INEEL/EXT-02-01022

Variability of the Aquifer Thickness Beneath the Idaho National Engineering and Environmental Laboratory (INEEL)

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Bechtel BWXT Idaho, LLC

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ABSTRACT

The bounds of the aquifer thickness for the WAG-10 OU 10-08 groundwater model needs to be defined. Direct information about aquifer thickness is available for only a few places at the INEEL where deep exploration wells penetrate the effective base of the aquifer. Direct detection of the effective base of the aquifer can be attained in these deep wells by temperature gradient variations in the well, by lithologic variations observed in drill cores, and by pumping tests done in the well. The major drawback in using direct detection methods for the INEEL is that only six wells with temperature logs are deep enough to penetrate the entire aquifer thickness, only five wells have drill core for examination, and only one well has a pump tests for intervals both above and below the base of the aquifer.

Despite the insufficiency of data at the INEEL, aquifer temperature is the most widely available detection method for aquifer thickness. The data limitation can be partially overcome by viewing aquifer temperature in site-wide cross sections. Such cross sections provide a rational basis for interpolation of the base of the aquifer in places where no deep drilling exists. Several such cross sections were constructed to evaluation the aquifer thickness distribution across the site, and to construct alternative maps of aquifer thickness contours that covers most of the INEEL.

The results of this evaluation show alternative aquifer thickness interpretations that honor the observed thickness information. The information about thickness of the Snake River Plain aquifer shows that the aquifer ranges from greater than 400 meters to less than 100 meters thick in the INEEL area. Such dramatic variations in thickness are likely to cause great spatial variation in the transmissivity of the aquifer. Therefore, predictive contaminant transport models should not assume a constant thickness for the aquifer, but should make every effort to incorporate all available aquifer thickness information.

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Variability of the Aquifer Thickness Beneath the Idaho National Engineering and Environmental Laboratory (INEEL)

1. EFFECTIVE BASE OF THE AQUIFER

1.1 Direct Detection of the Effective Base of the Aquifer

Most wells at the Idaho National Engineering and Environmental Laboratory (INEEL) are water supply wells or monitoring wells and penetrate only a short distance into the Snake River Plain (SRP) aquifer. Therefore, direct information about aquifer thickness is available for only a few places where deep exploration wells penetrate the effective base of the aquifer. Direct detection of the effective base of the aquifer can be attained in these deep wells by temperature gradient variations in the well, by lithologic variations observed in drill cores, and by pumping tests done in the well (see Appendix A). Temperature profiles of deep wells can be used to identify the base of the aquifer because the inflection from nearly isothermal conditions to a regional conductive temperature gradient mark the depth at which the cold, fast-flowing aquifer waters are no longer able to dominate the geothermal gradient. Likewise, lithologic changes that seal the rocks' porosity and permeability are recognizable in drill cores of deep wells. One well (INEL-1) has hosted a pumping test (Mann 1986) that shows orders-of-magnitude reduction in hydraulic conductivity below about 800 to 1200 feet compared to that in the active aquifer above.

1.2 Indirect Interpretations of Effective Base of the Aquifer

Two interpretative approaches have been used to estimate aquifer thickness in the INEEL region. They each rely on a conceptual model that the base of the aquifer is controlled by a Tertiary stratigraphic unit that underlies the Quaternary basalts of the INEEL area. The rationale for one approach is that the older Tertiary rocks, known as the Glenns Ferry formation where they are exposed at the surface in the central and western Snake River Plain, have been altered and mineralized to the extent that their permeability is impaired and they do not conduct significant quantities of water compared to the overlying Quaternary basalts. Alternatively, in a second approach, a thick sequence of sediments separating the Quaternary basalts from the underlying Tertiary basalts may possess reduced permeability compared to the active aquifer above, and may therefore mark the base of the active aquifer. The first approach (Ackerman, 2000) uses regional geophysical data (electrical resistivity) to infer the thickness of rocks saturated with fresh (low resistivity) aquifer waters, and equates this inferred thickness to the thickness of Quaternary basalts. A problem with use of the electrical resistivity interpretation is that the predicted aquifer thickness do not agree with those determined from temperature logs in most cases. The method has the potential to refine aquifer thickness over large areas, but should first be calibrated against known aquifer thickness in several deep wells. The second approach (Anderson and Bowers, 1995; Anderson and Liszewski, 1997) uses borehole intercepts of the thick sediment unit as the effective base of the aquifer. Both of these approaches are described in Appendix A.

2. AQUIFER THICKNESS ESTIMATION FOR WAG-10 GROUNDWATER MODELING

2.1 Observational Evidence

For purposes of defining aquifer thickness for WAG-10 groundwater modeling, the methods of direct detection of the aquifer bottom are given priority. This is because they do not depend on interpretation and because they provide an internally consistent estimate of aquifer thickness in wells in which more than one of the direct detection methods have been used. For instance, the aquifer bottom indicated by alteration and mineralization of basalts in drill core coincide with that indicated by inflections in temperature profiles of the same wells (Morse and McCurry, 2001). In addition, the aquifer pumping tests done at depths of 1500 feet and deeper in well INEL-1 show that hydraulic conductivity is greatly restricted compared to typical aquifer values (Mann, 1986). This is consistent with the position of the temperature inflection in INEL-1, which shows the aquifer bottom at a depth of about 720 feet.

The major drawback in using direct detection methods to identify the bottom of the aquifer is that only six wells with temperature logs are deep enough to penetrate the entire aquifer thickness (Appendix A), only five of these have drill core for examination (Morse and McCurry, 2001), and only one (INEL-1) has pumping test data for intervals both above and below the base of the aquifer. Despite the paucity of data, aquifer temperature is the most widely available detection method for aquifer thickness (Figures 1 and A-2). The data limitation can be partly overcome by viewing aquifer temperature in site-wide cross sections (Figure 2). Such cross sections provide a rational basis for interpolation of the aquifer bottom in places where no deep drilling exists. Several such cross sections were constructed (Figure 3) in order to gain greater confidence in aquifer thickness distribution across the site.

The resulting information can be used to construct alternative maps of aquifer thickness contours that covers most of the INEEL (Figure 4). Although some adjustments are possible in the positions and shapes of contours on the maps, the general configuration is defined. The southwestern part of the INEEL, north of the Radioactive Waste Management Complex (RWMC), is characterized by aquifer thickness less than 100 meters and perhaps approaching zero in the vicinity of well USGS-22, where high aquifer temperature and evolved water chemistry suggest that water is moving very slowly. An elongate east-northeast trending zone (trough) in which the aquifer is more than 400 meters thick, extends from the Power Burst Facility (PBF) area through ANL-West, and perhaps farther east. The southwestern extent of this trough is poorly constrained by existing data, and the two cases shown in Figure 4 illustrate the range of possibilities. The uncertainty derives from the lack of any aquifer thickness information between wells C1A near RWMC and CH-1 near the southeast corner of INEEL, and points up the necessity to gain additional information there. The aquifer thins to about 330 meters in north-central INEEL and about 170 meters or less in the vicinity of Corehole 1 near the southeastern corner of the INEEL.

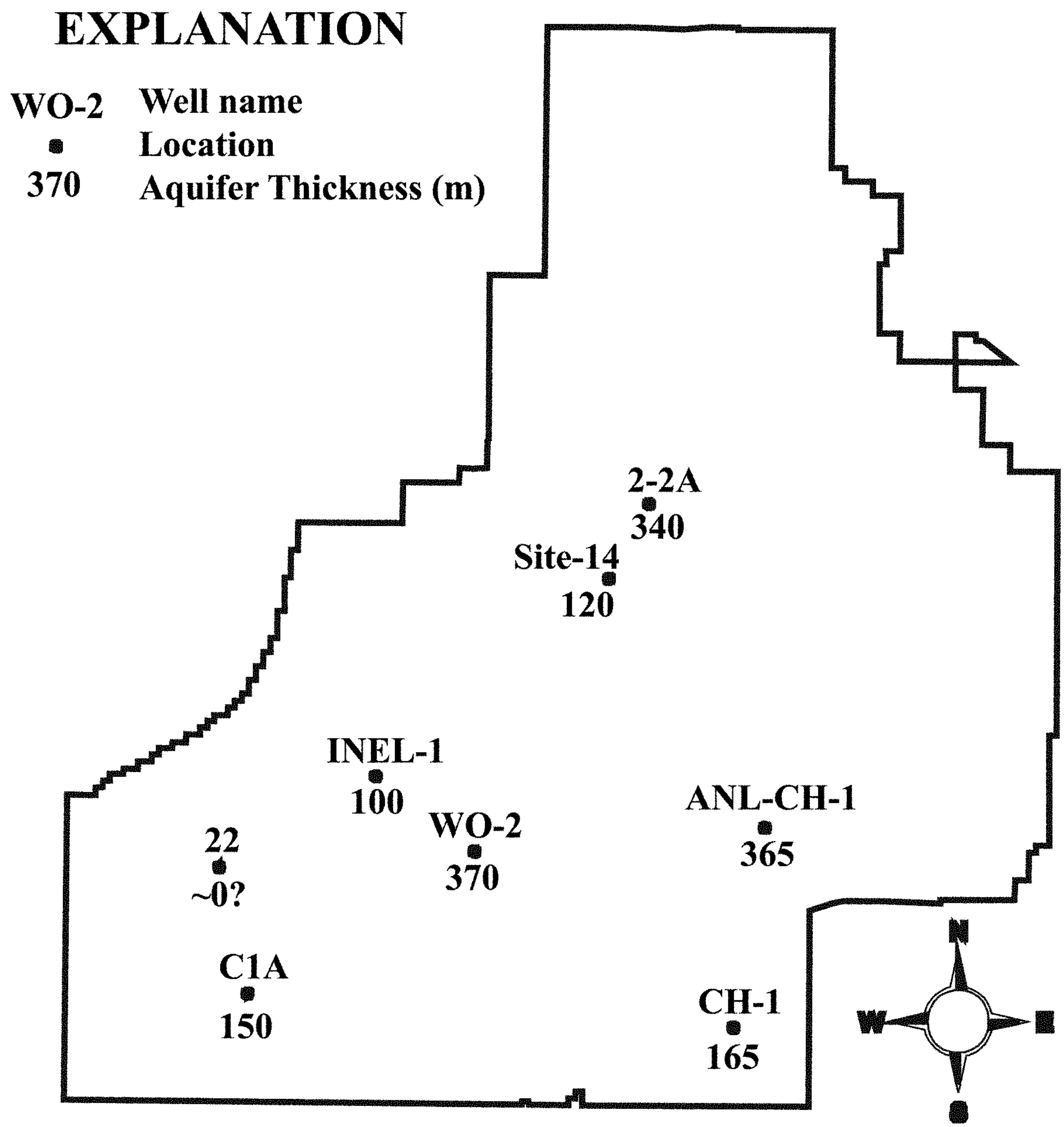

Figure 1. Map showing wells for which aquifer thickness is known from inflections in temperature logs (see Appendix A).

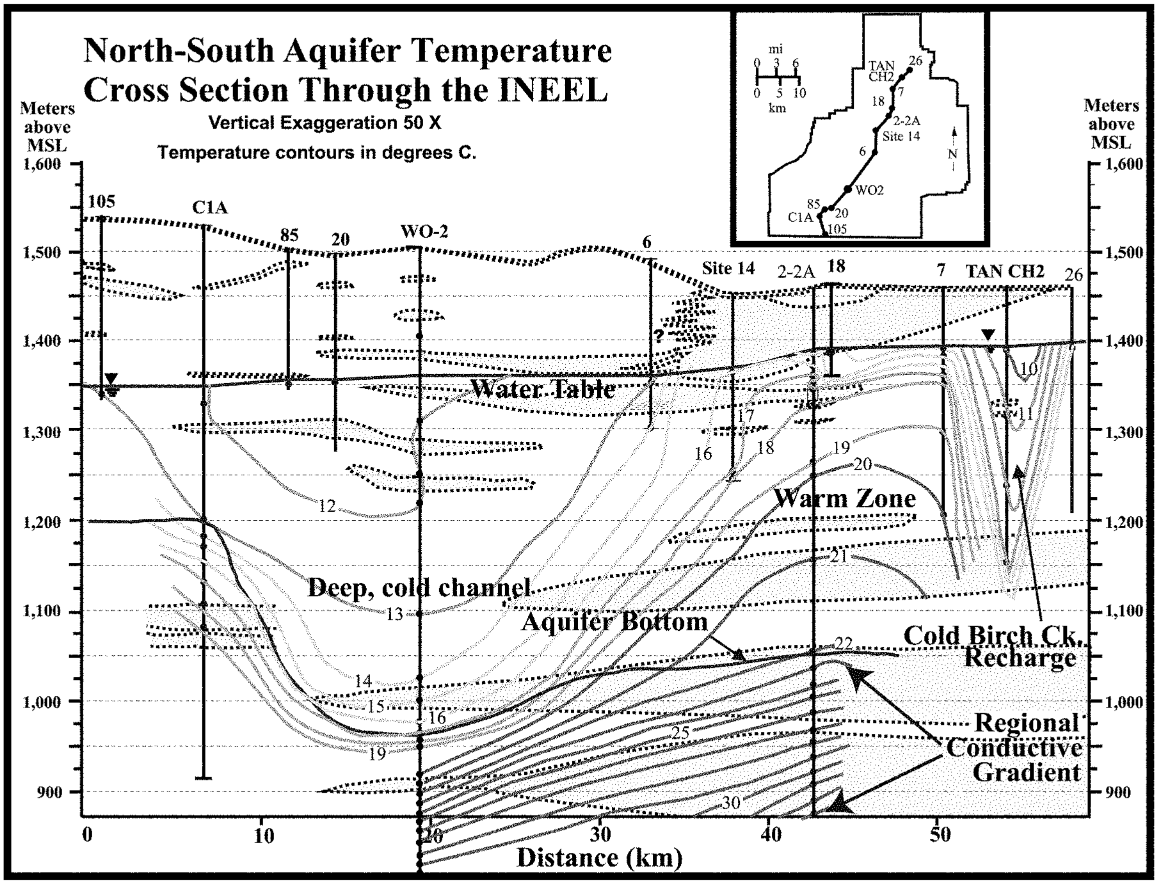

Figure 2. Aquifer temperature cross section showing cold an warm zones, aquifer bottom, and relationship to major sedimentary interbeds (layers with light gray shading).

Aquifer Temperature Cross Sections

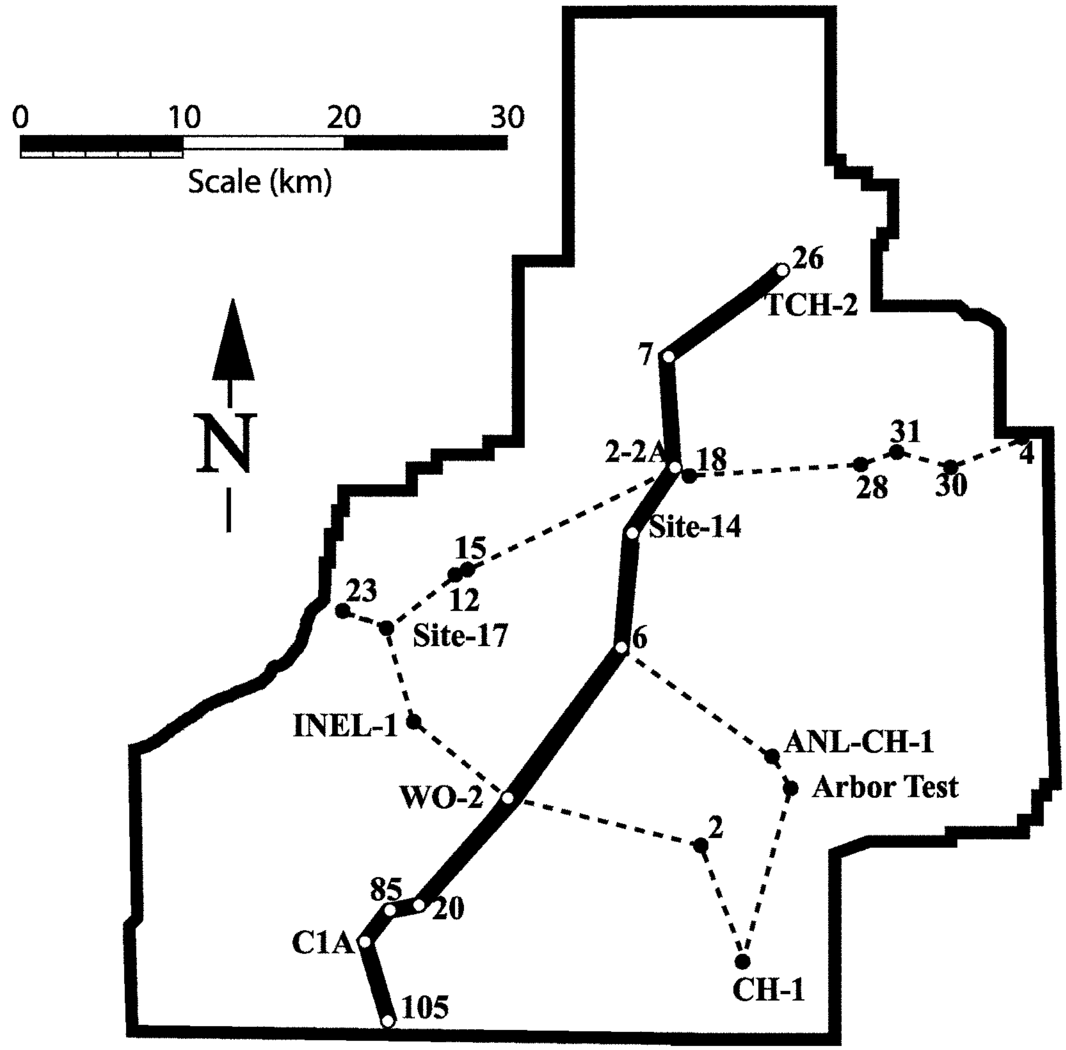

Figure 3. Map showing location of all aquifer temperature cross sections drawn to refine configuration of aquifer bottom.

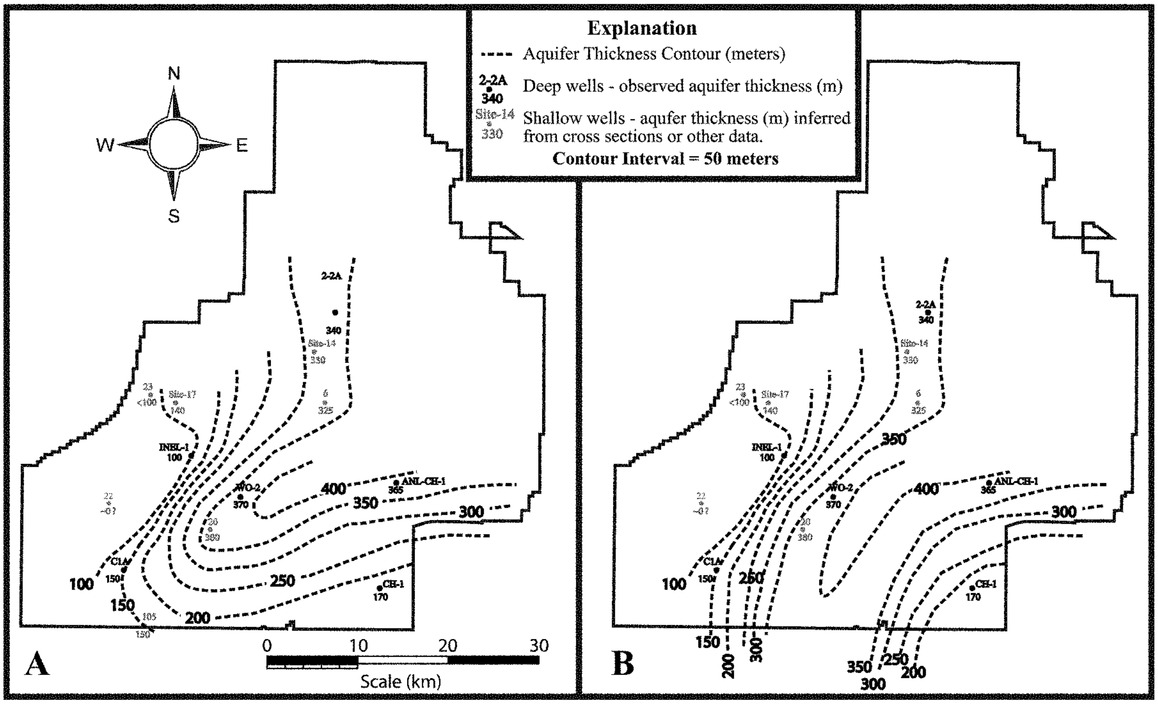

Figure 4. Two alternative interpretations for configuration of contours of aquifer thicknes.

NOTE: Both interpretations honor the observed aquifer temperature profiles in deep wells. In Case A, the deep trough north of ANL-W is assumed to be closed near the southern boundary of the INEEL. In Case B, the deep trough is assumed to be continuous to the southwest and south.

2.2 Alternatives for Regional Aquifer Thickness

There is direct observational evidence for aquifer thickness structure only in the area of Figure 4 encompassed by the thickness contours. In the areas of major uncertainty about aquifer thickness, the areas upgradient (NE) and downgradient (SW) of the contoured area, bounding cases of aquifer thickness have been estimated. Only two datasets extend upgradient and downgradient sufficiently far to provide guidance on aquifer thickness in these areas. These two are aquifer temperature and electrical resistivity (Whitehead 1986, see Appendix 1).

Using these data, a "maximum thickness" (or thick) scenario and a "minimum thickness" (or thin scenario) are estimated for each of the cases in Figure 4. Although the electrical resistivity interpretation (Figure A-6) consistently overestimates aquifer thickness in places where direct observations have been made (Figure 4), it suggests that there is a very thick section of aquifer downgradient of INEEL, and the Thick Scenarios (Figures 5 and 6) reflect this as a north-trending area of thickness greater than 400 meters. The aquifer upgradient of the INEEL is assumed to have a thickness of greater than 400 meters because of the cold aquifer temperatures there. This is based on the general observation that aquifer thickness is inversely correlated with aquifer temperature in the area where aquifer thickness is known from deep temperature logs. Figures 5 and 6 show this inverse relationship; in two areas where temperatures are highest (the western edge of INEEL and the area near Corehole 1 at the southeast corner of INEEL) the thickness is less than 200 meters. Also the east-trending area of low temperature just north of Argonne West in southeastern INEEL has the greatest aquifer thickness at over 400 meters.

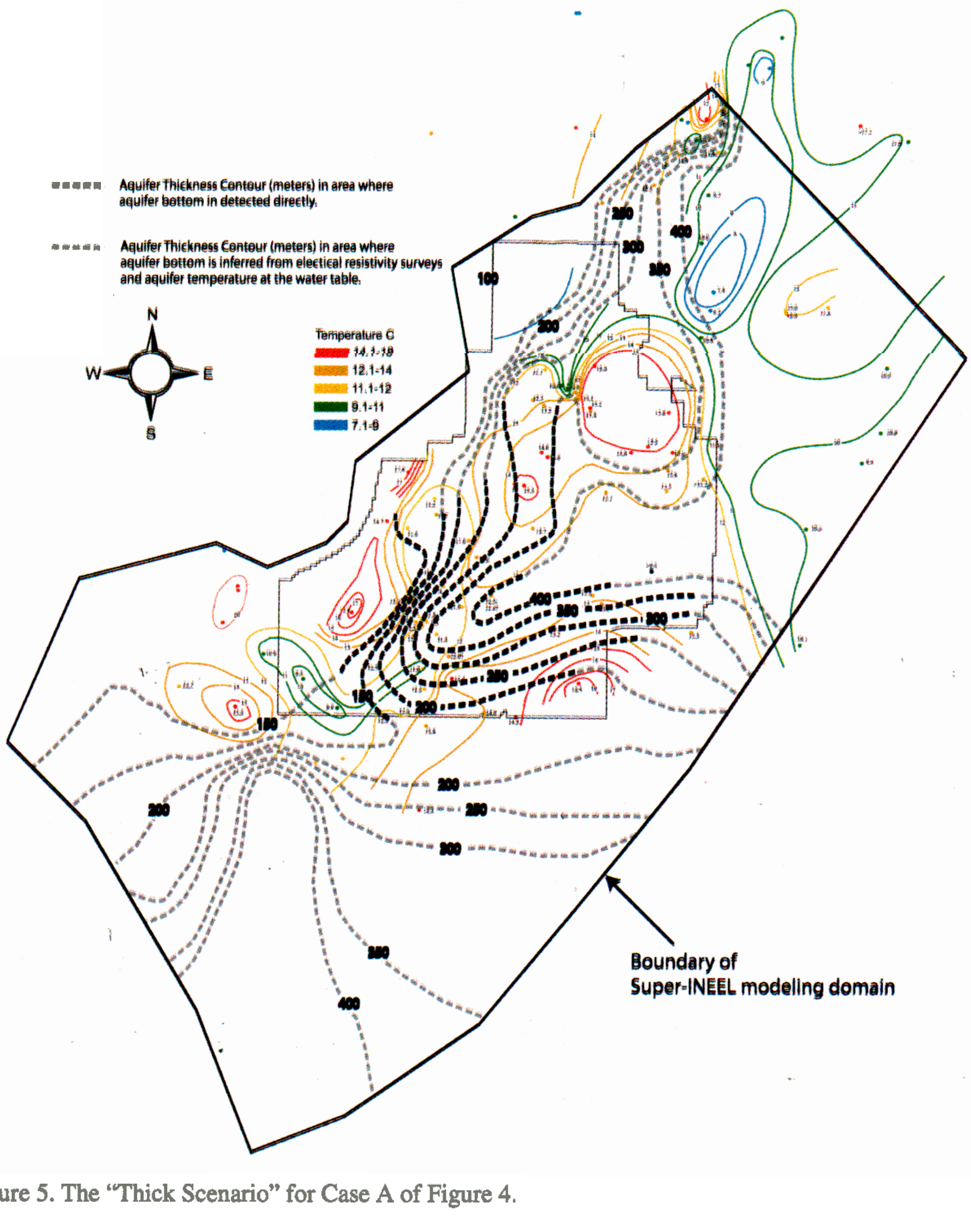

Figure 5. The "Thick Scenario" for Case A of Figure 4.

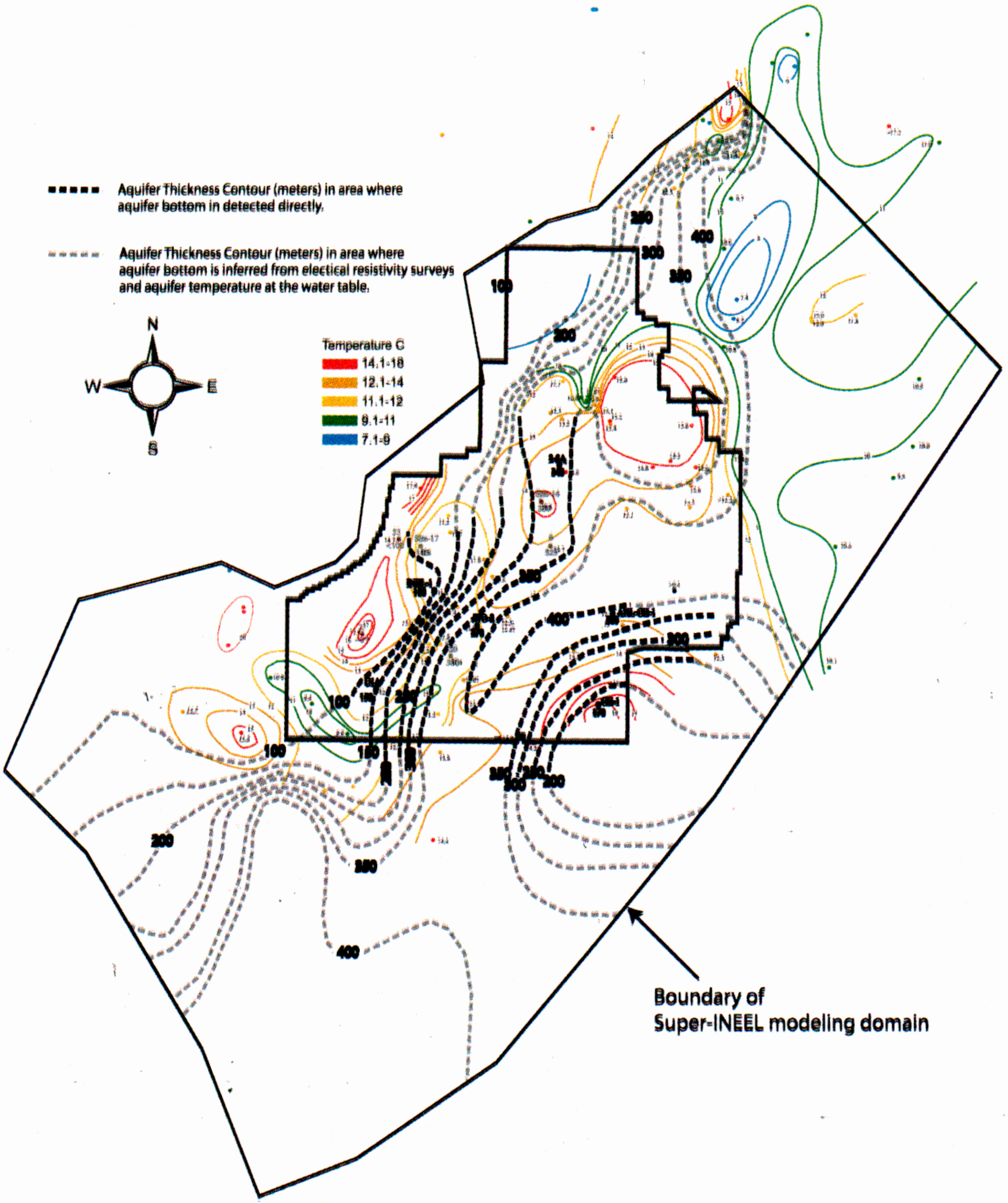

Figure 6. The "Thick Scenario" for Case B of Figure 4.

Two thin aquifer scenarios are also presented (Figures 7 and 8). Here an effort to minimize aquifer thickness in both the upgradient and downgradient areas is used. The thin scenarios assume nothing more that a general tendency for the aquifer to thicken towards the center of the Plain from 100 meters or less near the northwest margin of the Plain.

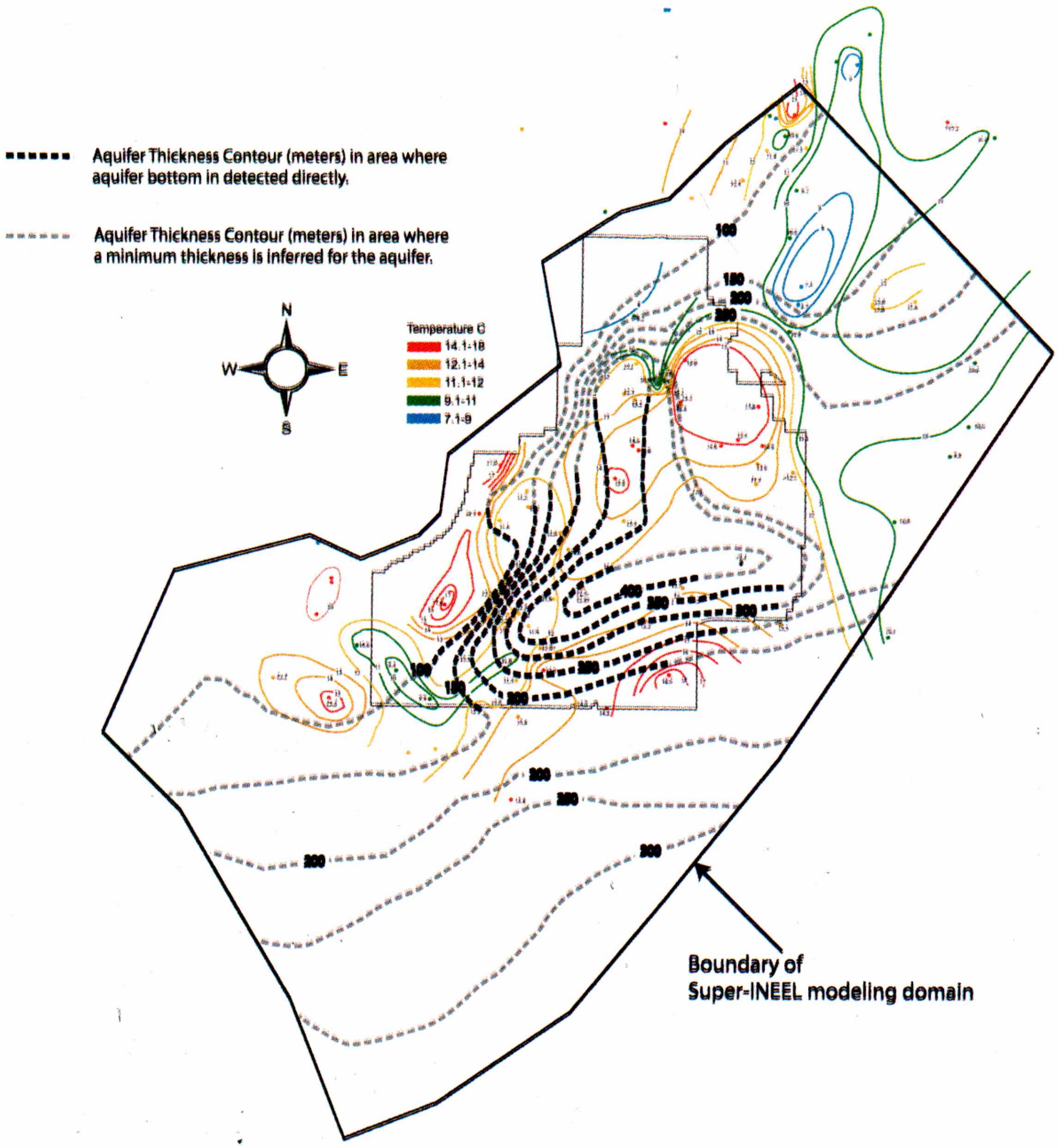

Figure 7. The "Thin Scenario" for Case A of Figure 4.

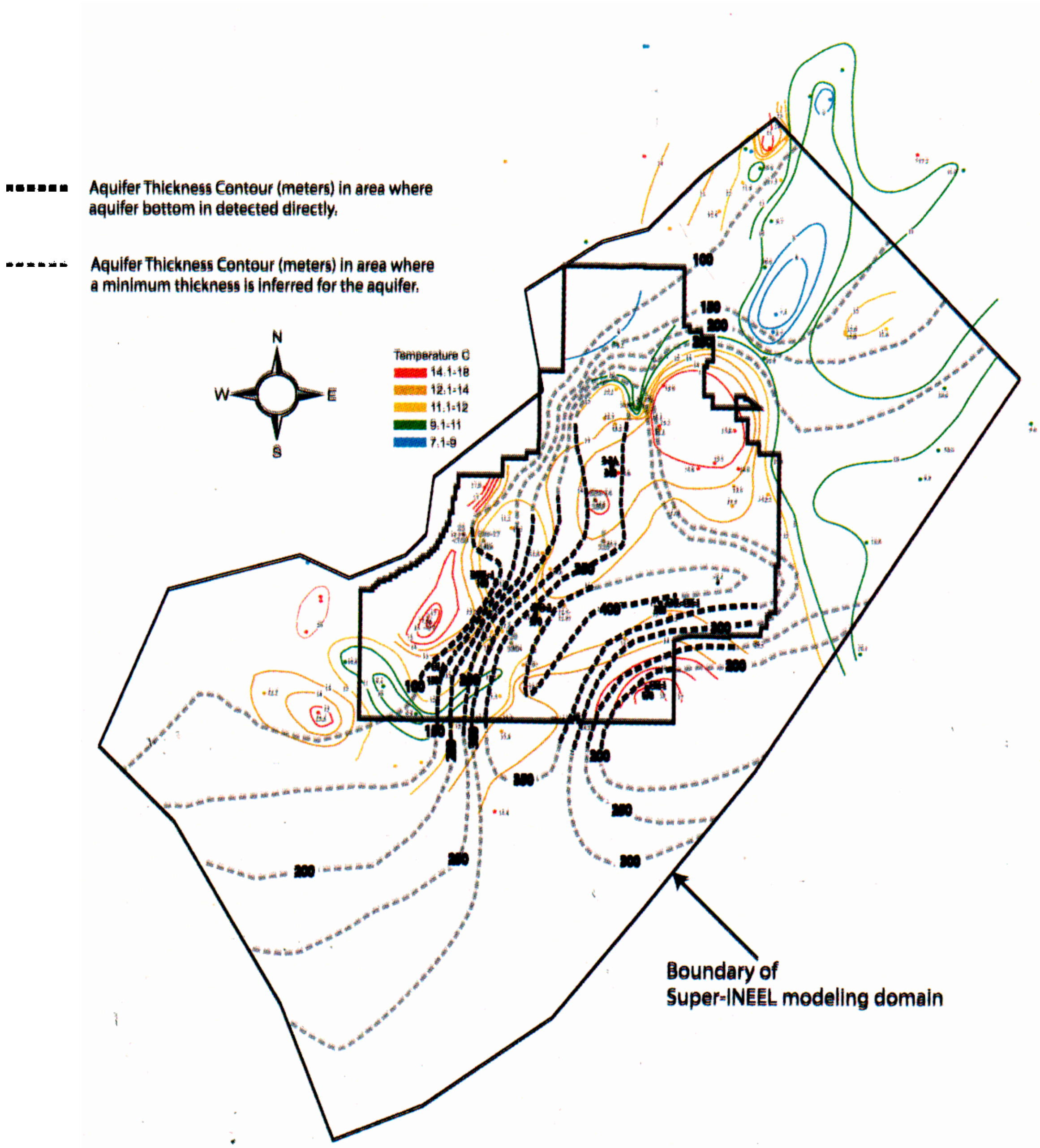

Figure 8. The "Thin Scenario" for Case B of Figure 4.

3. CONCLUSIONS AND RECOMMENDATIONS

The existing information about thickness of the Snake River Plain aquifer shows that the aquifer ranges from greater than 400 meters to less than 100 meters thick in the INEEL area. Such dramatic variations in thickness are likely to cause great spatial variation in the transmissivity of the aquifer. Therefore, predictive contaminant transport models should not assume a constant thickness for the aquifer, but should make every effort to incorporate all available aquifer thickness information. The maps showing alternative aquifer thickness interpretations that honor observed thickness data (Figure 4), and alternative regional aquifer thickness interpretations based on electrical resistivity surveys and aquifer temperature (Figures 5 through 8) are provided to facilitate incorporation of thickness data into models. Case B of Figure 4 (continuous deep trough through the southern INEEL boundary) is most consistent with the southerly preferred flow-paths suggested by geochemical and isotopic data. Therefore, Figures 6 and 8 should be given higher priority in development of alternative models of aquifer thickness for transport modeling.

4. REFERENCES

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Appendix A

Summary of Approaches to Determine Aquifer Thickness

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Summary of Approaches to Determine Aquifer Thickness

A-1. APPROACH 1. TEMPERATURE LOGS OF DEEP WELLS

Only a few wells and deep exploration wells extend to depths sufficient to completely penetrate the aquifer, and it is only these holes that provide information on aquifer thickness. For those drill holes that penetrate the entire thickness of the aquifer, the inflection point in the temperature gradient beneath the relatively isothermal section (as illustrated in Figure A-1) can be used to identify the effective base of the aquifer, the depth at which the regional conductive geothermal gradient is unaffected by movement of cool aquifer waters. Temperature logs for those INEEL-area wells that penetrate the entire thickness of the aquifer are shown in Figure A-2.

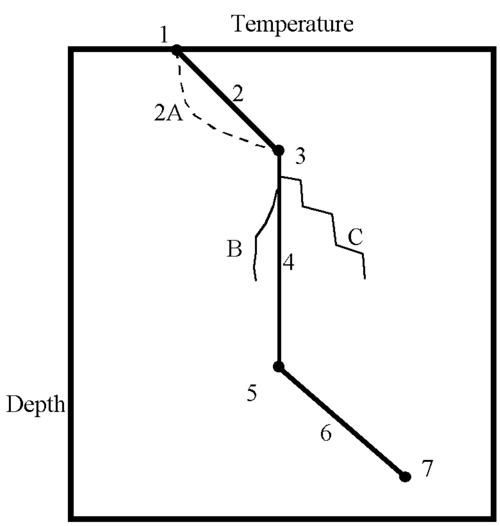


Figure A-1. General characteristics of INEEL-area temperature logs.

1. Temperature of the surface. Varies with season and time of day.
2. Conductive gradient in the vadose zone – characterized by a linear increase in temperature between the average annual temperature at the surface and the temperature of aquifer water at the water table.

2A. Convective gradient in the vadose zone. The basaltic bedrock in some areas of the INEEL is so fractured and permeable that barometric changes force air into and out of the vadose zone, causing temperatures to remain at or near the average annual temperature to significant depth, commonly nearly to the water table.

3. Temperature of the aquifer at the water table.
4. An isothermal temperature gradient in the aquifer is typical of many Snake River Plain wells because the aquifer waters are so fast-moving that the cold water from high-altitude source areas overcomes the high geothermal gradient and controls the temperature to depths at which aquifer waters cease to flow effectively.

4B. Aquifer gradient in cases where water infiltrates from the surface to recharge the cooler aquifer or where cool waters from recharge sources along the flanks of the Plain recharge the aquifer at depths below the water table.

4C. A case observed in some wells (especially in the northeastern part of INEEL) in which confined aquifers flow between impermeable layers (perhaps clay-rich interbeds).

5. Base of the aquifer. The depth at which flow of cool aquifer waters is no longer effective in controlling temperature. Below this depth the conductive processes predominate and the ambient geothermal gradient is expressed.
6. Ambient geothermal gradient.
7. Bottom-hole temperature.

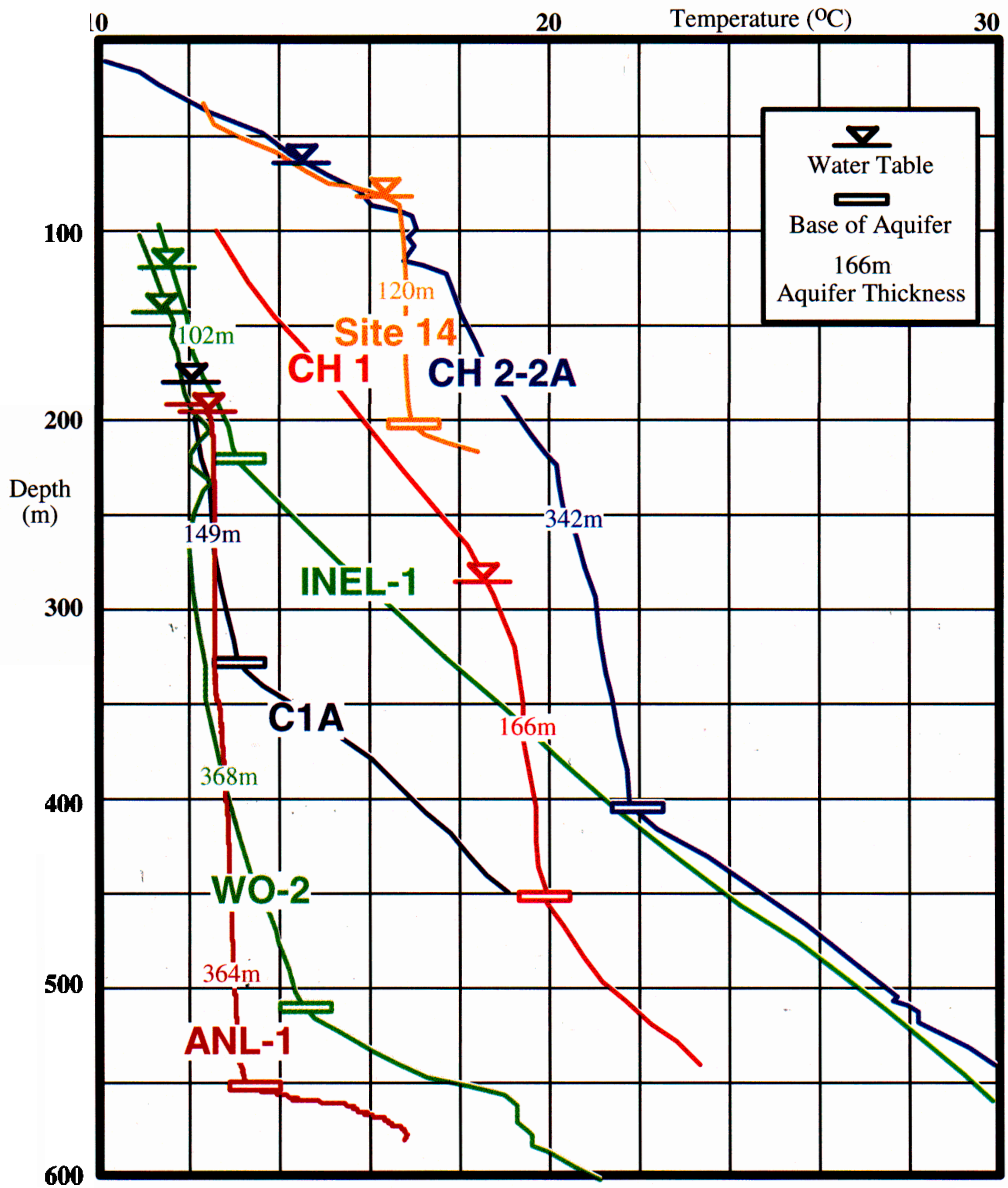


Figure A-2. Temperature logs of wells and exploration drill holes that penetrate the base of the aquifer. The temperature inflection for the Site 14 well is probably affected by down-flow of cool water and not indicative of the aquifer bottom.

Aquifer thickness ranges from over 360 meters at ANL-l and the NPR site (WO-2) to 100 meters at INEL-1, and perhaps to vanishingly small thickness at USGS-22 (Figure A-3). The aquifer thickness contours shown on Figure A-3, representing two of the many ways valid contours could be drawn to honor the few data points, are drawn in a configuration that conforms most closely to aquifer thickness distributions obtained by the other methods described below. The temperature log of Site-14 (Figure A-2), shows an inflection at a very shallow depth compared to other wells in the area and probably reflects down-flow of cool water to the depth of the inflection rather than the actual base of the aquifer.

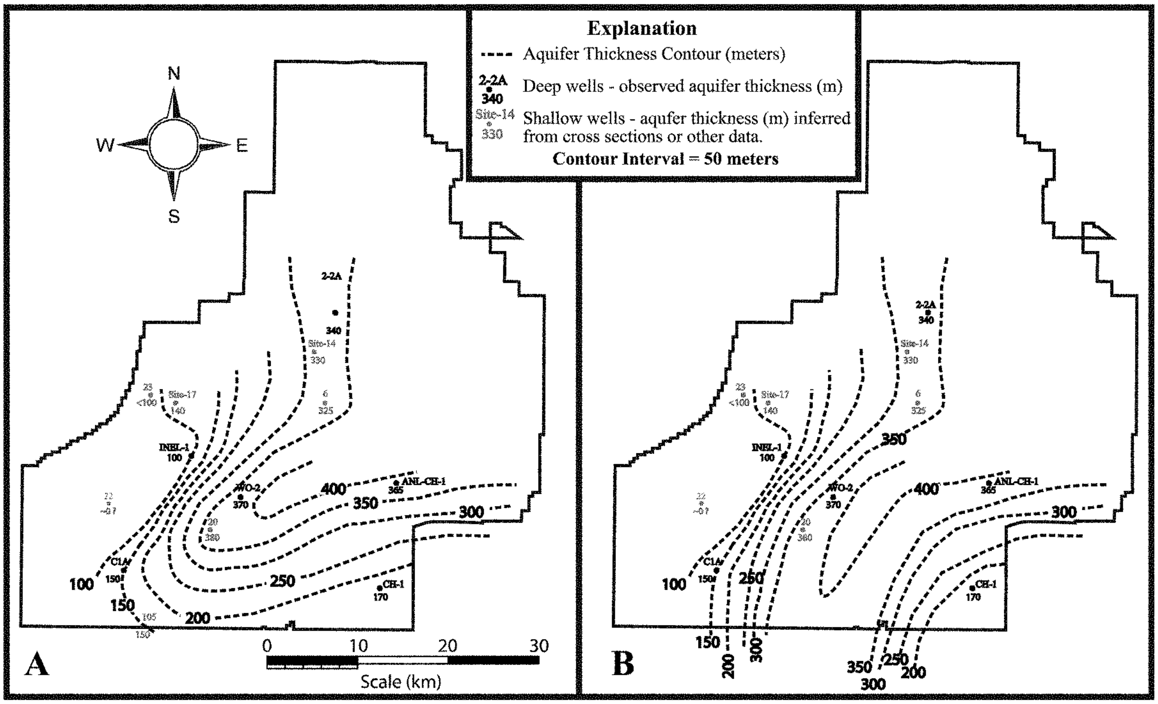


Figure A-3. Maps showing aquifer thickness at deep INEEL wells and two alternative interpretations of contours of aquifer thickness based on identification of aquifer bottom using inflections in the temperature logs.

A-2. APPROACH 2. ALTERATION AND MINERALIZATION OBSERVED IN DRILL CORES

Morse and McCurry (1997, 2001) have made macroscopic and microscopic examinations of drill core from several of the INEEL deep holes. They find that, within a fairly narrow depth interval, the basalt bedrock becomes altered and mineralized. The rock-forming minerals (plagioclase, olivine, pyroxene) and the glass in the fresh rocks become altered to an assemblage of hydrothermal alteration minerals (smectite clays and calcite). At the depth range were the rocks become altered, fractures, vesicles, and other openings in the rock are filled with clays, calcite, and minor zeolites, apophyllite, chalcedony, opal, and aragonite. This alteration and void-filling mineralization effectively destroys porosity and reduces permeability to near zero. The depth range at which alteration and mineralization occurs corresponds to the depth range of temperature inflections in deep wells and suggests that the effective base of the aquifer is marked equally well by either dataset. Thus the aquifer bottom estimates from alteration and mineralization are almost identical to aquifer bottom estimates made from inflections in temperature profiles of the wells.

A-3. APPROACH 3. PUMPING TESTS IN DEEP WELLS

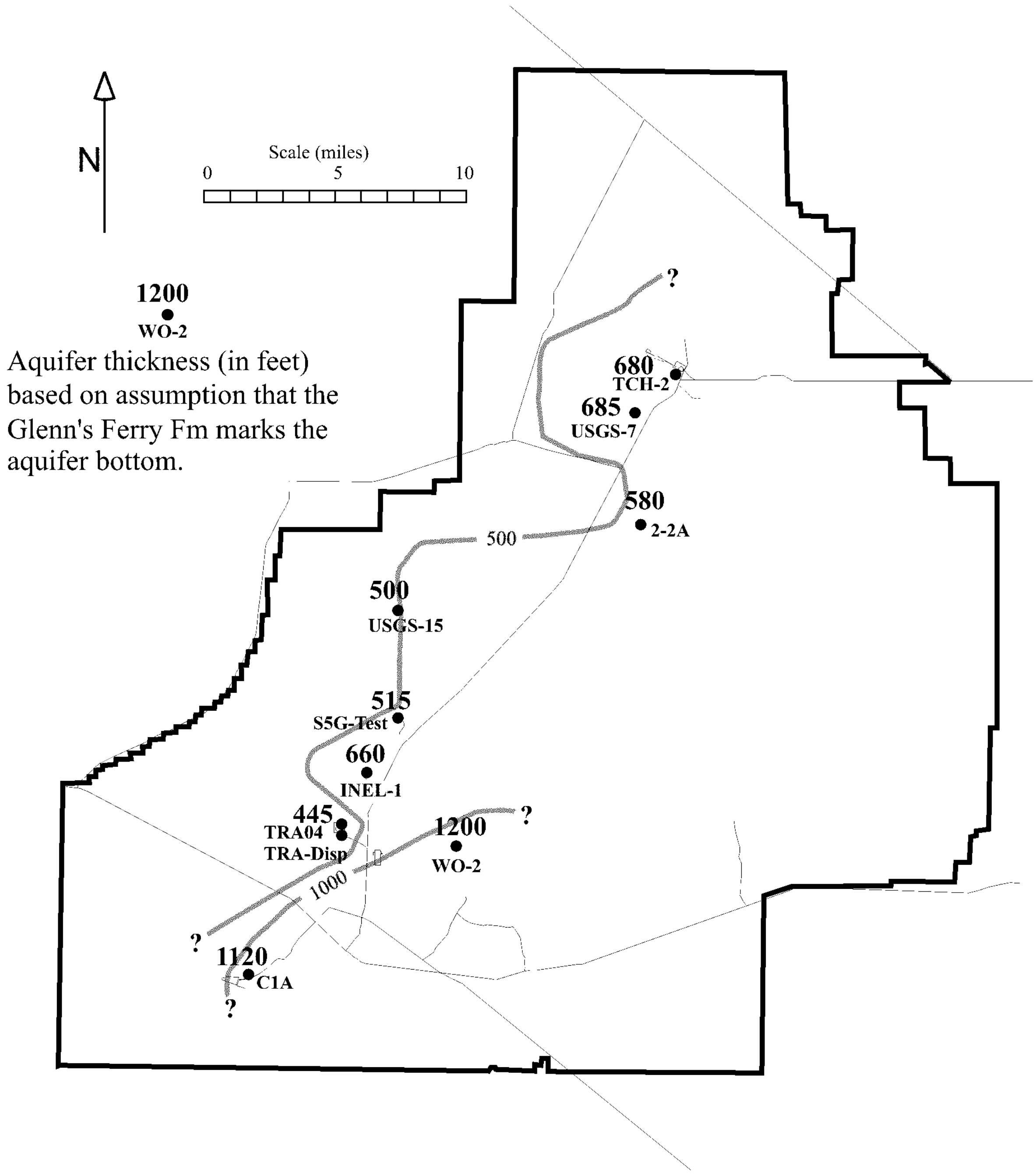
In one case, estimates of aquifer thickness is made from pumping tests done in well INEL-1 (Mann 1986). The hydraulic conductivity results from these tests show that the maximum depth to the effective base of the aquifer near INEL-1 is 850 to 1200 ft below the land surface. Hydraulic conductivities below that depth range are orders of magnitude lower than those within the actively flowing aquifer waters above that depth.

A-4. APPROACH 4. GLENNS FERRY EQUIVALENT ROCKS

Anderson and Bowers (1995) and Anderson and Liszewski (1997) make the case that the effective base of the aquifer coincides with the top of "a thick widespread layer of clay, silt, sand, and altered basalt that is older than about 1.8 million years and equivalent in age to the Glenns Ferry Formation." Several wells at the INEEL penetrate to that layer and they are summarized in Table A-1. In this approach, aquifer thickness ranges from 445 ft (135m) to 1200 ft (365m); it could be thicker in the eastern part of the INEEL because no data exists for that area, and it is reasonable that the depth to the sediment and altered basalt layer is deeper towards the center of the Snake River Plain.

Table A-1. Wells that penetrate the aquifer bottom based on Glenns Ferry equivalent rocks (modified from Anderson and Liszewski (1997).

Well Name	Total Depth (ft)	Depth to Base (ft)	Aquifer Thickness (ft)
C1A	1805	1710	1120
USGS CH 2-2A	3000	846	580
INEL-1	10,365	965	660
NPR WO-2	5000	1660	1200
S5G Test	1276	884	515
TAN CH-2	1114	883	680
TRA-4	970	909	445
TRA Disposal	1275	907	445
USGS 7	1200	895	685
USGS 15	1497	815	500



**Wells show USGS Estimate of Saturated Aquifer Thickness (ft)
Based on Assumption that the Glenn's Ferry Formation
Marks the Aquifer Bottom. Contours in feet.
(Map constructed from Anderson and Liszewski, 1997, Table 3)**

Figure A-4. Aquifer thickness estimate based on interpretation that the Glenn's Ferry Formation recognized in wells marks the aquifer bottom. Data from Anderson and Liszewski 1997. Contour interpretation by R. P. Smith.

A-5. APPROACH 5. THICKNESS OF SEDIMENTS PLUS QUATERNARY BASALT FROM WHITEHEAD (1986)

The approach used for sub-regional aquifer modeling by the USGS for FY2001 assumes that only Quaternary basalts and intercalated sediments host the active aquifer, and that older, more altered basalts and sediments do not conduct significant quantities of water compared to the younger rocks. Maps which show interpreted contours of sediment and Quaternary basalt thickness based on electrical resistivity surveys (Whitehead 1986) are used to define the base of the saturated aquifer according to the following formula:

SAT = AWT – [LSE – (ST + QBT)]

Where:

SAT	=	saturated aquifer thickness
AWT	=	altitude of water table
LSE	=	land surface elevation
ST	=	thickness of sediments (from Whitehead, 1986)
QB	=	thickness of Quaternary basalt (from Whitehead, 1986)

The resulting map is shown in Figures A-5 and A-6.

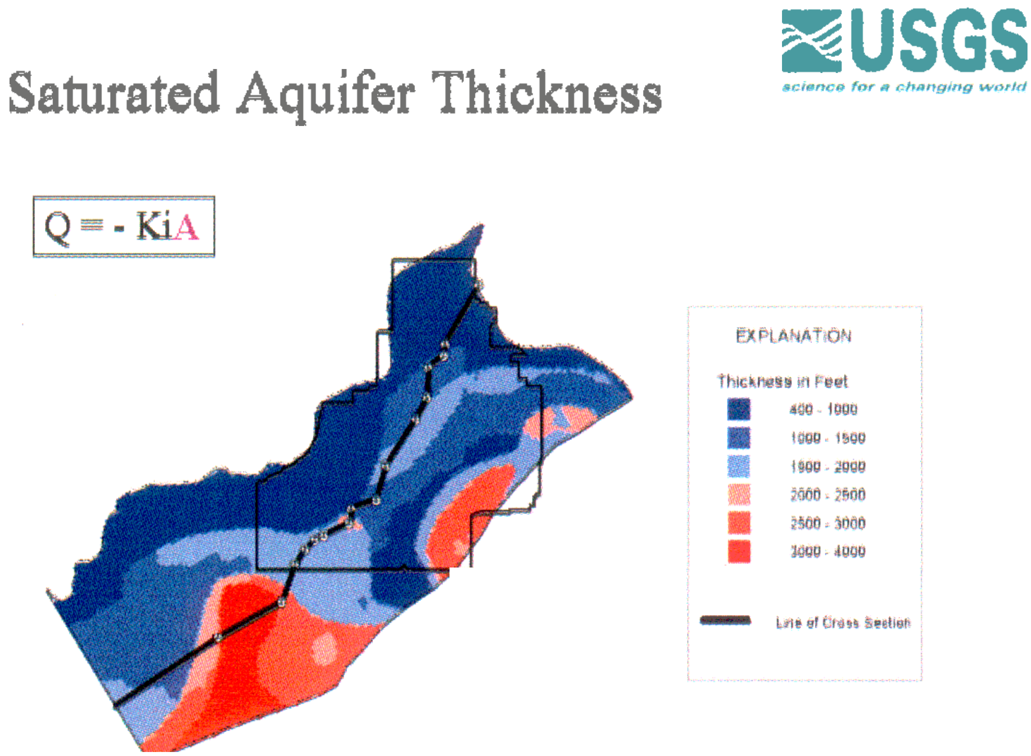
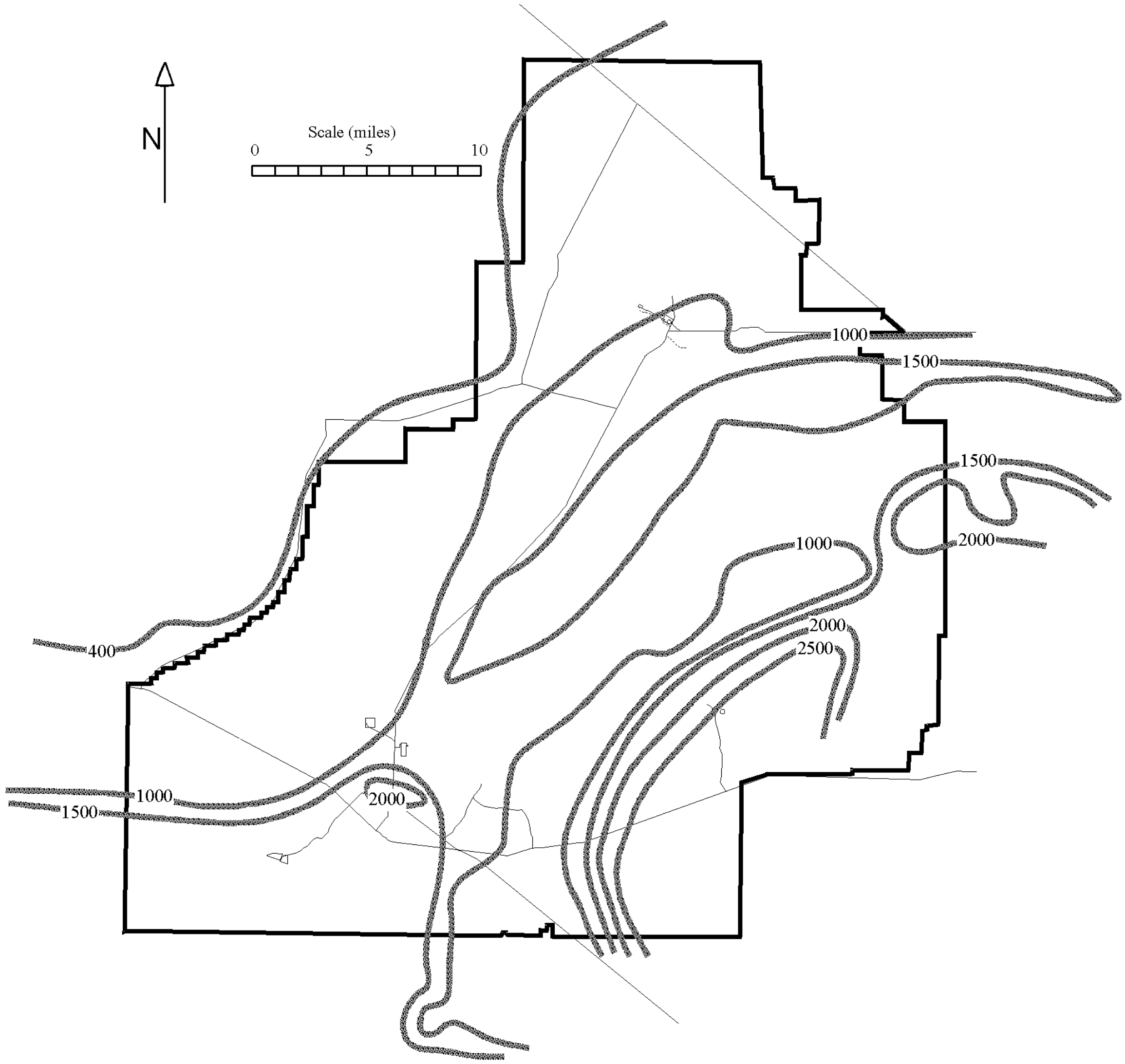


Figure A-5. Map showing inferred saturated aquifer thickness for USGS sub-regional aquifer modeling (From Ackerman 2000).



Contours show USGS Estimate of Saturated Aquifer Thickness (in feet)
(modified from Ackermann, personal communication, 12/2000)

SAT=AWT - [LSE-(ST + QBT)]

where:
SAT = saturated aquifer thickness
AWT = altitude of water table
LSE = land surface elevation
ST = thickness of sediments (from Whitehead, 1986)
QBT = thickness of Quaternary basalt based on electrical resistivity surveys (from Whitehead, 1986)

Figure A-6. Contours of aquifer thickness based on USGS formula.