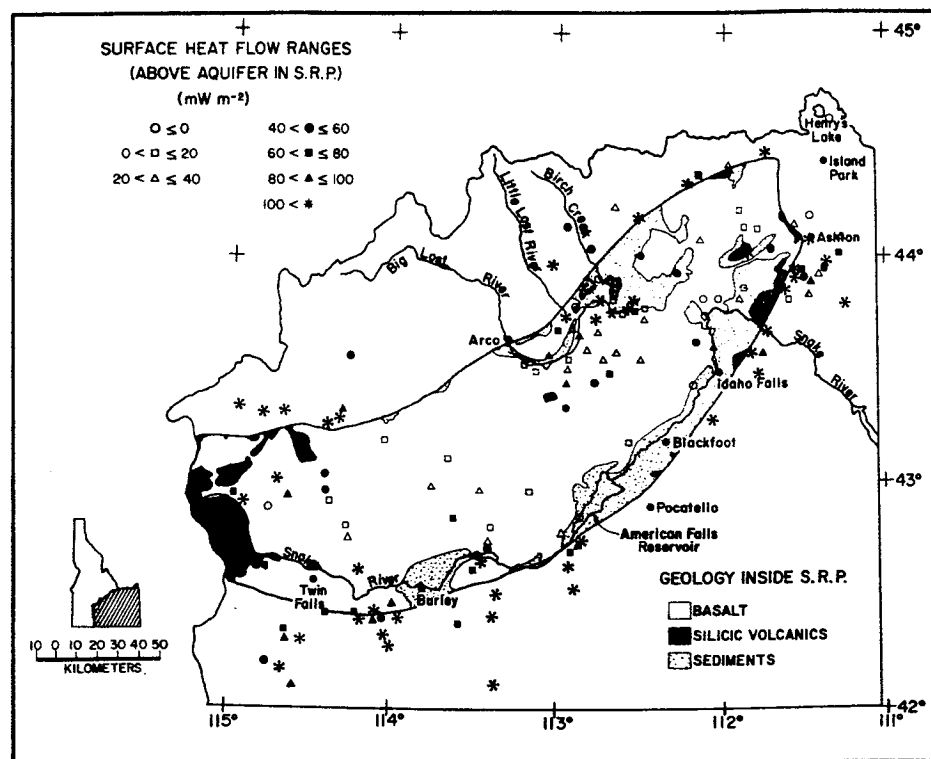


Fig. 1. Generalized heat flow map of southeast Idaho. The heat flow values are coded as shown. The values are listed in Table 1. The eastern Snake River Plain is outlined, and the geology is generalized after Bond [1978] and Ross and Forrester [1947]. The inset map shows the location of the study area with respect to the state of Idaho.

detail below. Below the aquifer system the heat flow regime appears to be generally conductive because positive, constant gradients occur in three of the four deep holes.

Figure 2 shows a composite cross section of the heat flow values across the far eastern part of the Snake River Plain. The heat flow values are plotted on a scale which shows their

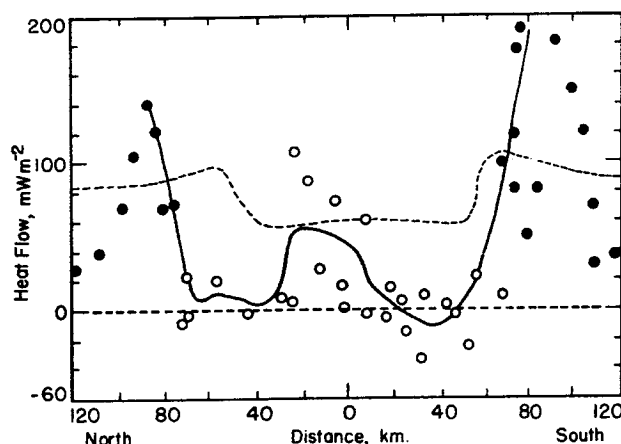


Fig. 2. Two heat flow profiles perpendicular to the axis of the Snake River Plain. The solid curve is the smoothed eastern Snake River Plain profile (fit to the data represented by solid and open circles) and the dashed curve is a theoretical heat flow profile (from model 1, 12.5 m.y. solution of Brott *et al.* [1978]) which best fits the western Snake River Plain data. The open and solid circles represent data taken inside and outside the Snake Plain aquifer. These data are projected into the composite profile from a 50-km strike length extending east from a line between Arco and Pocatello. The values are plotted on a scale which shows their perpendicular distance from the axis.

perpendicular distance from the axis of the Snake River Plain. The figure shows generally high heat flow values (many over 100 mW m^{-2}) on the margins and lower values (mostly in the range of -30 to 20 mW m^{-2}) in the Snake Plain aquifer. Although a qualitatively similar heat flow distribution is observed in the western Snake River Plain (shown as the dashed curve on Figure 2), i.e., low heat flow in the Snake River Plain and high heat flow on the margins, the causes for the pattern are completely different. The low heat flow in the western Snake River Plain results from large-scale refraction of heat due to crustal thermal conductivity contrasts, while the low heat flow in the eastern Snake River Plain is caused by regional cold groundwater circulation in a major aquifer system. The thermal refraction effect in the eastern Snake River Plain is minor because a large, deep sedimentary basin (as observed in the western part) has not yet developed.

Using the large quantity of data, the average heat flow and gradient values for five different areas are listed in Table 2.

TABLE 2. Heat Flow and Gradient Averages for the Eastern Snake River Plain

Location	Number	Gradient, $^{\circ}\text{C km}^{-1}$	Heat Flow, mW m^{-2}
Northern Margin	23	55 ± 9	93 ± 13
Northeastern	13	36 ± 6	73 ± 12
Northwestern	10	74 ± 12	112 ± 14
Southern Margin	80	71 ± 7	113 ± 11
Southeastern	42	66 ± 6	124 ± 13
Southwestern	38	76 ± 7	101 ± 8
Snake River Aquifer	125	18 ± 2	27 ± 4

Plus or minus values shown are standard errors.

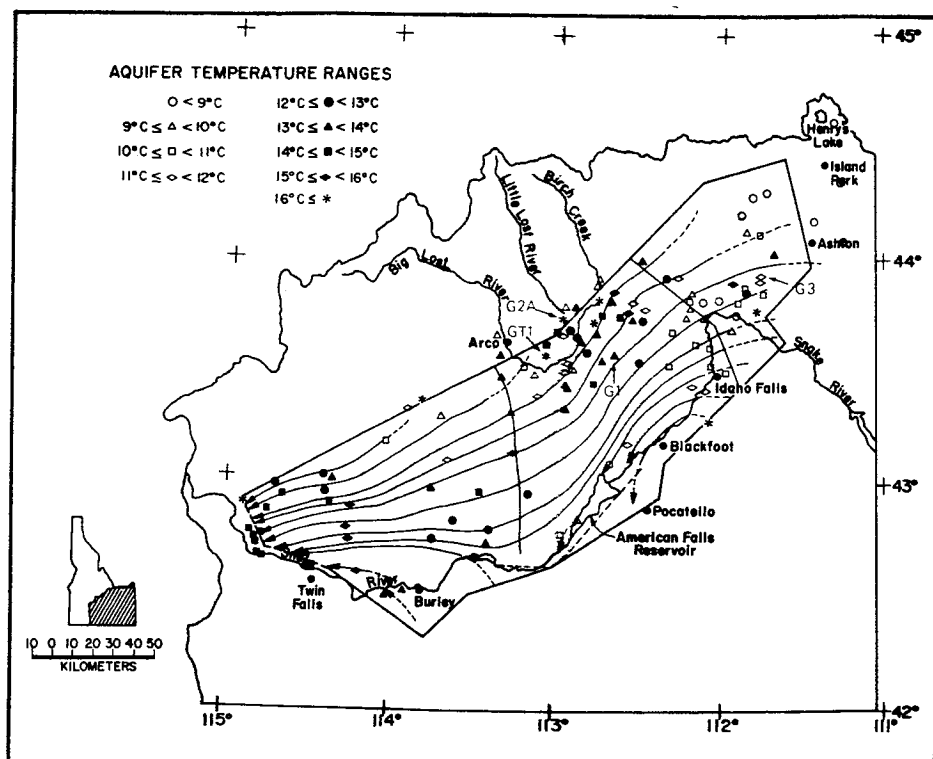


Fig. 3. Temperatures in the Snake Plain aquifer. The solid heavy lines show the locations of recharge and the dashed lines show the locations of discharge [after Mundorff *et al.*, 1964]. The internal heavy solid lines show the location of the Mud Lake (western) and Arco (eastern) hydrological barriers [after Hasket and Hampton, 1979]. The aquifer temperatures are listed in Table 1. The locations of four deep (i.e., >400 m) holes are shown. Each narrow line is a flow line representing $18.5 \text{ m}^3 \text{ s}^{-1}$ of water flow.

The division of the northern and southern margins of the eastern Snake River Plain (east and west) 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 a lateral movement of groundwater into the Snake Plain aquifer, and these values are not included in the averages. The large variation of values internal to 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 Plain aquifer. 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, 8 out of 11, were drilled specifically for heat flow. In spite of these complexities, the average surface heat flow values are clearly anomalously high on the margins and anomalously low in the Snake Plain aquifer.

Snake Plain Aquifer

Introduction

The Snake Plain aquifer (see Figure 3) is approximately 95 km wide and 300 km long [Mundorff *et al.*, 1964]. The heavy solid lines on Figure 3 show the recharge areas, and the dashed lines show the discharge areas of the aquifer. Each flow line on the figure represents $18.5 \text{ m}^3 \text{ s}^{-1}$ flow of groundwater. The two solid lines which cross the aquifer show the locations of the Mud Lake (eastern) and Arco (western) hydrologic barriers. The water table drops approximately 30 to 60 m across each of these barriers. Hasket and

Hampton [1979] suggested that these barriers may be sediment zones on the 'downstream' side of old centers of volcanic activity which now are covered by younger basalt flows. Wells from Table 1b are shown on Figure 3 with the observed aquifer temperature given by the coded symbols. Generally, the aquifer temperature ranges from 8° to 9°C in the recharge zones to 14° to 15°C in the discharge zone. The temperatures in the central part of the aquifer vary from 10° to 20°C, with a general trend toward high aquifer temperatures to the west.

The hydrological features of the Snake Plain aquifer have been extensively described (Mundorff *et al.* [1964], Norvitch *et al.* [1969], Hasket and Hampton [1979], and many others). The total discharge of the aquifer is approximately $185 \text{ m}^3 \text{ s}^{-1}$ and occurs primarily on the western edge of the aquifer at Thousand Springs. Reported horizontal flow rates range from about 1 m to several meters per day, but the average horizontal flow rate is less than 1.6 km yr^{-1} . The aquifer system is composed of many Quaternary basalt flows with occasional interbedded sediments. In the western part of the Snake Plain aquifer the younger flows (basalt of the Snake River Group) overlie a thick sequence of older basalt flows, consolidated sedimentary rocks, and silicic volcanic rocks of Cenozoic age [Malde and Powers, 1962]. In general, the permeability of these older rocks is less than that of the Snake River Group, and they are not considered to be part of the aquifer system. Moreland [1976] reported that a large number of the springs in the canyon walls at Thousand Springs occur at the contact between the Tertiary and Quaternary rocks.

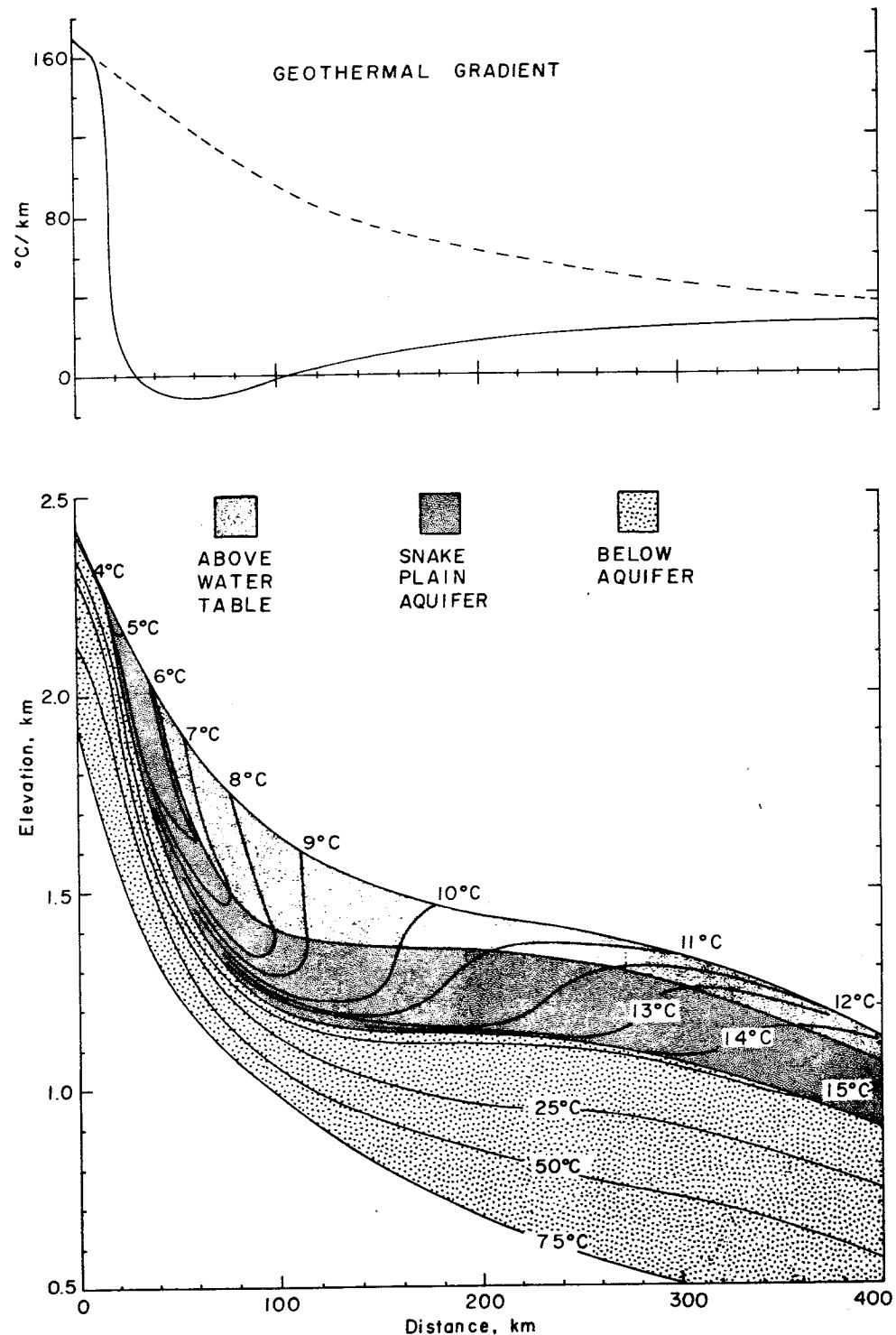


Fig. 4. Two-dimensional transient Snake Plain aquifer model. The model contains three layers. The upper layer represents the rocks above the aquifer, and the mechanism for the transport of heat in this layer is purely conductive. The center layer represents the aquifer convection zone and the mechanisms for the transport of heat are convection and conduction. The lower layer is below the aquifer, and the mechanism of heat transfer is purely conductive. The surface geothermal gradient profiles before initiation of convection and in the presence of convection are shown above the model (dashed and solid lines, respectively).

Hydrological models of the Snake Plain aquifer were constructed by Mantei [1974] (electrical analog model) and Moreland [1976] (digital model). The aquifer parameters used in our thermal model were selected to be consistent with these hydrological models.

SNAKE PLAIN AQUIFER THERMAL MODEL

The two-dimensional Snake Plain aquifer thermal model (Figure 4) is a transient model; the solution was obtained by a finite difference solution of the two-dimensional heat flow

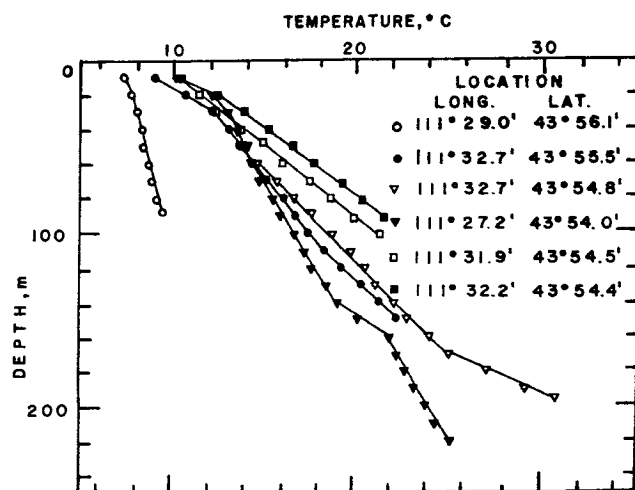


Fig. 5. Temperature-depth curves of wells 10–30 km away from the southeastern margin of the Snake Plain Aquifer. The longitude and latitude for each well are given on the figure.

equation with a one-dimensional velocity term [Brott, 1976]. The initial temperature distribution and the heat flow at the base of the model were obtained from the finite-width moving-source model which will be discussed below. The surface temperature distribution of the model was obtained from a least squares linear fit to surface temperature versus elevation for 300 wells in the eastern Snake River Plain. The surface elevation in the model was obtained from a third-order polynomial fit to the observed elevation in the Snake River Plain. The surface geothermal gradient profile without convection is shown above the model (dashed line at top of Figure 4). The individual isotherms without convection (which are not shown) have approximately the same shape as the topographic surface.

Given the initial temperatures, convection was allowed to occur in the aquifer. The model velocity assumed for the flow in the aquifer was 1 km yr^{-1} (about 3 m d^{-1}). The active convection zone shown in Figure 4 extends from approximately the Island Park area to Thousand Springs. The top of the convection zone is the water table and corresponds to the result of a third-order polynomial fit to the observed

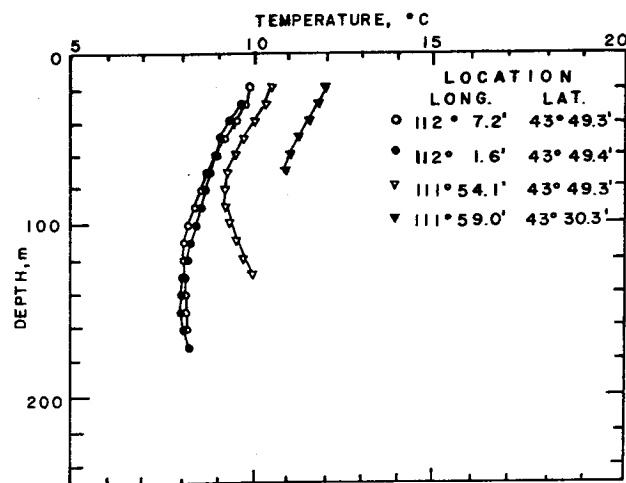


Fig. 6. Temperature-depth curves of wells in the major recharge areas of the Snake Plain aquifer. The longitude and latitude for each well are given on the figure.

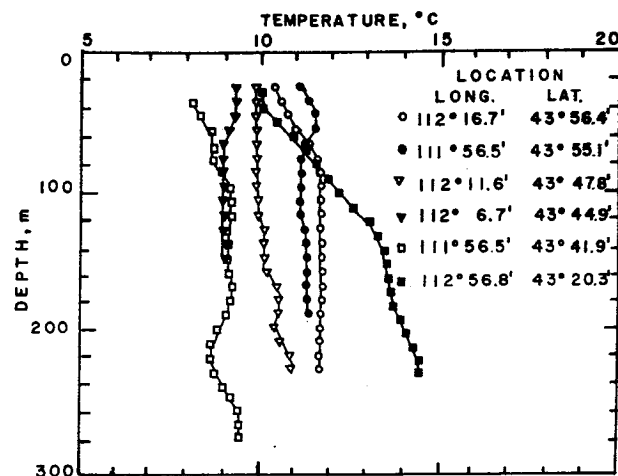


Fig. 7. Temperature-depth curves of wells in the Snake Plain aquifer which are 100 km or more from the inflow areas of the aquifer. The longitude and latitude for each well are given on the figure.

water table. The thickness of the aquifer was assumed to range from about 200 to over 300 m. The aquifer may vary in thickness up to 750 m or more [Robertson *et al.*, 1974], but the effect of the aquifer on the near-surface isotherms would be the same. The temperature distribution does not change above and within the aquifer after a period of circulation of about 10,000 years. The temperature distribution below the aquifer shown in Figure 4 corresponds to the numerical solution after convection has occurred for a period of 100,000 years. The actual temperatures below the aquifer will depend on the history of evolution of the aquifer, which is currently unknown, and therefore the constructed isotherms are only hypothetical. At a distance of 5–10 km outside the aquifer the calculated gradient profile shows little to no effect from the aquifer system (top left side of Figure 4), but a rapid lateral geothermal gradient change is observed where the fluid enters the aquifer. In the aquifer approximately 100 km 'downstream' from the inflow region, the calculated gradient profile above the aquifer becomes positive, indicating that the fluid has been heated to a temperature greater than the surface temperature.

The simple two-dimensional aquifer model was developed to evaluate the effects of rapid groundwater flow and to see if such effects could explain the observed temperature-depth curves. The model is not to be taken literally because of its simplicity. For example, the western inflow regions (of which there are several) are not taken into account. In addition, many of the pertinent aquifer parameters are currently uncertain.

Comparison of Snake Plain Aquifer Model to Observed Data

Outside the boundaries of the aquifer, temperature-depth curves (Figure 5), as predicted, show little regional water effect. The curves shown as examples in Figure 5 are generally linear with gradients as high as $120^\circ\text{C km}^{-1}$. The location of the wells shown is approximately 100 km from the Yellowstone Plateau on the southern margin of the aquifer in the vicinity of Idaho Falls.

The temperature-depth curves of wells in the Quaternary basalts in the recharge areas show negative gradients (Figure 6). Negative heat flow and very low aquifer temperatures are

common characteristics of wells which are located in the major recharge areas of the aquifer (Figures 1 and 3) because the recharge water, which originates mainly from snow melt at high elevations, is at a lower temperature than the mean annual surface temperature of the recharge areas. The resulting negative shallow gradients in the recharge areas are consistent with the predicted surface aquifer gradient profile shown at the top of Figure 4. The aquifer thermal model is two-dimensional, whereas in reality, water enters the aquifer at many locations along the aquifer boundary (see Figure 3). The calculated isotherms for the inflow region of the model aquifer tend to wrap around the fluid flow (Figure 4) which results in the negative shallow gradients.

As the groundwater becomes heated in the aquifer, the temperature of the water becomes equal to, or greater than, the mean annual surface temperature. At this point the temperature-depth curves will become isothermal. At greater distances, temperatures will increase with depth. Typical temperature-depth curves at various locations in the aquifer away from recharge zones (Figure 7) show that gradients become isothermal or positive at a distance of 100 km or greater from the inflow areas of the aquifer. Figure 3 shows that a trend of increasing aquifer temperatures, from 8° to 9°C in the recharge areas to values of 14° to 15°C in the discharge area in the southwest, is generally observed. Figure 1 shows a similar trend of increasing surface heat flow from negative values in the recharge areas to values of about 60 mW m⁻² in the discharge area of the aquifer. These observed trends and their magnitude are consistent with the model predictions.

Heat Flow Below the Aquifer

Temperature-depth curves of four wells which are deeper than 500 m (see heat flow data section) are shown in Figure 8. Well USGS-G3 is located in the recharge area near the eastern boundary of the aquifer. The other three holes were drilled near the northern margin of the aquifer east of Arco (see Figure 1 and Table 1). Two of the wells (USGS-G1 and -G2A) have positive gradients beginning between 400 and 500 m which locate a lower boundary for the aquifer. INEL-

GT1 has a positive gradient beginning at around 250 m, apparently indicating a shallower and thinner aquifer at that site. The curve labeled INEL-GT1 (Figure 8) shows a local gradient disturbance at 800 m. This disturbance is due to natural downflow along a fracture zone. Below the aquifer system, wells USGS-G2A and INEL-GT1 have heat flow values of 110 and 109 mW m⁻², respectively (Table 1).

The three wells drilled east of Arco are located in an area which is not characteristic of the Snake Plain aquifer temperatures and surface heat flow are higher than in the areas to the south and west (Figures 1 and 3). This difference implies that the flow rates and nature of the aquifer are somewhat different, probably because the rocks are less permeable and porous. Well USGS-G3 is also located in an area which is not characteristic of the aquifer. The aquifer temperature near this well is higher than surrounding areas in the aquifer, which may indicate leakage of hot water from the Newdale geothermal anomaly (which is about 10 km to the east [Brott *et al.*, 1976]) into the aquifer system.

Heat Budget Analysis

The surface heat flow within the boundaries of the Snake Plain aquifer (Figures 1 and 3) was areally integrated, and the total loss of heat above the aquifer was calculated to be 42.3 MW. The total discharge of the aquifer is approximately 185 m³ s⁻¹. The heat required to change the temperature of this volume of water from 8° to 14.5°C is 287.3 MW. Thus the total amount of heat required from below the aquifer system would be 329.6 MW or an average heat flow of approximately 190 mW m⁻². The heat flow values actually measured below the aquifer in wells USGS-G2A and INEL-GT1 are 110 and 109 mW m⁻², respectively (Table 1). The average heat flow from the heat budget calculation is 190 mW m⁻², but the heat flow is predicted to be much higher to the east of these holes where the age of the volcanic activity is less. These observed trends are consistent with the model predictions. A similar areal integration was done using the heat flow predicted by the finite-width time-progressive model which will be presented later in this paper. The predicted heat loss is 221 MW, and the predicted temperature increase is 4.9°C. The predicted increase is consistent with the observed temperature increase.

REGIONAL THERMAL MODELS

Introduction

The geological and geophysical characteristics of the eastern and western Snake River Plain are somewhat different (see previous discussion). The important question is whether or not the origin of these differences is related to the same or to different thermal-mechanical mechanisms. In this section, we will present a moving-source thermal model and will argue that the observed spatial geological and geophysical differences can be explained as different stages in a time-related sequence of thermal events.

The observed low surface heat flow in the eastern Snake River Plain is not characteristic of the regional heat flow. In the discussion of the Snake Plain aquifer, three different arguments supporting anomalously high heat flow below this circulating water are given: modeling which shows that high heat flow below the aquifer is transported laterally; two deep wells which penetrate the aquifer and have observed heat flow values greater than 100 mW m⁻² in the section of the

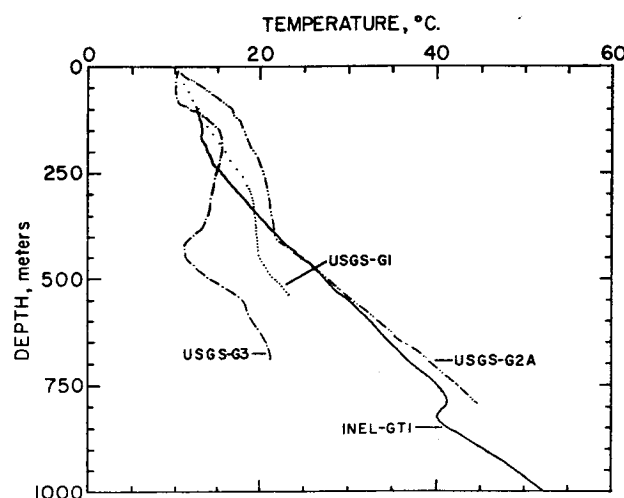


Fig. 8. Temperature-depth curves of wells greater than 500 m in depth. The longitude and latitude of each well are as follows: USGS G1, 112°41.1' and 43°29.4'; USGS G2A, 112°41.3' and 43°46.0'; USGS G3, 111°45.3' and 43°52.2'; and INEL GT1, 113°4.0' and 43°34.7'. The locations of these wells are shown on Figure 3.

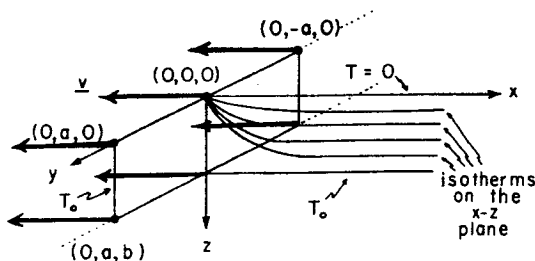


Fig. 9. Finite-width moving-source model. The model consists of a plane rectangular source moving through a medium with an initial linear temperature distribution. The velocity of the moving plane is v . The width of the plane is $2a$ and the depth of the plane is b . The source distribution on the plane is such that the temperature on the plane is equal to T_0 (a constant temperature). The surface temperature of the medium is zero, and the temperature at a depth of b in the medium is held at T_0 . Isotherms for the x - z plane are shown on the figure.

holes below the aquifer; and a heat budget analysis which shows the need for a large heat input to generate the observed water temperature distribution in the aquifer. A fourth argument is that heat flow values of 100 mW m^{-2} and greater are observed at many locations along the margins (Figure 1). Thus we conclude that high regional heat flow exists below and along the margins of the Snake Plain aquifer.

The earlier work of Brott *et al.* [1978] showed that the observed heat flow profile across the western Snake River Plain could be reproduced by cooling of a large (mafic) intrusion assumed to be emplaced 10–15 m.y. ago which is presently responsible for an anomaly of 13 mW m^{-2} above Basin and Range values over the center. The time period of

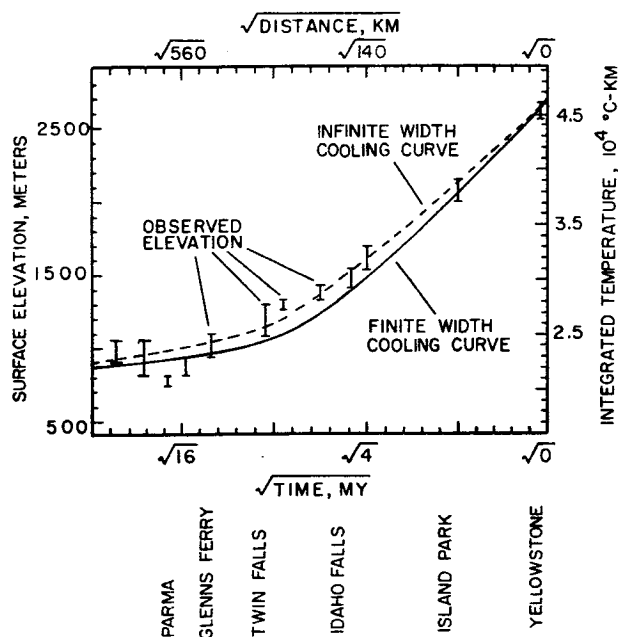


Fig. 10. Integrated temperature-elevation curves for the infinite-width constant-temperature moving-source plane and the finite-width constant-temperature moving-source plane (dashed and solid lines, respectively). Average observed elevation along the axis of the Snake River Plain is shown on the figure. The elevations and integrated temperatures are scaled for comparison. The top scale is square root of distance, and the bottom scale is square root of time. Various towns and other locations along the Snake River Plain are given below the graph.

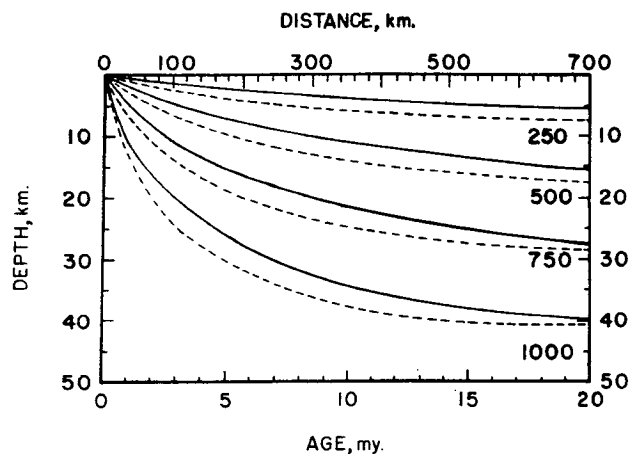


Fig. 11. Predicted subsurface isotherms (250° , 500° , 750° , and 1000°C) below the axis (solid lines) and margins (dashed lines) of the Snake River Plain.

emplacement spans the ages of silicic volcanics in the western Snake River Plain (9–13 m.y. [Armstrong *et al.*, 1975]). The silicic volcanics probably originated from crustal melting and/or differentiation of the magma chambers at the time of emplacement. This time correlation coupled with the age progression of the silicic volcanics and the observed systematic decrease of elevation going from east to west in the Snake River Plain supports the hypothesis of a time-progressive thermal event.

Finite-Width Moving-Source Model

The finite-width model is a refinement of the model which McKenzie [1967] proposed for oceanic ridges, and its ramifications are used here to explain many of the observed physiographic and tectonic features of the Snake River Plain. The mathematical details of the finite-width model are discussed in the appendix. The parameters of the model were chosen to be consistent with geological and geophysical data (see previous discussions). The initial temperature-depth distribution in a 42-km-thick slab of lithosphere was calculated using the Basin and Range value for mantle heat flow (60 mW m^{-2} [Blackwell, 1978]). A 120-km-wide source plane was moved through this medium at a uniform rate of 35 mm yr^{-1} . The lithosphere is assumed to return (cool off) to the initial temperature distribution at a great distance behind the source. The geometry is shown in Figure 9 where the rectangular source of width $2a$ and thickness b (120 km and 42 km, respectively) moves at velocity v through a medium with an initial linear temperature distribution versus depth. The source distribution on the plane is such that the temperature on the plane is constant.

The predicted temperature distribution was integrated from the surface to a depth of 42 km along the axis of symmetry of the model. The integrated temperature profile (solid line in Figure 10) was scaled so that it and the observed average elevation along the axis of the Snake River Plain could be directly compared. The cooling curve for an infinite-width constant-temperature source plane [Brott *et al.*, 1978] is shown as a dashed line on the figure. Both curves give a reasonable fit to the observed elevations along the axis of the Snake River Plain.

Figure 10 shows that the observed elevation difference of about 1.7 km corresponds to about $2.3 \times 10^4 \text{ }^\circ\text{C km}$ change

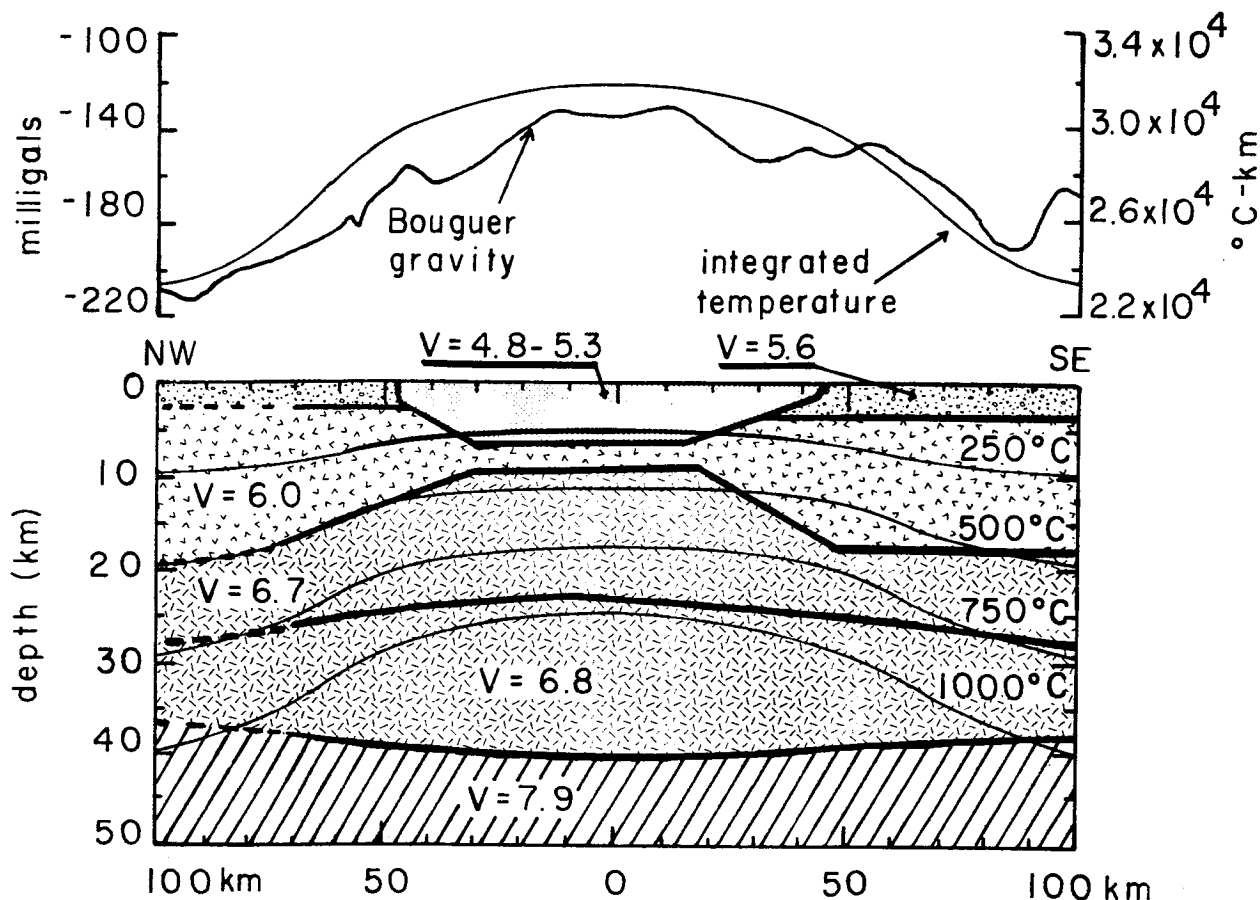


Fig. 12. Seismic and thermal structure of the eastern Snake River Plain. The isotherms from the 175 km (5 m.y.) solution are shown on the model. The Bouguer gravity [Mabey, 1978] and integrated temperature profiles across the Snake River Plain, which are shown above the model, are scaled for comparison. The seismic P wave velocities and refraction boundaries are from Sparlin [1981].

in integrated temperature. The coefficient of linear thermal expansion required to produce this elevation change is approximately 7.4×10^{-5} cm/cm $^{\circ}\text{C}$. This value cannot be taken too literally because of the simplifications of the model; however, the order of magnitude is the same as the value reported for ocean lithosphere (3.2×10^{-5} cm/cm $^{\circ}\text{C}$ [Parsons and Sclater, 1977]). This simple relationship of the integrated temperature and elevation suggests that the primary cause of the systematic change in elevation from east to west along the Snake River Plain is thermal contraction of the lithosphere. Figure 11 shows the predicted subsurface isotherms (250°, 500°, 750°, and 1000°C) as a function of time and distance behind the thermal event in the center and at the margin of the thermal event (0 and $\pm a$ in Figure 9). The isotherms do not include the effect of the Snake Plain aquifer which would cause the isotherms to be depressed near the surface. The isotherms indicate that the subsurface below the margins of the source cools off more rapidly than below the axis. The isotherms also show that the upper 10 km of the crust is over 2/3 of the way to the equilibrium state 5 m.y. after the passing of the thermal event.

The finite-width model also predicts that lateral thermal contraction will occur across and along the Snake River Plain. The lateral contraction across the Snake River Plain was calculated by integrating the lateral temperatures at a depth of 6 km, from the center to ± 60 km from the center of the model. The change in the lateral integrated temperature after 15 m.y. of cooling (525 km from the source) is $2.0 \times$

10^4 °C km. Assuming the coefficient of thermal expansion to be 7.4×10^{-5} cm/cm $^{\circ}\text{C}$, a lateral contraction of about 1.5 km (1.3%) is predicted to occur across the Snake River Plain as the crust cools. The normal faulting, which is characteristic of the western Snake River Plain margins and apparently absent in the eastern Snake River Plain, may in part be related to this lateral contraction. Many rift zones which are perpendicular to the axis are mapped in the eastern Snake River Plain by Kuntz and Covington [1979]. They suggest that the locations of these rifts are controlled by structural weakness due to preexisting normal faults in the Basin and Range province before the development of the Snake River Plain. Longitudinal contraction along the axis of the Snake River Plain is a mechanism which could account for the opening of these rifts.

The vertical integrated temperature profile for 175 km (5 m.y.) across the finite-width model and an observed Bouguer gravity profile [after Mabey, 1978] are shown at the top of Figure 12. The gravity profile extends on a line which passes approximately through Arco and Blackfoot, Idaho (see Figure 1) and is at a location approximately 175 km west of the Yellowstone caldera. The seismic refraction profile [after Sparlin, 1981; L. W. Braile, personal communication, 1980] shown at the bottom of Figure 12 extends approximately along the same line. The isotherms shown on the seismic section in Figure 12 are from the 175 km (5 m.y.) solution of the finite-width model. The integrated temperature profile, which was scaled to the gravity profile for

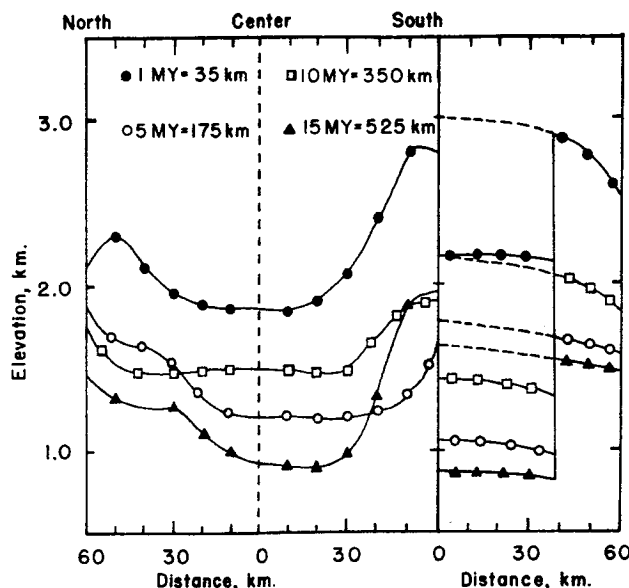


Fig. 13. Predicted elevation and observed topographic profiles across the Snake River Plain at various locations (or times) along the axis. The predicted elevation profiles before and after the density increase of the modified model are shown on the right-hand side (dashed and solid lines, respectively). Because of symmetry, only half of each predicted profile is shown. The corresponding smoothed topographic profiles are shown on the left-hand side of the figure. Each set of profiles is coded with a different symbol. The moving source extends 50 km on either side of the axis.

comparison, predicts that greater subsidence has occurred along the margins of the Snake River Plain, as suggested by Mabey [1978] (see the previous gravity and magnetic data discussion). The correlation between the integrated temperature and the gravity profiles suggests that the regional gravity anomaly observed in the Snake River Plain may, in part, be related to density and structure changes caused by thermal processes. The mechanism for these processes will be presented in the next section.

Modified Model

Thermal events in the western United States commonly produce lithospheric density changes which eventually result in lower elevation. For example, the Basin and Range province has a thinner crust, lower elevation, and higher heat flow than the Colorado Plateau to the east and the Sierra Nevada Mountains to the west. Similarly, the Snake River Plain has lower elevation and higher heat flow than its adjacent regions. To account for this lower elevation, the finite-width model was modified to include a density increase associated with the thermal event with resulting decrease in elevation (a denser crustal section) after cooling of the 42-km slab compared to the prethermal event setting. The density increase could be caused by such mechanisms as extension, extrusion of ash flows and their dispersion of granitic material away from the source, and/or erosion while the source region was elevated. All three effects probably combined to produce the actual density change.

A density increase was introduced into the model by fitting the 35-km (1 m.y.) predicted elevation profile across the model to the average topographic profile across the western edge of the Yellowstone Plateau (Figure 13). The location of the topographic profile is obtained by assuming a uniform velocity of 35 mm yr⁻¹ for the thermal source and

using the Yellowstone caldera as the present location of the source. The 1 m.y. predicted elevation profile (dashed line on right side of Figure 13) was constructed from the integrated temperature profile for the finite-width model assuming a uniform thermal expansion coefficient of 7.4×10^{-5} cm/cm °C for the 42-km slab. In order to fit the predicted elevation to the observed topography a uniform density increase of 0.06 g cm⁻³ is required over a lateral distance of 40 km on both sides of the axis of the Snake River Plain. The 0.06 g cm⁻³ density increase corresponds to the replacement of 4.8 km of upper crust (density of 2.68 g cm⁻³) with 3 km of mantle material (density of 3.2 g cm⁻³) or with 8.4 km of lower crust (density of 2.9 g cm⁻³).

The same density increase is assumed to be uniform along the length of the model and is applied to the predicted elevation profiles for 5, 10, and 15 m.y. Since the predicted profiles have symmetry about the center axis, only one half is shown (the right side of Figure 13) before and after the density change (dashed and solid lines, respectively). The corresponding actual topographic profiles are shown on the left side of the figure. The reasonable fit between the predicted and observed elevation profiles suggests that the lower elevations which are observed in the Snake River Plain are, in part, related to upper mantle and crustal density changes associated with the initial passage of the thermal event.

DISCUSSION

Surface Heat Flow

Earth temperatures are dominated by the Snake Plain aquifer to depths of 200–700+ m in most of the eastern Snake River Plain. Measurements have been made in as many holes as possible to investigate the regional variation of aquifer temperatures, geothermal gradients above, in, and below the aquifer. The results cannot be related to the crustal heat flow in a conventional sense, and so a numerical model of the aquifer was calculated to investigate the significance of the observed parameter variations. Along the margins, heat flow rates are high but variable, and many of the values are probably also related to fluid convection but in geothermal systems rather than groundwater systems.

Regional Heat Flow

The approach to the evaluation of the regional heat flow in the eastern Snake River Plain has been somewhat unusual because conventional heat flow measurements are not possible in the geologic setting there. On the basis of the heat budget studies the apparent heat flow is 190 mW m⁻², while the heat flow in the two holes which penetrate well below the aquifer is about 110 mW m⁻². Both values are well above regional values [Blackwell, 1978]. Both holes are about 175 km from the active hot spot (corresponding to an age of about 5 m.y.) and are near the edge of the source track where the temperatures and heat flow are lower than in the center of the propagating source (see Figure 11). Many objections and qualifications can be applied to both numbers, and the fact is that the best evidence for the high heat flow in the eastern Snake River Plain is the general consistency of the elevation-distance (time)-volcanic age relationship and the fact that the hot spot thermal model predicts many heretofore uncorrelated phenomena, such as the elevation relationship, the reversal of ash flow dips (presently dipping toward their source in the Snake River Plain), the origin of a thick

sedimentary basin on top of a volcanic center, the contemporary subsidence of the Snake River Plain while the Yellowstone region is rising, and others. The volcanic age progression and the identical crustal structures of the Yellowstone caldera and the eastern and the western Snake River Plain are also uniquely explained by the model.

Discussion of the Thermal Model

The theoretical age, elevation, and integrated temperature relationships are approximate because of the simplicity of the models. For example, erosion and sedimentation, which are not taken into account, would modify these relationships. In fact, lithological logs from deep wells in the western Snake River Plain show that the basalt and sediment sequence is as thick as 3 km [Bowen and Blackwell, 1975]. Other factors not taken into account are phase and temperature changes in the upper few kilometers of the crust due to the Snake Plain aquifer. Even though these complexities are not taken into account, their effect will not be large enough to change the conclusion that the age-elevation relation observed in the Snake River Plain is primarily related to the time-progressive thermal event.

Comparison With other Models

Most theories of the origin of the Snake River Plain proposed in the past 10 years have attempted to relate it to some facet of plate tectonics. These models all acknowledge the obvious effects of some source of heat but differ in how this heat was initiated. Did some mechanical event (i.e., a zone of weakness or a propagating crack) allow the hotter material from below to rise, or did some thermal instability in the upper mantle initiate the whole process?

Morgan [1972] suggested that the Snake River Plain represented the track of a mantle plume across western North America during the late Cenozoic. In this model the source of thermal energy would be similar to that at Hawaii. Smith and Christiansen [1980] and others have suggested a less precisely defined 'mantle hot spot.' A possible mantle thermal source, which is consistent with the regional tectonic history, is heat that was stored in the mantle wedge above the slab of Pacific Ocean lithosphere subducting beneath the western United States during much of the Cenozoic [Blackwell, 1978]. Various magma pockets may have developed and coalesced along the axis of the Snake River Plain more or less in the same manner as salt flows from the mother bed, laterally into some initial perturbation to form a salt dome. Another argument for this sort of model is that the ages of the silicic eruptions do not progress as uniformly northeasterly as most other mantle thermal models suggest [Prostka, 1979]. Since the crustal heat source dominates the surface heat flow pattern, surface heat flow data cannot be used to resolve the geometry of any thermal source structure in the upper mantle. Additional studies of elevation, gravity, and seismic wave propagation might allow examination of such a zone.

The second approach views the origin of the Snake River Plain as essentially a mechanical process in which the thermal effects are induced. In these models the Snake River Plain is treated as a propagating fracture or zone of extension [Smith, 1977, 1978; Furlong, 1979; Lachenbruch and Sass, 1978]. Our finite-width model is compatible with these mechanical models of the origin of the Snake River Plain

only if the mechanical effects are considered as an initiating effect which localizes the crustal expression and controls the direction of propagation of the heat source. For example, Smith [1977, 1978] suggested that a propagating fracture is rising over a diapir in the upper mantle which is related to the thermal effects of subduction. Thus the origin of the Snake River Plain in his model can be considered to be thermal.

Furlong [1979] pointed out that the seismically determined stress pattern along the southeast margin of the Snake River Plain could be satisfied by mechanically decoupling the north and south margins. A mechanism which would account for this decoupling and the aseismicity in the Snake River Plain is a corollary of the thermal model. The predicted temperatures are sufficiently high to allow for elastic decoupling of the margins with only aseismic creep occurring in the Snake River Plain in response to regional stresses. The deflection of the Intermountain Seismic Belt around the Snake River Plain at a distance of about 100 km is evidence for such a mechanism [Smith and Sbar, 1974].

Models that relate increased surface heat flux to spreading rate have been presented by Lachenbruch and Sass [1978], and it is tempting to apply these models to the Snake River Plain. If the decrease in elevation of the Snake River Plain is assumed to be related to lateral extension and if the dimensions of Yellowstone caldera are used for our calculations, then 1% of extension has occurred in 2 m.y. Thus with a background Basin and Range reduced heat flow value (60 mW m^{-2}) this extension rate would generate a steady state surface heat flow of $80\text{--}120 \text{ mW m}^{-2}$. However, the averaged observed combined conductive and convective surface heat loss at Yellowstone is $800\text{--}2000 \text{ mW m}^{-2}$ [Fournier et al., 1976; Morgan et al., 1977], so the maximum rate of extension is inadequate to generate more than 1–10% of the observed thermal anomaly.

Implications of the Thermal Modeling

The identification of a thermal-mechanical mechanism for the changes in elevation has important tectonic and geothermal implications which can be tested by other geophysical and geological observations. For example, the very interesting regional elevation (age) and heat flow (integrated temperature) relationship, which is explained by simple thermal contraction, is consistent with the regional downwarping in the eastern Snake River Plain described by Kirkham [1931] and the aseismic nature of the region [Pennington et al., 1974]. Also, the approximate isostatic equilibrium of the eastern Snake River Plain with its adjacent regions [Mabey, 1978] is consistent with the modified model. The hypothesis that most of the upper mantle and crustal density changes (or crustal loading) occur during passage of the heat source suggests that the subsurface temperatures are still high enough for plastic flow, which allows for rapid and relatively local isostatic compensation.

The thermal model predicts an interesting relationship between time and distance which is as follows: The past geologic history for any point along the Snake River Plain is identical to the different geological settings from Yellowstone caldera westward to the location of the point. The future geologic history is identical to the different geological settings from the point westward to the western Snake River Basin. For example, consider the Oregon-Idaho border area.

Approximately 17 m.y. ago, extensive rhyolitic ash flows were erupted and large calderas formed, associated with regional uplift to 2 km or more, similar to the present-day Yellowstone region. A few million years later, the silicic volcanic activity progressed eastward, and the area began to subside and then resembled Island Park. Later, the surface of the caldera complex sank to a lower elevation than the surrounding terrain and was covered with basaltic lava flows and sediments similar to the eastern Snake River Plain. About 10 m.y. ago, normal faulting began at the margin of the trail of the extinct calderas because of lateral thermal contraction, and the area began to appear as a graben or rift structure. The area continued to subside and became filled with additional basalt flows and sediments which loaded the crust and caused additional subsidence and sedimentation. Thus, the observed structural differences in the eastern and western parts of the Snake River Plain represent the different stages in a sequence of thermally related events acting on a continental crust and upper mantle.

Geothermal Energy Potential

At this time, in spite of the many young volcanic features, the Snake River Plain–Yellowstone region has not been extensively explored for high-temperature geothermal resources. There are numerous areas where warm water is being used for various sorts of low-grade uses but as yet no temperatures in hydrothermal systems in excess of 100°C have been reported in literature. Of course, very high temperatures, over 250°C, have been reported from drilling in Yellowstone [White *et al.*, 1975]. In part, this apparent lack of high-temperature geothermal systems outside Yellowstone Park is probably due to the extensive cold groundwater aquifer circulation in the eastern Snake River Plain. The youngest extensive silicic volcanism outside Yellowstone Park has come from Island Park. There, resistivity data have been interpreted as suggesting very low geothermal potential [Stanley *et al.*, 1977]; however, the geology and the model presented in this paper suggest that, in fact, the geothermal potential of Island Park should be quite high and only the ubiquitous shallow circulation of cold groundwater is hiding the geothermal sources present at depth. Throughout the remainder of the Snake River Plain there has been extensive basaltic volcanic activity up to quite recent times as well as minor silicic volcanic activity as far west as Big Southern Butte (near Arco) as recently as 300,000 years ago [Armstrong *et al.*, 1975]. The only major characteristic possibly required for the occurrence of high-temperature geothermal resources lacking in the Snake River Plain is active faulting to open and maintain passageways for deep fluid circulation. Because of the high temperature the crust is plastic at relative shallow depths. Still the crust should be brittle to depths of 5–10 km, and there will be regional and local stresses in this depth range which could cause fracturing. Whether or not the fracturing is sufficient for formation of geothermal systems is at present unknown. Indeed the whole nature of circulation of groundwater beneath the Snake River Plain is a complete mystery except at the sites of the deep drill holes. In two of these, USGS-2A and INEL-GTL, there is no evidence for fluid circulation below the Snake River Plain Aquifer. In a third, USGS-3, there is evidence for the circulation of cold groundwater to depths of 800 or more. At this time therefore geologic and other evidence points to the

location of significant geothermal resources in the Snake River Plain; however, not enough exploration has occurred to illuminate the form or location of these geothermal resources.

APPENDIX

The finite-width thermal model is similar to the moving-slab model of McKenzie [1967] for oceanic spreading centers. The finite-width model consists of a temperature plane which moves through a slab of given thickness (Figure 9). The initial temperature-depth distribution in the slab is linear and the temperature at the base of the slab is T_0 . The temperature distribution on the moving plane is such that the combined temperature on the slab and plane is T_0 . The boundary conditions are as follows: the bottom of the slab is at T_0 , and the top of the slab is at zero. Therefore, the mathematical representation of the moving plane must extend from negative to positive infinity (Figure 14). If steady state is assumed and internal heat generation is neglected, then the temperature distribution is governed by the time-independent equation of heat transport:

$$\mathbf{v} \cdot \nabla T = \kappa \nabla^2 T \quad (\text{A1})$$

where $\mathbf{v}$ is velocity of moving plane, T is temperature and κ is diffusivity. If $\mathbf{v}$ is v_x in the x direction (Figure 3), the Green's function for (A1) has the form

$$(1/4\pi R) \exp(-v_x(R - (x - x')/2\kappa)) \quad (\text{A2})$$

where $R^2 = (x - x')^2 + (y - y')^2 + (z - z')^2$, (x, y, z) are the space coordinates, and (x', y', z') are the source coordinates [Carslaw and Jaeger, 1959, section 10.7]. The origin of the system is assumed to be the moving plane, and the temperature distribution on the moving plane source can be expressed as

$$T(y', z') = \sum_{n=-\infty}^{\infty} T_0 ((1 + 2n) - z'/b) \quad \text{for } |y'| \leq a \quad 0 \leq z' \leq 2b \quad (\text{A3})$$

$$T(y', z') = 0 \quad \text{for } |y'| \geq a \quad 0 \leq z' \leq 2b$$

where b is thickness of the slab and a is the half width of the plane (Figure 9). The temperature in the slab as a function of x, y, z is

$$T_{(x,y,z)} = T_0 z/b + (k/\kappa)(T_0/4\pi) \sum_{n=-\infty}^{\infty} \int_{2nb}^{2(n+1)b} dz' \cdot \int_{-a}^a dy' [(1 + 2n - z'/2b)(1/R) \exp(-v_x(R - x)/2\kappa)] \quad (\text{A4})$$

where k is the thermal conductivity.

The space coordinate x , which is the x distance from the plane (see Figure 9), is related to time t by the velocity v_x :

$$x = v_x t \quad t = x/v_x \quad (\text{A5})$$

Therefore, distance can be expressed as the time elapsed after passage of the source plane. For example, at a large distance from the moving plane or a long time after the

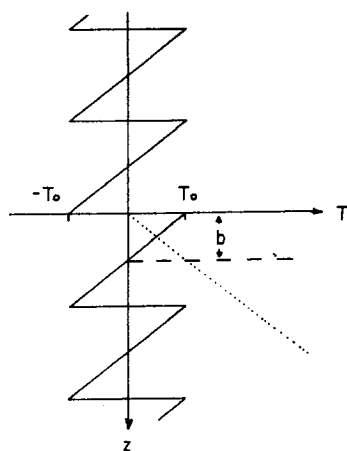


Fig. 14. Temperature distribution on a moving-source plane. The linear temperature distribution in the medium is shown as a dotted line. The limits of the temperature distribution on the plane extend from negative to positive infinity because of the upper and lower boundary conditions.

passing of the plane, the vertical temperature distribution in the slab will return (cool off) to the initial linear temperature-depth distribution.

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