Stratabound Geothermal Resources in North Dakota and South Dakota

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Geothermal energy resources in North Dakota and South Dakota occur as low ($T < 90°C$) and intermediate ($T < 150°C$) temperature geothermal waters in regional-scale aquifers within the Williston and Kennedy Basins. The accessible resource base is approximately 21.25 exajoules (10^{18} J = 1 exajoule, 10^{18} J ~ 10^{15} Btu = 1 quad) in North Dakota and 12.25 exajoules in South Dakota. Resource temperatures range from 40°C at depths of about 700 m to 150°C at 4500 m in the Williston Basin in North Dakota. In South Dakota, resource temperatures range from 44°C at a depth of 550 m near Pierre to 100°C at a depth of 2500 m in the northwestern corner. This resource assessment raises the identified accessible resource base by 31% above the previous assessments and by 310% over an earlier assessment. The large increases in the identified accessible resource bases reported in this study result from including all potential geothermal aquifers and better understanding of the thermal regime of the region. These results imply that a reassessment of stratabound geothermal resources in the United States that includes all geothermal aquifers would increase significantly the identified accessible resource base. The Williston Basin in North Dakota is characterized by conductive heat flows ranging from 43 to 68 mW m^{-2} and averaging 55 mW m^{-2}. Comparisons of calculated and bottomhole temperatures measured in oil fields over the Nesson Anticline and the Billings Nose show temperature differences which suggest that upward groundwater flow in fractures on the westward sides of the structures slightly perturbs the otherwise conductive thermal field. The maximum heat-flow disturbance is estimated to be of the order of 10 to 20 mW m^{-2}. These thermal anomalies do not alter significantly the accessible geothermal resource base. Anomalous heat flow in south-central South Dakota is caused by heat advection in gravity-driven groundwater flow in regional aquifers. Heat flow is anomalously high ($Q >$ 130 mW m^{-2}) in the discharge area in south-central South Dakota and anomalously low (≈30 mW m^2) in the recharge area near the Black Hills and along the western limb of the Kennedy Basin in western South Dakota. Heat-flow disturbances are the result of vertical groundwater flow through fractures in the discharge area of the regional flow system in South Dakota are minor and may be significant only in deeply incised stream valleys. An important factor that controls the temperature of the resource in both North Dakota and South Dakota is the insulating effect of a thick (500–2000 m) layer of low thermal-conductivity shales that overlie the region. The effective thermal conductivity of the shale layer is approximately 1.2 W m^{-1} K^{-1} in contrast to sandstones and carbonates, which have conductivities of 2.5 to 3.5 W m^{-1} K^{-1}. This low conductivity leads to high geothermal gradients ($dT/dz > 50°C$ km^{-1}), even where heat flow has normal continental values, that is 40–60 mW m^{-2}. Engineering studies show that geothermal space heating using even the lowest temperature geothermal aquifers ($T \approx$ 40 °C) in North Dakota and South Dakota is cost effective at present economic conditions.

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The Inyan Kara Formation of the Dakota Group (Cretaceous) is the preferred geothermal aquifer in terms of water quality and productivity. Total dissolved solids in the Inyan Kara Formation ranges from 3,000 to more than 20,000 mg L^{-1}. Porosities normally are higher than 20%, and the optimum producing zones generally are thicker than 30 m. The estimated water productivity index of a productive well in the Inyan Kara Formation is 0.254179 l s^{-1} MPa^{-1}. Deeper formations have warmer waters, but, in general, are less permeable and have poorer water quality than the Inyan Kara.

KEY WORDS: Continental heat flow; Williston Basin; geothermal anomalies.

INTRODUCTION

Stratabound geothermal resources are hot waters contained in permeable sedimentary formations. More than one-half of the area of North and South Dakota is underlain by deep sedimentary basins (Fig. 1); thus, there is significant potential for the occurrence of stratabound geothermal resources. Previous studies (Sorey and others, 1983; Gosnold, 1984, 1987) identified large quantities of geothermal resources in the well-known aquifers of these basins (Table 1) and gave promise of potential for additional resources in the remaining aquifers. Sorey and others (1983) included only the Dakota (Cretaceous) and Madison (Mississippian) aquifers. Subsequently, Gosnold (1984, 1987) used additional stratigraphic data to include four aquifers in North Dakota and seven aquifers in South Dakota to increase significantly the identified geothermal resource. This study includes compilation of more extensive stratigraphic and hydrologic data (Rahn, 1981; Downey, 1986) and temperature data (Gosnold, 1991, 1999) to facilitate analysis of remaining aquifers and further increase the identified resource base.

Identification and understanding of the origins of geothermal resources are critical for planning utilization of those resources. Thus, this study focused on origins as well as identification and quantification of the resources. Gosnold (1984, 1987) attributed the

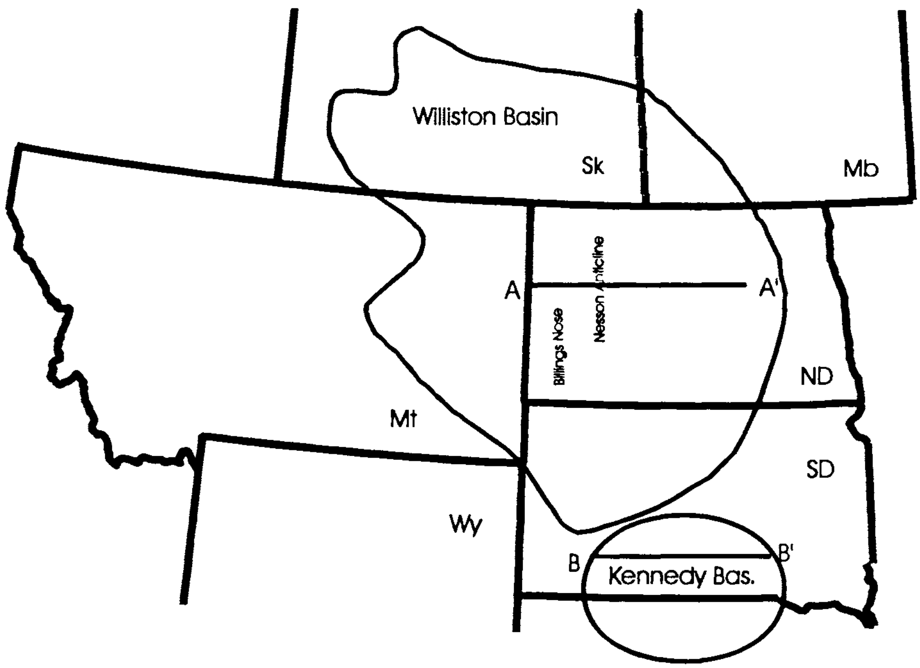

Figure 1. Location of Williston and Kennedy Basins. Lines A–A′ and B–B′ show locations of cross sections in Figures 2 and 3.

Table 1. Results of Previous Research

Formation	Period	Rock type	Accessible resource (10^{18} J)
North Dakota			
Two aquifers[a]			
Inyan Kara	Cretaceous	Sandstone	628
Madison	Mississippian	Carbonate	5,800
Total			6,428
Four aquifers[b]			
Inyan Kara	Cretaceous	Sandstone	1,100
Madison	Mississippian	Carbonate	6,600
Duperow	Devonian	Carbonate	2,200
Red River	Ordovician	Carbonate	3,600
Total			13,500
South Dakota			
Two aquifers[a]			
Dakota	Cretaceous	Sandstone	1,490
Madison	Mississippian	Carbonate	310
Total			1,800
Seven aquifers[c]			
Dakota Group	Cretaceous	Sandstone	805
Minnekahta	Permian	Carbonate	91
Minnelusa	Perm. - Penn.	Carbonate	2,530
Madison	Mississippian	Carbonate	2,826
			2,787
Winnipeg and Red River	Ord.-Sil.-Dev.	Carbonate	2,168
Deadwood	Cambrian	Carbonate	1,043
Total			12,250

[a] Sorey and others, 1983.
[b] Gosnold, 1984.
[c] Gosnold, 1987.

resource to a thick insulating blanket of low thermal-conductivity shale, which produces high temperatures in the underlying aquifers. Recently, it has been shown that anomalously high heat flow in South Dakota is the result of heat advection by regional groundwater flow (Gosnold, 1999).

Necessary properties for an economical geothermal resource include adequate temperature, adequate production capacity, and favorable water chemistry. Stratabound geothermal resource temperatures range from low temperature ($T < 90°C$) to intermediate temperature ($90°C < T < 150°C$). Production capacity is a function of the fluid pressure, permeability, and thickness of the aquifer. Water chemistry is a key factor in engineering design for use and disposal of the geothermal fluids. In most sedimentary basins, the near-surface waters tend to have lesser amounts of total dissolved solids and the deeper waters tend to have larger amounts of total dissolved solids.

GEOTHERMAL SETTING OF THE NORTHERN GREAT PLAINS

Geology

The study area (Fig. 1) includes the Williston and Kennedy Basins which contain essentially equivalent stratigraphic units (Table 2). The Williston Basin (Fig. 2) is a large intracontinental basin, which underlies most of North Dakota and northwestern South Dakota, as well as eastern Montana, southern Manitoba, and southeastern Saskatchewan (Majorowicz, Jones, and Osadetz, 1988). The Kennedy Basin (Fig. 3) is a smaller structure, which adjoins the Williston Basin in south-central South Dakota. At least 12 regional aquifers in the Williston Basin contain waters warm enough for development as geothermal resources. Many of the geothermal aquifers occur throughout the Great Plains, but the formation names may differ across

Table 2. Generalized Stratigraphy of Williston Basin North Dakota and South Dakota Beneath Tertiary[a,b]

System		Formation	Lithology	Max. thickness (m)
Lower Cretaceous		Pierre Shale	Shale	700
		Niobrara Formation	Chalk	75
		Carlile Formation	Shale	120
		Greenhorn Formation	Impure limestone	45
		Belle Fourche Shale	Shale	105
		Mowry Shale	Shale	55
	A	Newcastle Sandstone	Sandstone	45
		Skull Creek Shale	Shale	40
	A	Inyan Kara Group	Sandstone	135
Jurassic		Swift Formation	Shale	150
		Rierdon Formation	Shale	30
		Piper Formation	Shale/limestone	190
Triassic		Spearfish Formation	Sandy Shale	225
Permian	A	Minnekahta Limestone	Limestone	12
		Opeche Formation	Shale/sandstone	120
Pennsylvanian	A	Minnelusa Group	Sandstone/limestone	315
Mississippian	A	Madison Group	Limestone	600
Devonian	A	Jefferson Group	Limestone/dolomite	180
	A	Manitoba Group	Limestone	160
	A	Interlake Formation	Dolomite/limestone	335
	A	Red River Formation	Dolomite/limestone	215
Ordovician		Winnipeg Group	Shale	125
Cambrian	A	Deadwood Formation	Sandstone	300
Precambrian			Metamorphic and igneous rocks	

[a] After Bluemle and others, 1986.
[b] Units potentially containing geothermal waters are noted **A**

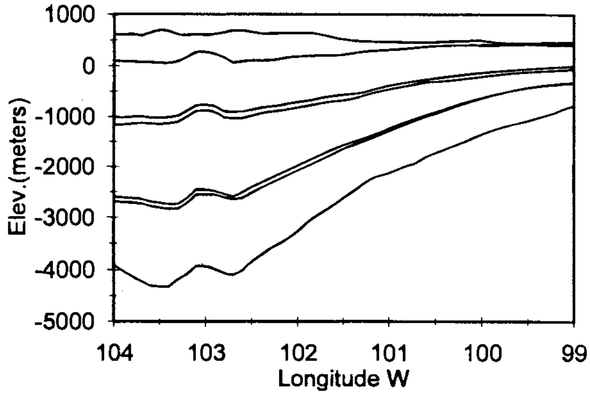

Figure 2. General cross section of Williston Basin. Formation tops represented from top to bottom of cross section are: Tertiary, Pierre Formation, Dakota Group, Jurassic, Madison Formation, Three Forks Formation and Duperow Formation. Nesson Anticline is prominent in all subsurface data at about longitude 103W.

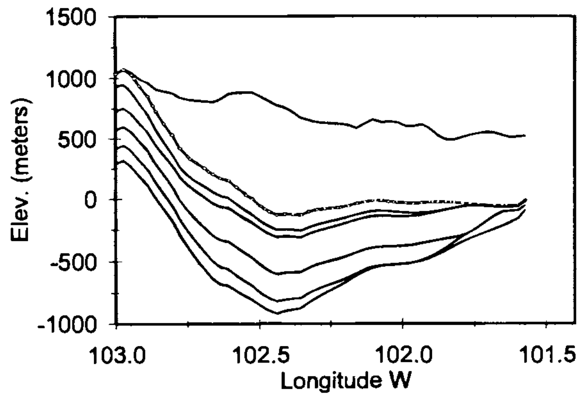

Figure 3. General cross section of Kennedy Basin. Formation tops represented from top to bottom of cross section are: Pierre Formation, Dakota Group, Jurassic, Minnekahta Formation, Minnelusa Formation, Madison Formation, Deadwood Formation. Note pinch out of Minnelusa Formation across Midcontinental Arch at longitude 102W.

the province (compare with Bluemle and others, 1986; Rahn, 1981).

Hydrology

Downey (1986) provided extensive data and analyses of the subsurface extent and hydrologic characteristics of several Paleozoic and Mesozoic aquifers in the study area. Detailed data on depth, thickness, subsurface extent, and permeability of all aquifers for the western half of South Dakota was given by Rahn (1981). Research by Bredehoeft, Neuzil, and Milley (1983), Neuzil and Pollock (1983), and Neuzil, Bredehoeft and Wolff (1984) provided an understanding of groundwater flow systems in a thermally anomalous region of South Dakota.

Subsurface Temperature and Geothermal Studies

Primary data sources on subsurface temperatures are U.S. Department of Energy reports for North Dakota (Harris and others, 1982; Gosnold, 1984), Nebraska (Gosnold, 1980; Gosnold and Eversoll, 1982), Kansas (Blackwell and Steele, 1989), and South Dakota (Gosnold, 1987, 1991). Geothermal resources in South Dakota were assessed previously by Schoon and McGregor (1974) and Gries (1977). Resources in North Dakota were assessed by Harris and others (1982) and Gosnold (1984, 1987, 1991). Quantitative estimates of the accessible resource bases were given by Sorey and others (1983) and Gosnold (1984, 1987, 1991). Schoon and McGregor (1974) developed a database of subsurface temperatures for the Dakota Sandstone (Cretaceous) and the Madison limestone (Mississippian). Gries (1977) focused on the Madison limestone and on applications of geothermal waters produced from the Madison limestone at three locations in South Dakota. Harris and others (1982) statistically analyzed bottomhole temperature data and water-quality data and produced contour maps of geothermal gradients and water chemistry. Sorey and others (1983) estimated the accessible resource base in North Dakota as $6{,}428 \times 10^{18}$ J, based on the Dakota and Madison aquifers. Gosnold (1984) added the Duperow and Red River aquifers to raise the accessible resource base in North Dakota at $13{,}500 \times 10^{18}$ J. Estimates for South Dakota were 1800×10^{18} J, based on the Madison and Dakota aquifers (Sorey and others, 1983), and $12{,}250 \times 10^{18}$ J, based on seven aquifers (Gosnold, 1987).

Heat Flow

Heat-flow studies indicate a stable continental heat-flow regime for most of the area (Fig. 4) with values of the order of 50 to 60 mW m^{-2} (Blackwell, 1969; Combs and Simmons, Simmons, 1973; Gosnold, 1990, 1999). However, heat-flow values ranging from 80 to 130 mW m^{-2} extend over a large region in South Dakota and Nebraska (Combs and Simmons, 1973; Gosnold and Eversoll, 1982; Sass and Galanis, 1983; Gosnold, 1990, 1999).

The thermal regime is conductive except in southern South Dakota and northern Nebraska where heat advection by regional groundwater flow in regional aquifers on the flanks of the Kennedy Basin has a significant impact. Usually, groundwater disturbances to heat flow are termed convective regimes. In the

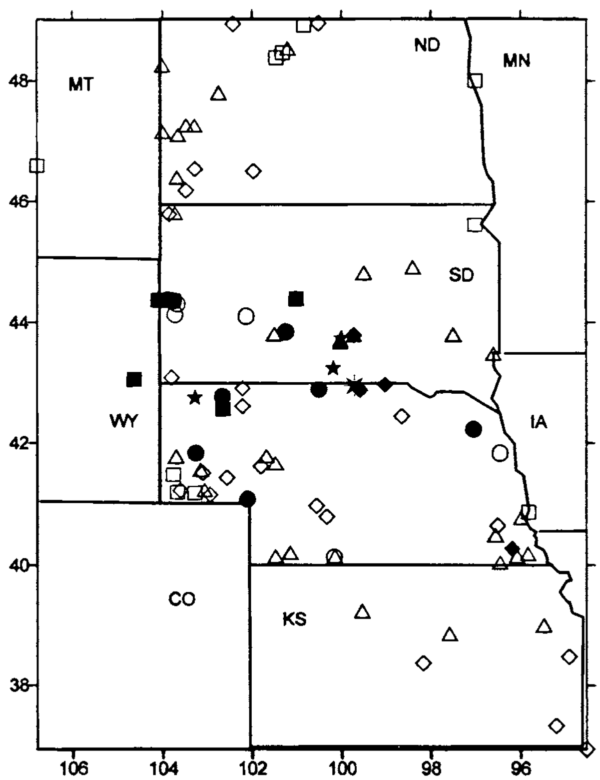

Figure 4. Heat-flow data in northern Great Plains. Heat-flow key; units are: mW m^{-2}. ○, < 40; □, 40–50; △, 50–60; ◇, 60–70; ●, 70–80; ■, 80–90; ▲, 90–100; ◆, 100–110; ★, 110–120; → *, > 120.

Kennedy Basin, anomalous heat flow is caused by groundwater flow in the recharge and discharge zones of regional aquifers. Therefore, the term advection is preferred instead of convection, which might be taken to indicate a closed circulation system.

Throughout the region, subsurface temperatures vary significantly according to variations in thermal conductivities within the sedimentary strata. Formations within the two intracontinental basins are continuous over most of the region and generally are uniform in lithology. Consequently, thermal conductivities measured on samples from a few sites may be applied to the lithologic units throughout the region. Where heat flow is known, one-dimensional thermal profiles, i.e., thermostratigraphy, can be projected using the relationship:

$$T(z) = T_0 + \sum_{i=1}^{n} \frac{QZ_i}{\lambda_i} \tag{1}$$

where T_0 is surface temperature, Q is heat flow, Z_i is the thickness of the ith stratum, and λ_i is the thermal conductivity of the ith stratum.

High-temperature gradients characterize the Pierre, Carlile, Graneros, and Belle Fourche formations (Cretaceous), all of which are shales having low ($\lambda \approx 1.2$ W m^{-1} K^{-1}) thermal conductivities. Low-temperature gradients characterize the high thermal conductivity ($\lambda \geq 3.0$ W m^{-1} K^{-1}) Paleozoic carbonates that underlie most of the region. High- and low-temperature gradients also occur where upward or downward flowing groundwater in discharge and recharge zones advectively disturbs the conductive gradient. Although heat advection can alter significantly the thermal profile of a basin, the degree of thermal disturbance can be determined and included in calculations of subsurface temperatures if quantitative data on recharge and discharge are available.

ORIGINS OF GEOTHERMAL ANOMALIES IN SOUTH DAKOTA

Gosnold (1999) has shown recently that a substantial part of the geothermal anomaly in South Dakota arises from advective heat transport in groundwater flow in the sedimentary units. Two possible flow systems were investigated: (1) vertical flow in fractures may cause local heat flow anomalies and (2) advection in confined aquifers affects heat flow on a regional scale. Because groundwater flow is a factor in the thermal regime, understanding the hydrogeology of the region is fundamental to this analysis. Existing data and analyses by Downey (1986), Rahn (1981), and Bredehoeft, Neuzil, and Milley (1983) provide a framework for understanding the groundwater flow systems. Bredehoeft, Neuzil, and Milley (1983) and Neuzil, Bredehoeft, and Wolff (1984) suggest that upward groundwater flow through fractures in the Cretaceous shales in South Dakota occurs at vertical velocities of the order of 10^{-11} m s^{-1}. Such vertical flow could be a source for local anomalies under certain conditions. Downey (1986) determined that regional groundwater flow in large aquifer systems in both North Dakota and South Dakota is eastward and northeastward at velocities ranging from about 10^{-8} to 10^{-7} m s^{-1}. These regional systems have potential to cause large magnitude advective heat-flow anomalies over large regions.

Fracture Leakage

In South Dakota, vertical groundwater flow from the confined Dakota aquifer to the surface through fractures in the overlying confining layers was deduced during an extensive study by Bredehoeft, Neuzil, and Milley (1983). They determined vertical flow velocities of the order of 3×10^{-11} m s^{-1} for upward flow near the Missouri River.

The data of Bredehoeft, Neuzil, and Milley (1983) show that the highest velocity, upward flow occurs predominantly in the broad stream valleys. Neuzil and Pollock (1983) theorized that flow should be focused in the deeply eroded stream valleys as a consequence of unloading because of stream erosion. Unloading causes a reduction in pore-fluid pressure, which serves to increase the hydraulic gradient between the deep aquifers and the surface in the unloaded zone. Consequently, any heat-flow anomalies associated with fracture leakage should occur in the stream valleys. The effects of heat advection by fracture leakage in stream valleys were investigated both analytically and empirically.

Analytical Test

An analytical relationship between heat flow, water velocity, and distance of flow for a vertical one-dimensional system was given by Stallman (1963) as:

$$\ln \frac{Q_2}{Q_1} = \frac{VD\sigma C_p}{\lambda} \qquad (2)$$

where Q_1 is heat flow at the base of the zone of flow, Q_2 is heat flow at the top, V is Darcy velocity in m s^{-1}, D is the length of the zone in meters, σ is density of the fluid in kg m^{-3}, C_p is heat capacity of the fluid in W s kg^{-1}, and λ is thermal conductivity in W m^{-1} K^{-1}.

Conductive heat flow outside the advection zone averages about 58 mW m^{-2} (Gosnold, 1999) and this value was assumed for Q_1. The depth to the Dakota aquifer in the advection zone west of the Missouri River is about 500 m and the effective thermal conductivity of the shale layer is 1.2 W m^{-1} K^{-1}. Using these values, Equation (2) predicts the threshold velocity for a significant heat-flow disturbance is about 10^{-10} m s^{-1}. Thus, the maximum flow velocity ($\sim 3 \times 10^{-11}$ m s^{-1}) suggested by Bredehoeft, Neuzil, and Milley (1983) would increase surface heat flow by only 5%.

Empirical Test

Even though the analytical test suggests that the advective heat flow in fractures would not account for the observed heat flow, it is possible that water-flow velocities could be greater than estimated and cause an advective heat disturbance. This was tested empirically by examining temperature versus depth and temperature-gradient versus depth curves of three heat-flow holes were drilled in the deeply incised White River Valley west of Chamberlain, South Dakota (Fig. 5). The upper 140 m (±10 m) of the boreholes are in the Pierre Shale, which is assumed to have essentially the same thermal conductivity everywhere (Gosnold, 1999). The sections of the holes below 140 m are in the Niobrara Formation, which exhibits a gradual facies change from a marl to a shale from top to bottom. The facies change in the Niobrara Formation has a corresponding change in thermal conductivity. The shale sections have a lower thermal conductivity and, consequently, a higher geothermal gradient than the marl sections. These effects are apparent in the temperature versus depth (T–z) profiles (Fig. 6), and clearly are evident in the gradient versus depth (Γ–z) profiles (Fig. 7). However, neither the Γ–z plots nor the T–z plots show evidence of fracture leakage. Therefore, this test supports the fracture leakage velocity determinations of Bredehoeft, Neuzil, and Milley (1983) and suggests that vertical leakage is not a significant factor in causing the thermal anomaly.

Advection in Regional Groundwater Flow

In South Dakota, four large aquifer systems (Downey, 1986), the Dakota (Cretaceous), Madison (Mississippian), Minnelusa (Pennsylvanian), and lower Paleozoic units comprising the Deadwood (Cambrian), Red River (Ordovician), and Englewood (Devonian) recharge in the Black Hills and transmit groundwater in confined updip flow into the area of the positive heat-flow anomaly.

Analytical Tests

A model for advective heat transport across a tilted basin proposed by Domenico and Palciauskas (1973) offers a feasibility test for the advection hypothesis in an unconfined basin. It is expressed as

$$\Gamma = \Gamma'\left(1 + \left(\kappa \frac{B}{2\alpha}\right) \cos\left(\pi \frac{x}{L}\right) \tanh^2\left(\pi \frac{D}{L}\right)\right) \qquad (3)$$

where Γ' is the average temperature gradient, κ is the hydraulic conductivity, α is the thermal diffusivity of the basin, L is basin length, D is basin depth, and B is the mean watertable height above the lower end of the basin. For a basin length of 250 km, a depth of 2.5 km, and a 0.8 km drop in the watertable, this model predicts a change in geothermal gradient of 130% over its mean value at the ends of the basin. This simple rectangular model of an unconfined system does not describe accurately the confined flow system in South Dakota, but it does demonstrate that groundwater flow across the basin could easily cause the observed heat-flow disturbance.

An analytical model that better describes the thermal effects for basin-scale, confined groundwater flow is the wedge model (Jessop, 1991), which is based on the effects of flow in a fracture and is expressed as

$$\lambda\ \delta\Gamma = q\ a\ \rho\ C_p\ \Gamma\ \sin(\phi) \qquad (4)$$

where q is volumetric flow rate, λ is thermal conductivity, a is aquifer thickness, C_p is specific heat, ρ is fluid density, and Γ is the geothermal gradient. Assuming appropriate parameters for the Kennedy Basin, that is, vertical limb = 2 km (2.5 km less 0.5 m of surface

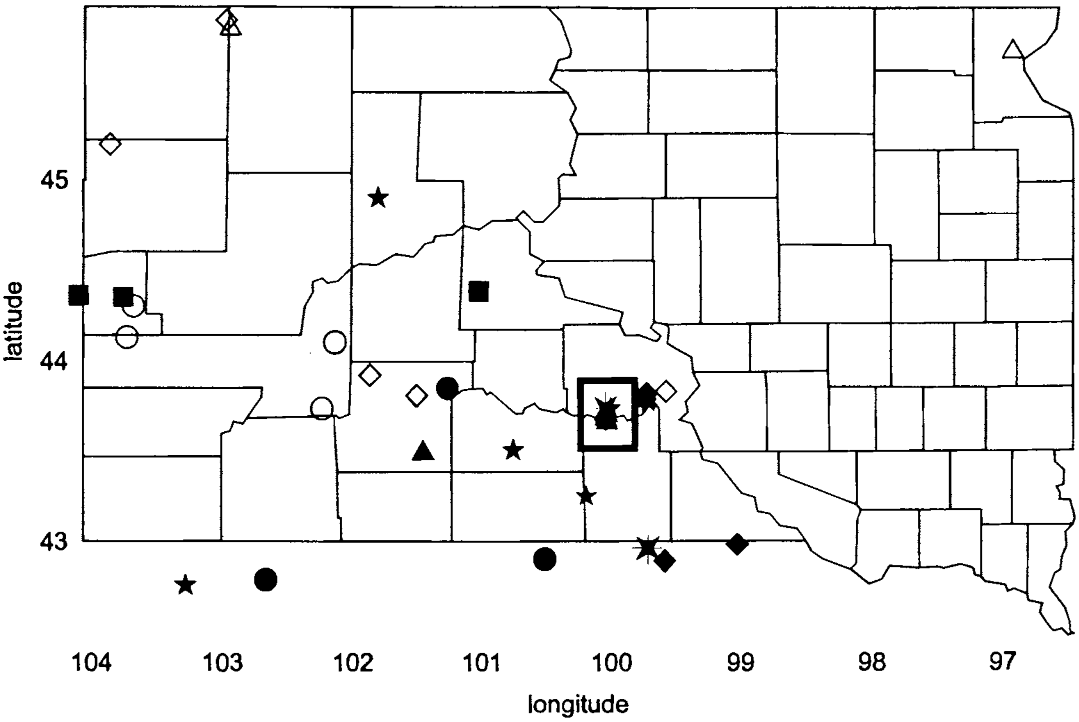

Figure 5. Heat-flow contour map and heat-flow sites in South Dakota. Region of three boreholes along White River is within bold box at longitude 100W.

cover), flow length = 120 km (the updip length in South Dakota), thermal conductivity = 1.2 W m^{-1} K^{-1}, aquifer thickness = 400 m, and water-flow velocity = 4.75 m s^{-1}, Equation (4) yields a doubling of surface heat flow at the upflow margin of the basin.

Interestingly, in a regional study of groundwater flow velocities, Downey (1986) calculated velocities ranging from 2×10^{-8} to 7.3×10^{-7} m s^{-1} in the lower Paleozoic aquifers and from 2×10^{-8} to 2×10^{-7} m s^{-1} in the upper Paleozoic aquifers. These flow velocities suggest that advective heat transport in a confined aquifer system easily could account for the thermal anomaly.

Gosnold (1999) tested this hypothesis by assembling data from 94 heat-flow sites and an additional 62 geothermal gradient measurements in the Pierre Shale. The results of that study provide confirming evidence that gravity-driven, groundwater flow in a confined aquifer system that extends several hundred kilometers eastward from the Black Hills causes the anomalous surface heat flow. Downward groundwater flow in the recharge area on the eastern side of the Black Hills reduces surface heat flow to about 20 mW m^{-2} whereas updip flow along the eastern flank of the basin produces surface heat flows as high as 140 mW m^{-2}. Gosnold (1999) determined that average heat flow in the northern Great Plains, exclusive of the anomalous area, is 58 ± 9 mW m^{-2}.

This result may establish a paradigm for the occurrence of stratabound geothermal resources. Advection resulting from confined groundwater flow, where flow is across a basin, may affect significantly subsurface temperatures and create a large stratabound geothermal resource on the ascending limb of the

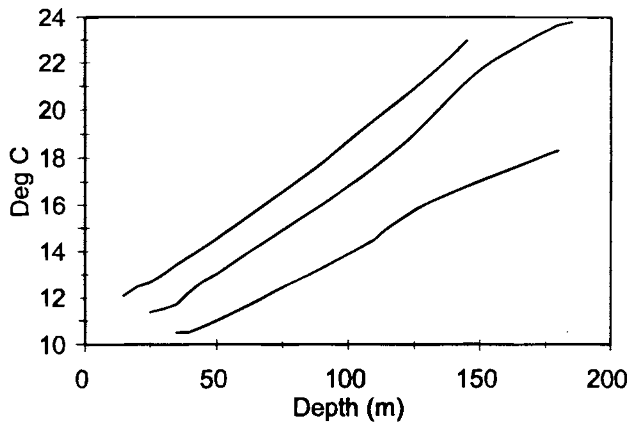

Figure 6. T–z plots of three boreholes in White River Valley. Thermal conductivity changes within Niobrara Formation cause changes in profiles. Datum is land surface.

basin. Interestingly, this finding has a close parallel with previous work on heat-flow anomalies associated with groundwater flow (Swanberg and Morgan, 1979, 1980, 1981). High heat-flow areas inferred from analyses of silica in groundwater (Swanberg and Morgan, 1979) coincide with the discharge areas of regional flow systems in the Denver, Williston, and Kennedy Basins.

Radioactive Heat Production

It is possible that radioactive heat production in the basement rocks underlying the Williston and Kennedy Basins contributes a significant component to the anomalously high heat-flow areas. Therefore, although necessarily speculative, a discussion of the possible role of radioactive heat production is instructive. From the linear relation between heat flow and heat production (Roy, Blackwell, and Birch, 1968) it is possible to estimate the contribution of radioactivity in the crust. The relationship is written

$$Q = Q_0 + Ab \tag{5}$$

where Q (mW m^-2) is surface heat flow, Q_0 (mW m^{-2}) is reduced heat flow and is characteristic of a heat-flow province, A(μW m^{-3}) is radioactive heat production at the surface, and b, the slope (km) is characteristic radioactive layer thickness (depth) of a heat-flow province (Roy, Blackwell, and Birch, 1968). From the initial observation of characteristic values of Q_0 and b for the eastern United States, Sierra Nevada, and Basin and Range (Roy, Blackwell, and Birch, 1968), 17 continental heat-flow provinces have been

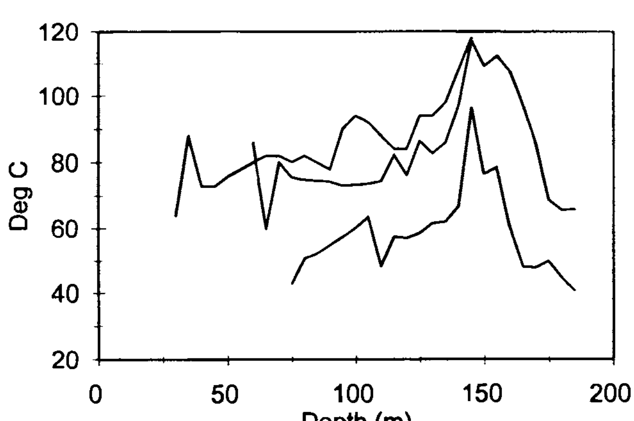

Figure 7. Gradient versus depth plots of three T–z plots in Figure 6 showing increase in temperature gradient at base of Niobrara Formation Datum is base of Niobrara–Carlile contact.

recognized (Pollack, 1982). The significance of Equation (5) in this analysis is that, assuming a conductive heat-flow regime, general values for A can be estimated where Q, Q_0 and b are known.

Q_0 and b values of 33 mW m^{-2} and 7.5 km for the Great Plains province in the United States first were suggested by Roy, Blackwell, and Decker (1972), and these values generally were acceptable by subsequent workers (for example, Combs and Simmons, 1973; Sass and others, 1971), although Morgan and Gosnold (1989) used additional data from Scattolini (1977) and proposed values of 27 mW m^{-2} and 8.1 km. Scattolini (1977) obtained heat production values of basement samples obtained from six boreholes that penetrated the Trans-Hudson and Superior provinces underlying the Williston Basin in North Dakota but obtained inconsistent results for Q_0 and b. Elimination of two samples from Scattolini's (1977) data, one in iron formation, which is unrepresentative of basement lithology, and one heat-flow site on the Nesson Anticline where advection is indicated (Gosnold and Fischer, 1986), yields Q_0 and b values of 24 mW m^{-2} and 14.5 km, respectively. No other heat-production data are available for either North or South Dakota and the nearest data are from surface outcrops of the Trans-Hudson and Superior in Canada (Jessop and Lewis, 1978; Drury, 1985; Guillou-Frottier and others, 1995) and from the Central Plains province in Oklahoma (Cranganu, Lee, and, Deming, 1998). Heat production in these rocks is of the order of 3 μW m^{-3}. The only estimations for Q_0 and b were by Jessop and Lewis (1978) who proposed a Q_0 value of 21 mW m^{-2} and a depth value of 14 km.

Assuming Q values of 21 and 33 mW m^{-2} and b values of 7.5 and 14 km, the region in South Dakota having heat flows of 130 mW m^{-2} would have estimated heat production values ranging from 14.5 to 6.9 μW m^{-3}. These estimates are significantly greater than both the nearest observed values and the average crustal heat production estimate of 3.0 μW m^{-3} (Wollenberg and Smith, 1987), but such values are plausible and are known elsewhere. Values of the order of 4 to 5.3 μW m^{-3} were reported for some Precambrian batholiths in the Colorado Front Range (Phair and Gottfried, 1964) and values of 6.3 μW m^{-3} were determined in some Precambrian granites in Australia (Heier and Rhodes, 1966). Anomalous heat-production values on the order of 2 to 10 times the average for the continental crust were reported for samples from nine Precambrian localities and one Mesozoic locality in the United States (Rosholt, 1983). Doe, Stuckless, and Delevaux (1983) reported high amounts of uranium and thorium from the UPH-3 deep drillhole in northern Illinois and Rahman and Roy (1981) obtained a heat-production value of 15.9 $\mu W\ m^{-3}$ on samples from the borehole.

Alternatively, Equation (5) was used to estimate the nonadvective component of Q. Assuming Q_0 ranges from 21 to 33 mW m^{-2}, b ranges from 7.5 to 14 km, and $A = 2.5\ \mu W\ m^{-3}$, the estimated heat flow ranges from 40 to 68 mW m^{-2} and generally agree with measured heat-flow values of 40 to 60 mW m^{-2} outside the anomalous region in South Dakota (Gosnold, 1990). This analysis is speculative and it neither proves nor disproves radioactivity as a source for the anomalous heat in South Dakota. This question may be answered ultimately only by heat-production and heat-flow measurements in deep wells in the geothermal anomaly.

HEAT-FLOW ANOMALIES IN THE WILLISTON BASIN

Conductive Heat Flow

The first heat-flow value reported for the Williston Basin was 58.6 mW m^{-2}, based on a measured geothermal gradient of 39.8 mK m^{-1} and an estimated thermal conductivity of approximately 1.5 W m^{-1} K^{-1} (Blackwell, 1969). Later, Combs and Simmons (1973) measured geothermal gradients of 56 and 55 mK m^{-1} in two oil test holes drilled within 50 km of Blackwell's (1969) site, and, using a thermal conductivity value of 1.7 W m^{-1} K^{-1}, calculated a heat-flow value of 92 mW m^{-2}. Subsequently, heat-flow values on the order of 70 to 90 mW m^{-2} were determined for 13 sites in western North Dakota (Scattolini, 1977). These data were conventional heat-flow determinations using measured geothermal gradients with measured or inferred thermal conductivities. Majorowicz, Jones, and Jessop (1986) combined geothermal gradients calculated from oil field bottomhole temperatures in the basin with thermal conductivities estimated from lithology to estimate heat-flow values ranging from 70 mW m^{-2} to greater than 100 mW m^{-2} in southeastern Saskatchewan, southwestern Manitoba, and northwestern North Dakota.

These conventional and estimated heat-flow values are significantly greater than typical heat-flow values for a stable continental interior (Roy, Blackwell, and Birch, 1968); thus they could have significance for tectonics, kerogen maturation, and geothermal resources. Consequently, analysis of possible origins of the high heat flow is a critical part of this study.

However, not all data from the Williston Basin indicate high heat flow. A number of heat-flow determinations by Scattolini (1977) were on the order of 50 to 60 mW m^{-2}, and Gosnold (1984) reported heat-flow values of 43, 47, 48, and 52 mW m^{-2} in four boreholes specially completed for heat-flow determination. These latter four sites are within about 50 km of the 92-mW m^{-2} sites of Combs and Simmons (1973) and the 58.6-mW m^{-2} site of Blackwell (1969), and they lie within the 100-mW m^{-2} zone projected by Majorowicz, Jones, and Jessop (1986). Thus, at the beginning of this study, the status of heat-flow observations was that recent determinations differed from earlier ones and conventional heat-flow determinations disagreed with estimated values.

Differences in heat-flow values at sites relatively close together within a tectonically stable province suggest several possible explanations, including concentrations of radioactive elements in basement rocks, groundwater flow, local tectonics, and inaccurate determination of thermal properties. In fact, the latter explanation satisfies most of the differences in heat-flow values (Gosnold, 1990, 1999). The high heat-flow values reported by Scattolini (1977) and Combs and Simmons (1973) result from using thermal conductivity values for shales that were about 40% too high (Sass and Galanis, 1983; Blackwell and Steele, 1989; Gosnold, 1990). Gosnold (1990) recalculated 11 heat-flow values using thermal conductivities ranging from 1.1 to 1.5 W m^{-1} K^{-1} and determined heat-flow values ranging from 54 to 68 mW m^{-2} with an average of 58 mW m^{-2}. Thus, the high heat-flow zone previously reported in the North Dakota portion of the Williston Basin was based on inaccurate thermal conductivity values and does not exist.

Advective Heat Flow

Although evidence for a conductive heat-flow anomaly in the Williston Basin is doubtful, there is some evidence for advective heat transport in parts of the basin. Conceptually, anticlinal structures, such as the Nesson Anticline and Billing's Nose (Fig. 1), could exhibit advective heat transport on the up and downdip flanks. Groundwater flow in the extensive regional aquifer system of the basin occurs in both Paleozoic and Mesozoic strata at flow rates ranging from approximately 6×10^{-8} to 3×10^{-8} m s^{-1} (Downey, 1986).

As previously demonstrated for South Dakota, confined groundwater flow in dipping aquifers can cause substantial heat-flow anomalies. The flanks of the Williston Basin dip gently, only about 2 to 3 degrees at most, and confined groundwater flow at such low angles would have a vertical velocity of less than 10^{-10} m s^{-1}, which is an order of magnitude below the detectable threshold for heat advection. However, the anticlinal structures within the basin contain steeper slopes and, consequently, provide sufficient conditions for advective heat transport.

Analyses of bottomhole temperature (BHT) data in the Canadian portion of the Williston Basin (Majorowicz, Jones, and Jessop, 1986) and in the Prairies Basin in Alberta (Majorowicz and others 1984, 1999; Bachu, 1999) does indeed suggest that regional groundwater flow generates heat-flow anomalies in the basins. Jones and Majorowicz (1985) and Majorowicz, Jones, and Jessop (1986) suggested that hydrodynamic factors caused differences in heat-flow values on the order of 40 mW m^{-2} between the Mesozoic/Cenozoic and Paleozoic rocks of the Williston Basin. Gosnold and Fisher (1986) interpreted BHT data from three different formations on the Billings Nose, a small anticlinal structure in the southwestern part of the Williston Basin, as indicative of advective heat transport.

Majorowicz, Jones, and Jessop (1986) and Jones and Majorowicz (1985) recognized evidence of advective heat transport in the eastern part of the basin where heat flow in the Paleozoic is substantially higher than in the Mesozoic units. The units are separated by impermeable evaporites. Their interpretation is that updip flow in the Paleozoic units causes higher heat flow and that groundwater recharge in the Mesozoic units causes lower heat flow.

A test for similar hydrologic disturbances in the North Dakota portion of the Williston Basin was considered, but the BHT data were of unsatisfactory quality. The data were too disparate to show trends that had any reasonable relationships with groundwater flow, structures, or lithology.

METHOD OF RESOURCE ASSESSMENT

Methodology

The accessible resource base was calculated using the expression

$$Q_r = p_c V(T - 15°) \quad (6)$$

where Q_r is the accessible resource base, p_c is the volumetric specific heat of the aquifer, V is the volume of fluid that can be produced, and T is the average temperature of the aquifer (Sorey and others, 1983).

The essential elements of any resource assessment using this method are to identify aquifers and to determine their average temperatures and volumes. Consequently, the stratigraphic and hydrologic databases compiled by state geological surveys and other research institutions provide two essential components of the resource assessment.

The temperature field of the subsurface is determined using the mean annual surface temperature, the thermal conductivities and thicknesses of strata, and local heat flow, which is known from direct temperature measurements in boreholes. Assuming a conductive thermal regime, subsurface temperatures may be determined using Equation (1). The essential data in the temperature analysis are the heat flow and the thermal conductivities of all units in the stratigraphic section.

Application of Equation (1) is shown in Tables 3 and 4 and computed temperature depth profiles for North and South Dakota are shown in Figures 8 and 9. Table 3 gives subsurface data for the principal stratigraphic formations in the Williston Basin assuming a constant heat-flow value in each vertical section and using the appropriate thermal conductivity for each formation. Table 4 gives subsurface data for the region of normal heat flow (58 mW m^2) in northwestern South Dakota and for the high heat-flow (130 mW m^2) area west of Pierre.

Determinations of the thermal conductivities for specific formations were based on interpretations of numerous, measured temperature-depth curves, and on thermal-conductivity measurements of core samples of carbonates from the North Dakota Geological Survey's Core and Sample Library. Heat-flow data used in calculation of subsurface temperatures include those data summarized by Gosnold (1990, 1999).

Procedure

Elevations of tops from irregularly spaced data on each formation were used to generate an evenly spaced grid of points. A 51 column by 33 row point grid with 10 km spacing on each side was used for North Dakota and a 49 column by 53 row point grid with 6.2 km spacing was used for South Dakota. The gridding process generated smoothed data sets that do not represent precisely the formation tops. However,

Table 3. Thermostratigraphy of Generalized Section of Williston Basin

Rock unit	Lithology	Thickness (m)	Depth (m)	Thermal conductivity (W m^{-1} K^{-1})	Gradient (mK m^{-1})	Temp. (°C)
Tongue River	Si Cl	375	0	1.2	48.3	10
Hell Creek Formation	S	101	375	1.7	34.1	28
Fox Hills Formation	Silt & Sh	119	475	1.7	34.1	32
Pierre Formation	Sh	686	594	1.2	48.3	36
Colorado Group	Sh	396	1280	1.2	48.3	69
Dakota Group	Ss	122	1676	1.6	36.3	88
Swift Formation	Sh	168	1798	1.2	48.3	92
Rierdon Formation	Sh	15	1966	1.2	48.3	100
Piper Formation	Ls Sh	152	1981	1.6	36.3	101
Spearfish	Sis	259	2134	1.8	32.2	107
Minnekahta	Ls	15	2393	3.1	18.7	115
Opeche Formation	Sh	15	2408	1.2	48.3	115
Minnelusa Group	Ss & Do	137	2423	3.1	18.7	116
Otter Formation	Sh	76	2560	1.2	48.3	119
Kibbey Formation	Ss	76	2637	2.5	23.2	122
Madison Group	Ls	616	2713	3.5	16.6	124
Bakken Formation	Ls	24	3328	1.0	58.0	134
Manitoba Group	Ls	305	3353	3.4	17.1	136
Elk Point Group	Ls	91	3658	3.4	17.1	141
Interlake Formation	Do	274	3749	4.0	14.5	142
Big Horn Group	Do	280	4023	4.0	14.5	146
Winnipeg Group	Sh Ss	43	4304	1.8	32.2	150
Deadwood Formation	Ls Ss Sh	311	4347	2.4	24.2	152
Precambrian	Gr		4657	2.7	21.5	159

[a] Lithology symbols: S, sand; Ss, Sandstone; Si, silt; Sis, Siltstone; Sh, shale; Ls, limestone; Do, dolomite; Cl, clay; Gr, granite.

obvious discrepencies were adjusted by inspection so that formation thicknesses at each grid point agree with Rahn's (1981) isopachous maps.

Analysis of the resource area was done by state rather than as a total area because of constraints imposed by the available data. Although both North and South Dakota contain essentially the same stratigraphic units, the available data for the two states differ in that more individual units are well known in North than in South Dakota. This difference is the result of extensive petroleum exploration and data collection in the Williston Basin, which lies mainly in North Dakota, compared to a relatively minor amount of exploration in South Dakota. Consequently, merger of the two data sets would result in sacrificing detail in North Dakota.

CONCLUSIONS

The accessible resource base in the two-state study area was calculated to be about 33 exajoules. Twenty-one exajoules of accessible geothermal energy lie within the borders of North Dakota (Table 5) and about 12 exajoules lie within the borders of South Dakota (Table 6). The accessible resource base generally is estimated to be 0.001 times the resource base (Sorey and others, 1983) by assuming conservative values for porosity and permeability. The accessible resource estimates are larger than previous estimates because of the inclusion of all potential aquifers in this resource assessment. This increase of the estimated resource base has broad implications for the stratabound geothermal resource base for the entire United States, because all previous assessments of stratabound geothermal resources in the United States have included only a few of the potential geothermal aquifers (Reed, 1983).

The significance of this resource to the region as an energy source for the future and for planning for sustainable development is demonstrated by comparison with fossil fuel resources in North Dakota (Table 7). Lignite ranks first with 118×10^{18} J, geothermal energy ranks second with 21×10^{18} J, oil ranks third with 17×10^{18} J, and natural gas ranks fourth with 3×10^{18} J (D.J. Daly, pers. Comm., 1990). The Ameri-

Table 4 Thermostratigraphy of South Dakota

Rock Unit	Lithology[a]	Thickness (m)	Depth (m)	Thermal conductivity (W m K)	Gradient (mK m)	Temp. (°C)
Williston Basin, northwestern South Dakota						
Pierre ~ Mowry Formations	Sh	1128	0	1.2	48.3	10
Dakota Group	Ss	43	1128	1.6	36.3	65
Jurassic	Sh Ss Ls	229	1171	1.4	41.4	66
Spearfish Formation	Sh Ss Si	168	1400	1.3	44.6	76
Minnekahta Formation	Ls	66	1568	3.1	18.7	83
Minnelusa Group	Ss & Do	137	1634	3.1	18.7	84
Madison Group	Ls	390	1771	3.5	16.6	87
Ord-Dev	Sh Ss Ls	369	2161	3.7	15.7	93
Deadwood Formation	Ss	207	2530	2.4	24.2	99
Precambrian			2737	2.7	21.5	104
High heat-flow area west of Pierre, South Dakota						
Pierre ~ Mowry Formations	Sh	543	0	1.2	108.3	10
Dakota Group	Ss	33	543	1.6	81.3	69
Jurassic	Sh Ss Ls	12	576	1.4	92.9	72
Spearfish Formation	Sh Ss Si	1	588	1.3	100.0	73
Minnekahta Formation	Ls	44	589	3.1	41.9	73
Minnelusa Group	Ss & Do	50	633	3.1	41.9	75
Deadwood Formation	Ss	10	683	2.4	54.2	77
Precambrian			693	2.7	48.1	77

[a] See footnote, Table 3.

can Wind Association estimates North Dakota's wind energy resources as approximately 95×10^{15} J y^{-1}.

Surface heat-flow values on the order of 90 to 130 mW m^{-2} in south-central South Dakota and north-central Nebraska have an anomalous component of about 40 to 70 mW m^{-2} because of advection of heat in flowing groundwater in the sedimentary cover overlying the Precambrian basement.

Analyses of BHT in the North Dakota portion of the Williston Basin do not show significant heat-flow anomalies. However, comparisons of calculated and measured temperatures over the Nesson Anticline and the Billings Nose indicate temperature disturbances of about 5°C. The nature of the temperature disturbances suggests that upward groundwater flow in fractures on the westward sides of the structures is a plausible mechanism. Regional groundwater flow over struc-

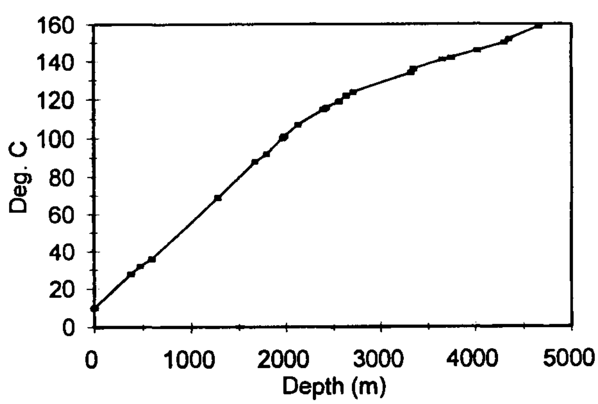

Figure 8. General T–z plot of Williston Basin derived from subsurface data in Table 3 and using Equation (1).

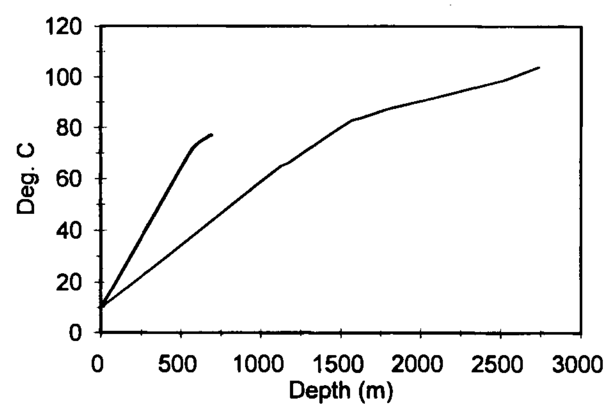

Figure 9. General T–z plots in South Dakota derived from subsurface data in Table 4 and using Equation (1). Deep profile represents conditions in northwestern corner of South Dakota and shallow profile represents conditions in high heat-flow area in south-central South Dakota.

Table 5. Geothermal Resource Base for North Dakota[a]

Formation	Resource (exajoules)	Avg. thick. (°C)	Avg. temp. (°C)	Max. temp. (°C)
Inyan Kara	0.54	74.6	44.5	85.8
Jurassic	2.06	265.2	47.8	90.5
Spearfish	1.83	251.1	57.7	100.4
Otter	1.87	242.0	62.5	109.0
Madison	3.16	301.4	67.7	111.8
Three forks	0.47	33.0	75.0	125.8
Duperow	1.38	102.2	75.6	127.6
Dawson Bay	2.56	232.7	77.3	130.9
Winnepegosis	1.05	96.3	81.3	131.6
Interlake	2.81	184.2	82.3	133.1
Red River	2.11	145.2	85.7	139.0
Deadwood	1.41	100.0	88.2	143.8
Total	21.25			

[a] Temperatures are given for formation tops. Average thickness values are calculated from top to top. All of the formations named are aquifers, which may produce water. Water quality is generally good for the upper Inyan Kara (Cretaceous), but becomes increasingly saline with depth below the Cretaceous.

Table 6. Geothermal Resource Base for South Dakota[a]

Formation	Resource (exajoules)	Avg. thick., (°C)	Avg. temp (°C)	Max. temp (°C)
Dakota	0.42	36.5	18.5	73.4
Jurassic	1.22	81.9	42.5	71.5
Spearfish	0.66	43.8	57.7	82.3
Minnekahta	0.52	36.8	46.4	85.4
Minnelusa	2.02	134.1	47.3	86.5
Madison	2.93	153.7	51.0	90.3
Ord. Dev.	2.90	140.2	53.7	97.2
Cambrian	1.85	110.0	56.1	104.8
Total	12.52			

[a] Temperatures are given for formation tops. Average thickness values are calculated from top to top. All of the formations name are aquifers, which may product water. Higher temperatures are typical for the Williston Basin in northwestern South Dakota.

Table 7. Energy Resources in North Dakota

Resource type	Accessible resource base
Coal-Lignite	$\sim 118 \times 10^{18}$ J
Geothermal	$\sim 21 \times 10^{18}$ J
Oil	$\sim 17 \times 10^{18}$ J
Natural Gas	$\sim 3 \times 10^{18}$ J
Wind	$\sim 95 \times 10^{15}$ J y^{-1}

tures in the Williston Basin in North Dakota generates local heat-flow anomalies on the order of 10 to 20 mW m^{-2}. These thermal anomalies do not alter significantly the accessible geothermal resource base.

The large quantity of thermal energy contained in sedimentary rocks is a valuable asset for the region and could be used to attract energy-intensive industry, such as food processing and manufacturing. If developed extensively, this resource could provide a new economic base for North and South Dakota.

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