Analysis and Documentation of Site Selection and Characterization Activities

Fuel Cycle Research & Development

Prepared for

U.S. Department of Energy
Used Fuel Disposition Campaign

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APPENDIX E

FCT DOCUMENT COVER SHEET [1]

Name/Title of Deliverable/Milestone/Revision No.	Analysis and Documentation of Site Selection and Characterization Activities
Work Package Title and Number	DR Deep Borehole Disposal - LBNL / FT-15LB081703
Work Package WBS Number	1.02.08.17
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Quality Rigor Level for Deliverable/Milestone[2]	☐ QRL-3	☐ QRL-2	☐ QRL-1 ☐ Nuclear Data	☒ Lab/Participant QA Program (no additional FCT QA requirements)

This deliverable was prepared in accordance with Lawrence Berkeley National Laboratory
(Participant/National Laboratory Name)

QA program which meets the requirements of
☒ DOE Order 414.1 ☐ NQA-1-2000 ☐ Other

This Deliverable was subjected to:

☐ Technical Review ☐ Peer Review

Technical Review (TR)

Review Documentation Provided

☐ Signed TR Report or,
☐ Signed TR Concurrence Sheet or,
☐ Signature of TR Reviewer(s) below

Peer Review (PR)

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NOTE 1: *Appendix E should be filled out and submitted with the deliverable. Or, if the PICS:NE system permits, completely enter all applicable information in the PICS:NE Deliverable Form. The requirement is to ensure that all applicable information is entered either in the PICS:NE system or by using the FCT Document Cover Sheet.*

NOTE 2: *In some cases there may be a milestone where an item is being fabricated, maintenance is being performed on a facility, or a document is being issued through a formal document control process where it specifically calls out a formal review of the document. In these cases, documentation (e.g., inspection report, maintenance request, work planning package documentation or the documented review of the issued document through the document control process) of the completion of the activity along with the Document Cover Sheet is sufficient to demonstrate achieving the milestone. If QRL 1, 2, or 3 is not assigned, then the Lab/Participant QA Program (no additional FCT QA requirements box must be checked, and the work is understood to be performed, and any deliverable developed, in conformance with the respective National Laboratory/Participant, DOE- or NNSA-approved QA Program..*

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ACRONYMS

AAPG	American Association of Petroleum Geologists
DOE	Department of Energy
U.S.	United States
USGS	United States Geological Survey

1. Introduction

This report reviews hydrogeological and geological aspects that may be evaluated for siting a deep borehole demonstration project. Generally speaking, the deep borehole will penetrate up to 2 km of sedimentary rock and up to 3 km of crystalline basement rock. In Section 2, the available data and analyses of hydrological behavior for some major regional groundwater basins in sedimentary rock are reviewed. There is far more information available about groundwater basins in sedimentary rock so these discussions are limited to the United States. Much less information is available on the hydrogeological behavior for deep crystalline rock; therefore, information for crystalline rock covers investigations in the U.S. and internationally. In Section 3, the types of different basement rock are identified and their distribution in the U.S. is described.

2. Hydrogeology of Sedimentary Basins and Crystalline Rock

The main characteristics of the system that can affect fluid movement are the rock permeability, fluid viscosity, and driving forces represented by spatial gradients in fluid pressure and fluid density. Fluid composition and temperature are also important through their influence on fluid density and viscosity. Rock permeability plays a central role in the magnitude of fluid flow in sedimentary and crystalline rock. The reason is that rock permeability in natural materials can vary over many orders of magnitude while fluid viscosity and driving forces vary over more limited ranges (Manning and Ingebritsen, 1999). While primary permeability of sediment deposits often controls the system permeability, the primary permeability of the rock matrix for crystalline rock is typically negligible and system permeability is usually controlled by fractures (Hiatt and Kyser, 2000; Stober and Bucher, 2015).

2.1 Hydrogeology of Sedimentary Basins

Reilly et al. (2008) provide an overview of groundwater basins in the U.S. Figure 2-1 shows the areal extent of the uppermost principal aquifers in the U.S. Because this is a two dimensional view, upper aquifers overlie and hide other productive aquifers on this map. Of the 57 principal aquifers identified in the continental U.S., 20 are unconsolidated sands or gravels or semi-consolidated sands, 15 are sandstone aquifers, 13 are carbonate aquifers, 4 are sandstone carbonate mixtures, 4 are volcanic or basaltic aquifers, and only 1 is a crystalline rock aquifer - the Piedmont and Blue Ridge crystalline-rock aquifers of the Mid-Atlantic States. This distribution of aquifer resources shows that crystalline rock is not a major source of groundwater in the U.S. and because of this, has not received much attention in terms of hydrogeological behavior in comparison with sedimentary aquifers consisting of unconsolidated sands and gravels, sandstones, and carbonates. Although there are some areas in Figure 2-1 that do not have aquifers, this map only shows the principal aquifers used for water resources. Figure 2-2 shows the depth to saline groundwater, which indicates saline groundwater in many areas shown without an aquifer in Figure 2-1. Therefore, we must expect that many locations to be considered for a deep borehole in crystalline rock will be located beneath a sedimentary basin aquifer.

Any aquifer overlying a crystalline rock disposal site will need to be considered as part of the hydrogeologic system that links the disposal interval of any deep borehole with the accessible environment. In many cases, hydrologic information will only be available for sedimentary aquifers because information about hydrological conditions in crystalline basement is generally not available. In these cases, the behavior of groundwater in sedimentary layers, particularly those layers immediately above basement rock, may provide the best estimate of hydrological activity for a given location.

Figure 2-1. Principal Aquifers of the U.S. (Reilly et al., 2008).

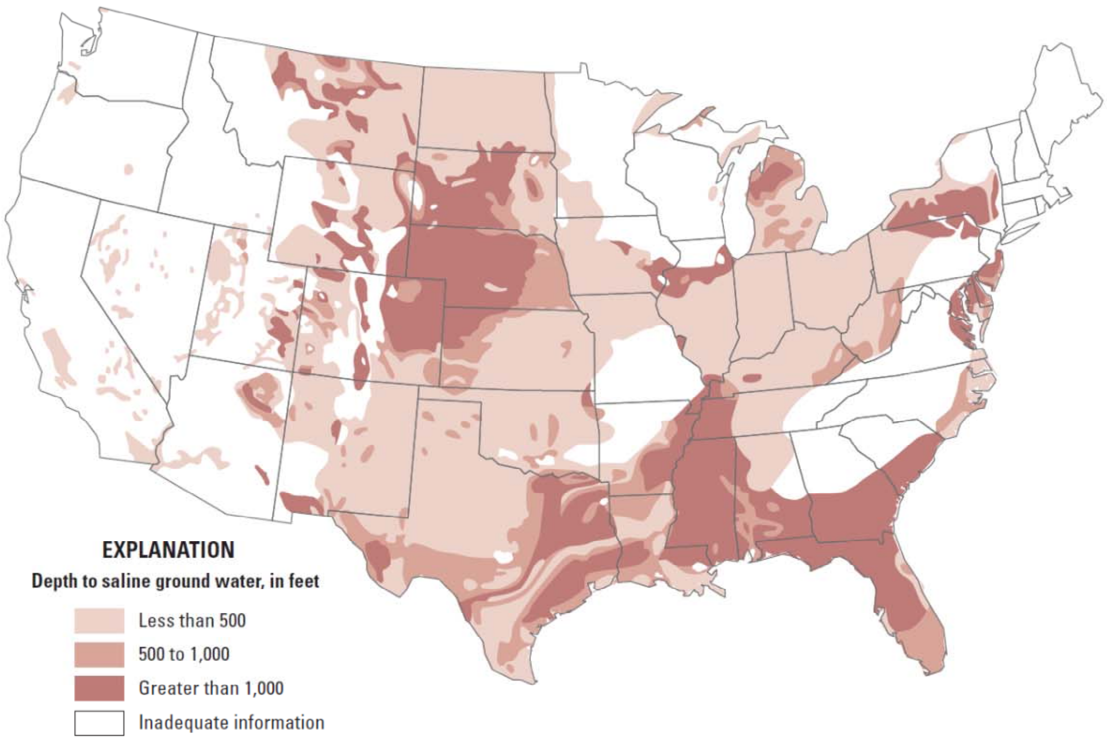
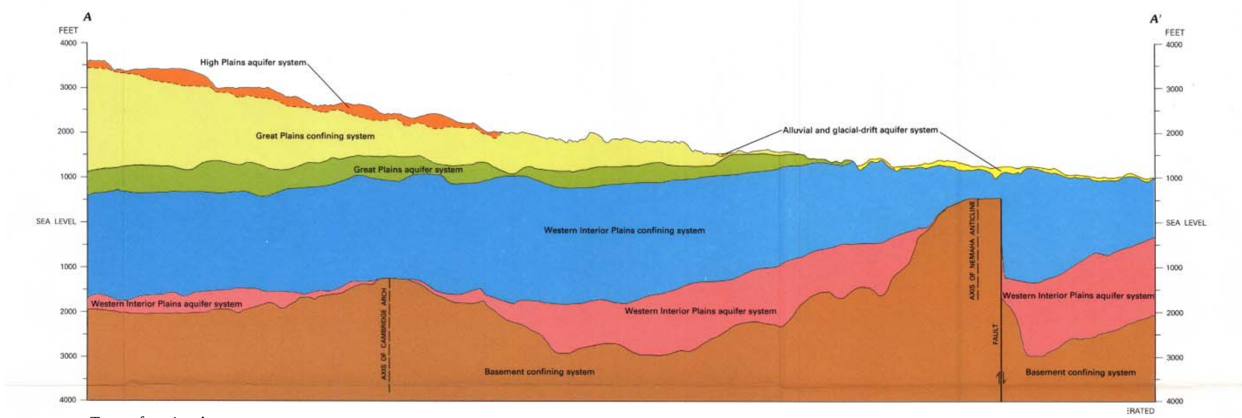


Figure 2-2. Depth to saline groundwater (Reilly et al., 2008).

More detailed regional groundwater studies have been conducted by the USGS for numerous groundwater basins. These existing studies are a resource that will be used to help assess the hydrogeological conditions around a proposed deep borehole site. An excellent source of information for the entire U.S. groundwater system is given in the USGS Groundwater Atlas (Miller, 2000). The atlas provides, in many cases, information about basin structure, lineaments, stratigraphy, flow directions, potentiometric contours, and salinity. Information for Kansas is presented here to provide examples of the types of information that may be available on a regional basis from the Groundwater Atlas and associated reports by the USGS and state geological surveys. A generalized stratigraphic column including associated hydrogeologic systems for Kansas is given in Figure 2-3. A cross section for Northern Kansas is shown in Figure 2-5, with the location of the cross-section identified in Figure 2-5. This shows an upper alluvial aquifer and the High Plains aquifer overlying the Great Plains aquifer, separated by the Great Plains confining system. The Western Interior Plains aquifer lies immediately above the Precambrian basement rock and is separated from the shallower aquifers by the massive Western Interior Plains confining system.

SYSTEM	Series	Provincial series	Geologic unit	Geohydrologic systems: Subdivisions	Geohydrologic systems: Major systems
QUATERNARY	Holocene		Undifferentiated Quaternary deposits		Alluvial and glacial-drift aquifer system
	Pleistocene				
TERTIARY	Miocene		Ogallala Formation		High Plains aquifer system
CRETACEOUS	Upper		Undifferentiated Upper Cretaceous rocks		Great Plains confining system
	Lower		Dakota Formation	Upper aquifer unit	Great Plains aquifer system
			Kiowa Shale	Confining unit	
			Cheyenne Sandstone	Lower aquifer unit	
JURASSIC	Upper		Morrison Formation	Upper unit	Western Interior Plains confining system
			Undifferentiated Upper Jurassic rocks		
PERMIAN	Upper		Big Basin Formation	Lower unit	
	Lower		Day Creek Dolomite Whitehorse Formation Nippewalla Group Dog Creek Formation Blaine Formation Flowerpot Shale Cedar Hills Sandstone Salt Plains Formation Harper Sandstone Sumner Group Stone Corral Formation Ninnescah Shale Wellington Formation Chase Group Council Grove Group Admire Group		
PENNSYLVANIAN	Upper	Virgilian	Wabaunsee Group Shawnee Group Douglas Group		
		Missourian	Undifferentiated Missourian rocks		
	Middle	Desmoinesian	Undifferentiated Desmoinesian rocks		
		Atokan	Undifferentiated Atokan rocks		
	Lower	Morrowan	Undifferentiated Morrowan rocks		
MISSISSIPPIAN	Upper	Chesterian	Undifferentiated Chesterian rocks		
		Meramecian	Undifferentiated Upper and Lower Mississippian rocks	Upper aquifer unit	Western Interior Plains aquifer system
	Lower	Osagean			
		Kinderhookian	Undifferentiated Lower Mississippian and Upper Devonian rocks	Confining unit	
DEVONIAN					
SILURIAN			Hunton Formation	Upper part of lower aquifer unit	
ORDOVICIAN	Upper		Maquoketa Shale		
	Middle		Viola Limestone Simpson Group		
	Lower		Arbuckle Group	Lower part of lower aquifer unit	
CAMBRIAN	Upper				
PRECAMBRIAN			Igneous, metamorphic, and metasedimentary rocks		Basement confining system

Figure 2-3. Generalized stratigraphic and hydrologic systems for Kansas (Wolf et al., 1990).



Trace of section A-A' shown in Figure 5

Figure 2-4. Geohydrologic section showing stratigraphic relations among principal geohydrologic systems in Kansas (Wolf et al., 1990).

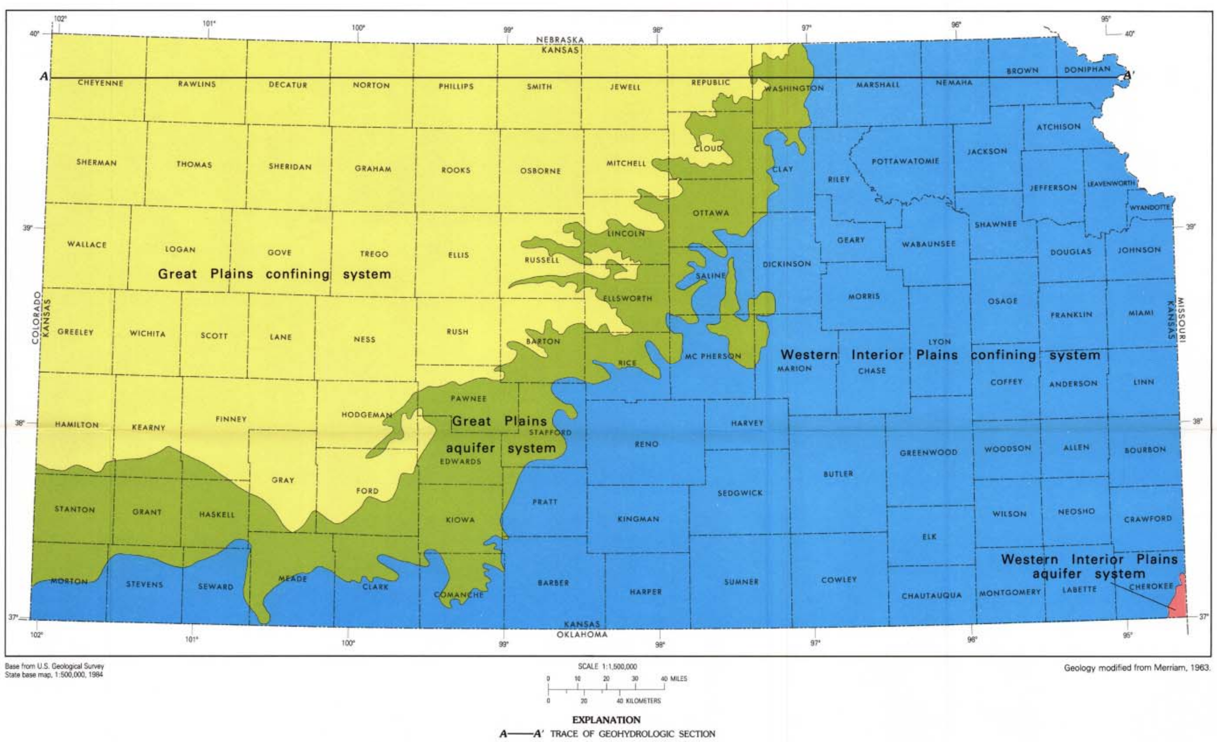


Figure 2-5. Map showing outcrop or subcrop of principal geohydrologic systems within Upper Cambrian through Lower Cretaceous rocks (Wolf et al., 1990).

Figure 2-6 presents the extent of the Western Interior Plains aquifer, which is present under nearly all of Kansas.

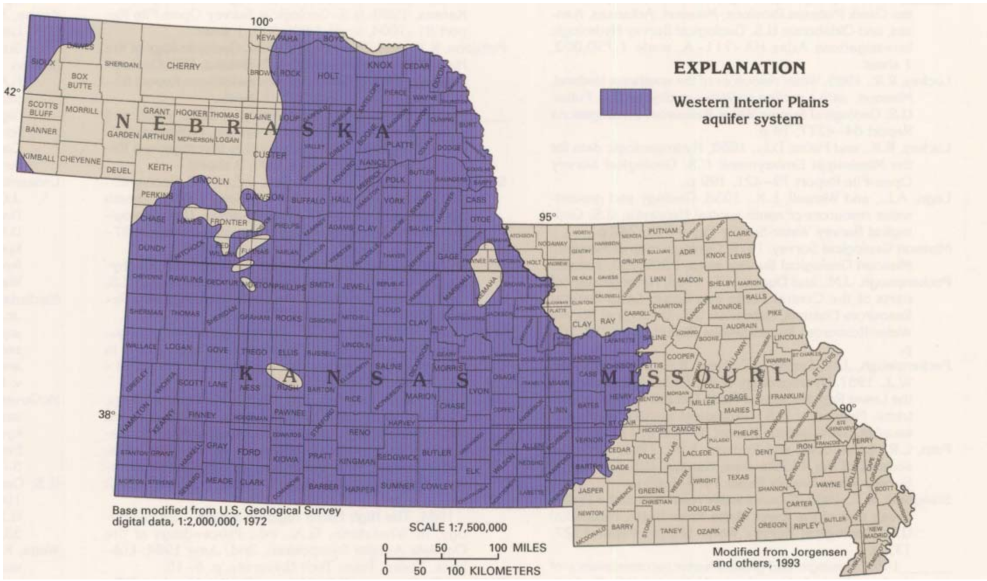


Figure 2-6. Western Interior Plains aquifer (Miller and Appel, 1997).

Figure 2-7 shows the potentiometric levels in the Western Interior Plains aquifer. The potentiometric gradient is found to be relatively low in northwestern Kansas with a somewhat undefined northerly or easterly flow direction and higher in southeastern Kansas with an easterly flow direction.

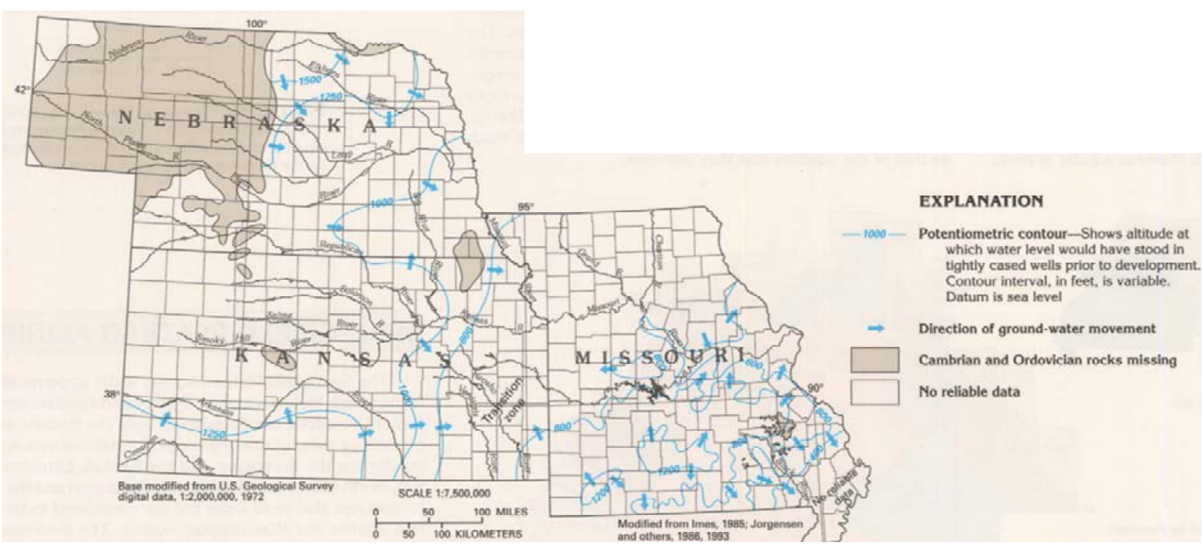


Figure 2-7. Potentiometric levels in the Western Interior Plains aquifer (Miller and Appel, 1997).

As discussed in Miller and Appel (1997), this aquifer has been compacted by deep burial that has reduced its porosity and permeability and the hydraulic gradient is low. Figure 2-8 shows that regional permeability in the lower section of the Western Interior Plains aquifer is low (~ 1 millidarcy) on the western and southern sides of the state, rising to the Darcy level on the eastern and north-central portions of the state. Little or no fluid leakage occurs across the thick (approximately 600 m, see Figure 2-4) Western Interior Plains confining system. As a result, movement of water is very slow.

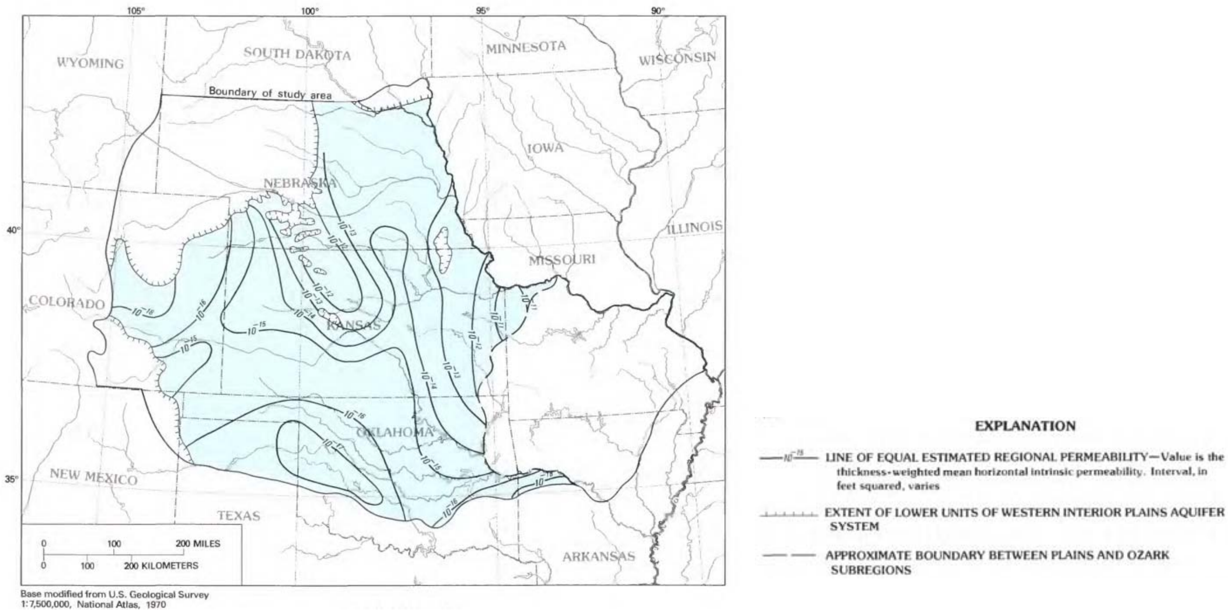


Figure 2-8. Regional permeability of the Western Interior Plains aquifer (permeability in m^2) (Jorgensen et al, 1993).

Figure 2-9 shows salinity levels within the Western Interior Plains aquifer in Kansas. Salinity in the aquifer system is high in some areas, in excess of 100,000 mg/liter along most of the southern part of the state and in areas of the northwest.

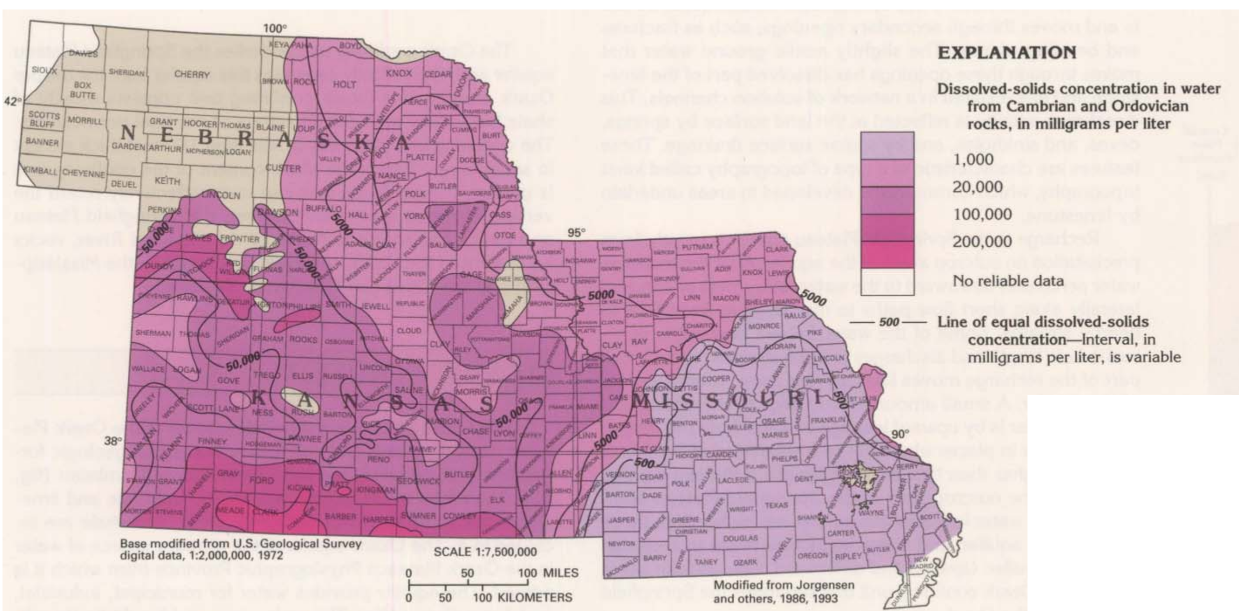


Figure 2-9. Salinity in the Western Interior Plains aquifer (Miller and Appel, 1997).

High salinity brines are believed to have originated in the geologic past and are a result of low recharge from low salinity percolation waters and long residence times (Jorgensen et al., 1993). Furthermore, high salinity brines will require higher potentiometric gradients to move upward as they are negatively buoyant relative to overlying waters of lower salinity (given thermal equilibrium).

The effects of abnormal pressure are also of interest for waste disposal. Abnormal pressures may be associated with transient or equilibrium flow conditions but generally require low permeability formations to be involved. A pressure compartment is the simplest configuration linked with abnormal pressures shown in Figure 2-10 (Bradley and Powley, 1994; Puckette and Al-Shaieb, 2003).

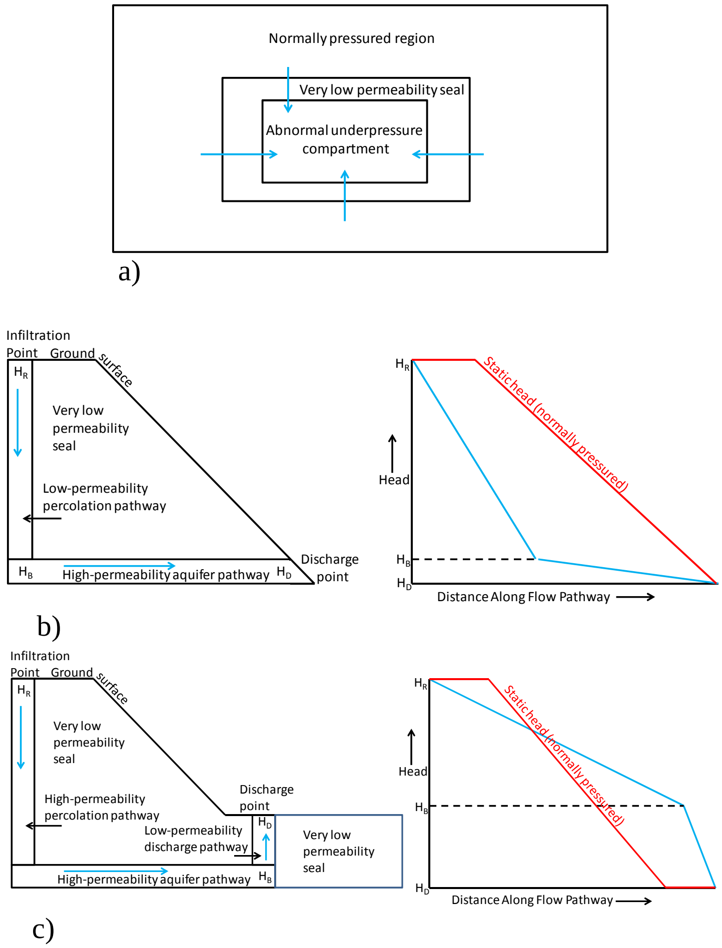


Figure 2-10. Abnormal pressure systems (blue arrows indicate flow direction). a) self-isolating flow system for an underpressure compartment; b) open circuit equilibrium flow system with abnormal underpressure and plot of flow potential along the flow pathway (modified from Belitz and Bredehoeft, 1988); c) open circuit equilibrium flow system with abnormal underpressure/overpressure and plot of flow potential along the flow pathway.

In this case the abnormal pressure zone is surrounded by low permeability seals and pressure equilibration only occurs as a transient flow process. Depending on the specific situation, the transient pressure equilibration process could require extremely long periods of time, even millions of years (Muggeridge et al., 2005). Pressure compartments can have abnormal overpressure or underpressure. However, abnormal pressure may also occur as part of an equilibrium flow process in which the abnormal pressure is not isolated from the surrounding formations (Belitz and Bredehoeft, 1986; 1988). Examples where abnormal pressure is part of an equilibrium flow process are shown in Figure 2-10, along with an abnormal underpressure compartment flow processes.

The important difference between the transient and equilibrium flow processes is that the transient process for underpressure is entirely inward (or self-isolating flow process) towards the low pressure compartment but the equilibrium underpressure involves a flow path through the low pressure that includes a component of flow directed away from the low pressure zone (or open circuit flow process). Abnormal overpressure is always associated with a pressure compartment, such a condition may be unfavorable because it leads to lower (or even tensile) effective stress conditions that may contribute to future fracturing and generally favors flow directed outwards. An underpressure compartment tends to be a more favorable condition because the rock is under greater effective (compressive) stress and any flow is directed inward.

For the Western Interior Plains aquifer, Nelson and Gianoutsos (2014) have mapped the difference between the potentiometric surface for the aquifer (which is called the Hunton by Nelson and Gianoutsos (2014), a stratigraphic unit used that corresponds to the lower member of the Western Interior Plains aquifer) and the ground surface as shown in Figure 2-11.

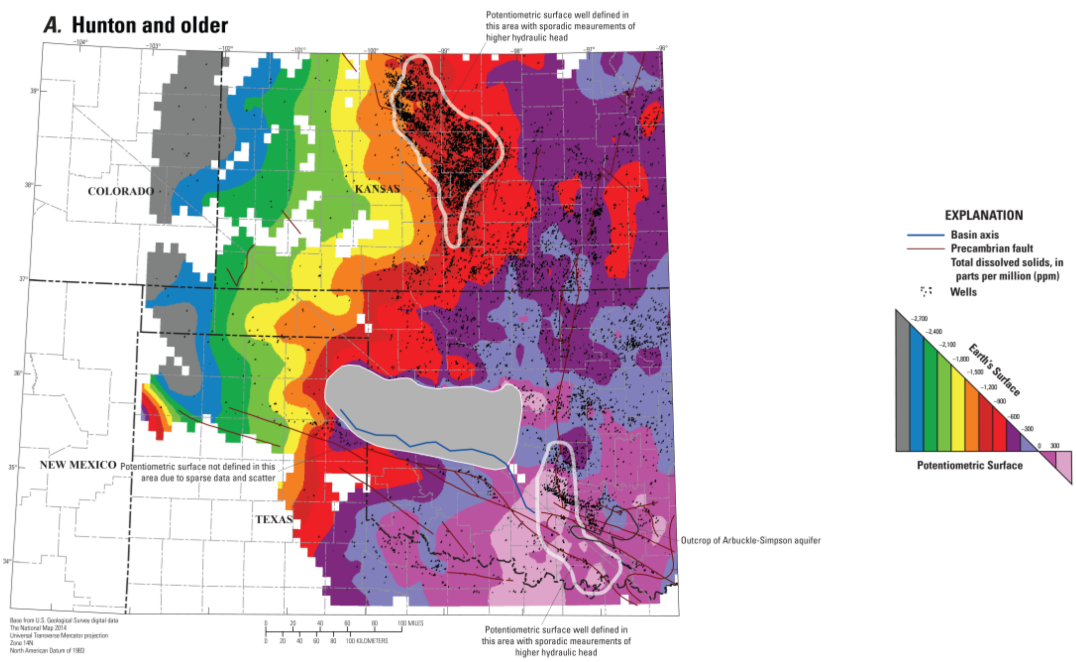


Figure 2-11. Potentiometric difference between the Western Interior Plains aquifer (lower unit) and the ground surface (Nelson and Gianoutsos, 2014).

Negative values indicate underpressure relative to hydrostatic conditions. Significant underpressure is found in the western part of Kansas, Oklahoma, and the Texas panhandle.

2.2 Hydrogeology of Deep Crystalline Rock

Although there is some regional information about sedimentary aquifers as just described, relatively little information is available about the hydrogeology of deep crystalline rock. In the case of the Western Interior Plains aquifer, the crystalline basement rock underlying this aquifer is described as “poorly permeable” and a “confining unit”. Although knowledge of crystalline rock hydrogeology is relatively poor compared to sedimentary systems, some information is available.

Several studies have been published documenting average crystalline rock permeability as a function of depth. Manning and Ingebritsen (1999) developed the following relationship for average crystalline rock permeability in active tectonic zones:

$$\log k = -14 - 3.2 \log z \quad (1)$$

where k is the permeability in m^2 and z is the depth in km. This predicts a permeability of about 3×10^{-16} m^2 at 3 km and 6×10^{-17} m^2 at 5 km. A similar relationship was developed by Stober and Bucher (2007b) using data from the Black Forest region of Germany,

$$\log k = -15.4 - 1.38 \log z \quad (2)$$

This predicts a permeability of about 9×10^{-17} m^2 at 3 km and 4×10^{-17} m^2 at 5 km. Both of these relationships are shown against data in Figure 2-12.

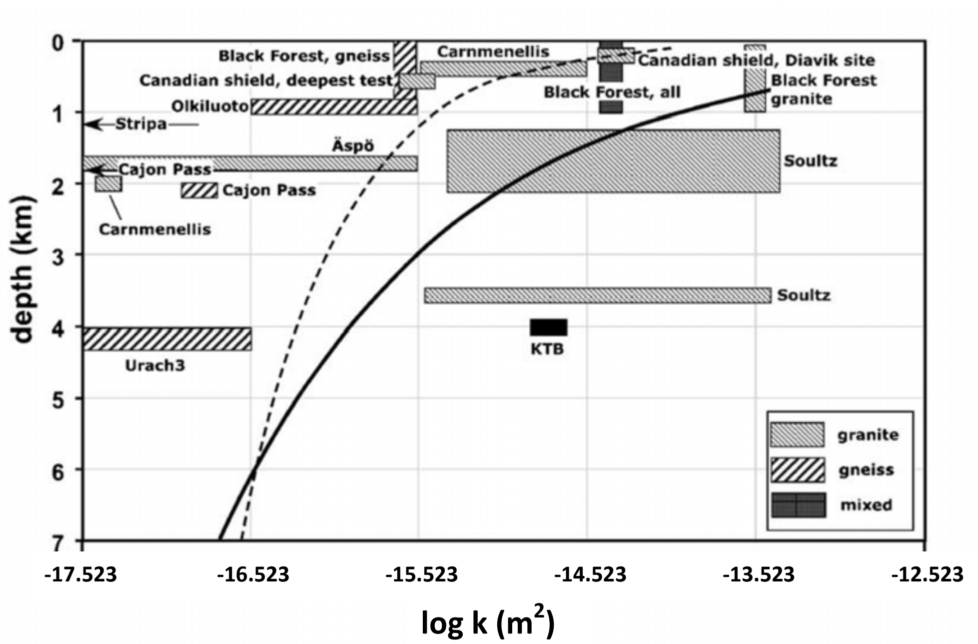


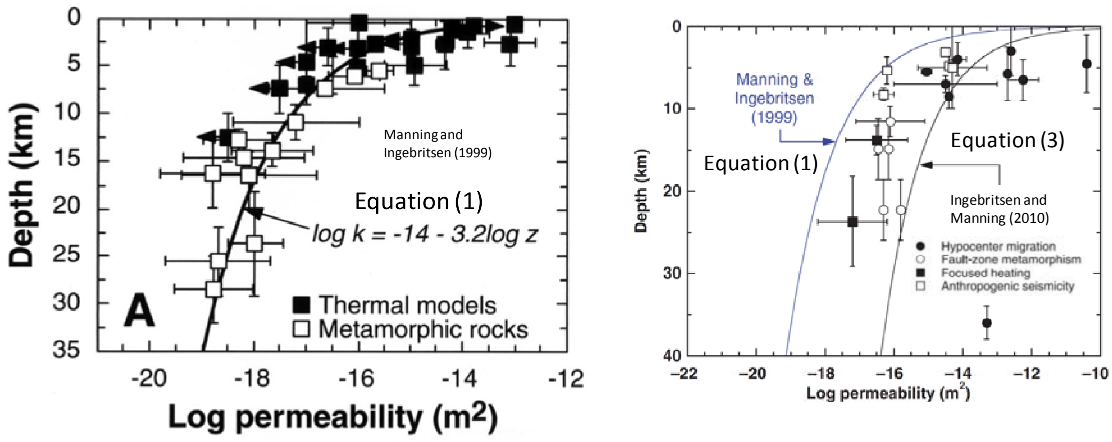
Figure 2-12. Permeability versus depth in crystalline rock (modified from Stober and Bucher, 2007a).

As noted earlier, these values are for tectonically active regions. A lower limit for permeability suggested by Ingebritsen and Manning (2010) is where the Sherwood number is approximately 2 (where diffusive and advective mass transport are of the same magnitude). Lower permeabilities would result in diffusive-dominated chemical transport, which is not supported by geochemical observations (Ingebritsen and Manning, 2010; Mazurek, 2010). For the upper 10 km, Ingebritsen and Manning (2010) determined that a permeability of about 10^{-16} m^2 corresponds to a Nusselt number of 2 (where heat conduction and advection are of the same magnitude). Therefore, a lower limit for permeability in the upper 10 km is likely to be ~ 10^{-20} m^2 given thermal diffusivity in rock is about 4 orders of magnitude larger than mass diffusivity.

Ingebritsen and Manning (2010) also found evidence for "dynamic" permeability changes over time in tectonically active areas. This involves the creation and healing of fractures in crystalline rock. The upper limit of permeability varying over time is also a function of depth given by

$$\log k = -11.5 - 3.2 \log z \quad (3)$$

or exactly 2.5 orders of magnitude higher than the long-term average permeability by Equation (1). The resulting curves are shown in Figure 2-13.



a) b)

Figure 2-13. Depth permeability relationships. a) Permeabilities based on broad geothermal-metamorphic data (Equation (1)) (Manning and Ingebritsen, 1999); b) Comparison of Equations (1) and (3), where Equation (3) reflects localized transient high permeability values based on data for the following situations: 1. seismic hypocenter migration, 2. fault zone metamorphism, 3. locations with temporally focused heating, and 4. anthropogenically enhanced permeability caused by fluid injection. (Ingebritsen and Manning, 2010).

High values of permeability indicated by Equation (3) are limited to short time periods generally less than 100 years (Ingebritsen and Manning, 2010). This rapid decrease is caused by mineral precipitation, hydrothermal alteration, and compaction.

Flow rates in crystalline rock are also affected by driving forces for flow. Deep vertical circulation is possible, however, this flow pattern generally requires steeply dipping structures (usually faults) with high vertical permeability and strong topographic relief (Stober and Bucher, 2015; Moeck, 2014). Temperature profiles have shown water circulation to depths of 3700 m, 2300 m into the crystalline basement, at the GPK-2 well near Strasbourg, France. Water temperatures indicate advective heat transfer by upwelling hot deep water.

Tidal forces caused by gravitational interactions between the Earth, sun, and moon generate stress changes in the earth on a 12-hour cycle. These stress changes induce changes in porosity and drive oscillatory flow in groundwater including deep crystalline rock. Tidal forces induce water table oscillations as large as 20 cm per day in the fractured crystalline rock at the Urach 3 deep drilling site in southwest Germany (Stober and Bucher, 2015). These oscillatory flows do not drive long-distance advection but do enhance dispersive transport and mixing processes and influence reaction kinetics, fluid composition, and rates of permeability alteration.

3. Crystalline basement rocks – what does this mean?

The proposed host rock type for deep borehole nuclear waste disposal is crystalline basement. One critical aspect of the upcoming request for proposal for the deep borehole site is to define what constitutes crystalline basement. In the 1986 DOE Crystalline Repository Project report, the following definition was provided:

"Crystalline rocks" are defined as intrusive igneous (e.g., granite) and high-grade metamorphic rocks rich in silicate minerals, with a grain size sufficiently coarse that individual minerals can be distinguished with the unaided eye.

This 1986 DOE report outlined the screening process that was used to identify 20 preliminary candidate sites form an initial 235 crystalline rock bodies, and to downselect these areas to 12 potentially acceptable sites. The initial suite of candidate sites had basement rocks that consisted of either intrusive bodies (ranging in composition from gabbros to granites) and high-grade metamorphic rocks (gneisses, but with some amphibolite and quartzite units). Some of the screening factors that were used to select the final candidate sites included the host rock geometry (size, shape, thickness, and subsurface lateral extent of the host rock, and the thickness of overburden), extent of exposure (the larger exposure the better), the degree of homogeneity of the rock unit (higher degree of homogeneity was deemed to be better), the lack of major structures cutting the rock, as well as the overall deformational history of the rock body (less deformation is better). Based on the screening process, all of the 12 final locations were in granitic host rocks.

Arnold et al. (2013) came up with a similar definition for crystalline basement:

The preferred host rock for deep borehole disposal is crystalline basement rock, which is a generic term that includes a diversity of rocks of igneous and metamorphic origin. Crystalline basement generally refers to the older, often Precambrian - age, rocks that underlie the sedimentary cover in stable continental interior regions and sedimentary basins. The term crystalline basement may also apply to geologically younger igneous and metamorphic rocks in more recent tectonically active terranes, such as the Mesozoic – age plutonic rocks exposed in the Sierra Nevada and similar rocks underlying the Central Valley in California.

The data sources for identifying the distribution of basement rock types and the depth to basement is varied. A national depth to basement map was generated through a joint effort of the AAPG and USGS (Flawn, 1968). This map has been reproduced by Blackwell et al. (2007) (Figure 3-1) as part of their Enhanced Geothermal System resource base assessment of the U.S.

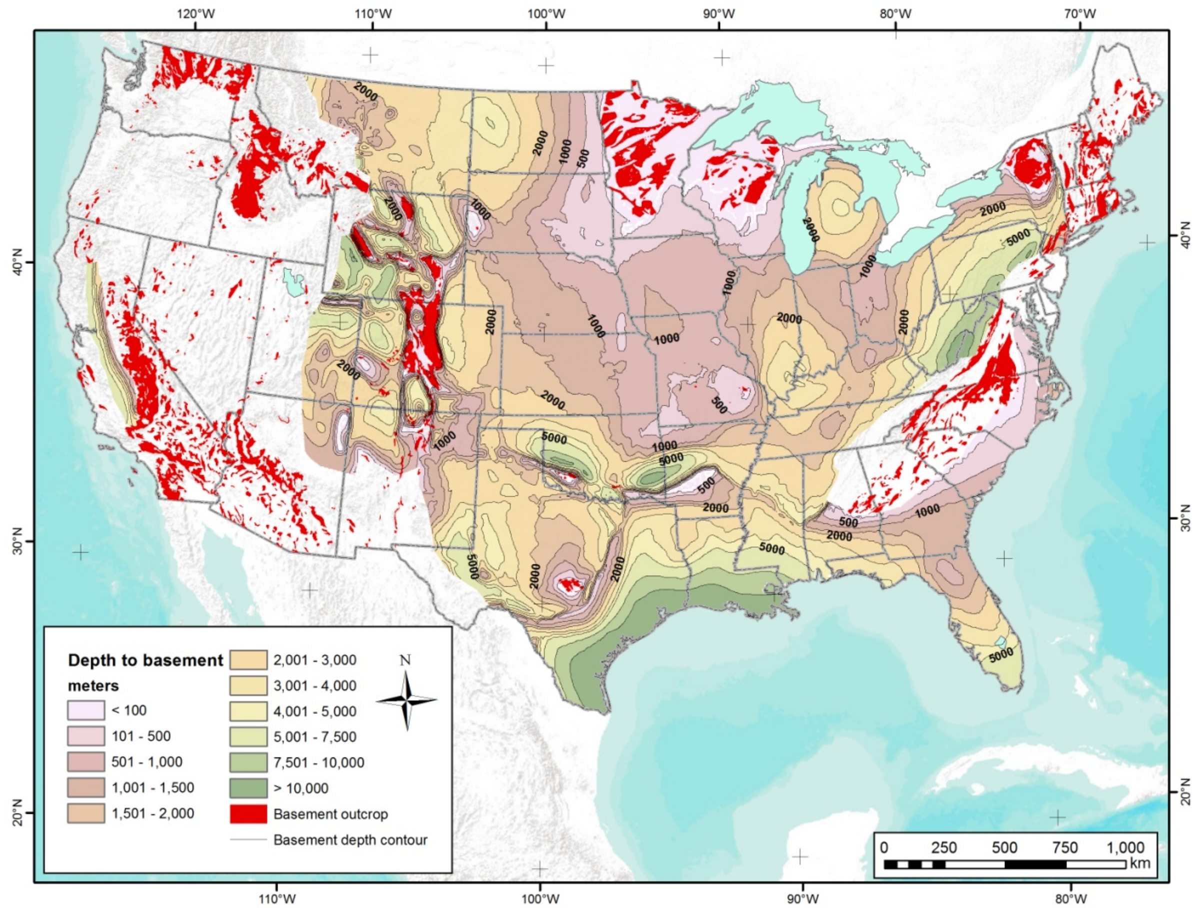


Figure 3-1. Depth to basement map, derived from data given in Blackwell et al. (2007) (crystalline outcrop shown in red from Garrity and Soller, 2009).

Regional aeromagnetic studies are commonly used to map basement rock terrains, as shown in Figure 3-2 (Sims et al., 2008). The magnetic signature reflects the abundance of magnetic minerals in rocks, which depends on the lithology and its history. Rocks with higher abundances of magnetic minerals (such as magnetite and ulvospinel) have a higher signal – metamorphism and alteration can lead to demagnetization. Sharp magnetic boundaries occur when rocks with different levels of magnetization are juxtaposed – such features can be used to identify different crustal provinces and major structures that cut them.

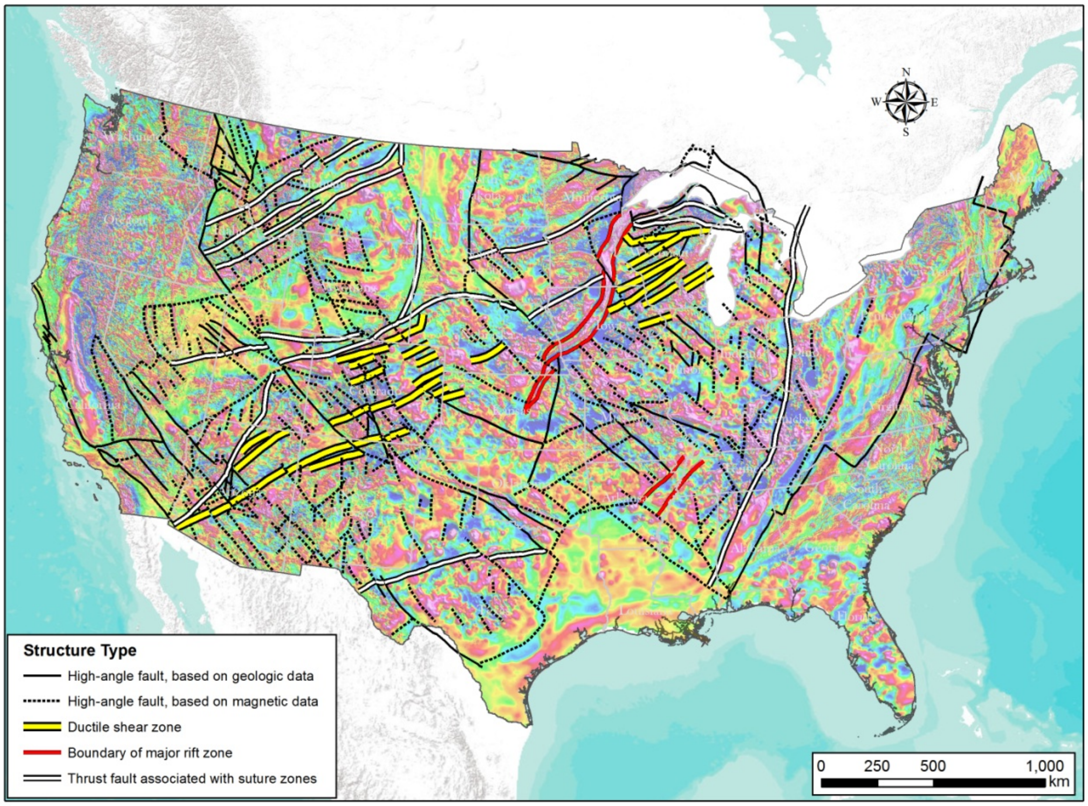


Figure 3-2. Precambrian basement structure map of the continental United States (derived from data given in Sims et al., 2008).

Reconstructions of the basement geology of the U.S. (Figure 3-3) have identified distinct geologic crustal provinces (Williams et al., 1991). These provinces range in age from the Archean (such as the Superior and Wyoming provinces), to the Proterozoic (e.g., Trans Hudson), to the Mesozoic Sierra Nevada batholith complex of California in the Cordilleran province of the western North American continental margin.

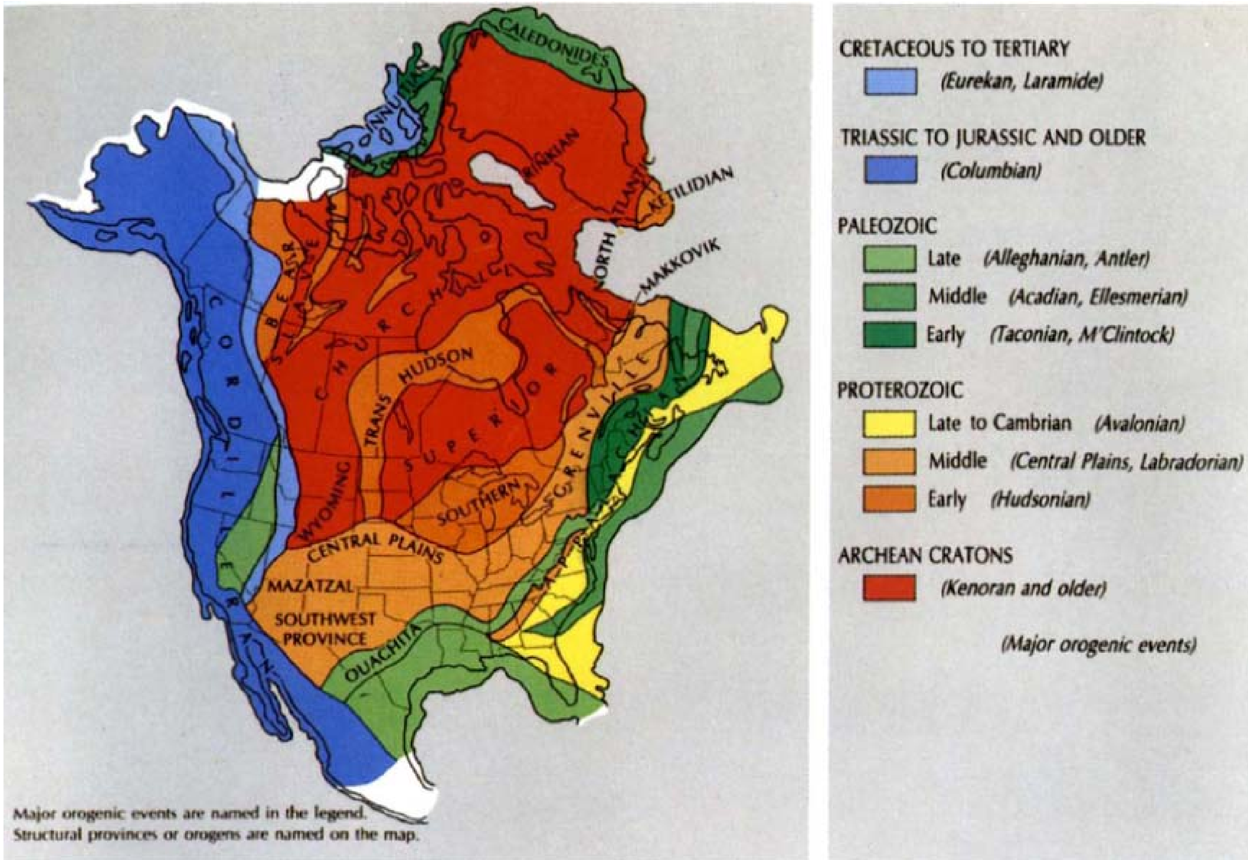


Figure 3-3. Map of structural provinces and the ages of their corresponding first major deformational events for North America. For orogenic belts, the time of the deformation corresponds roughly to the age of the rocks (Williams et al., 1991).

The complexity of the basement geology depends in part on the lithologic variability of the province and its integrated geologic history. Orogenic belts formed along ancient and current continental margins typically have more significant deformational histories, which are often reflected in the presence of major structures. Figure 3-4 depicts the distribution of ancient continental margins (miogeoclines) and accretionary terranes in North America (Williams et al., 1991).

While the stable craton of North America provides a tectonically quiescent location, the basement rocks contained within this region are varied in composition. For example, the Precambrian basement geology of Minnesota and Wisconsin consists of a wide variety of rock types, such as granitic plutons and high grade metamorphic rocks, extensive gabbroic intrusions, and banded iron formations (DOE, 1986). Some of the metasedimentary rocks (such as the schists associated with the banded iron formations) have pronounced rock fabrics which may be deemed to be unsuitable for deep borehole disposal (Arnold et al., 2013). Thus, it is important to note that there is significant variability in basement rock lithologies, and these variations may prove to be important.

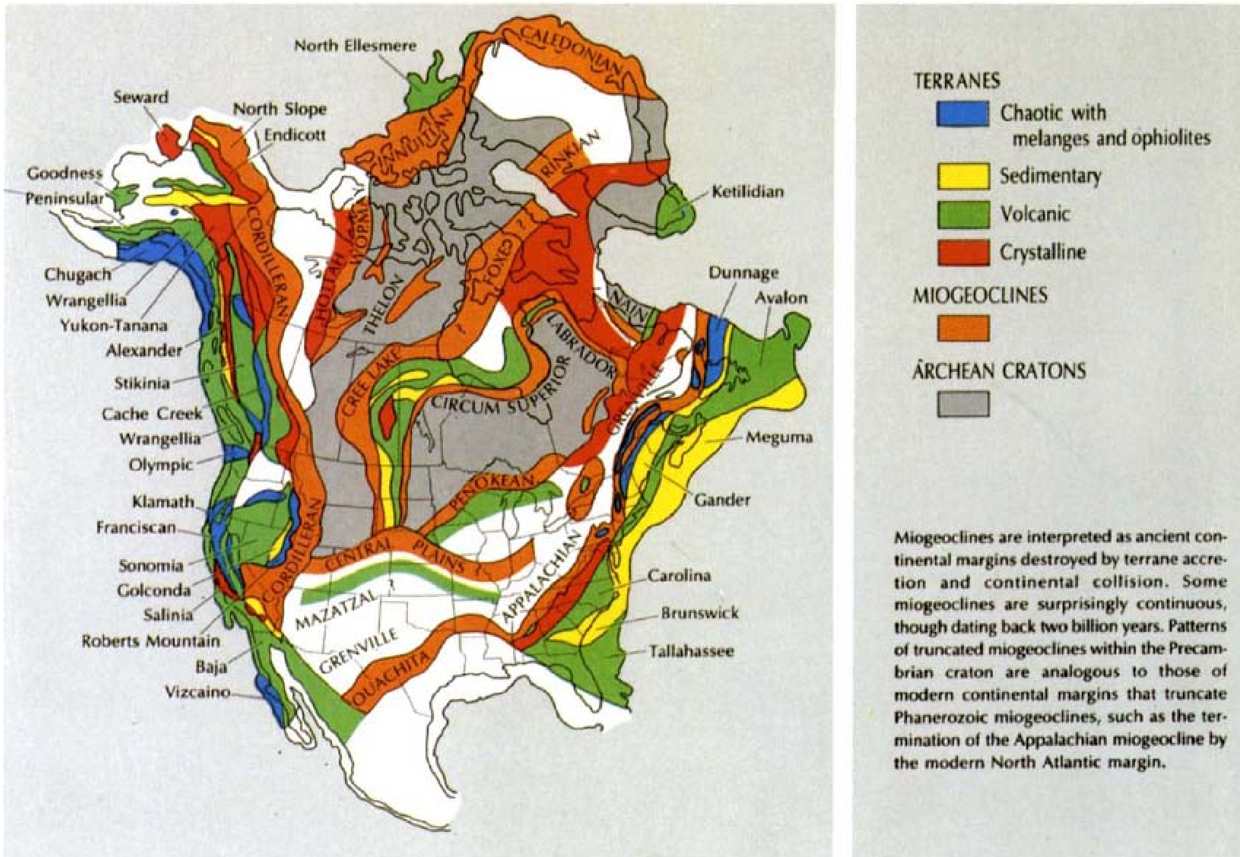


Figure 3-4. Ancient continental margins (Miogeoclines) and accretionary terranes, indicating the variations in host rock type (melanges and ophiolites, sedimentary, volcanic, and crystalline rocks). Note the large number of accretionary terranes along the western continental margin (Williams et al., 1991).

4. Summary

The hydrogeology of sedimentary basins in the U.S. is well documented in comparison to the hydrogeology of deep crystalline rock. Hydrogeologic processes in groundwater both in the sedimentary systems and in the underlying crystalline basement are influenced mainly by permeability and driving forces for fluid flow. The following factors are potentially favorable for low fluid flow conditions in both sedimentary and crystalline rock:

1. Low permeability
2. High groundwater salinity
3. Underpressured compartment (nonequilibrium) systems
4. Absence of major cross-formational features (e.g., faults)
5. Minimal topographic relief
6. Low seismic activity
7. Low thermal gradients

In the absence of hydrogeological characterization data, which is likely to be the case for crystalline basement rock, the evaluation of the hydrogeological character may be limited to aspects of the listed favorable characteristics available from regional geologic and geothermal characteristics (i.e., items 4 through 7).

There are a variety of rock types that fall under the general classification of “crystalline basement”. These include more common basement rocks such as granites and gneisses, but also other types such as schists. It is important to note that there is significant variability in basement rock lithologies, and these variations may prove to be important for the purposes of deep borehole disposal.

Acknowledgements

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