A GIS Database to Support the Application of Technical Siting Guidelines to a Deep Borehole Field Test

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Used Fuel Disposition Campaign

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USED FUEL DISPOSITION CAMPAIGN

A GIS DATABASE TO SUPPORT THE APPLICATION OF TECHNICAL SITING GUIDELINES TO A DEEP BOREHOLE FIELD TEST

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ACRONYMS

AAPG	American Association of Petroleum Geologists
AEC	Atomic Energy Commission
DEM	Digital Elevation Model
DOE	Department of Energy
FY	Fiscal Year
GIS	Geographic Information System
HLW	High-Level Waste
km	kilometers
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
m	meters
NOAA	National Oceanic and Atmospheric Administration
R&D	Research and Development
RFP	Request for Proposals
SMU	Southern Methodist University
UFDC	Used Fuel Disposition Campaign
US	United States
USGS	United States Geological Survey
WGS	World Geodetic System

USED FUEL DISPOSITION CAMPAIGN

A GIS DATABASE TO SUPPORT THE APPLICATION OF TECHNICAL SITING GUIDELINES TO A DEEP BOREHOLE FIELD TEST INTRODUCTION

1. Introduction

The Regional Geology GIS database (Perry et al. 2014a; 2014b) is being extended to support siting of a Deep Borehole (DBH) field test. This report provides a brief background on the Regional Geology GIS database and the methods used to prepare data for inclusion in the database (Section 2), an overview of data for siting guidelines compiled at the national scale (Section 3), and a comparison of depth to basement data at the national and state or basin scales (Section 4). Maps for siting guidelines at the national scale are useful for understanding the regional geologic context of potential DBH sites and for discerning fundamental differences between regions of the US, but require caution if applied for siting decisions at the local scale. All data for siting guidelines, whether compiled at the national scale or a larger, more detailed scale, will have to be evaluated to determine their suitability for use in making specific siting decisions. Some areas will have only have data available that were compiled at the national scale, while others will have data compiled at both the national and more local scales. It cannot be assumed in all cases that one type of data set is necessarily “correct” in terms of accuracy compared to the other. Where data is only available at the national scale, it will be important to understand the use and limitations of these data as they pertain to local siting decisions. In this report we focus on data for depth to crystalline basement as a critical siting guideline. We compare compilations of data for depth to crystalline basement at the national versus state or basin scales to understand how and why they may differ and the implications for using these data for DBH siting.

2. The Regional Geology GIS Database

The Used Fuel Disposition Campaign (UFDC) identified the need to build a regional geology database to support the site screening and site evaluation decision points identified in the Used Fuel Disposition Campaign Disposal Research and Development Roadmap (Nutt, 2011). The UFDC is considering three alternative geologic host rocks for mined repositories (granitic, salt and clay-bearing rock) and crystalline (granitic) basement rock for deep borehole disposal (Nutt, 2011). This report focuses on applying a geographic information system (GIS) database to siting of a DBH Field Test. The methods and data described in this report are also applicable to siting of a DBH disposal system should one be implemented in the future. A complete description of the Regional Geology GIS Database is presented by Perry et al. (2014a; 2014b). The methods used to incorporate data into the GIS database are described again briefly in this report with emphasis on methods related to siting in crystalline basement, based in information in Perry et al. (2014a and 2014b).

A GIS allows visualization and quantitative analysis of data layers and how the features represented by the data layers are spatially related to each other. Data layers can represent any information of interest as they pertain to siting and site characterization, including different types of geologic rock, geologic features and tectonic hazards, as well as cultural features and natural resources. Data utilized in a GIS may already exist in a digital form that can be readily imported into the GIS, or be in an “analog” format such as printed maps or figures that document information from previous geologic or HLW disposal studies. These types of data can be digitized and rectified into the appropriate geographic coordinate systems for incorporation into GIS.

2.1 Database description

GIS datasets for siting guidelines are being constructed using ArcGIS Desktop Version 10. The file geodatabase within ArcGIS uses an efficient data structure that is optimized for performance and storage. This system allows easy importation of spatial and tabular data from many different native formats and allows for easy extraction of data into many formats for future customer use. File geodatabases have no storage size limit. Individual datasets within a file geodatabase, such as a feature class or table, have a size limit of 1 terabyte, allowing for nearly unlimited attribution of data. In addition, both raster and vector data can be stored in the geodatabase. Some of the data obtained to date is already in a digital format that can be loaded into the file geodatabase. These formats included ArcGIS coverages and shapefiles, Microsoft Excel tables, DBF files, and delimited text files. If digital data is not available, paper media or published figures are processed by means of digitizing as described by Perry et al. (2014a).

2.2 Data Preparation and Calculation of Depth to Basement

The only borehole-based data that is publically available in digital format to depict depth to crystalline basement at the national scale was compiled as described by Blackwell et al. (2007) as a sediment thickness map. The sediment thickness map was created at the SMU Geothermal Laboratory by digitizing the AAPG (1978) structure (elevation) map of the basement of North America. The map was converted to a sediment thickness map by subtracting basement elevation values from a digital elevation map of the US. The digitized version of the AAPG (1978) basement map is the only digital representation of this map that we know exists. The digital data for sediment thickness was provided to LANL as a point grid (216,000 points) with a point spacing of 5 arc-minutes (approximately 10 km, depending on latitude). We interpolated these points in ArcGIS to produce a continuous raster surface with a grid resolution of 1.5 arc-minutes (approximately 3 km). We refer to this map of depth to basement as the “national” map throughout this report (Figure 3-1). A resolution of 1.5 are-minutes was used in order to create visually consistent maps when comparing maps at different scales and for ease and consistency of raster calculations when calculating depth differences using the GIS software (described below). Creating the depth surface (or “raster”, a matrix of cells in x,y space, with a z-value representing depth) allows us to mathematically manipulate the depth surface using GIS software and quantitatively compare it to other basement surfaces created at different scales.

Maps representing the structural relief of the crystalline basement are typically published as a structural contour map with the contours representing elevation of the basement surface in feet relative to sea level. These data have been compiled at the state scale or basin scale to support the oil and gas industry or for other uses of the subsurface. For structural contour maps, we typically converted the structural contours to a continuous raster surface representing the basement surface by using the ArcGIS “topo to raster” tool. The resulting raster surface is then converted from feet to meters as needed using raster math. The elevation surface is then subtracted from a DEM of the earth’s surface to create a calculated depth raster that we present as basement depth maps at different scales in this report.

3. Overview of Data for Technical Siting Guidelines at the National Scale

The siting guidelines presented in this report are intended to support siting of a DBH Field Test based on Siting Guidelines presented in the DOE RFP expected in the spring of 2015. The guidelines discussed in this report and included in the GIS database are:

- *Depth to crystalline basement – Less than 2 km (1.2 miles) depth to crystalline basement.*

- *Lack of conditions associated with fresh ground water flow at depth – Geologic information and bases should include conditions/features and the technical bases for those identified, that provide evidence of the absence of recharge at depth. This could include (but is not limited to) for example lack of significant topographic relief that would drive deep recharge, evidence of ancient groundwater at depth, and/or data suggesting high-salinity groundwater at depth.*
- *Geothermal heat flux – Geologic information and bases should include evidence of the geothermal gradient and/or geothermal heat flux at the proposed site. A heat flux of less than 75* mW/m^2 *is preferred.*
- *Low seismic/tectonic activity:*
    - *Less than 2% probability within 50 years of peak ground acceleration greater than 0.16 g (generally indicative of area of tectonic stability).*
    - *Distance to Quaternary age volcanism or faulting greater than 10 km.*

Geologic information and bases should provide evidence of the aspects listed above, as well as any evidence that is available on (a) existence, and orientation of, any foliation in the crystalline basement rocks and (b) the horizontal stress state at depth in the crystalline basement rocks. Lack of steeply dipping foliation or layering is preferred. Low differential horizontal stress is preferred.

- *Crystalline basement structural simplicity (lack of known major regional structures, major crystalline basement shear zones, or major tectonic features) – Geologic information and bases should include identification of major regional structures, basement shear zones, or other tectonic features within 50 km of the proposed site.*
- *Low potential for interference with testing from other surface and subsurface usage – Information and bases provided for the proposed site should identify any previous or current uses of the surface and/or subsurface that could interfere with the test investigations. Such activities include but are not limited to wastewater disposal by deep well injection, CO2 injection, oil and gas production, mining, underground drinking water extraction, and strategic petroleum reserve sites. Absence of potential resources in the crystalline basement and sedimentary overburden is preferable. The information and bases provided for the proposed site should identify existing drinking water aquifers and any previous or current uses of the surface and/or subsurface (such as listed above) within 30 km of the proposed site as far back as available records indicate.*

The data sets pertinent to siting of a DBH Field Test and included in the GIS database are listed in Table 3-1. These data and the discussion and maps that follow were first presented in Perry et al. (2014a). The data, maps and discussion have been updated and supplemented with new data when available to focus on DBH siting. The heat flow dataset for the US presented in Section 3.1.8 was purchased from the SMU Geothermal Laboratory to support siting of the DBH Field Test.

Table 3-1. Data Relevant to Technical Siting Guidelines for a Deep Borehole Field Test

Technical Siting Guideline	**Source**
Depth to Crystalline Basement	Southern Methodist University Geothermal Laboratory, courtesy of Maria Richards
Distribution of Crystalline Rocks exposed at the Earth's surface	Garrity and Soller (2009)
Heat Flow	Blackwell et al. (2011)
Natural Resources (Oil and Natural Gas)	Biewick (2008)
Quaternary Faults; Class A Seismic Hazard Features in the Central and Eastern US	USGS (2006); Crone and Wheeler (2000); GIS data for central and eastern US from CEUS-SSC (2012)
Seismic Ground Motion Hazard	Petersen et al. (2014)
Quaternary Volcanism	Garrity and Soller (2009)
Topography and Smoothed Slope	NOAA (2006); Slope calculated at LANL
Aeromagnetic Data and Structure within Crystalline Basement	Sims et al. (2008)
Horizontal Stress	Heidbach et al. (2008)

3.1.1 **Depth to Crystalline Basement**

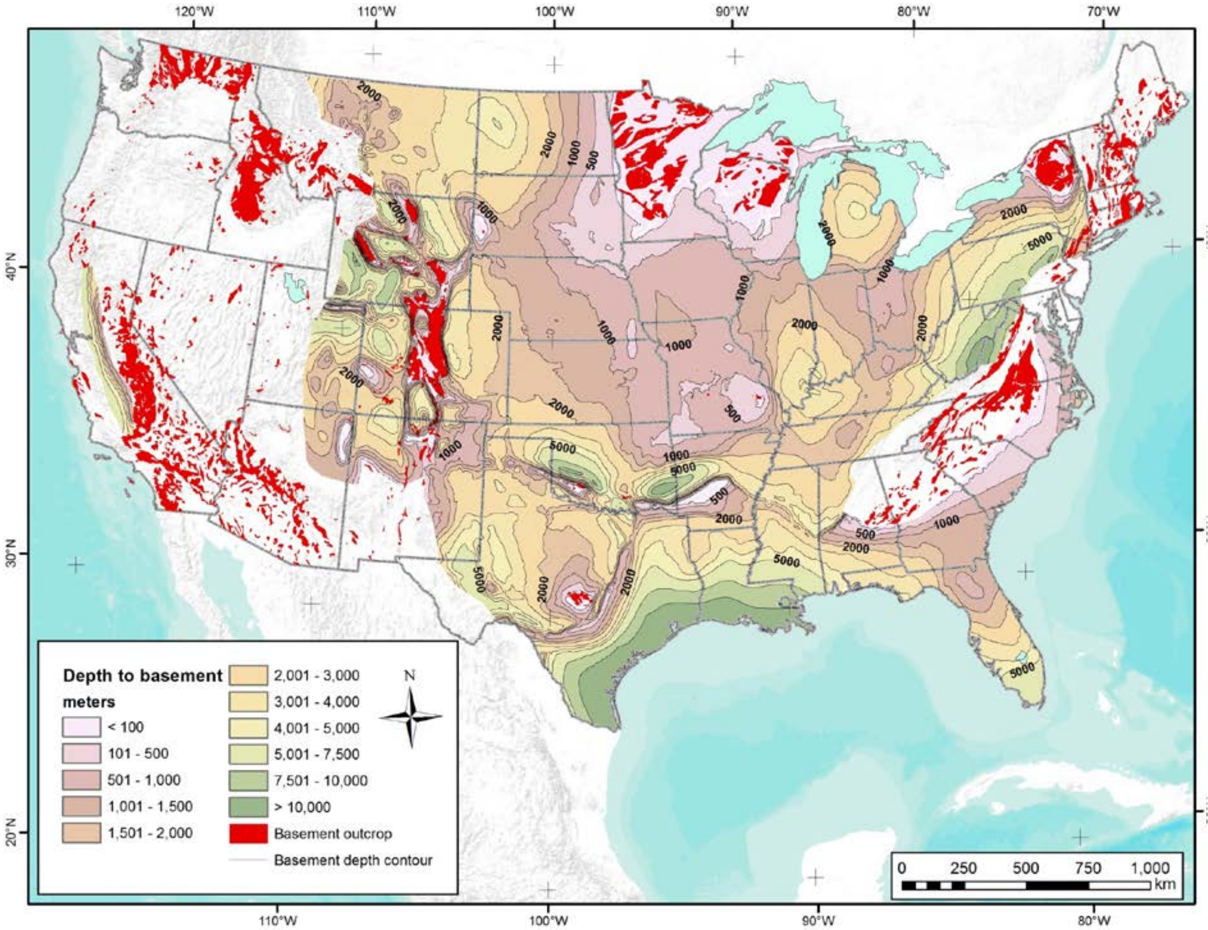

Figure 3-1. Depth to crystalline basement and distribution of crystalline outcrop (crystalline outcrop shown in red from Garrity and Soller, 2009).

Digital data for sediment thickness was obtained from the Southern Methodist University (SMU) Geothermal Laboratory (Blackwell et al., 2007). Sediment thickness is equivalent to depth to crystalline basement (Figure 3-1). The SMU data is the only dataset we are aware of that allows calculation of depth to basement on a national basis (with the major exception of much of the western US). It is therefore a primary dataset for consideration of siting options in crystalline basement.

Major features apparent on the map include a large region of the mid-continent with basement at depths of less than 2km. Broadly surrounding this region is a belt of deformation that includes deep sedimentary basins and uplifts related to the Appalachian-Ouachita Orogeny and the much younger Laramide Orogeny to the west. The western US and parts of the eastern US are not represented because of lack of data or structural complexity that could not be represented at the national scale (Blackwell et al., 2007).

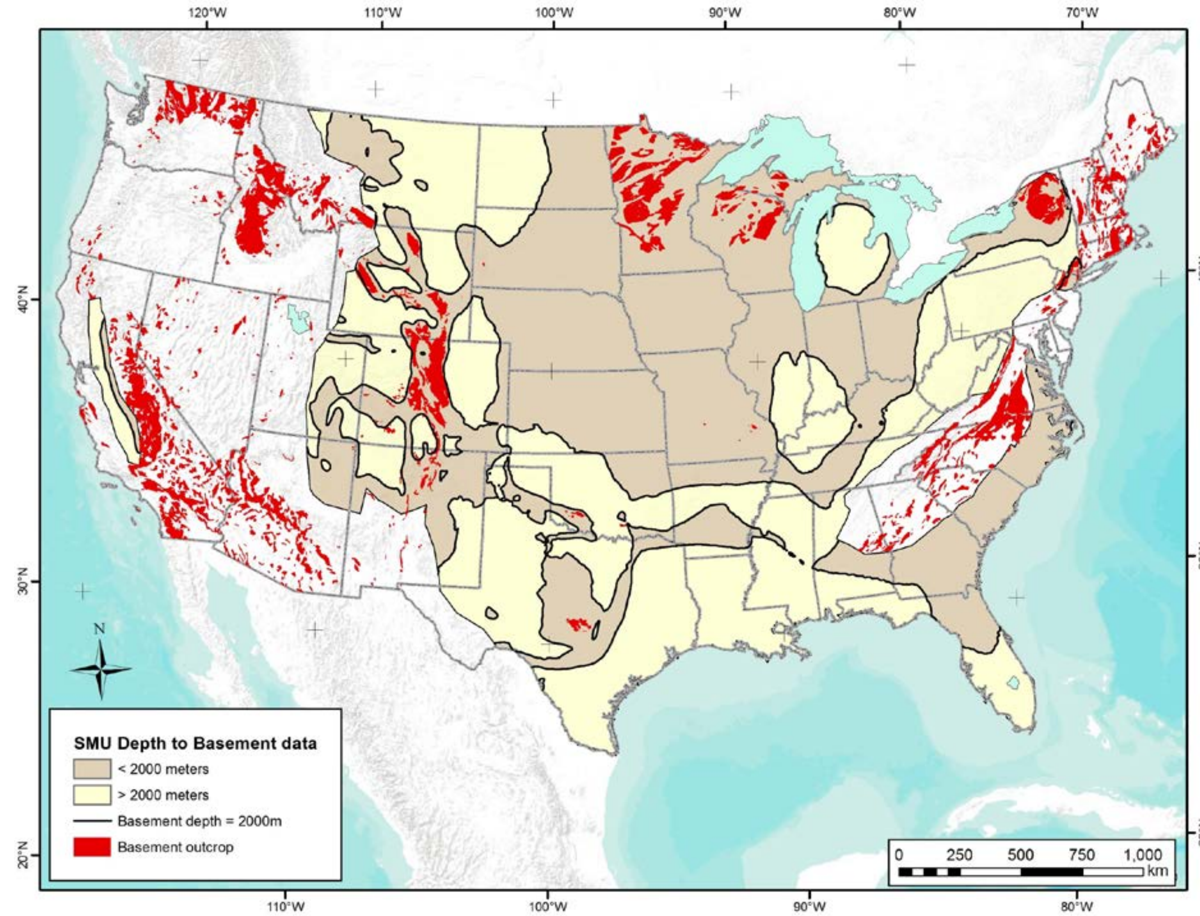

Figure 3-2. Distribution of crystalline basement at a depth of less than 2 km (tan shading) and granitic outcrop (red) in the contiguous US. Areas of yellow shading show the extent of the national (SMU) data and also indicates areas (primarily sedimentary basins) with basement depth of > 2 km.

The GIS data shown in Figure 3-1 can be queried to show only areas of the US that have crystalline basement at a depth of 2 km or less, consistent with the siting guidelines published in the RFP (Figure 3-2). Most of the mid-continent region of the US has crystalline basement at a depth of < 2 km with the exception of major sedimentary basins. Although not represented in the data, most of the New England region probably has basement at shallow depth based on the widespread distribution of crystalline outcrop.

3.1.2 Structures within Crystalline Basement

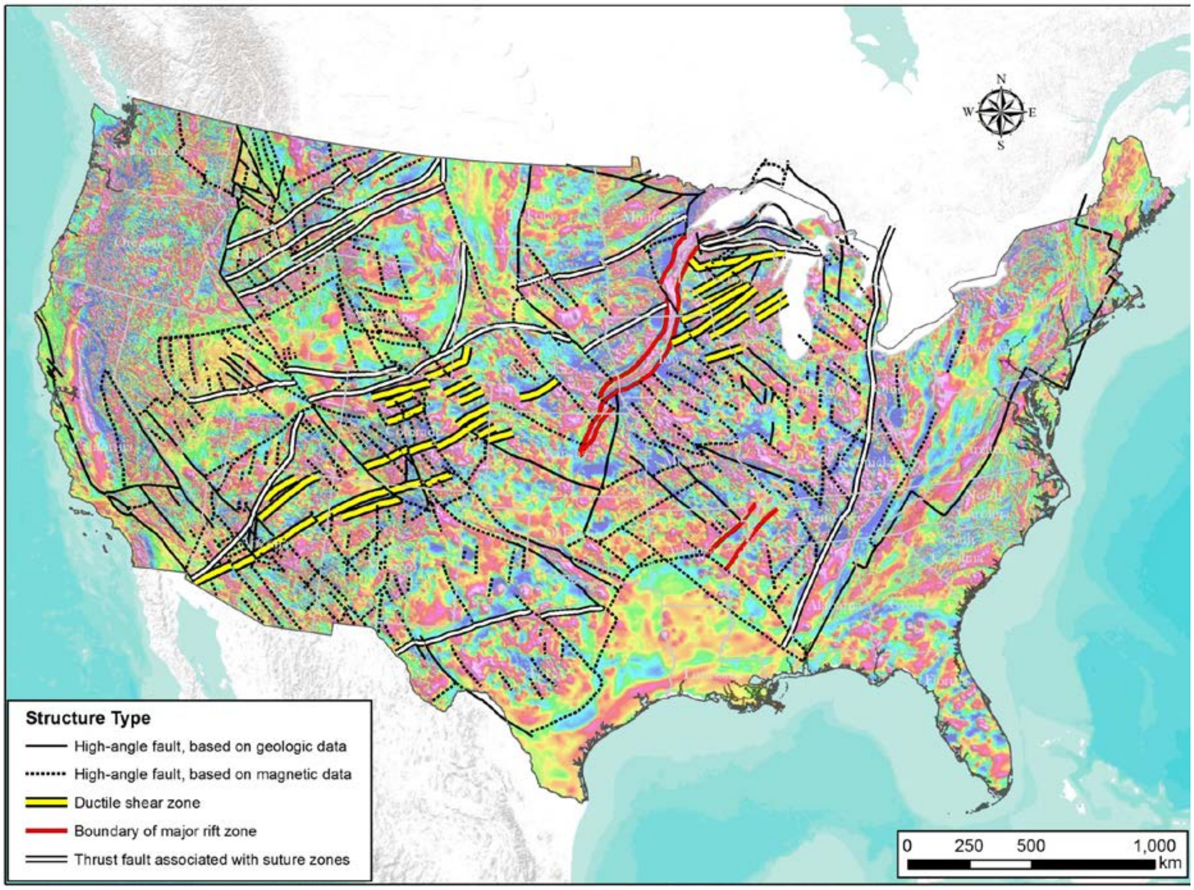

Figure 3-3. Aeromagnetic map and basement structure of the contiguous US from data presented in Sims et al. (2008).

Structures within crystalline basement rocks are interpreted primarily from geophysical data combined with generally less abundant geologic data that includes borehole data and interpretations of other geologic data such as basement age (Figure 3-3). Linear features and discontinuities in aeromagnetic data are generally interpreted to represent structures (faults, shear zones) that have offset and juxtaposed rocks with contrasting magnetic properties (Sims et al., 2008). These features largely formed during major tectonic episodes that took place during the Archean and Proterozoic Eons with episodic reactivation into the late Proterozoic (Sims et al., 2008).

The major impact to siting is that basement structures represent zones of geologic complexity or higher groundwater permeability. Basement structures present potential drilling problems as well as hydrologic conditions that could adversely affect waste isolation (Arnold et al., 2013).

3.1.3 **Horizontal Stress**

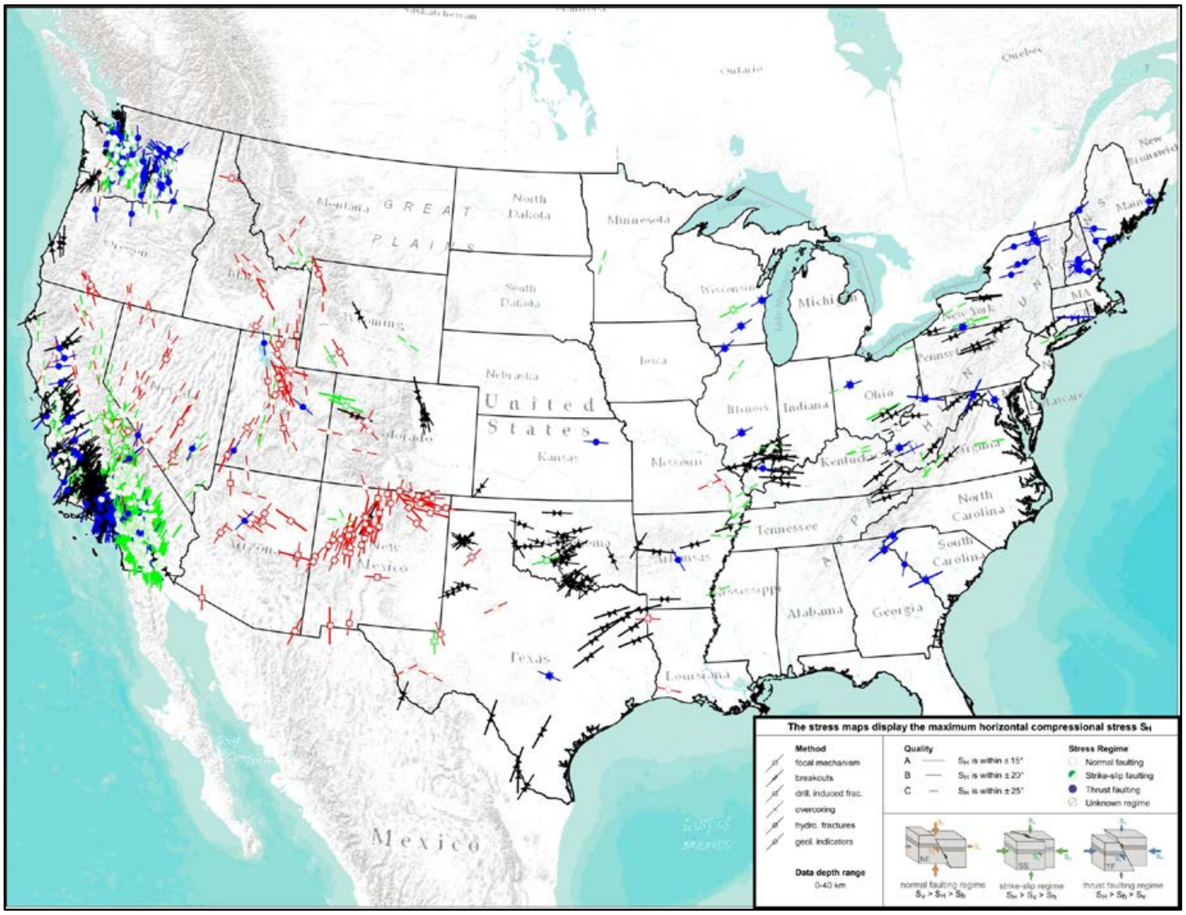

Figure 3-4. Map of maximum horizontal compressional stress in the contiguous US. Map legend is directly from Heidbach et al. (2009).

Data for horizontal stress in the US (Figure 3-4) was acquired from the World Stress Map Project (Heidbach et al., 2008). Technical siting guidelines related to horizontal stresses in the crust relative to deep borehole disposal are discussed in detail by Arnold et al. (2013). Large differential horizontal stresses can compromise borehole integrity through breakouts oriented in the direction of the minimum horizontal stress. Relatively homogeneous regions of the US with low differential stress, such as the mid-continent region, are therefore more favorable for a deep borehole disposal demonstration site (Arnold et al., 2013)

3.1.4 Natural Resources (Oil and Natural Gas)

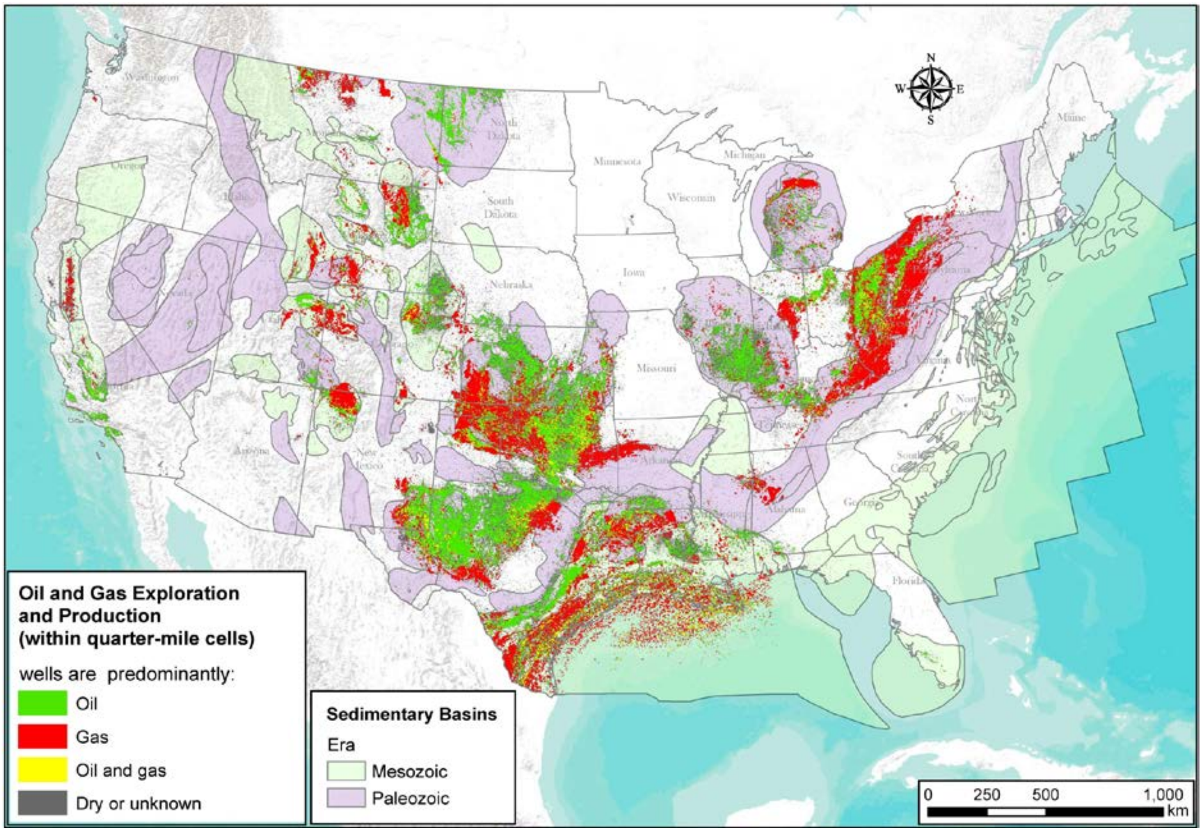

Figure 3-5. Distribution of oil and natural gas production in the contiguous US. Paleozoic and Mesozoic structural basins of the US are shown for reference (Coleman and Cahan, 2012mc). Cell sizes of oil and gas areas are exaggerated in figure to increase visibility.

Areas of oil and gas exploration production indicate areas of relative dense and deep drilling in the US (Figure 3-5). The map for the distribution of oil and gas exploration and production in the US represents over three million wells and is the most complete publically available database of wells available for the US (Biewick, 2008). Well location is represented by quarter-mile cells, where each cell has some number of wells that predominately produce oil, gas, oil and gas, or are dry or unknown (see map legend). Displaying the data in this way avoids the issue of using proprietary data from the oil and gas industry. Although substantial new drilling has occurred in the US since this data was finalized in 2005-2006, most new drilling represents “infilling” of areas of previous exploration and production versus drilling in new areas (for example, the Williston Basin of North Dakota). For this reason, the distribution of past drilling can be considered to approximate the distribution of future drilling.

Deep drilling is considered the most common mechanism of human intrusion of a mined geologic repository and could potentially impact the upper portion of a DBH system through horizontal drilling and hydraulic fracturing. Compared to other natural resources, oil and gas represent the most widely distributed natural resource within the US and therefore impact the largest areas of the US. However, as seen in Figure 3-5, exploration of oil and gas resources is focused in sedimentary basins where sediment thicknesses typically exceed 2000 meters (Figure 3-1). Based on the siting guidelines for depth to crystalline basement, these basins would not be considered for siting of a DBH Field Test. The impact of drilling for oil and gas should in general be minimal in areas of shallower crystalline basement.

3.1.5 Quaternary Faults and Quaternary Volcanism

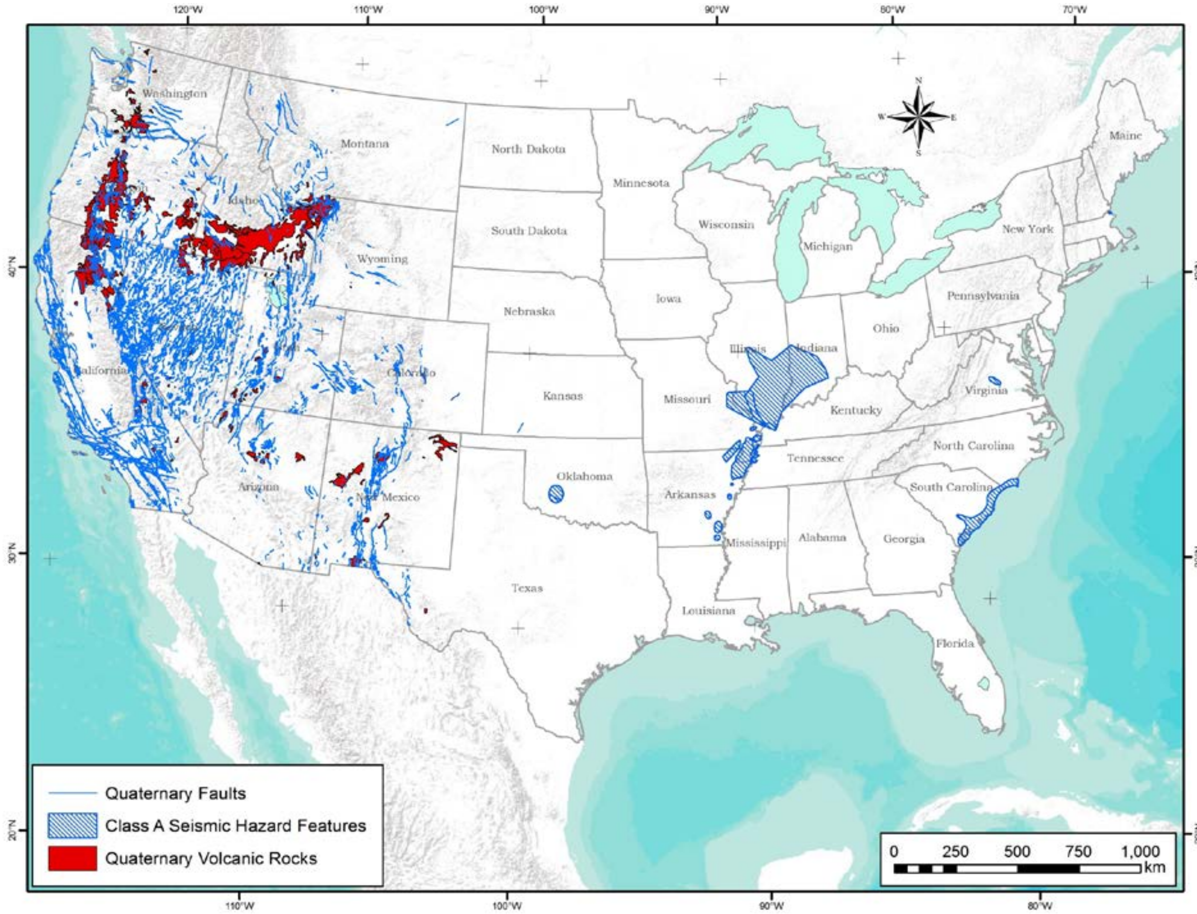

Figure 3-6. Distribution of Quaternary faults, Quaternary volcanic rocks and Class A seismic hazard features (in the central and eastern US). GIS data for Class A seismic hazard features are from CEUS_SSC (2012).

Active faulting and volcanism represent features and events that could potentially compromise the ability of a geologic repository to isolate waste. The major region of active faulting in the US occupies many of the western states while the most active areas of volcanism are the Cascade volcanoes of Washington and Oregon and the Snake River/Yellowstone system of Idaho and Wyoming. Scattered basaltic volcanoes of small volume have erupted during the last 10,000 years in Arizona, New Mexico, Utah, California, and Oregon.

Data for their distribution of faults and volcanoes in the US are important for identifying regions of active tectonics. The faults and seismic hazard features depicted in Figure 3-6 represent faults believed to have produced earthquakes of greater than magnitude 6 during the Quaternary Period (USGS, 2006). Combined with data for the distribution of Quaternary volcanism (Garrity and Soller, 2009), these data indicate regions that are likely to be tectonically active in the next few million years. Taken together, these regions include much of the western US, as well as the New Madrid and Charleston regions of the eastern US. The Class A seismic hazard features in the central and eastern US are areas where geologic evidence indicates the existence of Quaternary faults capable of producing significant earthquakes.

3.1.6 **Seismic Ground Motion Hazard**

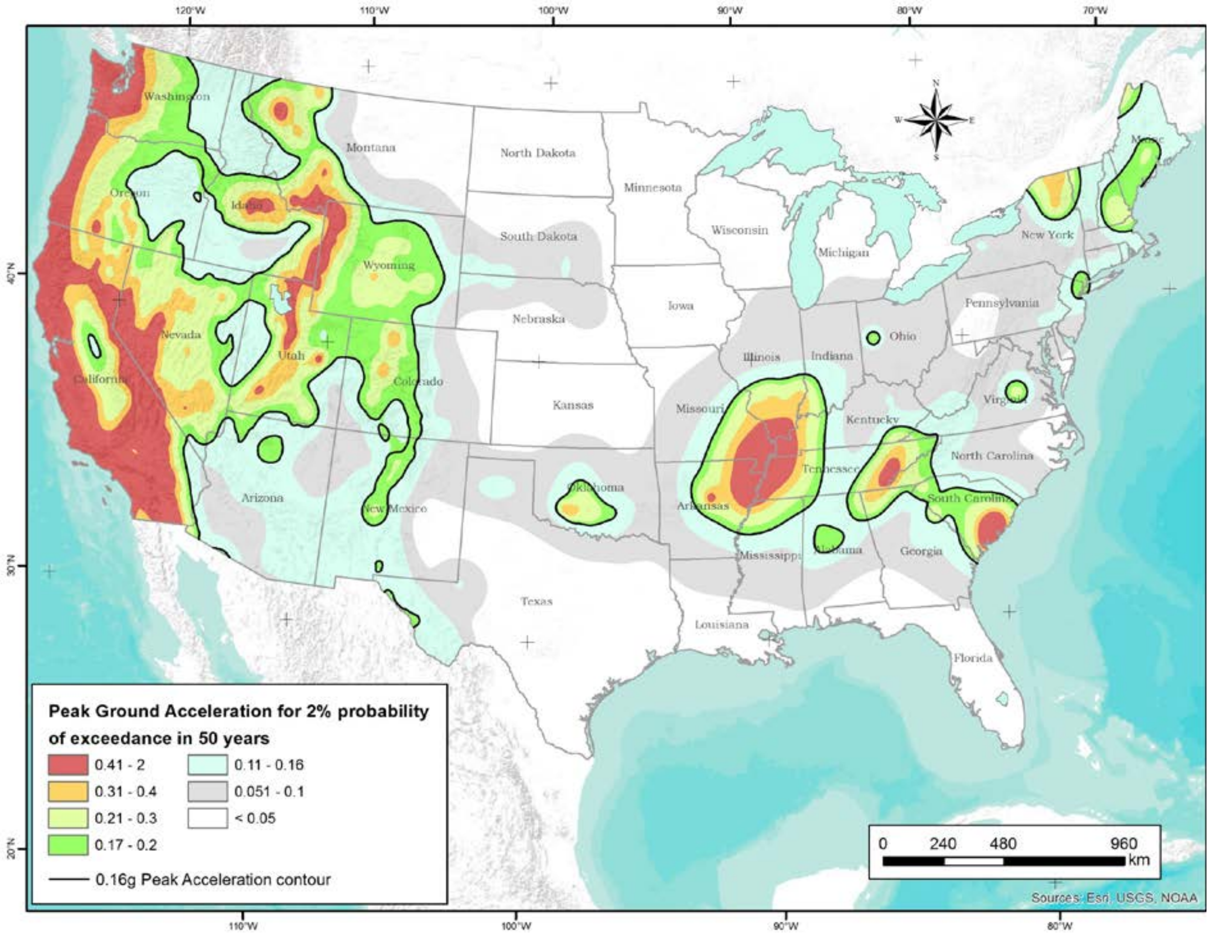

Figure 3-7. Color contours of peak ground acceleration values for a 2% probability of exceedance in 50 years. The contour line for a peak ground acceleration of 0.16g is shown for reference.

Strong seismic ground motion produced by fault displacement can adversely impact HLW disposal facilities and infrastructure and is indicative of regions of tectonic activity (Figure 3-7). The seismic ground motion hazard is represented as the probability of exceeding a certain peak ground acceleration within a defined period of time, for example, a probability of 2% in 50 years (Figure 3-7); data from Petersen et al. (2014). Since ground motion is caused by fault displacement, the distribution of the ground motion hazard reflects the distribution of Quaternary faults and fault areas in the US (Figure 3-10).

3.1.7 Topography and Smoothed Slope

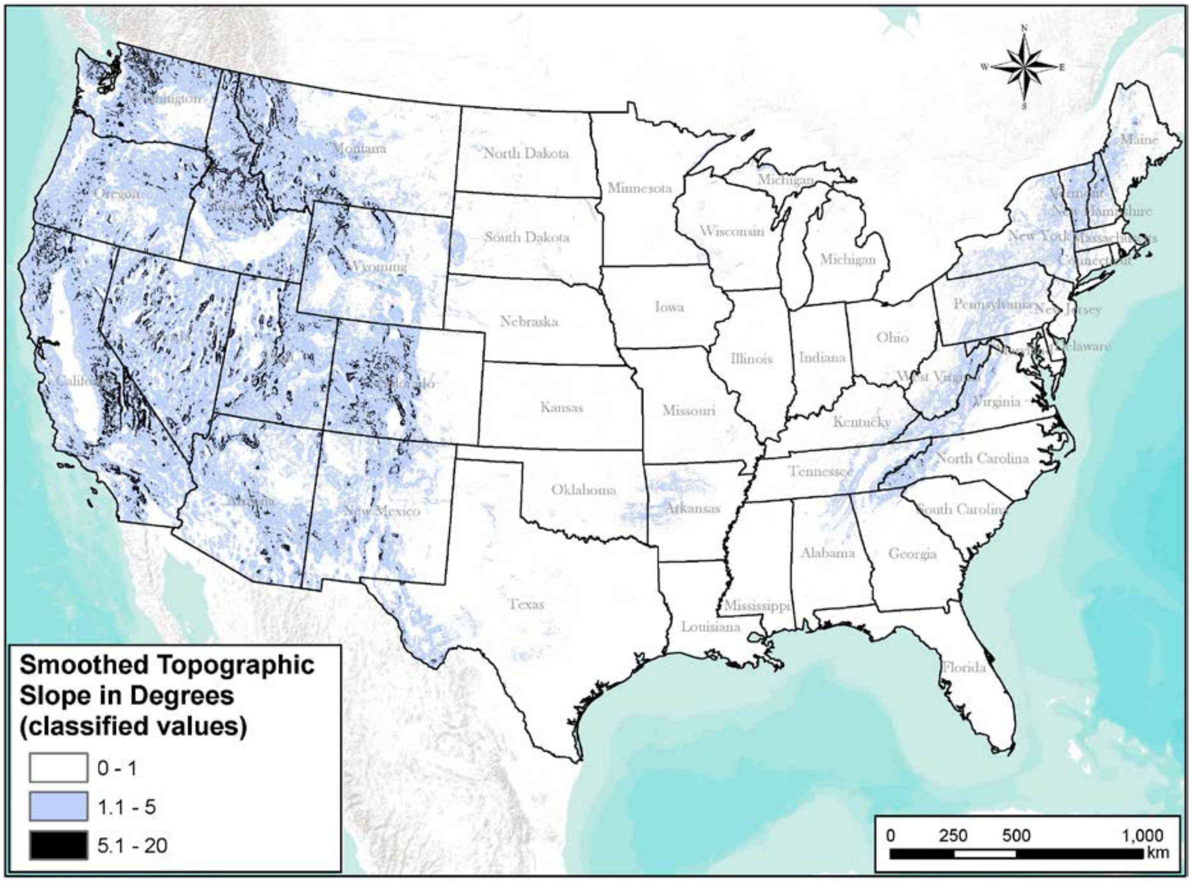

Figure 3-8. Topographic slope in the contiguous US classified by slope angle over a smoothing distance of 3 km.

Topography and topographic relief is a siting consideration for several reasons. Steep topography is a primary indicator of recent uplift and tectonism, high erosion rates, and increased landslide hazard from steep slopes (e.g., Montgomery and Brandon, 2002). Topography also exerts a primary control on hydraulic flow and groundwater recharge and discharge. These processes affect the isolation capability of a disposal system. Topographic data in the form of a global DEM was acquired from the ETOPO2 data set (NOAA, 2006). The average slope within 3-km grid cells was calculated using tools in the ArcGIS software that compares elevation values in adjacent DEM cells. The resulting grid of slope values quantifies the degree of topographic slope and relief for different regions of the US (Figure 3-8). Areas of more complex topographic relief are expected to have more complex groundwater systems driven by hydraulic gradients that are more variable over shorter distances.

The classified data is useful for quantifying areas of the US that are almost completely flat (<1 degree of slope), as well as their distance from areas of higher relief. Essentially flat areas far from areas of significant topographic relief might be expected to have groundwater systems with low groundwater flow rates because of a regionally low hydraulic gradient. These regions would include much of the interior US (Figure 3-8). Assumptions about deep groundwater flow rates and distance from recharge areas should be applied cautiously and tested against knowledge of regional groundwater systems including their geochemistry and age. Studies by Banner et al. (1989), for example, suggest that saline groundwater that discharges in central Missouri has an isotopic component consistent with meteoric recharge from the Front Range of Colorado, a distance of 1000 km.

3.1.8 **Heat Flow**

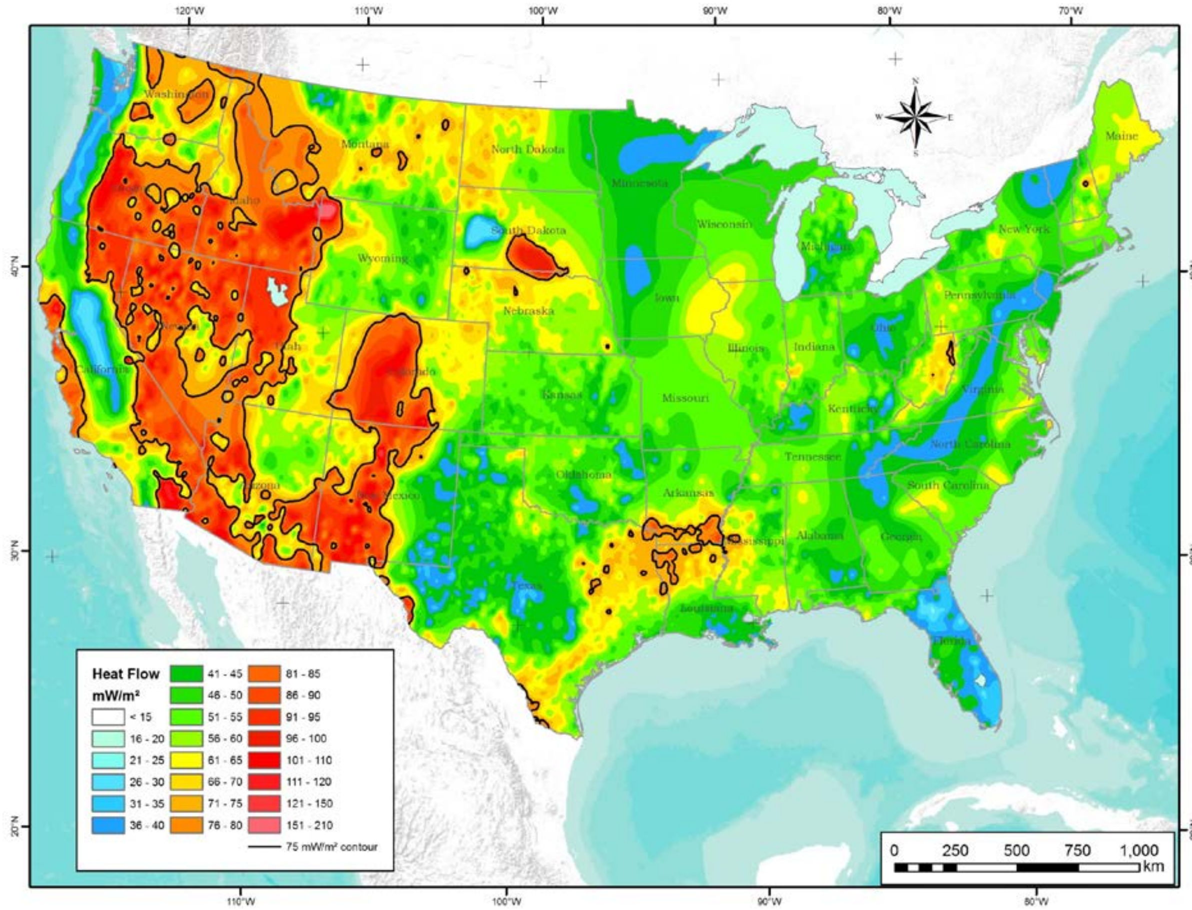

Figure 3-9. Heat Flow map of the US. The 75 mW/m^2 heat flow contour (black line) is shown for reference.

Heat flow data was obtained from the SMU Geothermal Laboratory as GIS data files (Blackwell et al. (2011). Heat flow data is derived using borehole temperature gradient and the thermal conductivity of rocks penetrated by the boreholes. These factors are in turn influenced by many factors including groundwater convection and the extensional tectonic regime and sediment composition and thickness (Blackwell et al., 2007). Areas of high heat flow are prevalent in the regions the western US dominated by extensional tectonics or recent volcanism, as well as other areas characterized by vertical groundwater flow. Heat flow correlates strongly with temperature at depth and is relevant to DBH siting in a number of ways including potential human intrusion through drilling of geothermal resources and as an indicator of upward groundwater flow that could impact the performance of a DBH disposal system (Arnold et al., 2013). These conditions are more likely in regions with heat flow of greater than 75 mW/m^2 , which often corresponds to regions of active extension and faulting in the western US (Figure 3-9).

3.1.9 Regions of Active Tectonics and Crustal Stability

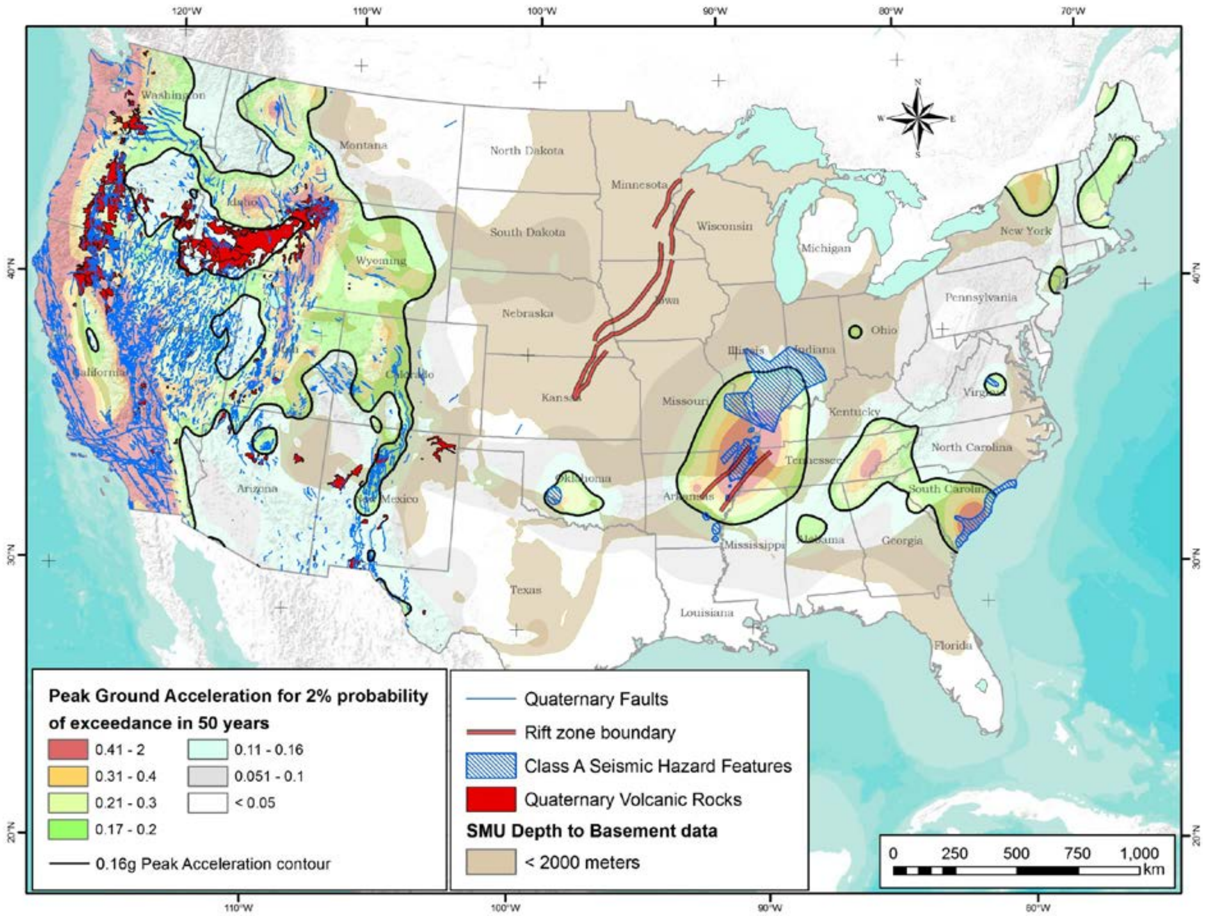

Figure 3-10. Seismic hazard overlain with the distribution of Quaternary faulting and Quaternary volcanic rocks in the contiguous US. In combination, these features indicate areas that can be considered tectonically active in the US. Also shown are regions of the US with basement depth of <2000 meters and Proterozoic rift zone boundaries within the mid-continent region.

An advantage of a GIS database is that data layers for technical siting guidelines can be overlain on a single map to provide insight into how siting factors relate to different regions of the US. For example, the distribution of Quaternary faults, volcanism and strong seismic ground motion hazard delineate the "tectonically active" regions of the US (Figure 3-10), which is dominated by the tectonic activity in the western US. The western US also includes the greatest topographic relief in the US and the major areas of high heat flow (see Figures 3-8 and 3-9). The tectonically active areas in the central and eastern US are the New Madrid and Charleston regions. Aside from these areas, large regions of the US mid-continent are tectonically stable with no evidence of significant tectonism in the past several hundred million years. This coincides with the largest contiguous region of the US with crystalline basement at depths of < 2 km (Figure 3-10). Although tectonically stable today, the mid-continent region includes numerous Archean and Proterozoic basement structures that would be need to be considered when assessing potential DBH sites (Figure 3-3). The most prominent of these structural features is the Midcontinent Rift shown for reference in Figure 3-10.

Figure 3.11 provides a more detailed view of the western US for DBH siting considerations by showing areas that lie within 10 km of Quaternary faults. Superimposed on fault data are the areas within the region that have a 2% probability in 50 years of exceeding a peak ground acceleration of 0.16g.

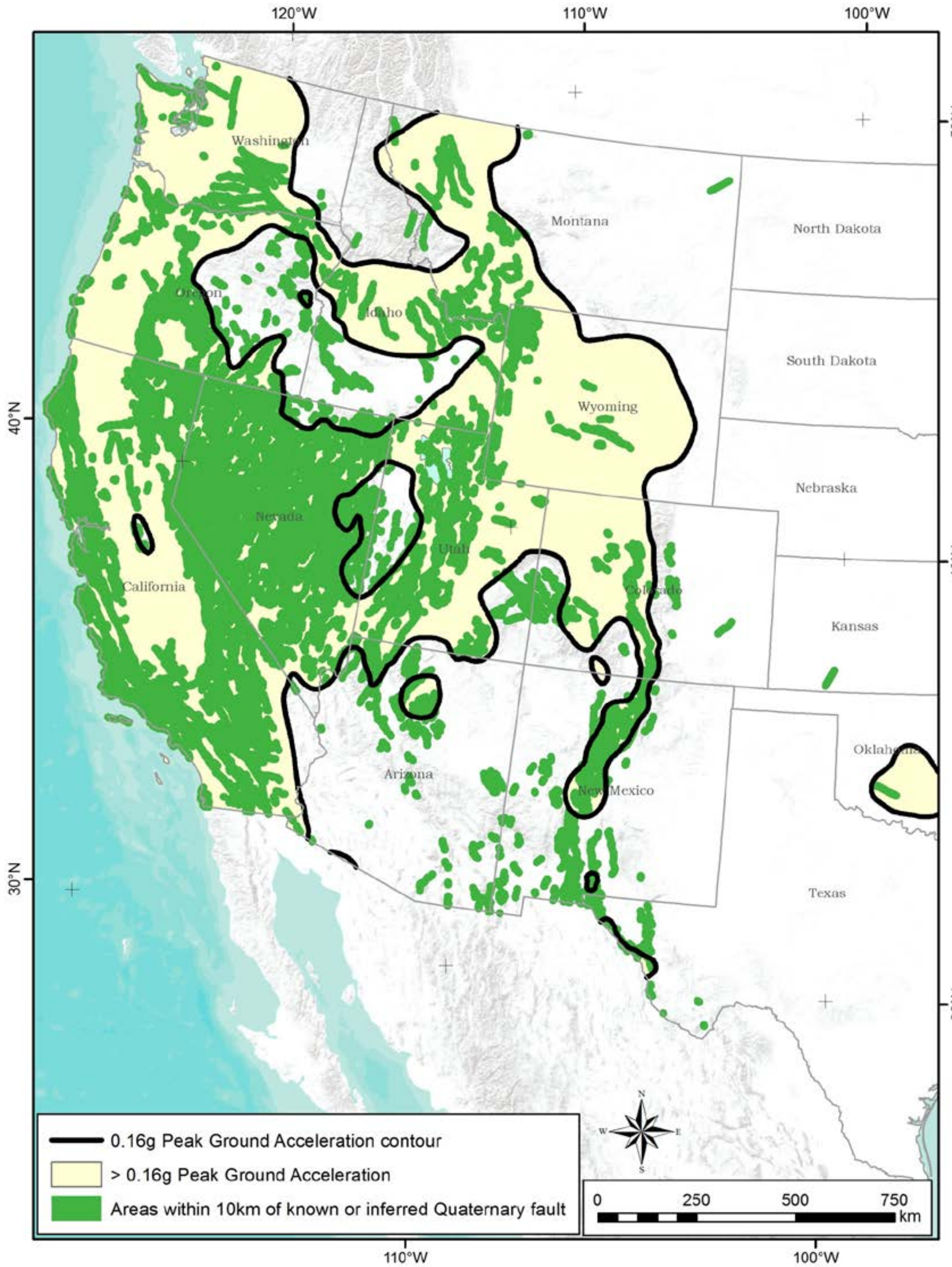

Figure 3-11. Quaternary faults surrounded by a 10 km buffer zone. Shown for additional reference is the 016g contour for peak ground acceleration based on a 2% probability of exceedance in 50 years.

4. Comparison of Data for Depth to Crystalline Basement at the National and State or Basin Scales

Identifying a suitable site for a DBH Field Test requires evaluation of available data for potential sites obtained at different scales and for different purposes. For example, understanding the geologic conditions at a potential site would involve evaluating available data from local studies as well as data from regional and national studies. If certain types of geologic data are not available through existing local studies, geologic data collected and compiled at a more regional scale would have to be evaluated to determine whether the data are suitable to understanding geologic conditions at the potential site.

The technical guideline requiring a depth to basement of less than 2 km is rigorous in order to be consistent with the DBH reference design. Depth to crystalline basement is not known a priori in every area of the country. Knowledge of depth to crystalline basement in any particular area of the US generally depends on the existence of boreholes that have penetrated (or not penetrated) crystalline basement, the complexity of the basement structure (i.e., large changes in basement depth over short distances) and any relevant geophysical surveys that may have been conducted previously in an area.

Since borehole data is not available everywhere, estimates of crystalline basement depths always involve estimates of basement depth in the areas between boreholes. This is done by interpolating depth values between boreholes and recognizing the presence of any potential structural features within the basement. The ability to accurately predict basement depth at a particular location therefore depends largely on the density of boreholes in the area and how simple or structurally complex the basement is beneath the area.

In the following sections of this report we compare recently published maps of basement structure compiled at the state and basin scale to the national basement map from AAPG (1978). We cannot locate information on the data that was used to produce the AAPG (1978) map, but know that it relied on borehole data in existence at that time (cf., AAPG, 1967, the likely precursor to the AAPG, 1978 map). More recent state and basin-scale maps are likely produced using a more recent and larger database of boreholes augmented by more recent geologic and geophysical studies.

Data for basement geometry in digital (GIS) format is available for the states of New Mexico, South Dakota and Nebraska, and the Permian Basin region of Texas (Figure 4-1). Borehole data used to create these maps is available as part of the GIS data for New Mexico, South Dakota, and the Permian Basin, but not for Nebraska (although it may be available upon request). We have identified data for other states and regions but do not consider them in this report because we have not obtained or not yet processed the data for use in the GIS database. All states and regions for which we know basement data exists are shown in Figure 4-1. Other data sets may exist and that we have not yet identified.

The data sets for the areas we analyze in this report are significant in that they represent relatively simple basement structure (South Dakota and Nebraska) to relatively complex basement structure (New Mexico and the Permian Basin). As a group they offer the opportunity to analyze differences in depth estimates from very different types of basement structural environments. In the following sections, we discuss these regions beginning with the simplest basement structure followed by the regions with more complex basement structure. For each of these areas, we calculated depths to basement, and the differences in depth between the national data set and the respective area data sets. These results are shown in Figures 4-2 through 4-9.

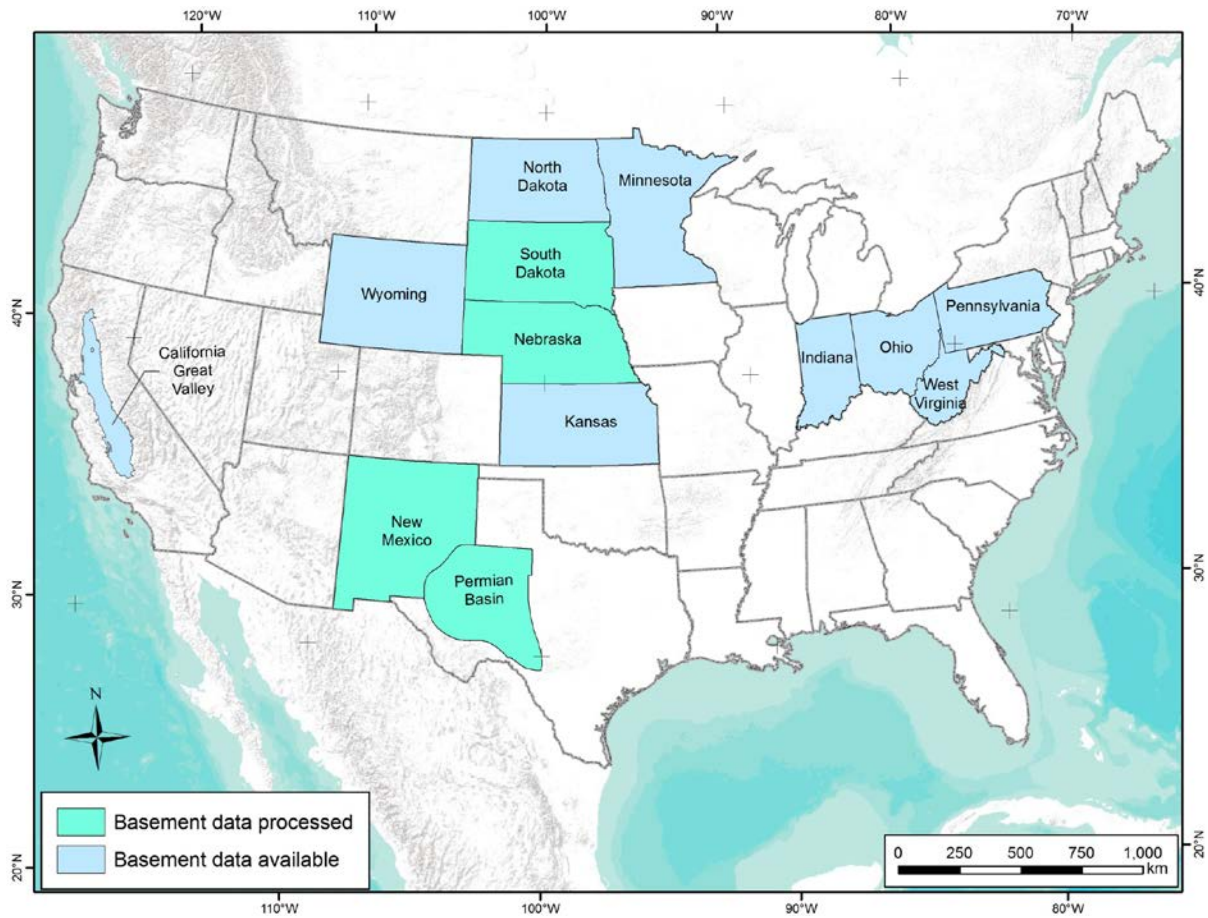

Figure 4-1. Reference map showing states and basins in the US with published maps of depth of crystalline basement. Data have been processed for the four areas shown in green and have been identified for the areas shown in blue. Data for these areas has not yet been processed for use in the GIS database. Other areas with data may be identified in the future.

We determined the depth differences between the national and state data sets by subtracting the raster representing the state data set from the raster representing the national data set. From this operation, we produce a difference map that shows positive and negative deviations from values represented on the national map as a function of location. Where the national map indicates a shallower depth, the difference map displays areas of negative values (shown as warm colors). Where the state maps indicate a shallower depth, the difference maps areas of positive values (shown as cool colors). To aid in visual interpretation of the difference maps, areas where the depth values from the national and state maps fall within 200 meters of each other (i.e., reasonable agreement) are left uncolored.

4.1 South Dakota

Depth to basement in South Dakota was calculated from basement structure contour data presented by McCormick (2010a). Structural contours on the basement were created using data from more than 7500 boreholes that constrain the elevation of the top of the crystalline basement. The GIS dataset for South Dakota GIS produced by McCormick (2010b) includes the borehole data used to constrain the basement structure. The major structural features of the crystalline basement are the Black Hills uplift in southwestern South Dakota and the southern part of the Williston Basin in Northwestern South Dakota (Figure 4-2). Apart from these features, depth to basement generally ranges from less than 250 meters in the eastern part of the state, with scattered outcrops of crystalline basement, to more than 1000 meters in the western half of the state (except for the area around the Black Hills). Depth to basement exceeds 3000 meters in the Williston Basin of northwestern South Dakota.

The depth difference map was created by subtracting the depth raster for South Dakota from the depth raster for the national depth map (Figure 4-3). For the majority of the state, depth to basement estimates agree to within 200 meters, with a few areas differing by as much as 500 meters. The major difference in depth estimates is confined to the area of high structural gradient on the northeast flank of the Black Hills uplift and the southern margin of the Williston Basin. In this area, differences in depth estimates are generally between 500-1100 meters with the state-scale data from McCormick (2010a) predicting the greater depth (Figure 4-3).

4.2 Nebraska

Structure contour data for the crystalline basement of Nebraska is available from the website http://snr.unl.edu/data/geographygis/nebrgisgeology.asp#precamb at the University of Nebraska, School of Natural Resources. The structural contours were based on data from over 19,000 boreholes and interpreted by state geologists. Information of the location of the boreholes is not provided. Other than a 2009 date for processing of the GIS file and information on the number of boreholes, little information is available on the location of boreholes or the methods used to create the structural contour map.

Nebraska, immediately to the south of South Dakota, has a similar overall basement structure in that the depth to basement ranges from less than 500 meters in the eastern part of the state and deepens gradually to the west to depths of between 1000 and 2000 meters beneath much of the state (Figure 4-4). Structural features in Nebraska include the Denver Basin in the western part of the state, the Midcontinent Rift in the far southeastern corner of the state, and the Chadron-Cambridge Arch in the northwest portion of the state. Depth to basement is greatest in the western part of the state with depths of greater than 2000 meters in the Denver Basin and more than 3000 meters in the extreme southwest corner of the state.

The depth difference map was created by subtracting the depth raster for Nebraska from the depth raster for the national depth map (Figure 4-5). As is the case for South Dakota, depth to basement estimates agree to within 200 meters in most of the state, with a few areas differing by more than 500 meters. The greatest calculated difference of 750 meters is in the Midcontinent rift area of southeastern Nebraska, an area of major basement faulting and high structural gradient. Lesser differences are seen in the areas of relatively high structural gradients of the Chadron-Cambridge Arch and the margins of the Denver Basin.

4.3 Permian Basin

The Permian Basin is comprised of the Delaware and Midland Basins separated by a structural high referred to as the Central Basin Platform (Figure 4-6). Borehole control on basement structure is sparse within the Permian Basin, but the structure of sedimentary units above the basement is much better known. Ruppel et al. (2005) used the structure of a well characterized overlying sedimentary sequence along with its thickness to extrapolate the structural surface of the crystalline basement. We used the structural data of Ruppel et al. (2005) to calculate basement depth (Figure 4-6). In this case, GIS data was supplied as both structural contours and a raster surface. We used the raster surface directly to calculate depth to basement, because we concluded that it represented the author’s best interpretation of the basement structure. Depth to basement based on the calculated depth map ranges from about 1100 meters on the greater basin margins and Central Basin Platform to more than 8000 meters on the eastern edge of the Delaware Basin (Figure 4-6)

The depth difference map was created by subtracting the Permian Basin basement depth raster from the national depth map (Figure 4-7). The largest differences in depth estimates occur along the basin and Central Basin Platform edges. Depth difference estimates reach values as great as 4500 meters on the eastern side of the Delaware Basin where the structural gradient is high (Figure 4-7). The national map indicates the shallower of the two depths (i.e., 4 km versus 8 km).

4.4 New Mexico

The map for depth to crystalline basement is calculated from structural contour data (Broadhead et al., 2009) with additional constraints from new borehole data (Shari Kelley, New Mexico Bureau of Mines, Personal communication, 2015) and our use of crystalline basement outcrop as a zero depth constraint (Figure 4-8). The crystalline basement beneath New Mexico is structurally complex and is characterized by a high degree of structural relief over short distances. Depth to basement ranges from zero on structural uplifts to more than seven km in the Albuquerque Basin of the Rio Grande Rift and in the Permian Basin region of southeastern New Mexico (Figure 4-8). The structural relief on the basement surface was interpreted by Broadhead et al. (2009) based on borehole data, gravity and aeromagnetic data (that aid in defining the shape of the basement surface, especially in areas of low borehole density), structure contour maps for sedimentary units overlying the basement and mapped faults and structures that penetrate the basement and control basement offsets. In general, a large amount of geologic interpretation is used in constructing a structural contour map of a state, with borehole data providing the definitive structural and depth information where present.

A comparison of the depth to basement from the national map and New Mexico map highlights an issue that is especially apparent in the north-central area of New Mexico. This region of the state has among the most complex structural relief in the US characterized by prominent basement uplifts and deep sedimentary basins related to the tectonics of the southern Rocky Mountains and Rio Grande rift. Because the national map and the more detailed state map of basement structure were created at different scales and with different intent, we do not believe a comparison of depth data is justified for the north-central portion of New Mexico. The national map is not intended to capture this level of detail and complexity in tectonically active regions of the western US that are characterized by highly variable basement depth (Blackwell et al., 2007).

In the more tectonically stable eastern half of New Mexico, differences in elevation estimates occur primarily in the more structurally complex (from north the south) Dalhart, Tucumcari and the Permian Basins, areas that include both basement faults and greater relief on the basement surface (Figures 4-8 and 4-9). Differences in depth estimates in these areas can be as great as 500-1200 meters. Differences in the Raton and Las Vegas Basins may also exceed 1000 meters.

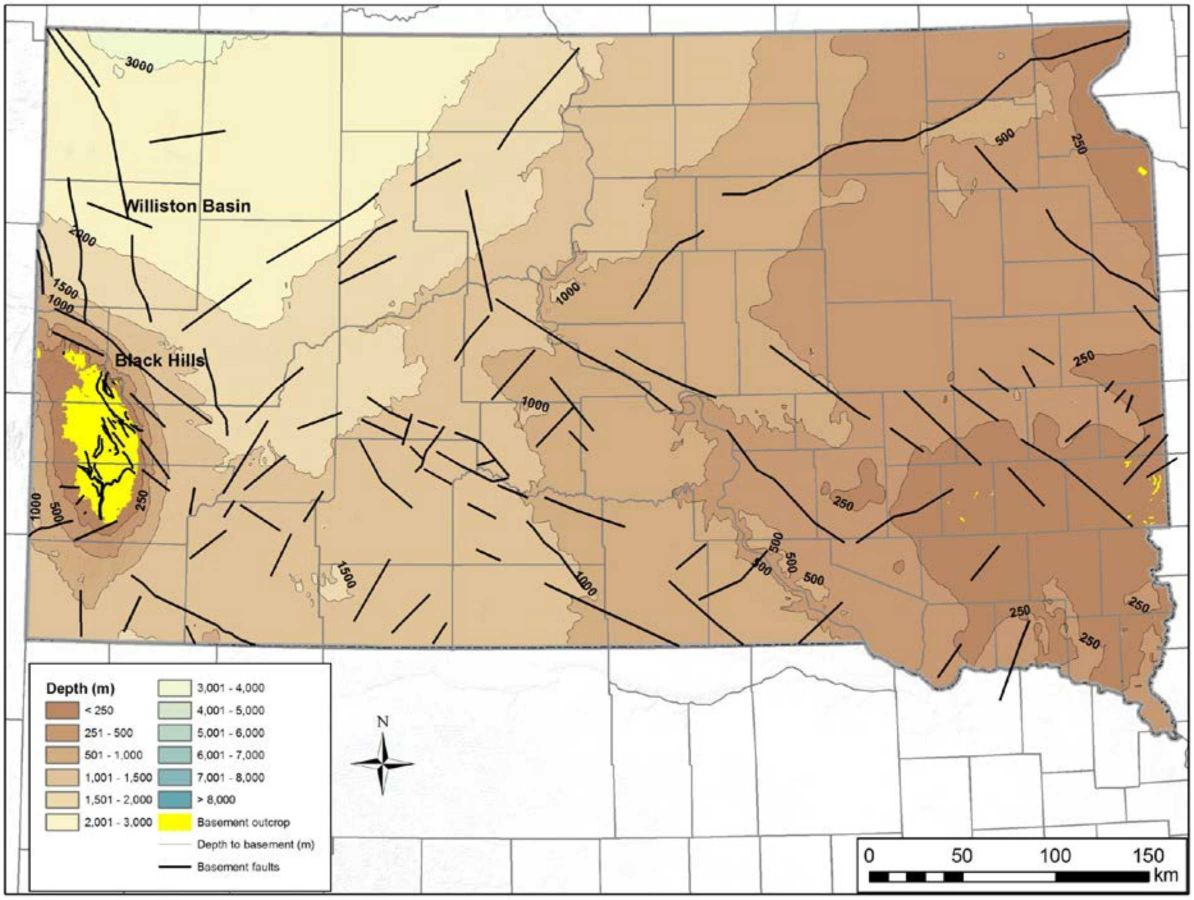

Figure 4-2. Depth to Basement and location of basement faults in South Dakota, Fault data from McCormick et al. 2010b.

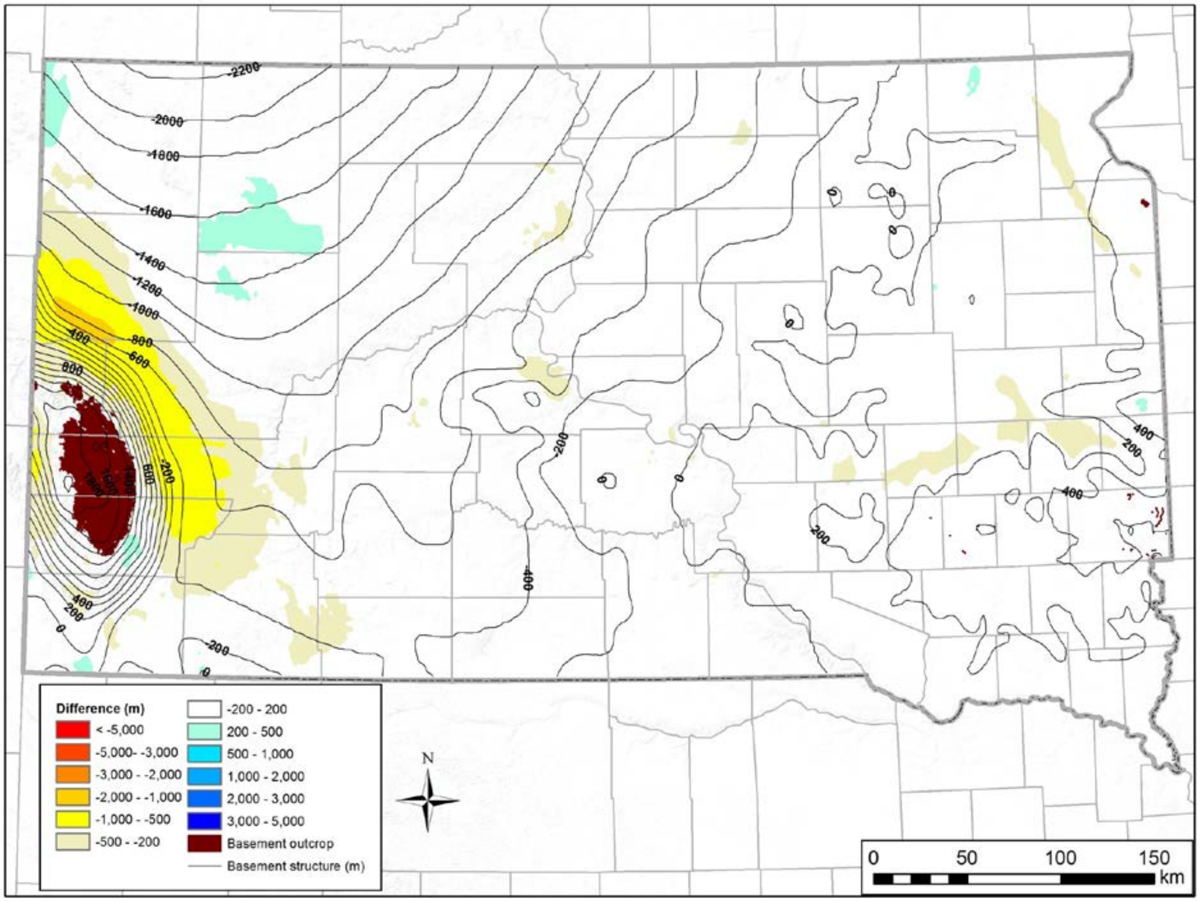

Figure 4-3. Calculated depth differences between national and state-scale depth maps superimposed upon the basement structural contour map of South Dakota.

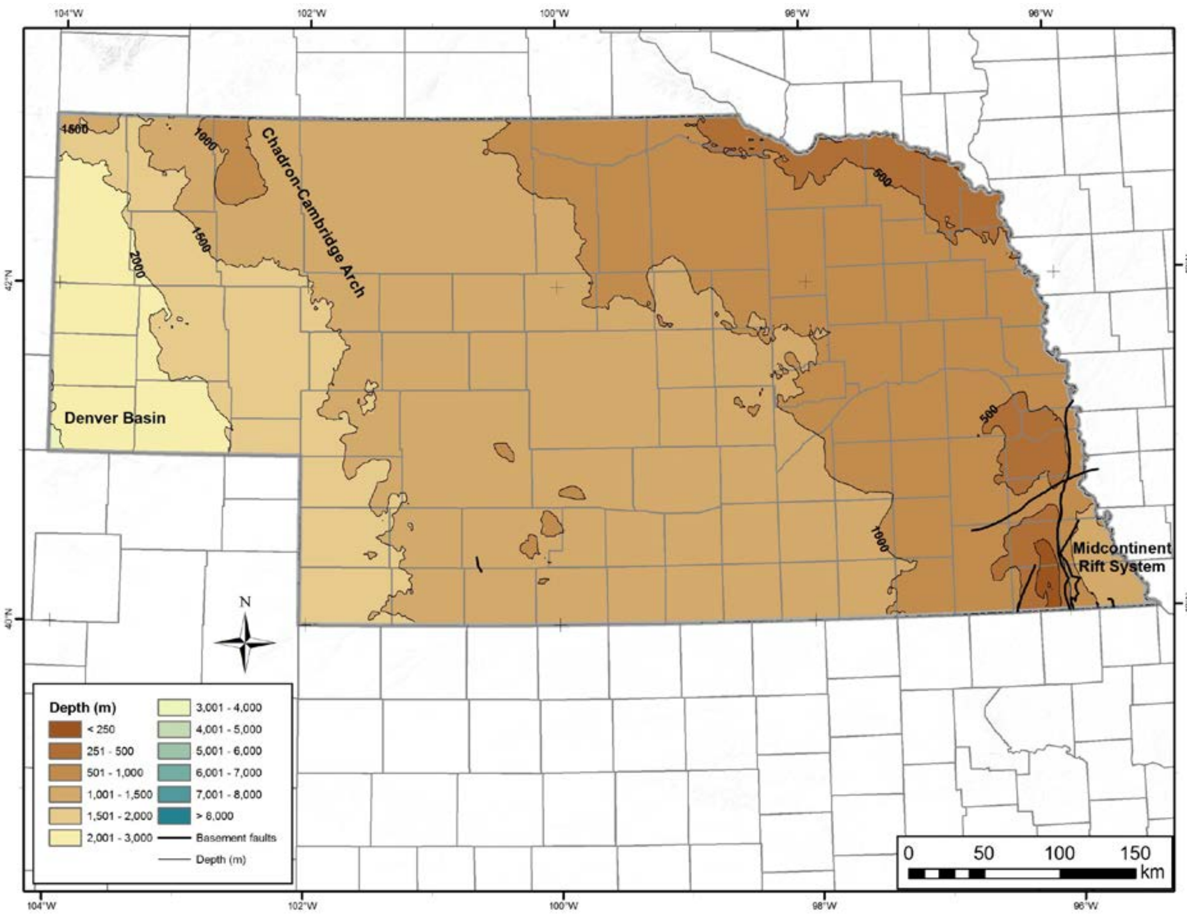

Figure 4-4. Depth to Basement and location of basement faults in Nebraska, Fault data is from the University of Nebraska, School of Natural Resources.

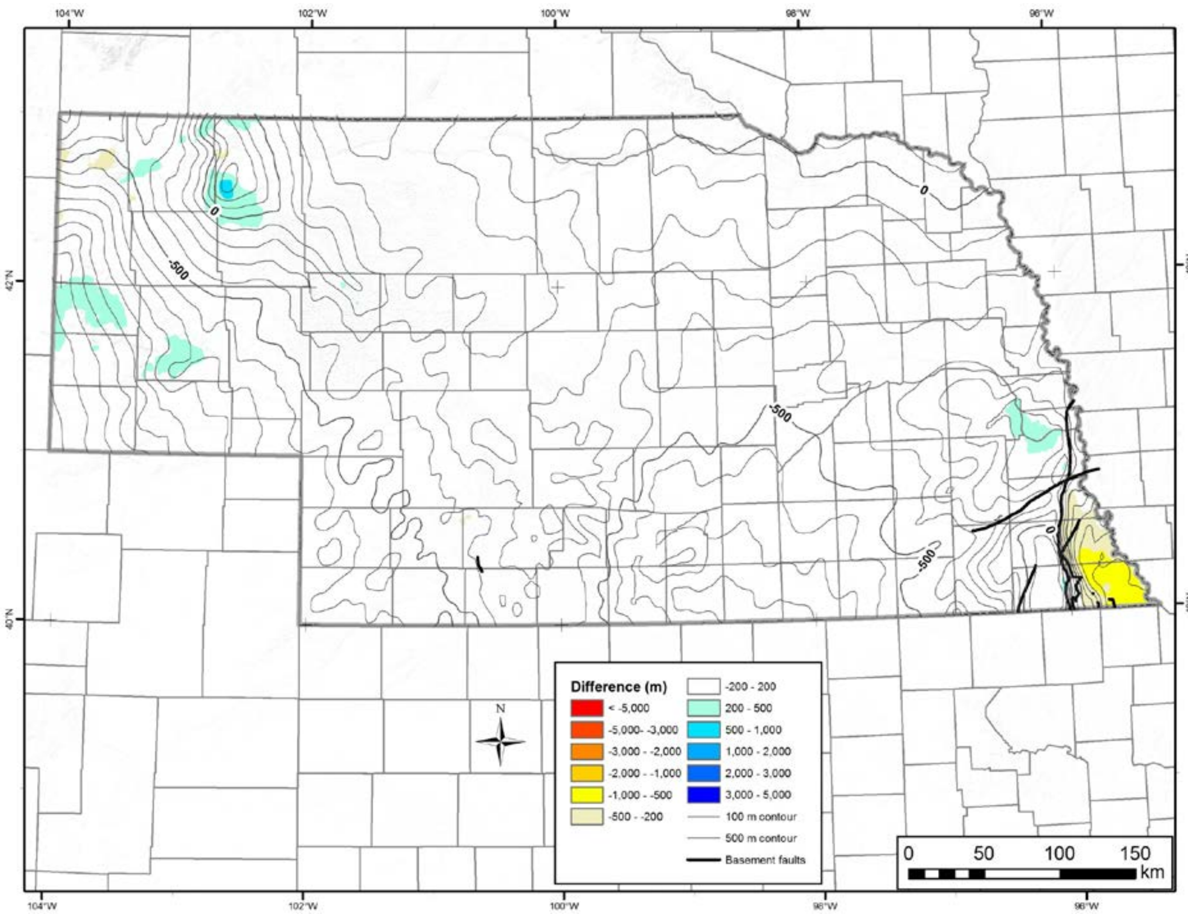

Figure 4-5. Calculated depth differences between national and state-scale depth maps superimposed upon the basement structural contour map of Nebraska.

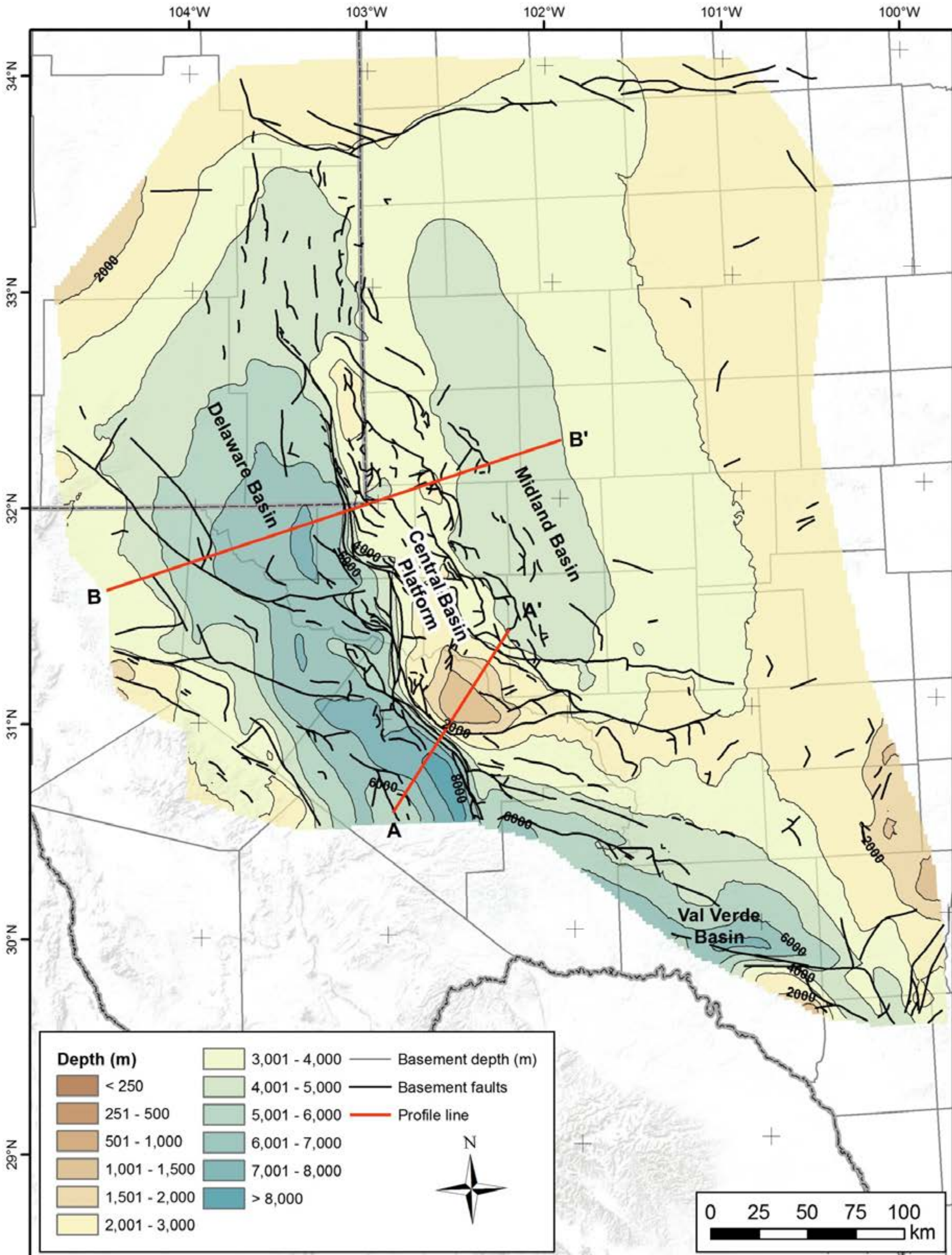

Figure 4-6. Depth to Basement map for the Permian Basin of west Texas and southeast New Mexico, based on basement elevation data from Ruppel et al. (2005). Basement faults are from Ewing (1990) and included in GIS data provided by Ruppel et al. (2005).

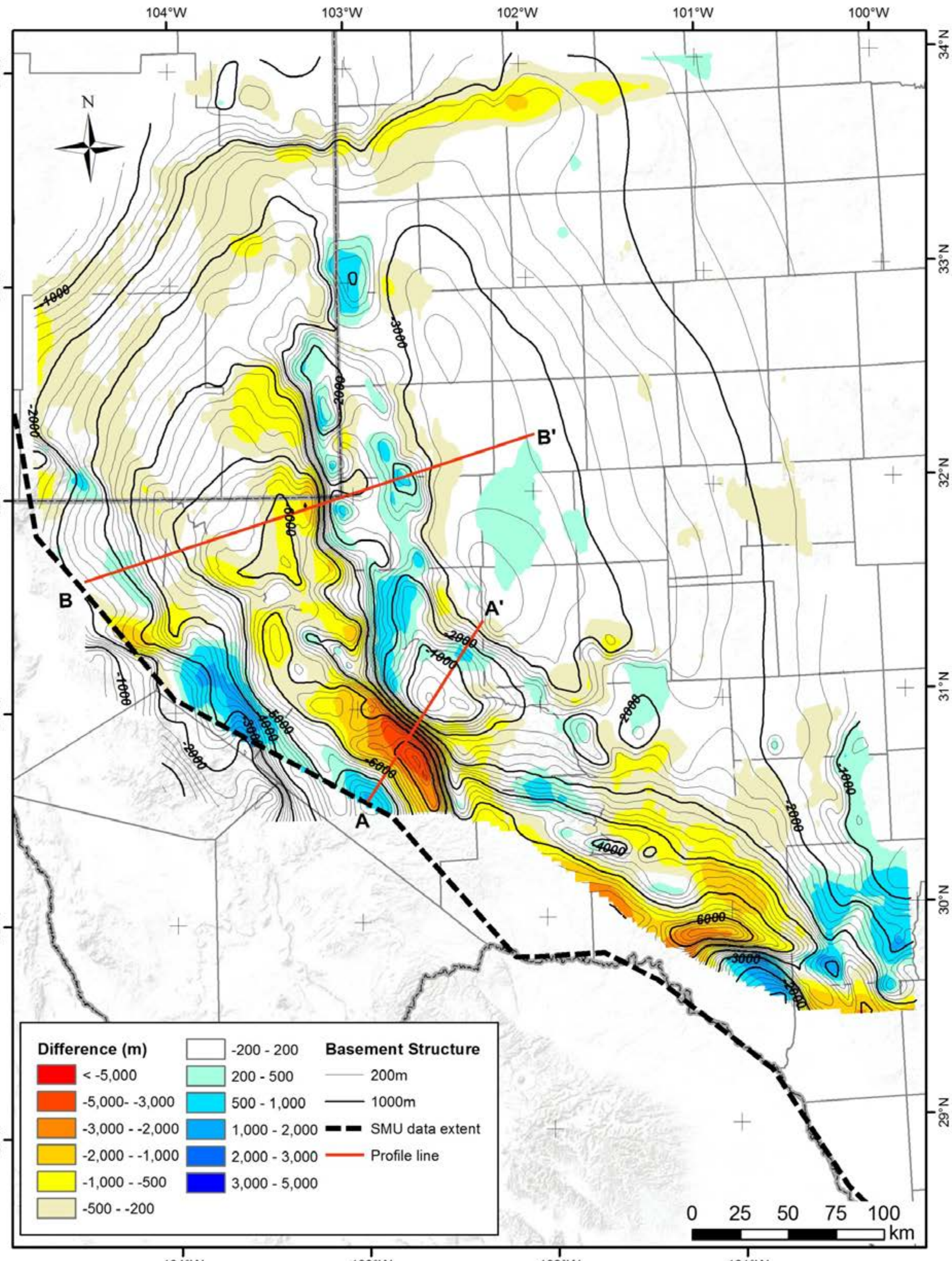

Figure 4-7. Calculated depth differences between national and state-scale depth maps superimposed upon the basement structural contour map of the Permian Basin of Texas and New Mexico..

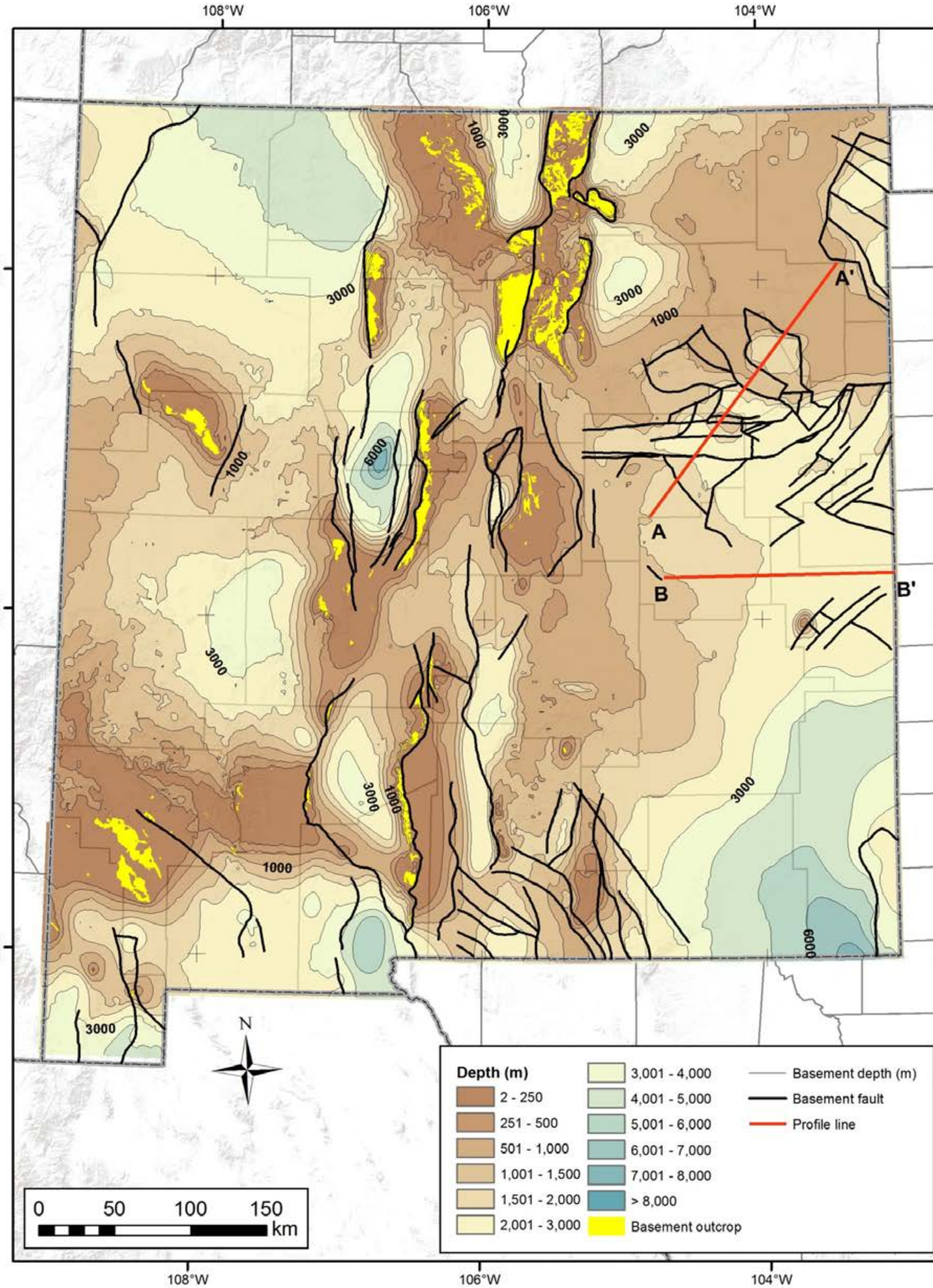

Figure 4-8. Depth to Basement map for New Mexico, based primarily on structural contour data from Broadhead et al. (2009) and other sources discussed in the text. Location of basement faults from Broadhead et al. (2009).

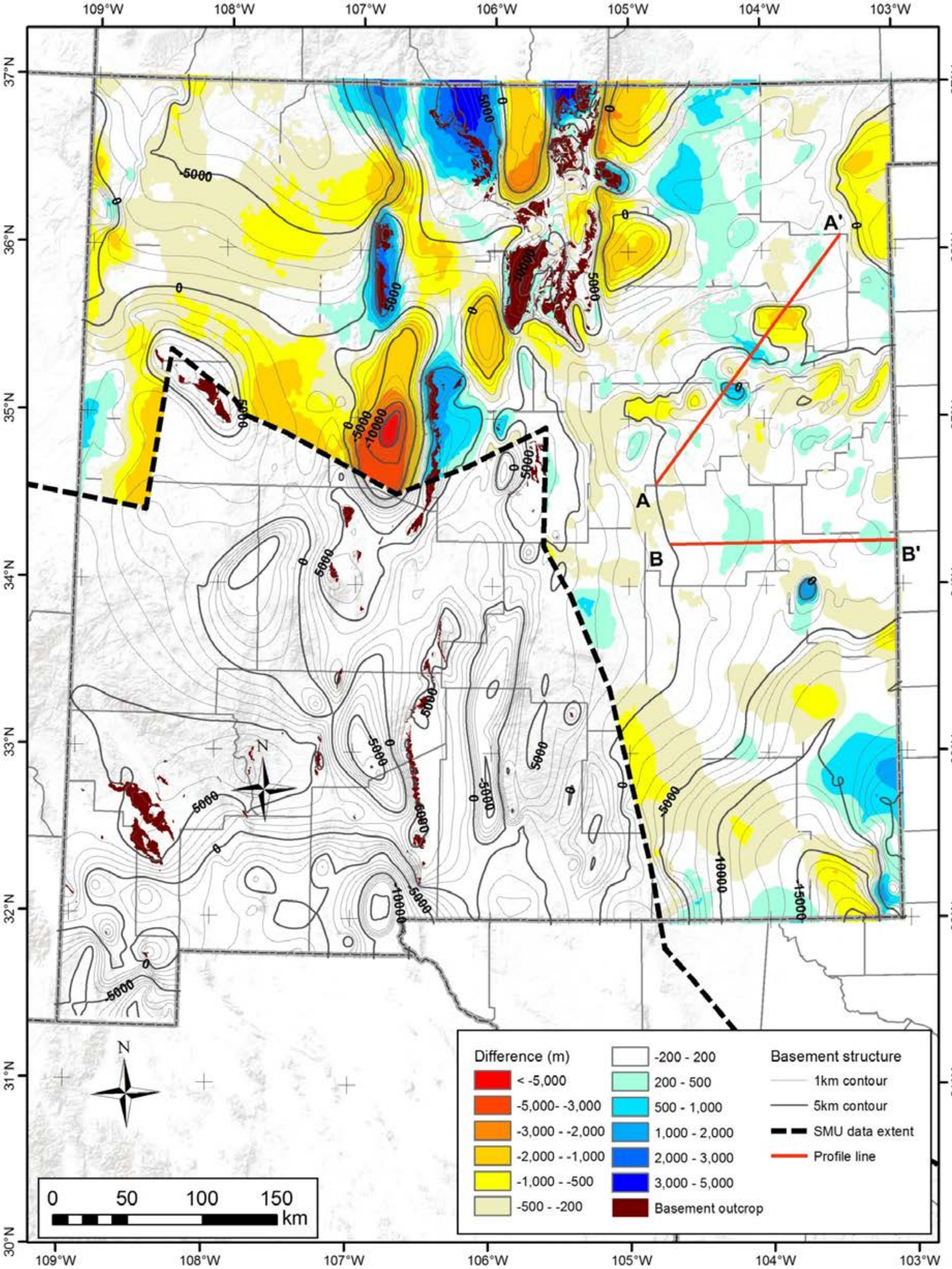

Figure 4-9. Calculated depth differences between national and state-scale depth maps superimposed upon the basement structural contour map of New Mexico. Note that the southwestern portion of the state has no values because the national map does not include data for this area.

4.5 Comparison of the 2 km Depth Contour from National and State Data Sets

The 2000 meter (2 km) contour for depth to crystalline basement is critical for siting a DBH Field Test. Assuming confidence in its location, the contour can be used to separate regions of the US with basement depth of less than 2 km from regions with depths greater than 2 km. Since basement depth from the national maps is the only data readily available for many areas of the US, a key question is: “How well can the location of the 2 km contour be relied on based on the national map?” To address this question we created a map comparing the location of the 2 km contour at the national scale with the more detailed 2 km depth contour data for the states where we currently have data available (Figure 4-10). If the state and national data agreed, the <2km depth surfaces shown in green and blue would line up perfectly with the national 2 km contour in areas where the two types of data overlap. In most areas, the agreement between local and state data is good.

In South Dakota, the Williston Basin region has depth to basement of greater than 2 km (Figure 4-2). The largest difference in where the 2 km depth contour occurs is at the far western edge of South Dakota where the state data indicates that basement at 2 km depth would occur up to 20 km south of where the national data would indicate (Figure 4-10). Assuming that the more detailed state data is more correct (which may not be true), a borehole near the national 2 km contour in these areas would encounter basement at a depth of 2200-2300 meters. Neither data set indicates basement at greater than 2 km except for the Williston Basin region.

In Nebraska, the area of basement at a depth greater than 2 km corresponds to the Denver Basin (Figure 4-4). At the northern edge of the Denver Basin, the 2 km contour from state data is approximately 10 km to the north of the national contour. A borehole near the national contour in this area would encounter basement at a depth of approximately 2050-2200 meters in this area assuming the state data is accurate. In west-central Nebraska, an area of basement occurs at depths less than 2 km based on the state data farther into the Denver Basin than the national data would indicate. A borehole in this area would encounter basement at depths of approximately 1800-2000 meters. Neither data set indicates basement at greater than 2 km except for the Denver Basin region.

Agreement between the Permian Basin and national data set is also good at the basin scale. In the center of the basin on the Central Basin Platform, a roughly circular area about 40 km wide has basement at depths of less than 2 km (Figure 4-4). Although both datasets indicate depths of less than 2 km within this area, depth differences of 200-400 meters occur within the area (for example, 1600 meters versus 2000 meters near the southern edge of this feature). Depth values where the national and basin data overlap on the eastern edge of the basin agree reasonably well within the 2 km contour of the national data. The two data sets can differ by 500 meters or more where the basin values of < 2 km extend into the basin side of the national contour. In these small areas, the national data indicates depths of > 2 km while the basin data indicates depths of < 2 km.

Agreement between the New Mexico dataset (Figure 4-8) and the national data set varies with location. Agreement in the structurally complex north-central portion of New Mexico is poor. This is not unexpected given the complex basement structure in this area and the intended use of the SMU national data set (Blackwell et al., 2007). The two data sets agree reasonably well for the San Juan Basin region in northwest New Mexico, with the exception of the eastern basin edge that is in effect part of the structurally complex region of north-central New Mexico. Both datasets show the interior of the San Juan Basin with basement deeper than 2 km.

At the western edge of the Permian Basin within New Mexico, three data sets overlap (national, New Mexico and Permian Basin). The 2 km contour for all three data sets lie within less than 10 km of each other and the depth values vary by approximately 200 meters across all the data sets.

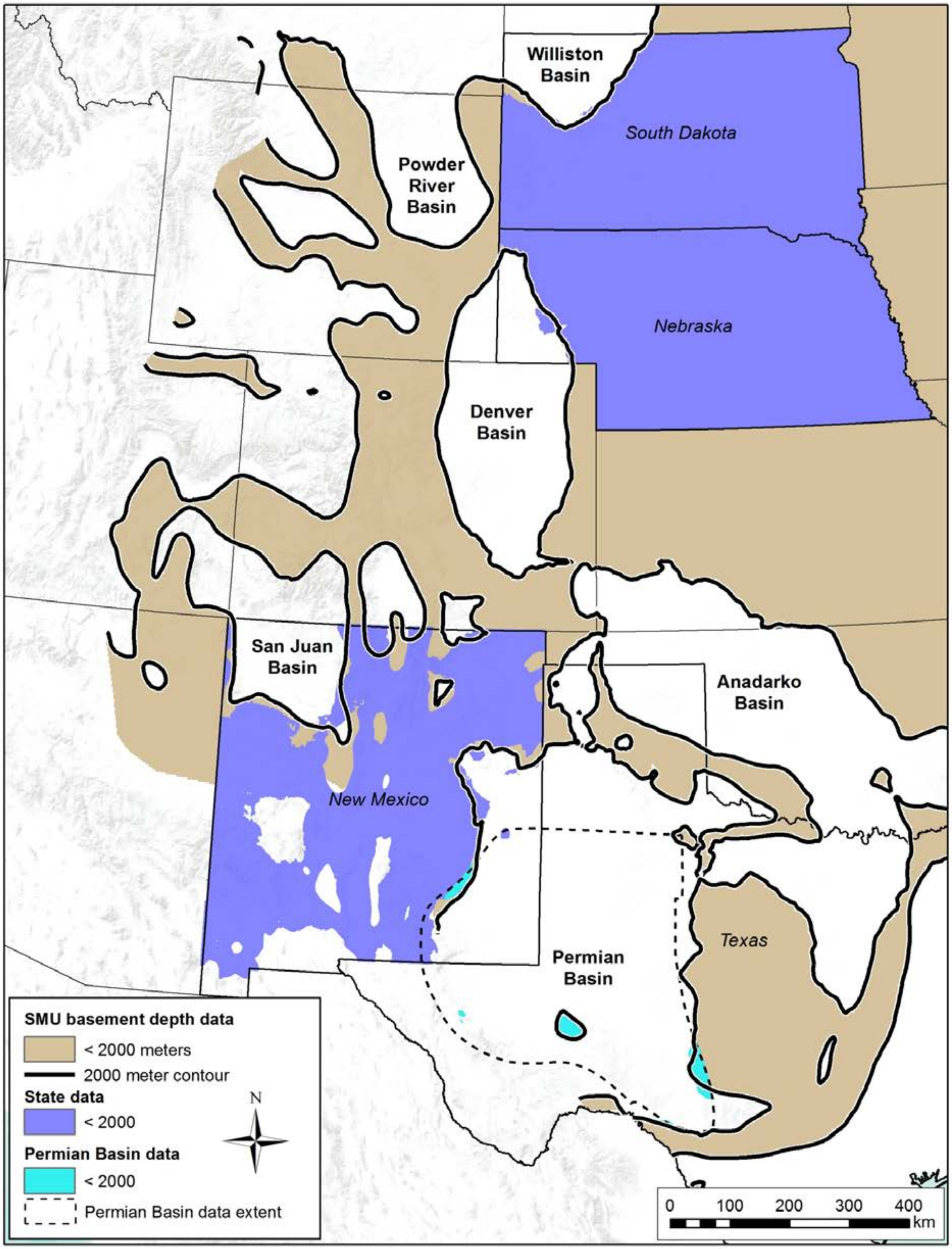

Figure 4-10. Comparison of national (SMU), state and basin data for depth of basement of < 2000 meters.

4.6 Comparison of Depth Profiles and Statistics of Difference Rasters

The overall level of agreement between national and state maps is reflected in the statistics of the depth difference rasters. If the depth values for the national and state maps agreed perfectly, the individual cell values in each difference raster would each have a value of zero, hence the mean and standard deviations of the cells within the rasters would be zero. Table 4-1 shows the statistics for each of four difference rasters. The statistics quantifies the results that can be discerned visually from the four difference maps (Figures 4-3, 4-5, 4-7 and 4-9). The map of Nebraska, for example, shows that large areas of the state show agreement with the national map, as indicated by a small mean depth difference, and relatively small differences in the standard deviation, and minimum and maximum compared to the other states. Note that the other states (and basins) have more complex basement structure and greater statistical values for depth difference, standard deviation in the depth, and the minimum and maximum. These results indicate that the national map does not capture variations in depth that are not gradual at the state scale as well as the state maps.

In all four cases, the mean depth has negative values, indicating that greater depth values are derived from state or basin depth maps with the largest depth differences and variances occurring in states or regions with the greatest structural relief, in particular deep basins. States with relatively smooth basement structure (South Dakota and Nebraska) yield similar depth values from either the national or state maps. This indicates that the scale and grid spacing used to create the national map does not capture small complexities and abrupt elevation differences in crystalline basement. This is not unexpected and is consistent with the stated limitations and uses of the national map (Blackwell et al., 2007).

Table 4-1. Statistics of difference rasters reflecting variations of the cell values within each raster

Difference Raster	Mean Depth Diff. (m)	S.D. Depth Diff. (m)	Min. Depth Diff. (m)	Max. Depth Diff. (m)
Nebraska	-20	94	-657	549
South Dakota	-60	157	-1130	438
Permian Basin	-138	442	-4562	1669
New Mexico	-153	706	-6285	4621

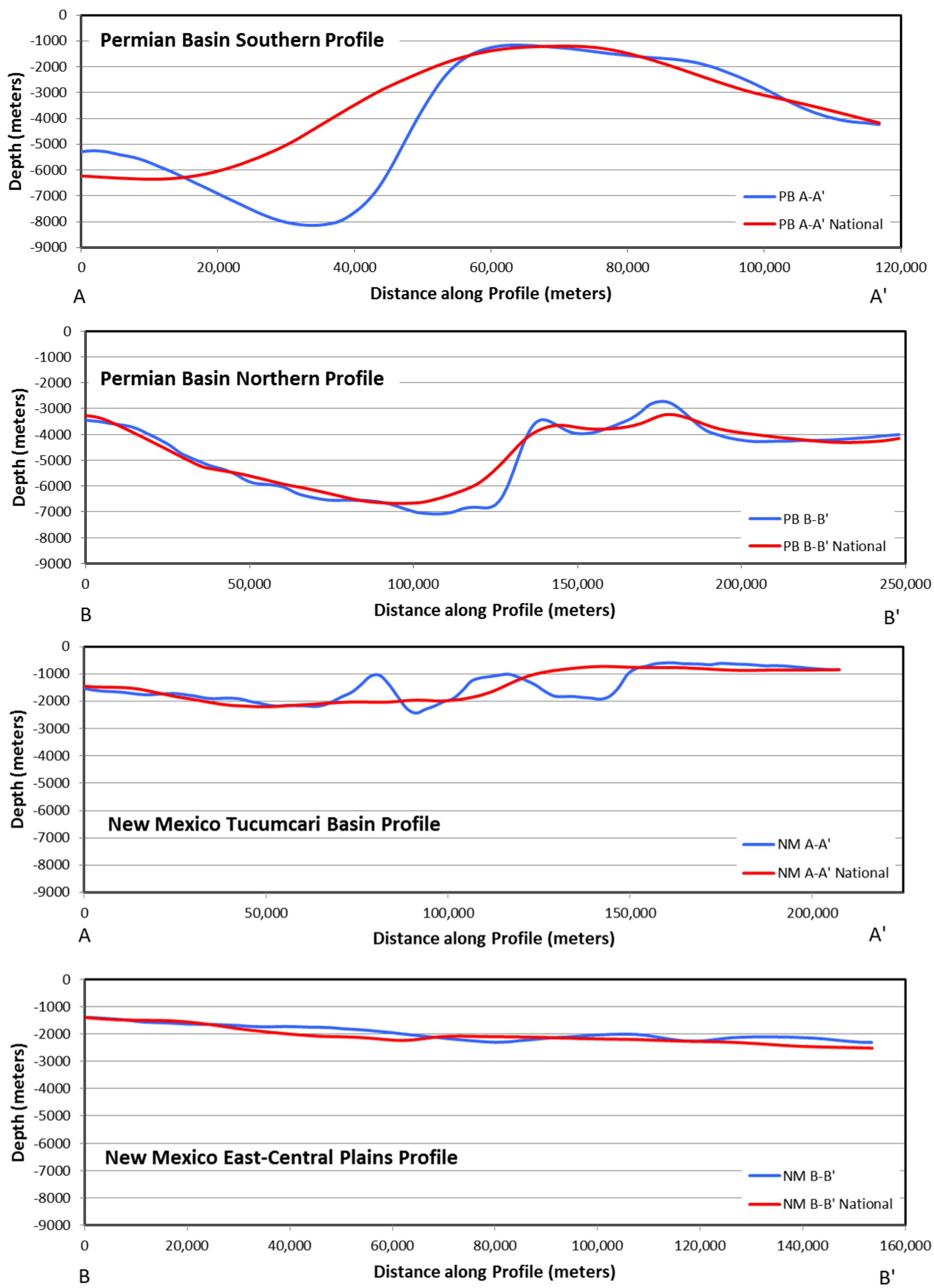

Figure 4-11. Depth profiles comparing national and state or basin data in New Mexico and the Permian Basin of Texas. Locations of profiles are shown in Figures 4-6 through 4-9. Note that the vertical scales are the same for each profile but exaggerated by different amounts compared to the horizontal length of each individual profile.

More detailed insight into the nature and origins of the depth differences between different data sets can be gained by comparing depth profiles in different basement environments (Figure 4-11). We selected four profiles for comparison, two in New Mexico and two in the Permian Basin of Texas (Figures 4-6 through 4-9). The Permian Basin profiles were chosen to illustrate the most extreme structural relief (~7 km) present in the southern Delaware Basin versus an area farther north in the same basin that has more moderate relief. In New Mexico, we avoided the structurally complex areas of north-central New Mexico and chose one profile across the moderately deep Tucumcari Basin and the other profile in an area of presumed simple and flat basement structure in eastern New Mexico. The latter profile was chosen to be more representative of the type of basement structure present beneath much of Nebraska and South Dakota (i.e., flat, or gently sloping).

An obvious feature of the profiles is that the nationally-based depth profiles (shown in red) appear smoothed compared to the state profiles (Figure 4-11). The greatest depth differences observed on the depth profiles are seen in areas of the greatest structural relief. In the case of the southern profile through Delaware Basin portion of the Permian Basin, these depth differences exceed 4000 meters with an apparent offset where the deepest part of the basin is located. A possible explanation, based on inspection of the profiles, is that the national data represents more highly smoothed data, consistent with a coarser grid spacing of 5 minutes (~10 km). Because of the larger grid size, basement features of as large as 20-30 km are not well resolved. The Delaware Basin does exceed a depth of 8000 meters, consistent with the Permian Basin study profile as depicted in Figure 4-11, based on data presented in AAPG and USGS (1967) and Ruppel et al. (2005).

We can conclude from the depth profiles that sudden changes in depth characteristic of structurally complex regions are not captured in as much detail on the national map compared to the state maps. In contrast, areas of relatively “flat” basement (New Mexico East-Central Plains Profile) show good agreement in depth estimates that are generally within 200 meters, as can be seen in Figures 4-9 and 4-11. These observations are consistent with the scale and limitations of the national map as described by Blackwell et al. (2007).

5. Conclusions

A GIS database is being developed that allows analysis of technical siting guidelines and their application to siting of a DBH Field Test. Datasets representing technical siting guidelines are represented as maps that can be used in a scoring system to rank potential DBH sites. For example, the heat flow map shows values of heat flow in the US and the location of the 75 mW/m^2 heat flow contour (Figure 3-9). A potential site could be scored in terms of the heat flow value at that site relative to the preferred value of 75 mW/m^2. As with other data for siting guidelines, data compiled at the national scale should be compared to data at the regional or local scale, if available, to determine suitability for supporting siting decisions.

The ability to accurately determine the depth to crystalline basement, particularly to determine whether it is at a depth of 2 km or less, is a key siting factor for siting of a DBH Field Test. A detailed comparison of data for depth to basement at the national and state scale shows that, in areas of relatively simple basement structure, agreement in basement depth between data at different scales is good. Thus, in these areas, the national map can probably be relied on for siting decisions based on depth to basement. For areas of structural complexity involving structural basins, uplifts and faulting, agreement between national and state-scale data sets are not as good, with differences of 1km not uncommon. We note that areas of basement structural complexity would not be preferred for siting based on other siting factors irrespective of the depth to basement.

Reasons for depth discrepancies are most likely due to smoothing of the sediment thickness values inherent in the 5 arc-minute grid spacing used to construct the national depth map. This grid resolution was consistent with the intended use to support a national assessment of geothermal resources. It was not intended to depict areas with a high degree of structural complexity (Blackwell et al., 2007). In addition, the AAPG (1978) basement map of the US (the basis of the digitized national map) may have relied on a smaller number or more restricted distribution of boreholes to constrain crystalline basement geometry compared to what may have become available in the last few years.

Analysis of different data sources for depth to basement highlights the uncertainties inherent in in areas without good borehole control on basement depth. When evaluating potential sites for a DBH Field Test, it will be critical to locate any borehole data near the site to constrain basement depth in concert with other interpretations of available geologic and structural data. Some of the GIS data we have evaluated contains information on the boreholes used to constrain basement depth. In some cases, it may be necessary to commercially acquire borehole data through organizations associated with the oil and gas industry.

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