GEOLOGY AND HYDROLOGY IN URANIUM AREAS
IN THE SOUTHERN BLACK HILLS

This paper provides a summary of the scholarly literature on the geology and hydrology of the southern Black Hills, and particularly of the area proposed for a uranium mine by Powertech Uranium (USA). This project is known as the Dewey-Burdock project, due to its location adjacent to the (very) small towns of Dewey and Burdock, along the Wyoming-South Dakota border.

While a few sources for this research were funded by the uranium industry during past uranium booms, most was either peer-reviewed or produced through the U.S. Geological Survey (USGS). I did not refer to the current permit application except for in a few cases, because I didn't want to use the applicant's information. I wanted to use independently-produced, scholarly information. I have tried to produce copious endnotes that will lead readers to more information.

First, a disclaimer – I am not a geologist or a hydrologist. I have looked at the available information about the area, used reference works, cross-checked sources with each other, and done the best I can. Most of the source information is located at the South Dakota School of Mines and Technology in Rapid City. I have a background in environmental policy, with a Ph.D. in Political Science.

Having said that, this is a summary of what I think the literature says about uranium areas in the Southern Black Hills.

A GEOLOGICAL OVERVIEW OF THE BLACK HILLS

The Black Hills, located in southwestern South Dakota and eastern Wyoming, were formed by a Laramide domal uplift, beginning about 62 million years ago. They are a geologic anomaly, often called "an island of trees in a sea of grass." The geology and hydrology of the Hills are complex. At their center, the Hills have a core of Precambrian granite. More recent Paleozoic and Mesozoic sedimentary rocks layer outward from that core in a series of concentric circles.[i]

These "circles" of layers of rock are the result of the uplift, which tilted underground rock layers from horizontal toward the vertical. The differing thicknesses of the layers – both when they are more vertical within the Hills and as they drop to horizontal on the edges of the uplift – make the geology of the area not only complex, but highly localized.[ii] We will return to this point below

The major developed aquifers of the region, from deepest to shallowest, are the Madison, Minnelusa, and Inyan Kara. See Figure 1 for a summary of the rock layers in the Black Hills region. Figures are located at the back of this report.[iii]

Where the rock layers of the aquifers are more vertical around the edges of the Black Hills, the aquifers collect rainwater and runoff. In some places, streams disappear underground as they run across the upturned edges of the aquifers. This water recharges the aquifers. Generally, the water moves through the rock and down gradient. Water captured by the Black Hills uplift provides important recharge for aquifers to the east toward the Missouri River and to the west to the Powder River basin, as shown in Figure 2. Within the United States, the rocks that contain the Inyan Kara formation, for example, underlie all of North Dakota, the eastern half of Montana, the northeastern part of Wyoming, and all of South Dakota except its southeast corner.[iv]

URANIUM DEPOSITS

The uranium in the Black Hills is found in the Inyan Kara group, which circles the Hills on its outer rim. The deposits that companies seek to exploit are along the northwest and southwest rims of the uplift. The Inyan Kara group is made up of the Lakota and Fall River formations, with the former underlying the latter. The

Lakota formation, in turn, is composed of the Fuson, Minnewaste ("good water"), and Chilson layers. The Fall River formation is the largest producing aquifer in Fall River County, which includes the southern part of the proposed mining area, and the Lakota formation is the second largest.[v] A map showing where the Inyan Kara group outcrops and -- where it is underground -- the depth to the top of the aquifer is shown in Figure 3.

To provide some idea of the irregularity of rock layers and the complexity of the area's geology, the Inyan Kara group is on top of the Morrison formation along the Wyoming-South Dakota border. To the east, it is on top of the Unkpapa sandstone. In the southwestern Hills, in some places the Fuson layer is at the center of the Lakota Formation. In others places, it directly overlays the Minnewaste limestone, or the Chilson layer, or the Morrison formation. In places, it is at the surface. In other words, its extent is sporadic and varies in depth. In places, erosion has removed one layer of rock, which was replaced by "fingers" of another type of rock. This, obviously, complicates any mining operation that relies on a series of drill holes to characterize a potential in situ leach mining site or to determine where excursions (underground leaks) are most likely.[vi]

The layer under the Inyan Kara group is generally described as a "semiconfining unit of Jurassic-age rocks," including the Morrison formation. The layer on top of the Inyan Kara is the Skull Creek shale. Where the two layers meet, the rock of the Inyan Kara is described as typically being "intertongued with sandstones and black shales of the Skull Creek Shale."[vii]

In the proposed mining area, the Skull Creek shale contains faults and sandstone dikes, which can act as conduits through the shale. It also has "cone-in-cone" structures, which are --- as the name implies – tubes shaped like ice cream cones. In the proposed mining area, these can be as much as two feet in diameter.[viii] In other words, there is neither a "tight fit" at the top of the Inyan Kara group nor at the bottom. The neighboring layers of rock would not necessarily stop mining fluids from moving either up or down.

The geology and hydrology of this area were first described in detail in the 1960s and 1970s. The Atomic Energy Commission (AEC) oversaw the creation of thirteen studies on geographic quadrangles in the southern Black Hills. The quadrangles stretched from just south of Newcastle in Weston County, WY, and went southeast around the rim of the Hills to Hot Springs and Angostura Reservoir in South Dakota. The studies focused on defining the area's geology more completely, so that uranium deposits could be identified. The studies were then summarized in 1974, as a new uranium boom was shaping up. Although a number of the maps – including key ones of uranium areas – are missing from the copy of these studies located at the South Dakota School of Mines and Technology, they are still a key resource.[ix]

GEOLOGY OF THE MINING AREA

The AEC summary report details each rock layer within the Inyan Kara group, its history, and its extent across the area. It then describes the general structure of the area, noting that there are 6,000 feet of structural relief. The uplift process that formed the Black Hills repeatedly deformed the sedimentary rocks of the Inyan Kara group. The location of current mining plans, is characterized as: "the southwest-dipping flank of the Black Hills, which is modified by the broad Dewey terrace, by three northwest-trending anticlines [domes], by the northeast-trending normal faults of the Dewey and Long Mountain structural zones … and by smaller normal faults."[x]

The report than describes the area's folds and faults in more detail. In the description of folds, the emphasis is on the dramatic rising and falling landscape features. The descriptions of faults focuses on the area near the proposed mining area. To the north of the proposed mining site is the Dewey Fault and Structural Zone. To the south is the Long Mountain Structural Zone. Faults run on both sides of both zones.[xi]

The larger faults are in the Dewey Zone, where the uplift zone is 500 feet, and the fault zone can be traced for thirteen miles. The report says that, "Although no direct evidence of horizontal movement along the faults is reported, the sinuous en echelon trace of the faults suggests that a minor strike-slip component of movement may possibly exist within the fault zone."[xii] The Long Mountain Zone involves faults in the Inyan Kara group and the deeper Sundance Formation that have as much as 40' of displacement, and in some places have another 60' of additional relief due to folding. There are also "randomly oriented" faults in the area of the proposed mine.[xiii]

Earthquake data from 1872 – 1986 show ten earthquakes in Custer and Fall River Counties, the counties targeted by Powertech's project. Eight earthquakes had epicenters just north of the town of Hot Springs, one was just south of the proposed mining project, and one was in eastern Fall River County. These earthquakes ranged from 1.5 to three on the Richter Scale.[xiv] A more recent map, which is updated to 2007, shows a stronger quake – about a 4.0 – in the active area north of Hot Springs.[xv]

HYDROGEOLOGY

There are four major aquifers in the proposed mining areas, which are shown on Figure 1. The deepest is the Deadwood, which we will not discuss further. From deepest to more shallow, the other three are the Madison (Pahasapa Limestone), Minnelusa, and Inyan Kara. The Minnelusa is directly on top of the Madison, and several layers of varying thickness are located between the Madison and the Inyan Kara group.

In the Madison and Minnelusa formations, scholars uniformly report substantial structural collapse. These include subsidence, breccia pipes [chimneys], and caverns. According to the US Geological Society, breccia pipes "are likely to develop at the intersection of fractures, particularly in zones of intense fracturing and (or) faulting, such as the Dewey and Long Mountain structural zones." Some faults in the area are known to have "served as pathways of vertical migration." This, of course, means that faults do not block water from either horizontal or vertical movement in the area that is proposed for uranium mining.[xvi] The breccia pipes are as much as 1300 feet high and several hundred feet across. They reach from the Minnelusa formation into the lower part of the Inyan Kara group, "even though relatively impermeable confining material intervenes."

A lot of the water in the proposed mining area is artesian – that is, it moves upward without being pumped. This is because it moves down the flanks of the Black Hills, first as rain and runoff and later underground, builds up a "head of steam," and then finds a way to the surface. Water movement from the Minnelusa to the Inyan Kara is primarily upward. Water can move either up or down between the Madison and the Minnelusa.[xvii] The additional pressure created by pumping solutions under pressure into the Inyan Kara as part of in situ leach mining could potentially reverse natural water flows or could be enough to push contaminants into areas not currently reached by artesian pressure.

Water from the Inyan Kara is also under pressure in places and discharges into springs or recharges alluvial [riverbank] aquifers. This connection mixes subsurface water with shallow wells and with surface water, greatly increasing the area potentially impacted by mining activities. In its application to the Nuclear Regulatory Commission, Powertech says there are 30 flowing wells within 2 km of its permit boundary. In 1970, there were shallow alluvial wells (8 – 59 feet deep) along the waterways in the area. There are also a number of old uranium mines and overburden piles in the proposed mining site – most of which are not reclaimed. Depending on the topography, this could also provide ways for runoff, spills, or excursions from mining to reach both surface and groundwater.[xviii]

But flowing wells are not the only issue. Subsurface water movement is also increased by the presence of other wells. A 1970 study located 269 wells in western Fall River County, with 123 of them tapping the Inyan Kara. According to reports from a 1983 study by the Tennessee Valley Authority (TVA), which explored the area in the 1970s, there were 35 wells in the Inyan Kara formation within four miles of an area just northwest of the proposed mine. A 1980 TVA report counted 49 domestic and stock wells tapping the Inyan Kara within four miles of their Burdock site. Powertech counted about 80 wells within 2 km of its permit boundary. Even if some of these wells are no longer in use, they may be improperly cased or plugged, allowing vertical and/or horizontal movement of water in the proposed mining area.[xix]

And, perhaps most problematic, there are also approximately 4000 exploratory drill holes in the proposed mining area. Maps provided by Powertech in its application shows the old holes across the site, with – not surprisingly – are concentrated in the areas they plan to mine.[xx]

In this case, this is not just a theoretical problem. Old exploration holes in the Burdock – or southern – part of the proposed mining area have been shown to leak vertically. Pumping tests done in 1979 by TVA showed leakage between the Fall River and Lakota formations of the Inyan Kara group, indicating that the Fuson layer, which is sometimes characterized as effectively separating the two formations, did not fill that function. According to the study's authors, Boggs and Jenkins, "The hydraulic communication between the two aquifers observed during the tests is believed to be the result of (1) general leakage through the primary pore space and naturally occurring joints and fractures of the Fuson shale, and (2) direct connection of the aquifers via numerous old unplugged exploration boreholes."[xxi]

This suggests that in situ leach mining should not rely on the Fuson as a confining layer to keep mine fluids within a certain boundary. And the research also shows that there is general communication among the major aquifers in the proposed mine area. Where water is under artesian pressure, mining contaminants could be moved between aquifers or moved into surface waters either during mining or after a company has completed its mining and left.

Remembering that, overall, water collected by the Black Hills moves downward and away from the Hills, the research on regional water movement is also important. Figure 4 shows the directions of water flow in the Madison aquifer. The details of flow in the Minnelusa aquifer are shown in Figure 5. The latter shows that water moves from the proposed mining area to the east and around the southern part of the Black Hills.

The available information indicates that the water in the Inyan Kara formation also flows to the east. Uranium in the Cascade Springs area indicates that there has been horizontal, eastward movement of uranium-bearing water from the Edgemont mining district. This is evidence of contamination moving through the aquifer that is proposed for mining from the proposed mine area to the Cascade Springs area.[xxii]

Whether subsurface mining contaminants reach distant water is governed, for the most part, by how fast the groundwater moves in an area. In a recent USGS study, the authors state that one of the threats to groundwater in the Black Hills is "relatively fast flow velocities." Fast flow velocities are, of course, site-specific. But the Inyan Kara is also the most porous of the major aquifers in the area.[xxiii]

This rapid movement (in geological terms) is present in the Inyan Kara group in the proposed mining area. In 1967, samples were taken from 26 wells in the Inyan Kara group to measure the amount of tritium in the water. Tritium is a radioactive isotope that was deposited in higher-than-natural amounts as a result of nuclear testing in the 1950's – 1960s. Because nuclear testing is a recent phenomenon, higher amounts of tritium indicate that water has reached a sampled area relatively recently. The 1967 samples showed that groundwater had moved 4 miles in approximately 15 years. Water flow was most rapid in three areas. One was just north of the Dewey fault zone, one was west of Edgemont near the Cheyenne River, and the third was southwest of Burdock. All three of these are within several miles of the proposed mining area. In the west-central part of the Burdock quadrangle, an area that could include the proposed mining site, water moved 15 feet per day.[xxiv]

The complex geology and hydrology of the proposed in situ mining area will not produce the controlled conditions necessary for pumping chemicals under pressure into the groundwater, taking radioactive materials and heavy metals out of a stable state, and pumping those materials back to the surface. As Boggs put it, "Hydrogeologic conditions in the site region are complex due to hydrologic boundaries (e.g., aquifer outcrop zone and the Dewey fault) and heterogeneity of the aquifer system. Under such conditions simple analytical methods cannot be applied with an acceptable level of confidence."[xxv]

Even under the best of circumstances, spills, leaks, and excursions are typical of in situ leach mining sites. To mine in an area with a number of known hydraulic connections and fast water movement is, at best, irresponsible. To mine in such an area when it is the source of water for a large, semi-arid region is unprincipled.

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FIGURE ONE: STRATIGRAPHIC COLUMN FOR THE BLACK HILLS

ERATHEM	SYSTEM	ABBREVIATION FOR STRATIGRAPHIC INTERVAL	GROUP	GEOLOGIC UNIT	THICKNESS IN FEET	DESCRIPTION
CENOZOIC	QUATERNARY & TERTIARY (?)	QTac		UNDIFFERENTIATED ALLUVIUM AND COLLUVIUM	0-50	Sand, gravel, boulders, and clay.
		Tw		WHITE RIVER GROUP	0-300	Light colored clays with sandstone channel fillings and local limestone lenses.
	TERTIARY	Tui		INTRUSIVE IGNEOUS ROCKS	--	Includes rhyolite, latite, trachyte, and phonolite.
MESOZOIC	CRETACEOUS	Kps		PIERRE SHALE	1,200-2,700	Principal horizon of limestone lenses giving teepee buttes. Dark-gray shale containing scattered concretions. Widely scattered limestone masses, giving small teepee buttes. Black fissile shale with concretions.
				NIOBRARA FORMATION	[1]80-300	Impure chalk and calcareous shale.
				CARLILE SHALE	[1]350-750	Light-gray shale with numerous large concretions and sandy layers. Dark-gray shale.
				GREENHORN FORMATION	225-380	Impure slabby limestone. Weathers buff. Dark gray calcareous shale, with thin Orman Lake limestone at base.
			GRANEROS GROUP	BELLE FOURCHE SHALE	150-850	Gray shale with scattered limestone concretions. Clay spur bentonite at base.
				MOWRY SHALE	125 230	Light-gray siliceous shale. Fish scales and thin layers of bentonite.
				MUDDY SANDSTONE / NEWCASTLE SANDSTONE	0-150	Brown to light-yellow and white sandstone.
				SKULL CREEK SHALE	150-270	Dark-gray to black siliceous shale.
		Kik	INYAN KARA GROUP	FALL RIVER FORMATION	10-200	Massive to thin-bedded, brown to reddish-brown sandstone.
				LAKOTA FORMATION	35-700	Yellow, brown, and reddish-brown massive to thinly bodded sandstone, pebble conglomerate, siltstone, and claystone. Local fine-grained limestone and coal.
	JURASSIC	Ju		MORRISON FORMATION	0-220	Green to maroon shale. Thin sandstone.
				UNKPAPA SS	0-225	Massive fine-grained sandstone.
				SUNDANCE FORMATION	250-450	Greenish-gray shale, thin limestone lenses. Glauconitic sandstone; red sandstone near middle.
				GYPSUM SPRING FORMATION	0-45	Red siltstone, gypsum, and limestone.
	TRIASSIC	TRPs		SPEARFISH FORMATION	375-800	Red silty shale, soft red sandstone and siltstone with gypsum and thin limestone layers. Gypsum locally near the base.
PALEOZOIC	PERMIAN	Pmk		MINNEKAHTA LIMESTONE	[1]25-65	Thin to medium-bedded, fine grained, purplish-gray laminated limestone.
		Po		OPECHE SHALE	[1]25-150	Red shale and sandstone.
	PERMIAN / PENNSYLVANIAN	PIPm		MINNELUSA FORMATION	[1]375-1,175	Yellow to red cross-bedded sandstone, limestone, and anhydrite locally at top. Interbedded sandstone, limestone, dolomite, shale, and anhydrite. Red shale with interbedded limestone and sandstone at base.
	MISSISSIPPIAN	MDme		MADISON (PAHASAPA) LIMESTONE	[1]<200-1,000	Massive light-colored limestone. Dolomite in part. Cavernous in upper part.
	DEVONIAN			ENGLEWOOD FORMATION	30-60	Pink to buff limestone. Shale locally at base.
	ORDOVICIAN	Ou		WHITEWOOD (RED RIVER) FORMATION	[1]0-235	Buff dolomite and limestone.
				WINNIPEG FORMATION	[1]0-150	Green shale with siltstone.
	CAMBRIAN	OЄd		DEADWOOD FORMATION	[1]0-500	Massive to thin-bedded brown to light-gray sandstone. Greenish glauconitic shale, flaggy dolomite, and flat pebble limestone conglomerate. Sandstone, with conglomerate locally at the base.
PRECAMBRIAN		pCu		UNDIFFERENTIATED IGNEOUS AND METAMORPHIC ROCKS		Schist, slate, quartzite, and arkosic grit. Intruded by diorite, metamorphosed to amphibolite, and by granite and pegmatite.

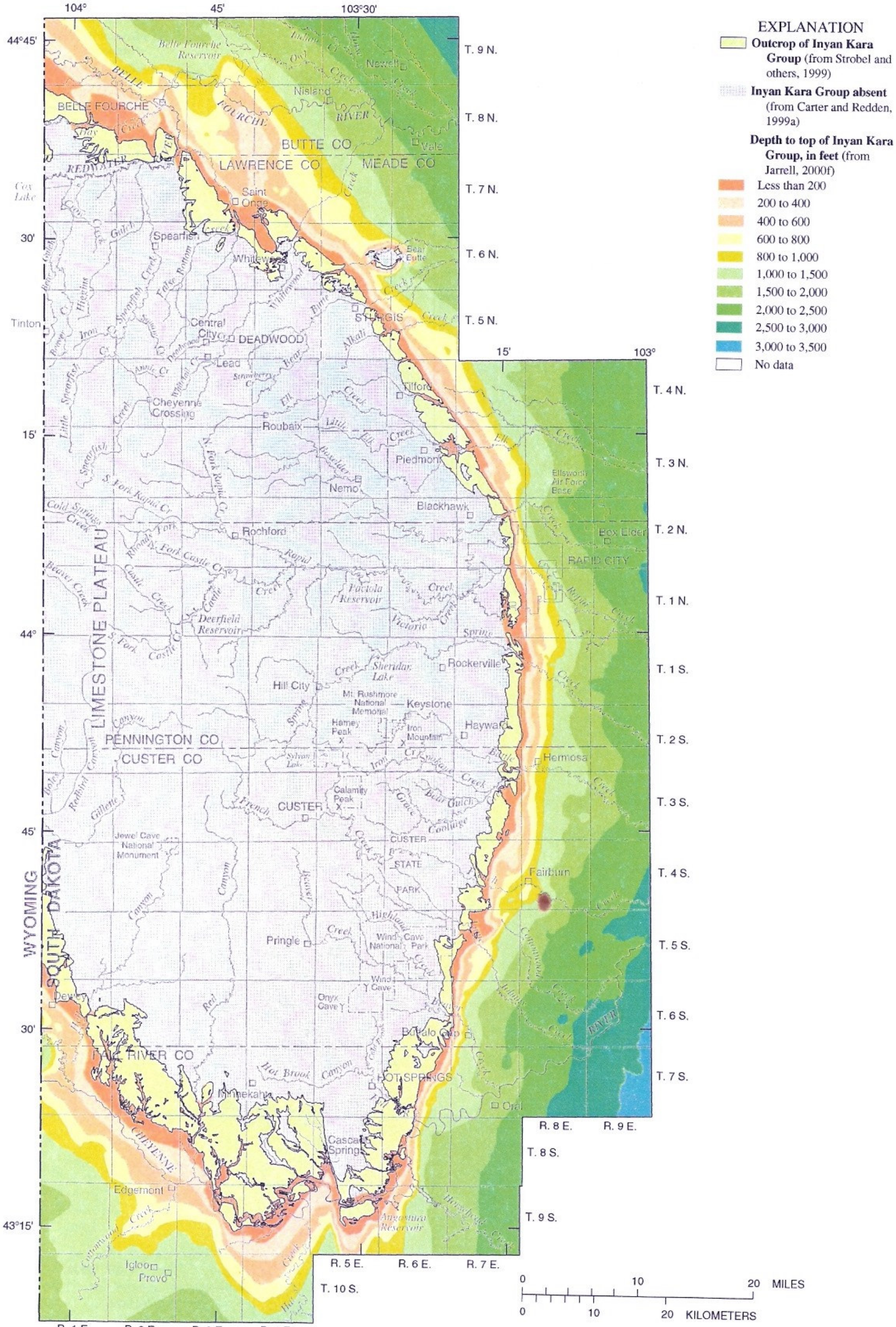
[1] Modified based on drill-hole data

Modified from information furnished by the Department of Geology and Geological Engineering, South Dakota School of Mines and Technology (written commun., January 1994)

FIGURE TWO: GENERAL WATER MOVEMENT IN THE NORTH CENTRAL STATES

Figure 17. General direction of ground-water flow in regional aquifer system within Paleozoic aquifer units (modified from Downey and Dinwiddie, 1988; Whitehead, 1996).

FIGURE THREE: DEPTH TO TOP OF INYAN KARA GROUP



Base modified from U.S. Geological Survey digital data, 1:100,000, 1977, 1979, 1981, 1983, 1985
Rapid City, Office of City Engineer map, 1:18,000, 1996; Universal Transverse Mercator projection, zone 13

Figure 52. Depth to top of Inyan Kara Group.

FIGURE FOUR: DIRECTIONS OF WATER FLOW IN THE MADISON AQUIFER

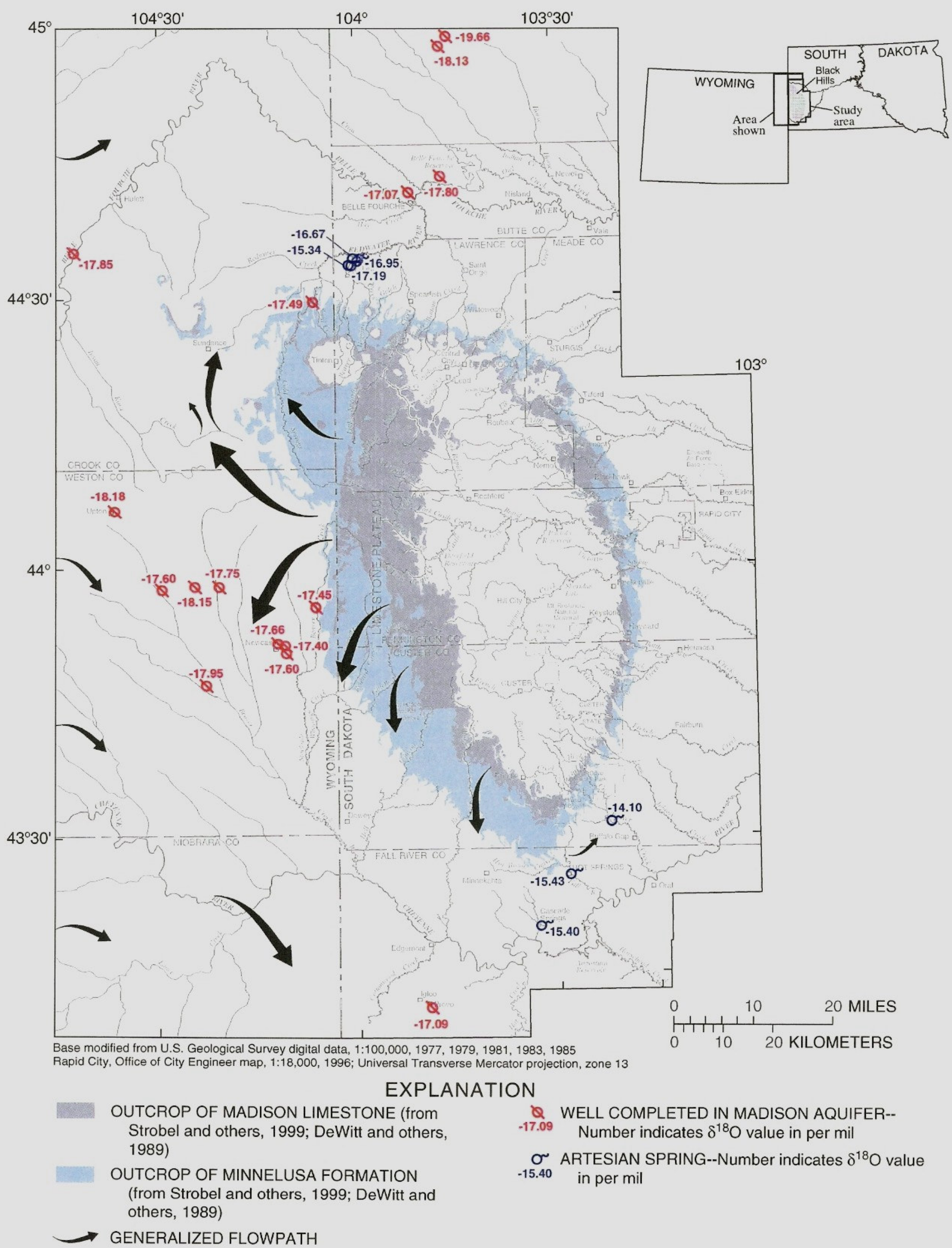


Figure 84. Distribution of $\delta^{18}O$ in selected Madison wells and springs and generalized flowpaths, based on $\delta^{18}O$ values, in the Black Hills of South Dakota and Wyoming (from Naus and others, 2001).

FIGURE FIVE: DIRECTION AND AMOUNT OF MINNELUSA AQUIFER FLOW

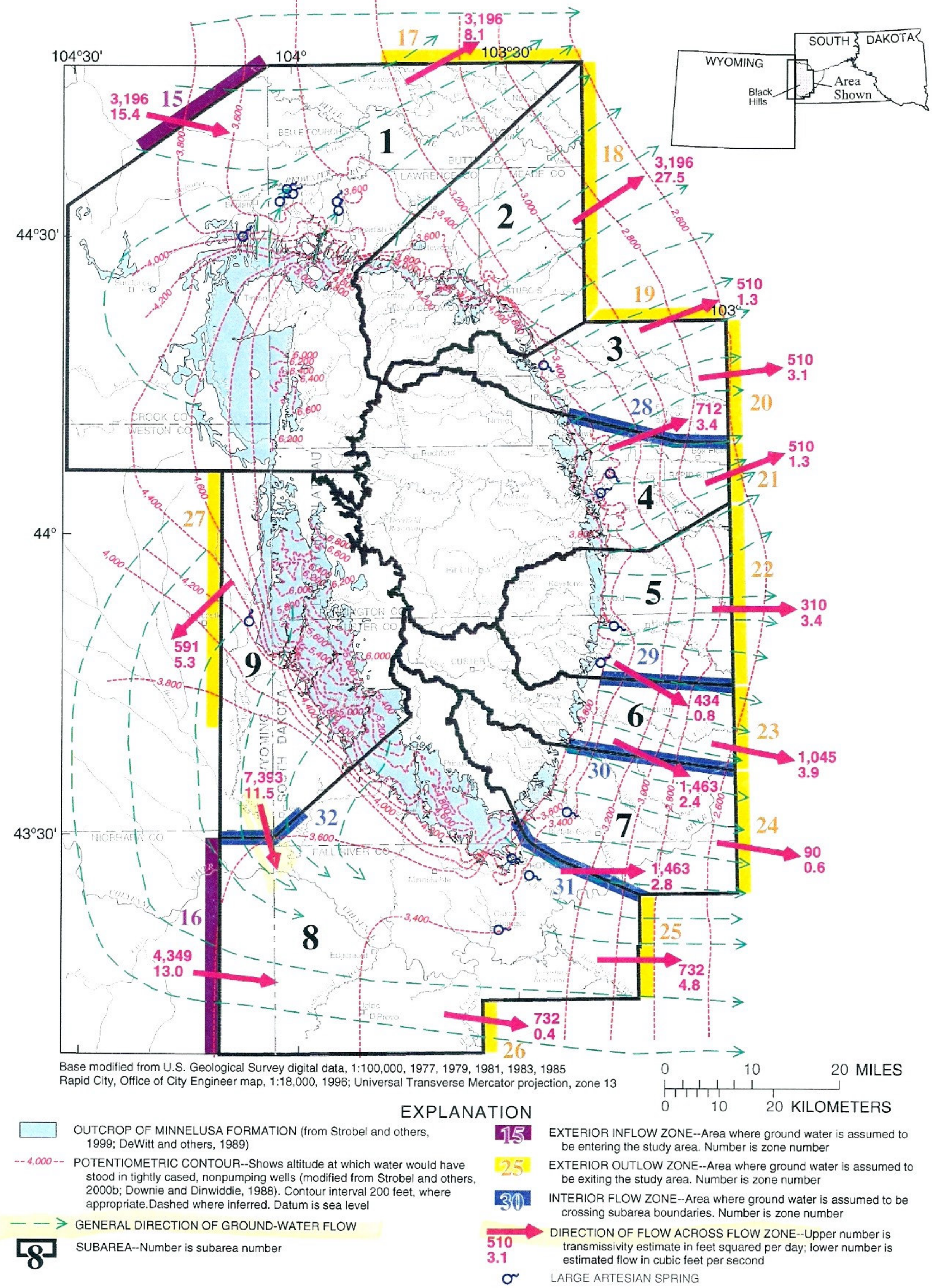


Figure 70. Subareas, generalized ground-water flow directions, and flow zones for the Minnelusa aquifer. Estimated transmissivities and flow components for flow zones also are shown (from Carter, Driscoll, Hamade, and Jarrell, 2001).

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[xxiv] *Op. cit*.,, Gott, Wolcott, and Bowles.

[xxv] *Op. cit*., Boggs.