Status of Shale Geology: Information on Extent, Thickness and Depth of Shale Deposits

Fuel Cycle Research & Development

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Appendix E
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☒ DOE Order 414.1 ☐ NQA-1-2000 ☐ Other

This Deliverable was subjected to:

☐ Technical Review

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Technical Review (TR)

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☐ Signed TR Report or,
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ACRONYMS

DEM	Digital Elevation Model
EIA	Energy Information Administration
GIS	Geographic Information Systems
LANL	Los Alamos National Laboratory
USGS	U.S. Geological Survey

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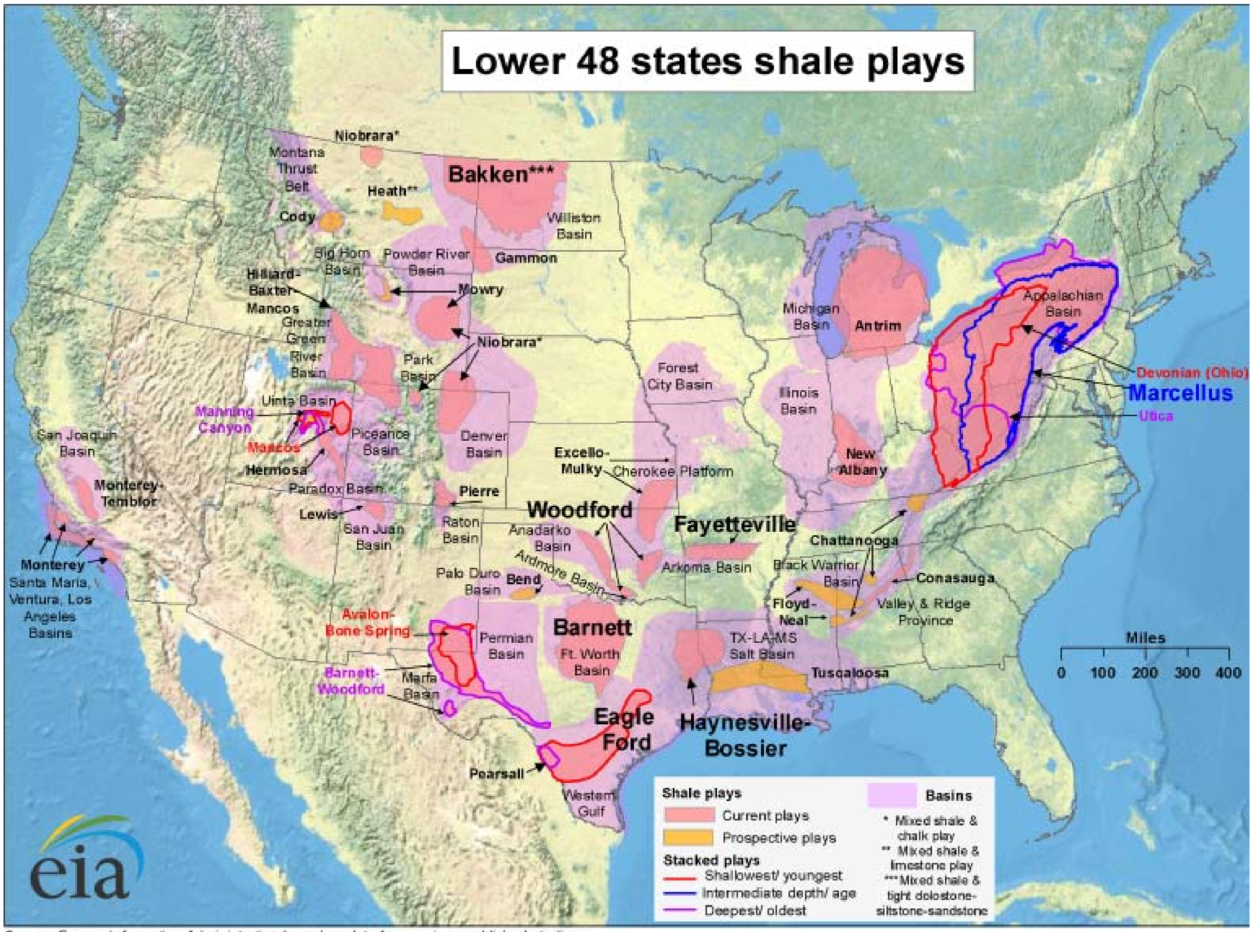
1. INTRODUCTION

The objective of this report is to build upon the compilation of shale formations within many of the major sedimentary basins in the US (e.g., Gonzales and Johnson, 1985; Dobson, 2011) by developing GIS data delineating thickness and structural depth maps for many of these units. These data are being incorporated into the LANL digital database being developed for determining host rock distribution and depth/thickness parameters consistent with repository design (Perry et al., 2011). Three main rock types are being incorporated into this database: salts, shales, and granitic basement rocks. This database can then be utilized for screening and comparison of potential repository sites (e.g., Rechard et al., 2011).

2. DATA SOURCES

Most of the shale data are from sedimentary basins where oil and gas deposits are present (Figure 1). EIA (2011) estimates that around 750 trillion cubic feet of undeveloped technically recoverable shale gas and shale oil resources are in discovered shale plays in the lower 48 states. Formations that have been identified as having at least 20 trillion cubic feet (tcf) of shale gas include the Marcellus Shale (410 tcf), the Antrim Shale (20 tcf), the Haynesville Shale (75 tcf), the Eagle Ford Formation (21 tcf), the Fayetteville Shale (32 tcf), the Barnett and Woodford Shales (97 tcf), and the Mancos Shale (21 tcf). While many areas within these sedimentary basins are sites of active and prospective oil and gas exploration and development activities, there may be locations (such as within the shallower basin margins) that could be possible candidates for a repository.



Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

Figure 1. Shale gas plays in the contiguous US. (EIA, 2011)

The data used for this report represent information that were either digitized using ArcGIS from published isopach and structure maps, or were available as GIS shape files that delineate formation isopachs and structural surfaces relative to a known datum, such as sea level or the ground surface. Many data sources were obtained from the references listed in the discussions in Hovorka et al. (2003) of seal thickness and seal continuity for different saline formations in US sedimentary basins. Where maps were used to create GIS data layers, a jpeg version of the map was georectified using multiple geographic reference points (such as country or state boundaries) and the thickness or structure contours were converted to vector format. Where depths are referenced to sea level instead of the ground surface, DEM data are used. In the case of GIS data, metadata files were used to ascertain the geodetic reference datum used. In some cases, multiple data sources were used.

3. ISOPACH AND STRUCTURE MAPS

Maps of shale formation extents, thicknesses, and depths were obtained for the following units as organized by sedimentary basin. Table 1 summarizes formations for which isopach and/or structural data have been obtained. More comprehensive lists of shale formations can be found in Dobson (2011) and Gonzales and Johnson (1985). Units listed in ***bold italics*** represent formations for which GIS data have been obtained or generated. This report represents the current status of data collection: this is an ongoing process to populate the LANL GIS database.

Table 1. Identified data sources for isopach and structural data for shale formations within major sedimentary basins.

Appalachian Basin	
Utica Shale	Patchen et al., 2006 (Plates 1-28 & 2-6) (GIS data obtained from West Virginia Geological and Economic Survey)
Marcellus Shale	Erenpreiss et al., 2011 (GIS data obtained from Ohio Department of Natural Resources)
Black Warrior Basin	
Chattanooga Shale	Pashin, 2008 (Figure 6)
Illinois Basin	
Maquoketa Shale	Willman et al., 1975 (Figure O-26); Collinson et al., 1988 (Figure 22); Kolata and Noger, 1990 (Figure 5-13); Bristol and Buschbach, 1973 (Plate 1)
New Albany Shale	Hasenmueller and Comer, 2000 (GIS data obtained from Illinois State Geological Survey)
Michigan Basin	
Eau Claire Formation	Catacosinos and Daniels., 1991 (Figure 6)
Antrim Shale	Wylie and Wood, 2004; 2005
Anadarko Basin	
Woodford Shale	Amsden, 1975 (Plates 3 & 4); Cardott and Lambert, 1985 (Figures 2 & 3); Rottmann, 2000
Sylvan Shale	Amsden, 1975 (Plates 7 & 8)
Ardmore Basin	
Woodford Shale	Party et al., 2008 (Slides 41 & 43); Cardott, 2012 (Figure 10); Rottmann, 2000
Arkoma Basin	
Woodford Shale	Blackford, 2007 (Plates 12 & 13); Rottmann, 2000
Gulf Coast Basin	

Wilcox Formation	Pitman, 2008
Eagle Ford Shale	Surles, 1987 (Figures. 5, 8, 9, 12, & 14); Pitman, 2008
Smackover Formation	Pitman, 2008
Fort Worth Basin	
Barnett Shale	Pollastro et al., 2007 (Figures 6 & 15)
Permian Basin	
Woodford Shale	Broadhead, 2010 (Figures. 4 & 12); Comer, 1991 (Plates 1 & 2); Ruppel et al., 2005 (GIS data obtained from University of Texas, Bureau of Economic Geology)
Williston Basin	
Big Snowy Group	Peterson, 1984 (Figure 12)
Pierre Shale	Schurr, 1977 (Figures. 5 & 6)
Powder River Basin	
Pierre Shale	Schurr, 1977 (Figures. 5 & 6)
Lebo shale member, Fort Union Formation	Lewis and Hotchkiss, 1981 (Plate 3)
Upper Hell Creek confining layer, Lance Formation	Lewis and Hotchkiss, 1981 (Plate 5)
Denver Basin	
Pierre Shale	Schurr, 1977 (Figures. 5 & 6)
Green River Basin	
Green River Formation	Mercier et al., 2010c
Piceance Basin	
Green River Formation	Mercier et al., 2010a; Mercier and Johnson, 2012
Uinta Basin	
Green River Formation	Mercier et al., 2010b; Mercier and Johnson, 2012

3.1 Appalachian Basin

The Appalachian Basin is a composite foreland basin that contains a thick sequence of Paleozoic sedimentary rocks (Ettensohn, 2008). These rocks have been subjected to a number of orogenic events, resulting in faulting and folding. The Marcellus Shale has been the primary focus for numerous geologic studies (e.g., Lash and Engelder, 2011) because of its prolific shale gas resources.

GIS data were obtained for two major shale formations in this basin: the Ordovician Utica Shale and the Devonian Marcellus Shale. The Utica Shale GIS dataset was developed as part of a comprehensive regional stratigraphic study conducted by the Trenton-Black River Research

Consortium of the Ordovician Trenton-Black River carbonate system (Patchen et al., 2006). This study generated an interval-thickness map for the Utica Shale (Figure 2) and structural map for the top of the Trenton Limestone (Figure 3), which serves at the base of the Utica Shale. GIS data obtained from the West Virginia Geological and Economic Survey will be used to generate isopach and structure maps for the Utica Shale.

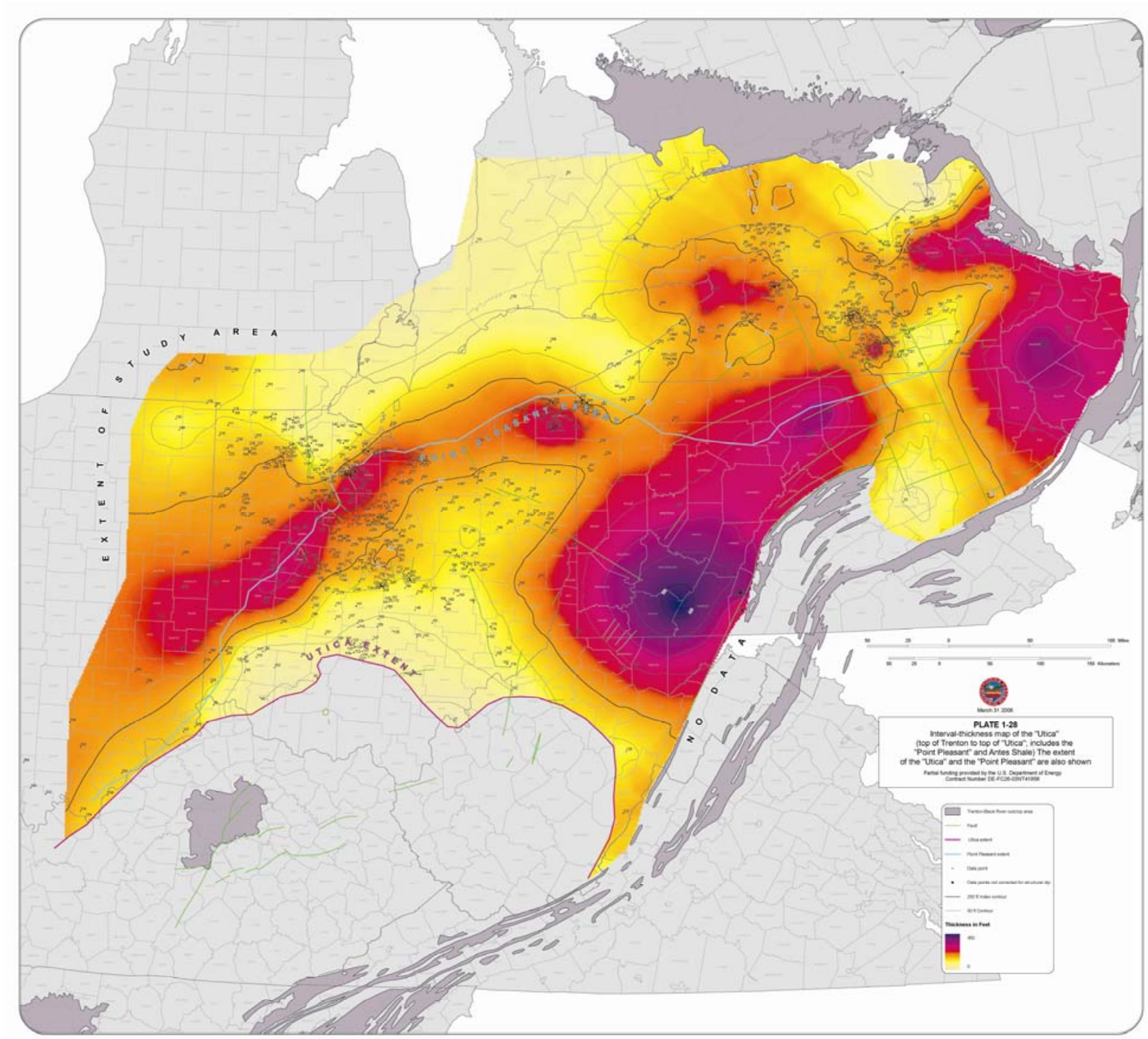


Figure 2. Interval-thickness map for the Utica Shale, Appalachian Basin (Patchen et al., 2006)

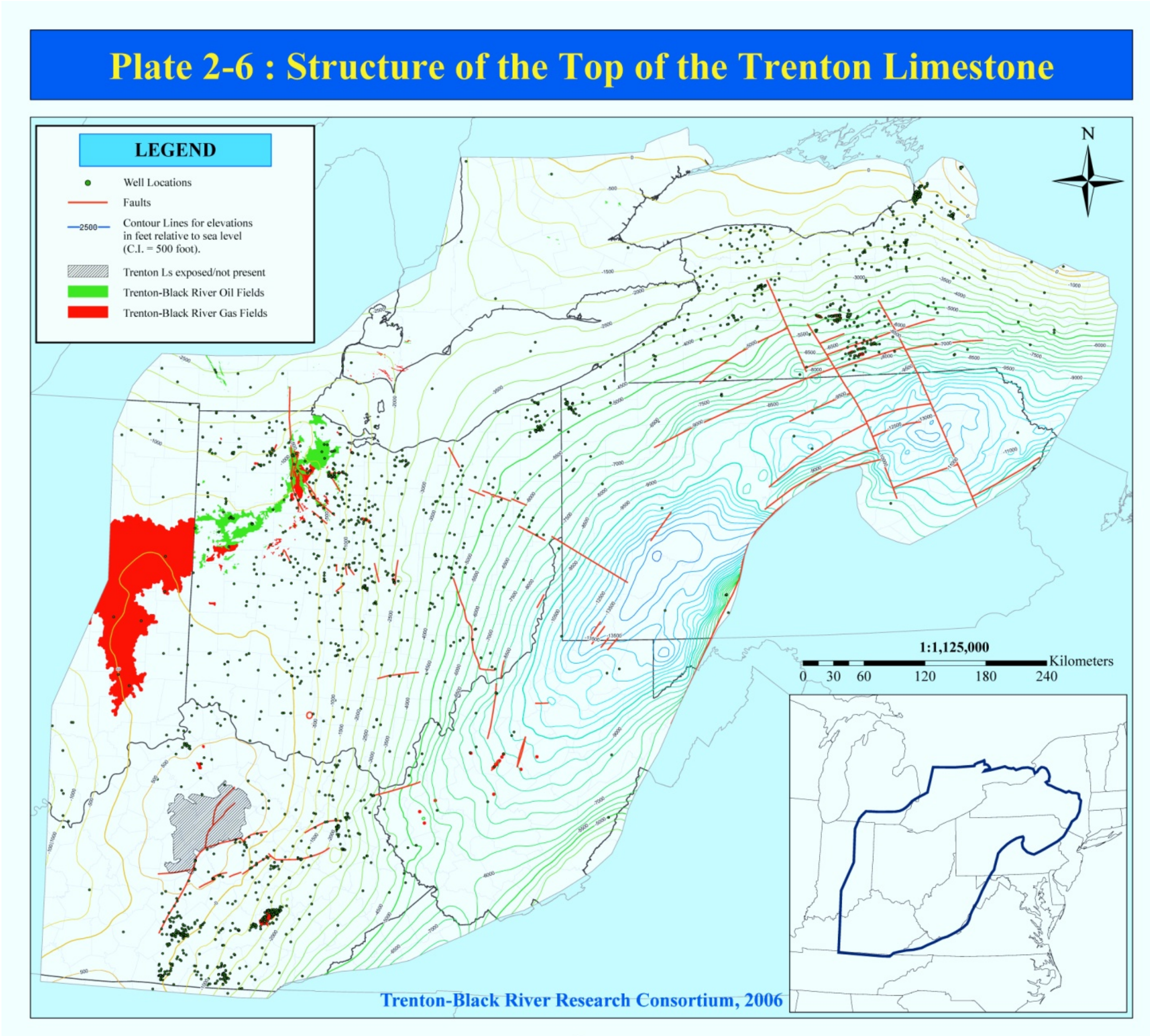


Figure 3. Structure map for the top of the Trenton Limestone, Appalachian Basin (Patchen et al., 2006)

GIS data obtained from the Ohio Department of Natural Resources was used to generate isopach and structure maps for the Marcellus Shale (Figure 4). This unit has a total area of 95,000 square miles (EIA, 2011). While this unit is very extensive, and is present in Ohio, Pennsylvania, West Virginia, Virginia, western Maryland and New York, there is only a limited area (in eastern Pennsylvania) where the shale thickness is at least 100 m at depths less than 1000 m.

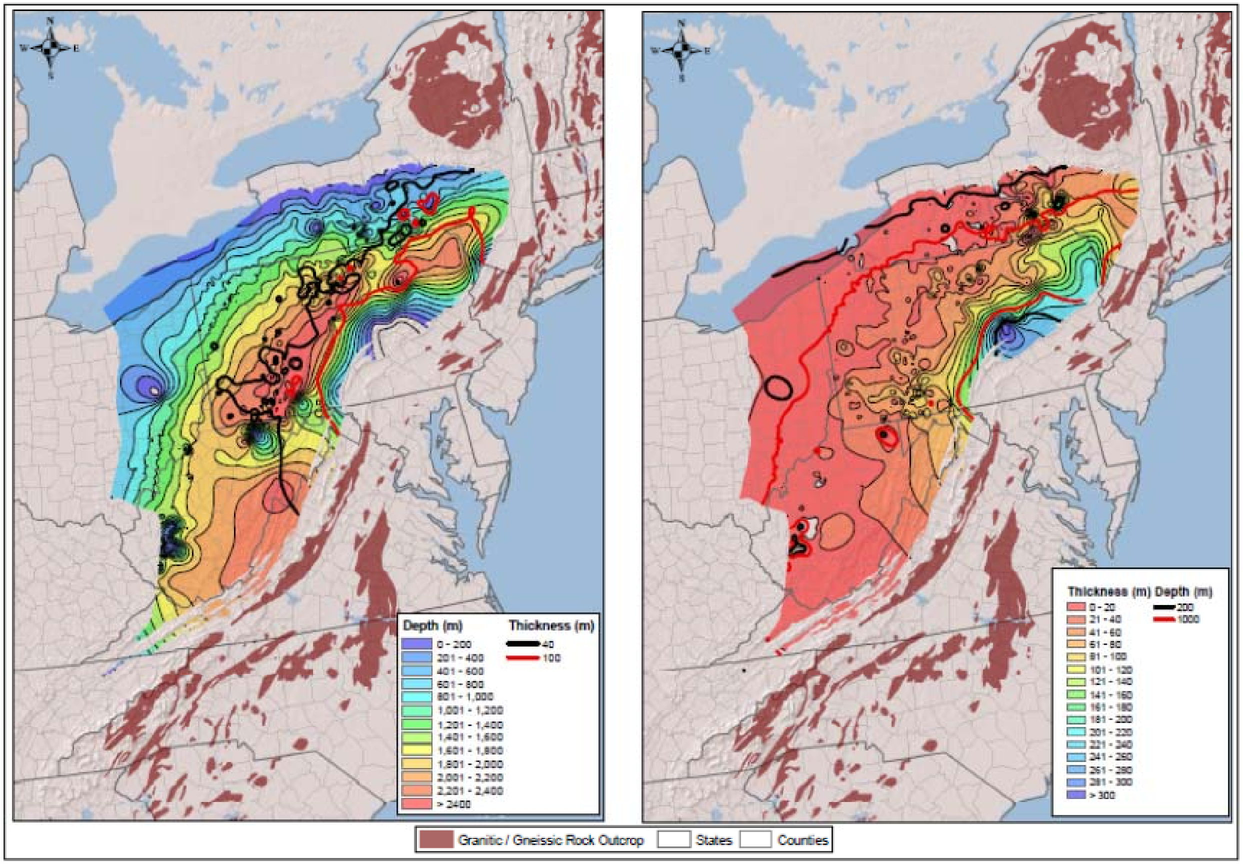


Figure 4. Depth and isopach maps of the Marcellus Shale, Appalachian Basin. Figure produced by LANL from shale data populated into the GIS database.

3.2 Black Warrior Basin

The Black Warrior Basin is a Paleozoic foreland basin located in Alabama and Mississippi (Thomas, 1988). It has three major shale formations: the Devonian Chattanooga Shale, the Mississippian Floyd Shale, and shale layers in the Pennsylvanian Pottsville Formation (Pawlewicz and Hatch, 2007). These shales have been identified as the source rocks for oil and gas deposits in the basin. Pashin (2008) has created an isopach map within the state of Alabama for the Chattanooga Shale (Figure 5). Almost all of the mapped section of the Chattanooga has a thickness less than 30 m.

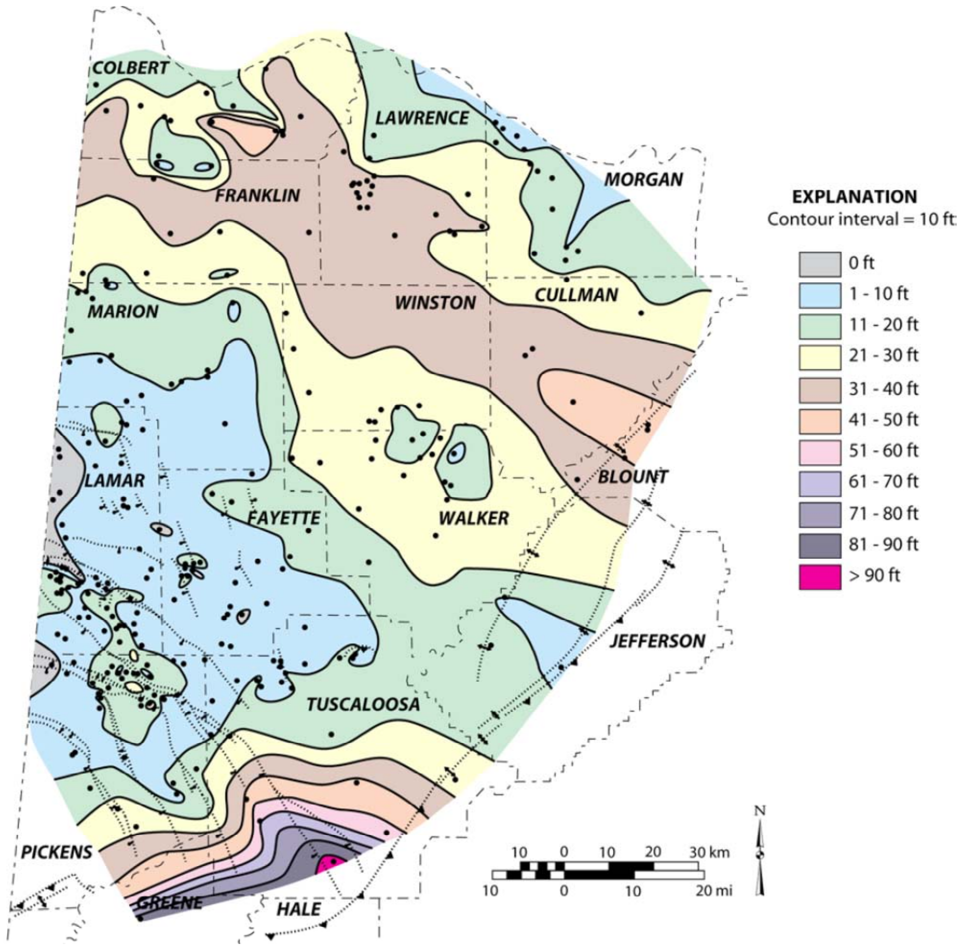
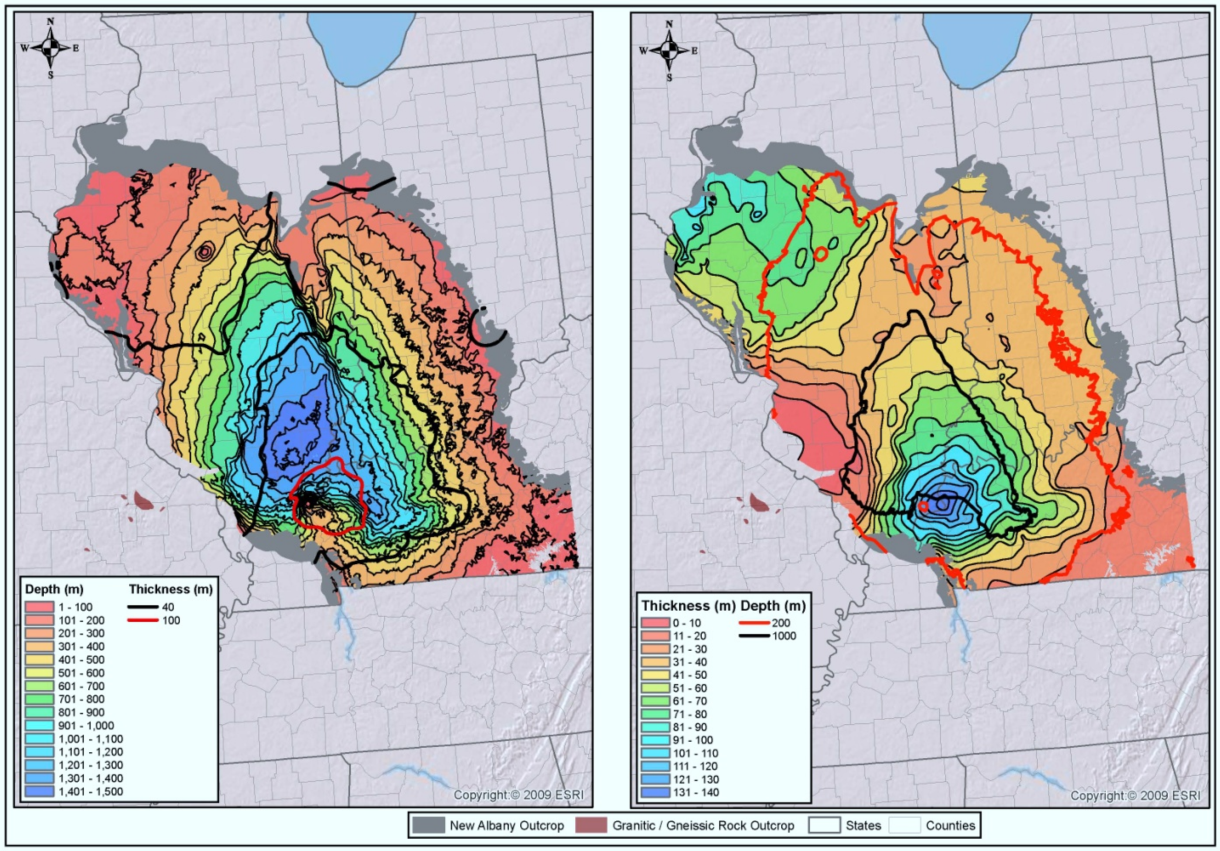


Figure 5. Isopach map of the Chattanooga Shale within the Alabama portion of the Black Warrior Basin (Pashin, 2008)

3.3 Illinois Basin

The Illinois Basin is filled primarily with Paleozoic age rocks, consisting of interbedded siliclastic and carbonate sediments (Collinson et al., 1988; Swezey, 2009). The Devonian to Mississippian New Albany Shale is the most prominent shale unit in the Illinois Basin, with an areal extent of about 43,500 square miles and a thickness of 100 to 300 ft (Hasenmueller and Comer, 1994; EIA, 2011). GIS data for this unit (Figure 6) is available over the entire basin (Hasenmueller and Comer, 2000). In the southern portion of the Illinois basin, there is a small section of this unit with thicknesses greater than 100 m at a depth of less than 1000 m.



Structure Contour and Isopach maps of the New Albany Shale in the Illinois Basin.

Figure 6. Depth and isopach maps of the New Albany Shale, Illinois Basin. Figure produced by LANL from shale data populated into the GIS database.

There are a number of studies with thickness and/or structural depth information on the Ordovician Maquoketa Shale. Bristol and Buschbach (1973) provide a plate depicting the top of the Galena Group, which represents the base of the Maquoketa Shale, for the state of Illinois. Willman et al. (1975) present a figure depicting the thickness of the Maquoketa Group, also restricted to Illinois. More regional depictions of the thickness of this unit (Figure 7) are presented by Collinson et al. (1988) and Kolata and Noger (1990). Given that this unit is older than the New Albany Shale, it is encountered at greater depths.

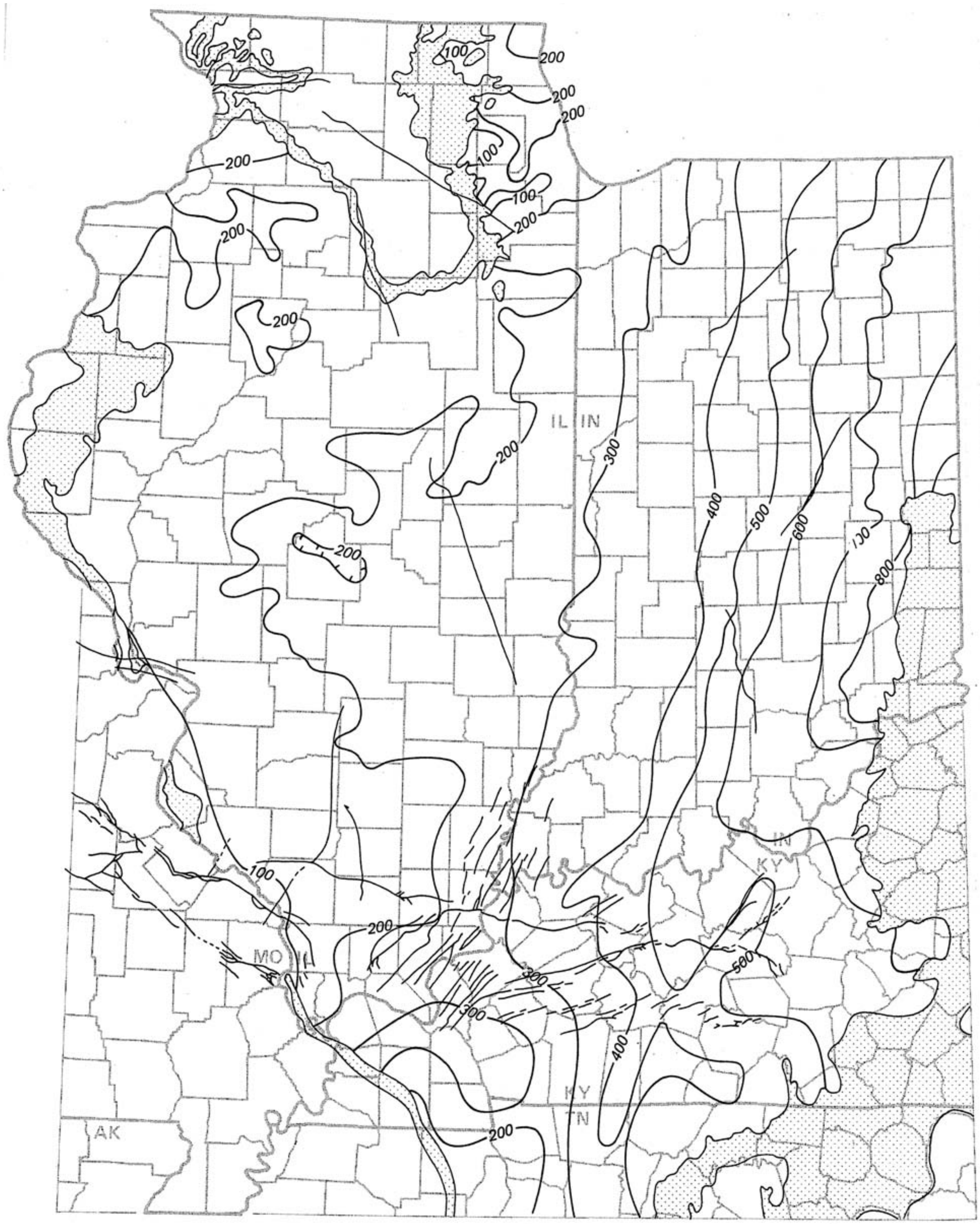


Figure 7. Isopach map of the Maquoketa Shale Group in the Illinois Basin (Collinson et al., 1988). Thickness contours are in feet. Stippled areas represent where the Maquoketa crops out and where it is unconformably overlain by rocks younger than Silurian in age.

3.4 Michigan Basin

The Michigan Basin has a thick sequence of Paleozoic evaporites, carbonates, and siliclastic sedimentary rocks (Catacosinos et al., 1991; Swezey, 2008). Shale formations found in this basin include the Ordovician Utica and Collingwood Shales, the Silurian Cabot Head and Pointe aux Chenes Shales, the Devonian Antrim, Ellsworth, and Bedford Shales and the Mississippian Sunbury and Coldwater Shales. The predominant shale formation in the Michigan Basin is the Antrim Shale, a major producer of natural gas, with estimated recoverable shale gas resources of 20 trillion cubic feet (EIA, 2011). Wylie and Wood (2004; 2005) generated GIS structure and isopach maps for a number of the hydrocarbon producing units in the Michigan Basin, including the Antrim Shale (Figure 8).

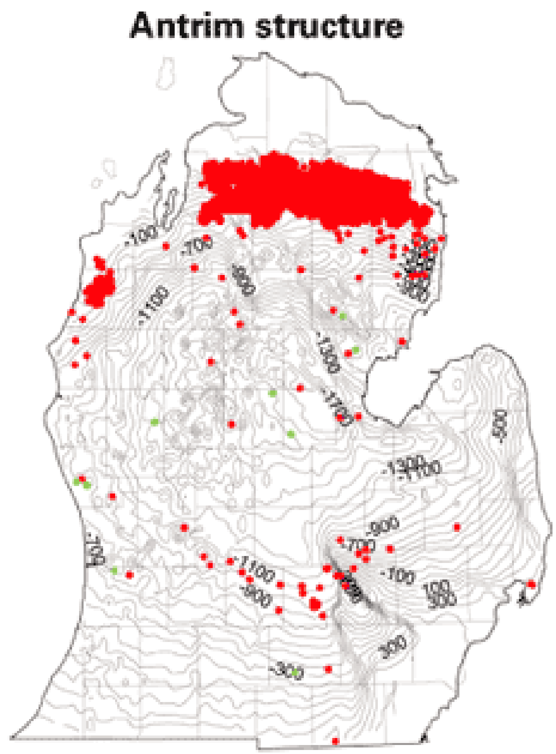


Figure 8. Structure map of the Antrim Shale, Michigan Basin (Wylie and Wood, 2005). Gas wells are depicted as red dots.

3.5 Anadarko, Ardmore, and Arcoma Basins

The Anadarko, Ardmore, and Arcoma Basins, located in Oklahoma and neighboring states, are a series of fault-bounded sedimentary basins containing abundant hydrocarbon deposits. Detailed structure and isopach maps have been published for a number of the shale-bearing formations in these basins, including the Sylvan and Woodford shales (e.g., Amsden, 1975; Cardott and Lambert, 1985; Rottmann, 2000; Blackford, 2007; Party et al., 2008; Cardott, 2012). Rottmann (2000) has generated a comprehensive thickness map for the Woodford Shale for all of Oklahoma and the Texas Panhandle (Figure 9). GIS data were generated from the structure and isopach maps of Amsden (1975) for the Woodford Shale within the Anadarko Basin (Figure 10).

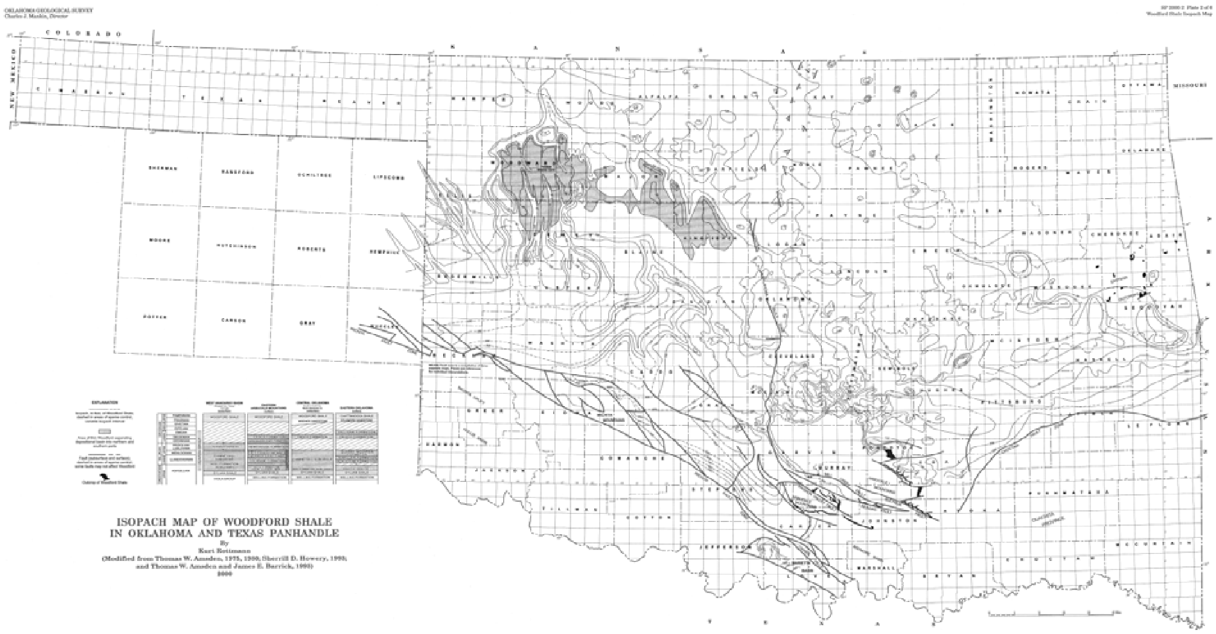


Figure 9. Isopach map of the Woodford Shale (Rottmann, 2000).

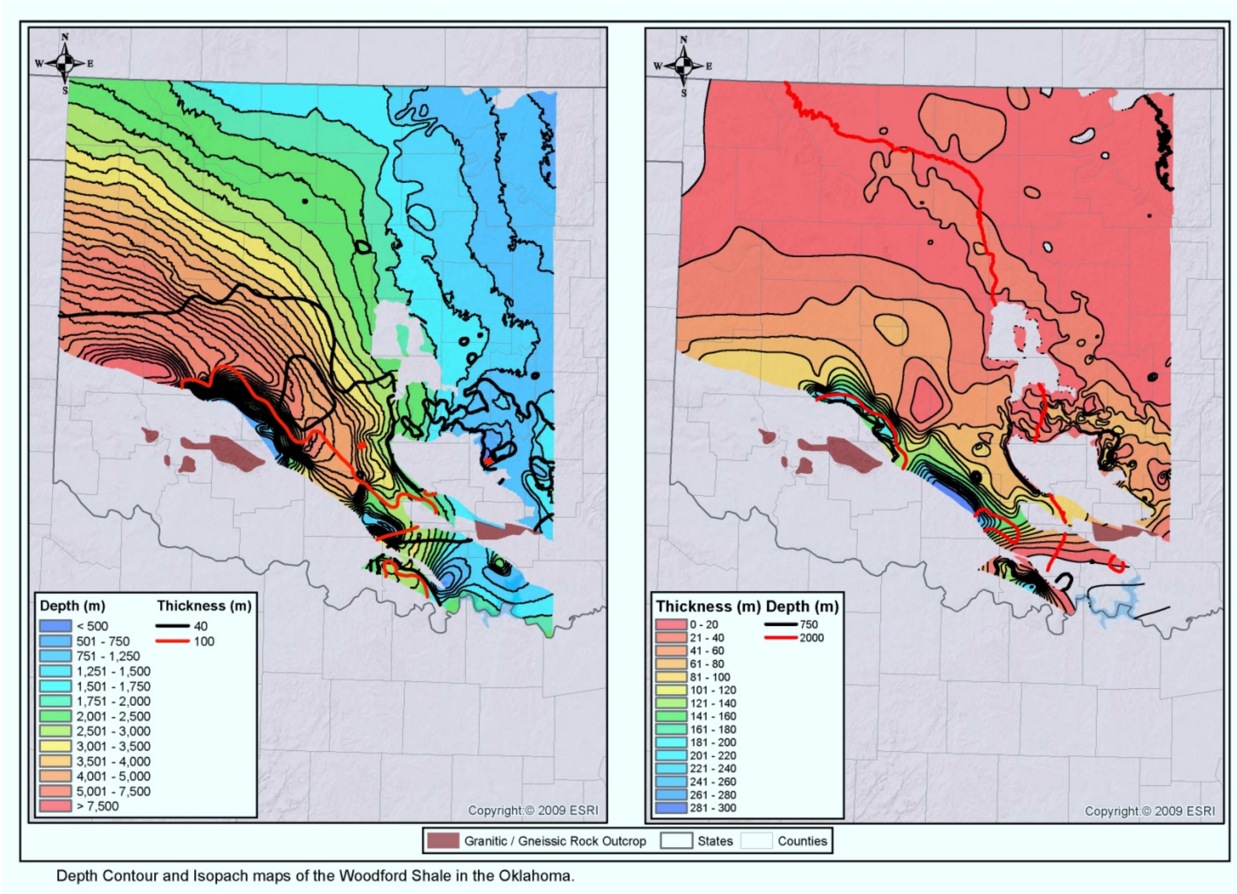


Figure 10. Depth and isopach maps of the Woodford Shale, Anadarko Basin. Figure produced by LANL from shale data populated into the GIS database.

3.6 Gulf of Mexico Basin

Pitman (2008) generated a comprehensive GIS database of petroleum reservoirs in Gulf of Mexico Basin, including delineation of the Smackover, Eagle Ford, and Wilcox Formations (Figure 11). Surles (1987) constructed isopach maps for the entire Eagle Ford shale and its members, as well as compiled information on the amount of sand and organic matter.

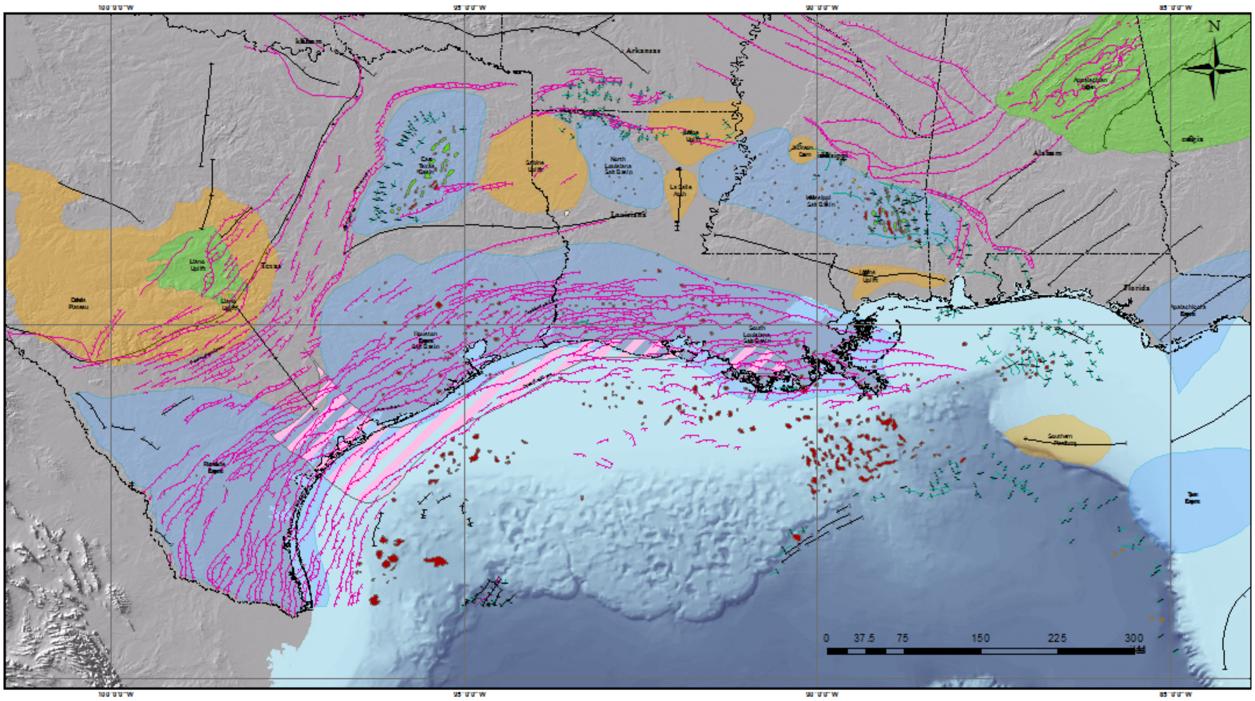


Figure 11. Oil and gas reservoirs in the Gulf of Mexico Basin (Pitman, 2008)

3.7 Fort Worth Basin

The Mississippian Barnett Shale is a major producer of shale gas in the Fort Worth Basin. Pollastro et al. (2007) conducted a detailed geologic study of this petroleum system, and generated isopach and structure maps for the Barnett Shale (Figure 12).

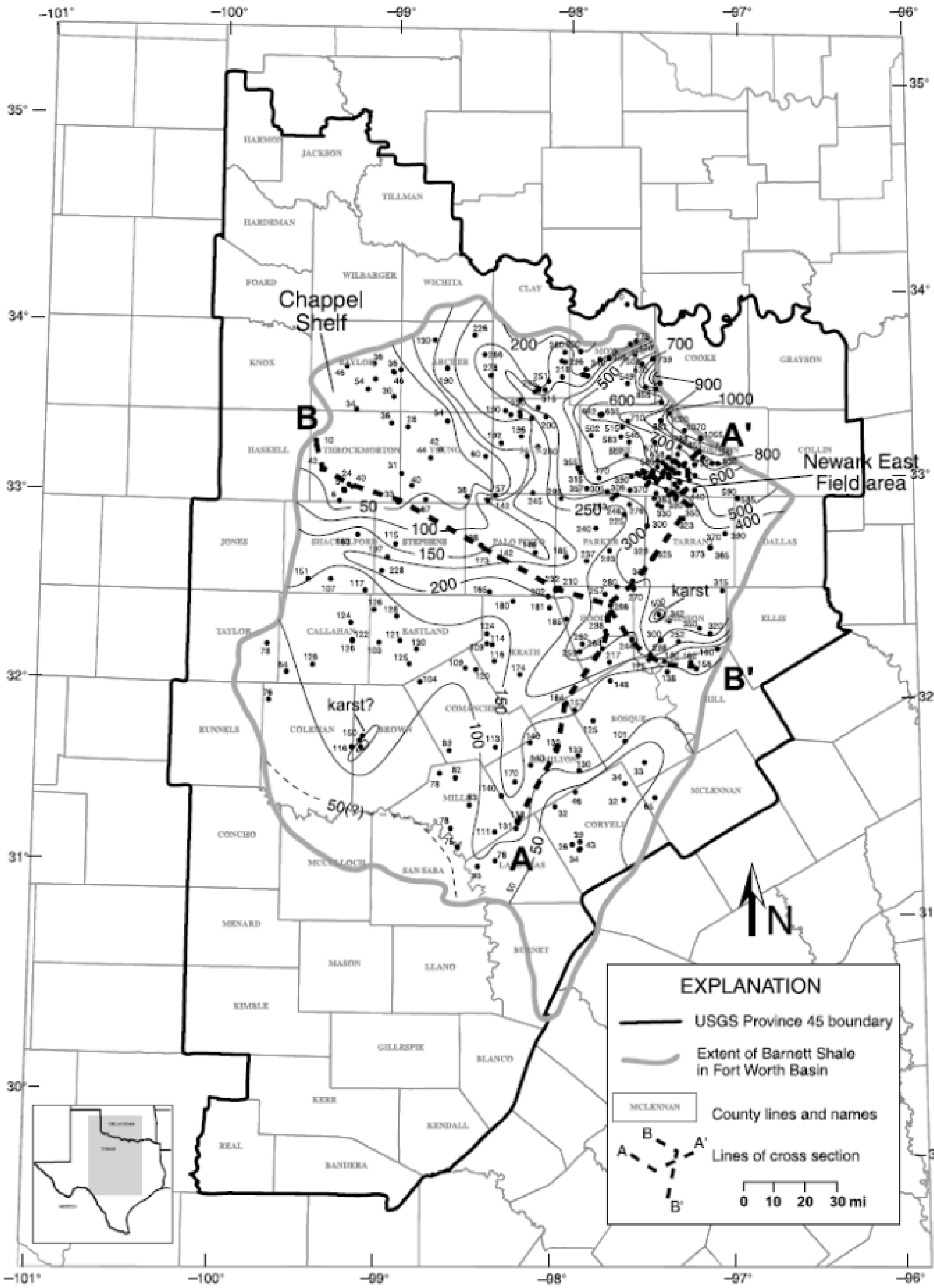


Figure 12. Isopach map for the Barnett Shale, Fort Worth Basin (Pollastro et al., 2007)

3.8 Permian Basin

While the Permian Basin is dominated by carbonate and evaporite sequences, it also hosts some siliclastic units, such as the Woodford Shale. Broadhead (2010) conducted a detailed study of the distribution and source rock characteristics of the Woodford Shale located within the New Mexico portion of the Permian Basin. Structure and isopach maps for the Woodford Shale (Comer, 1991) were converted into GIS surfaces by Ruppel et al. (2005), and are depicted in Figure 13.

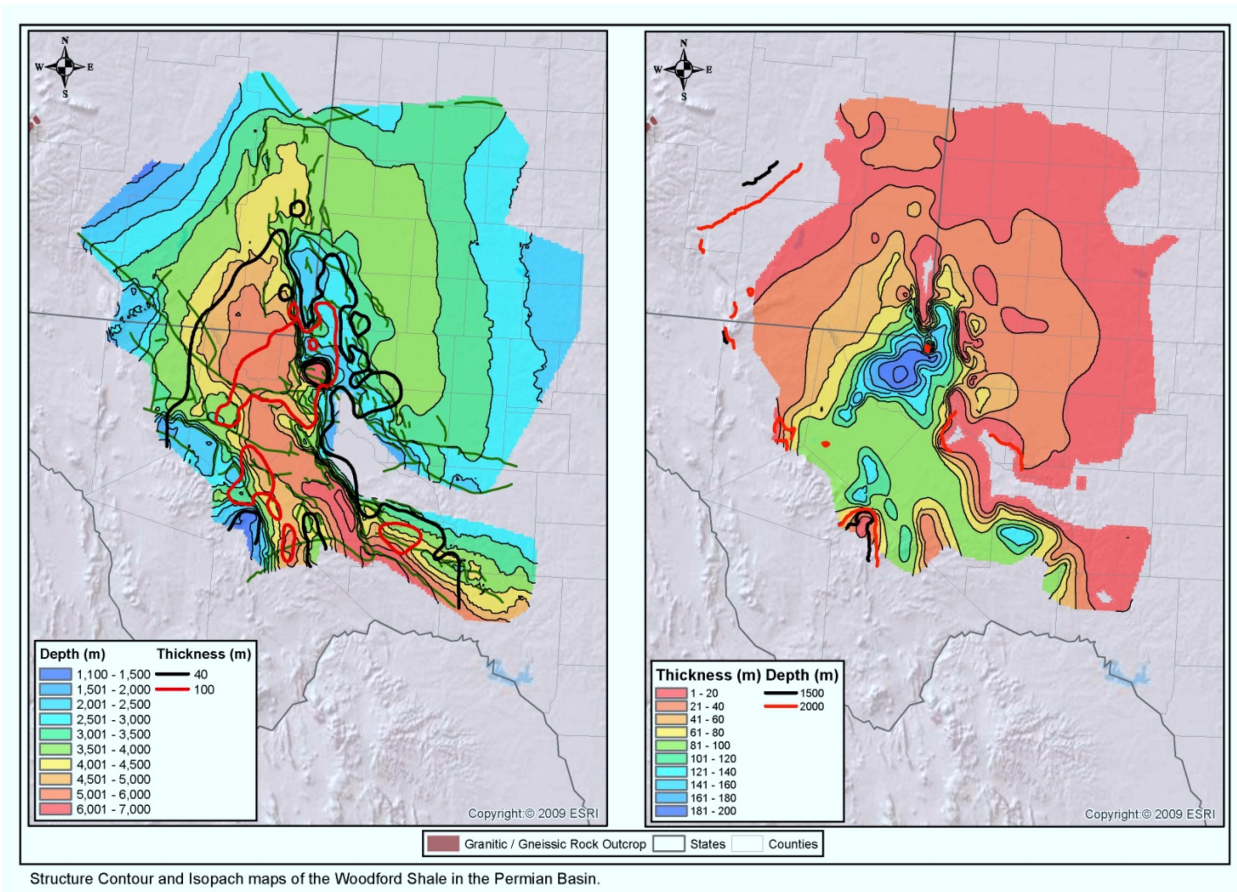
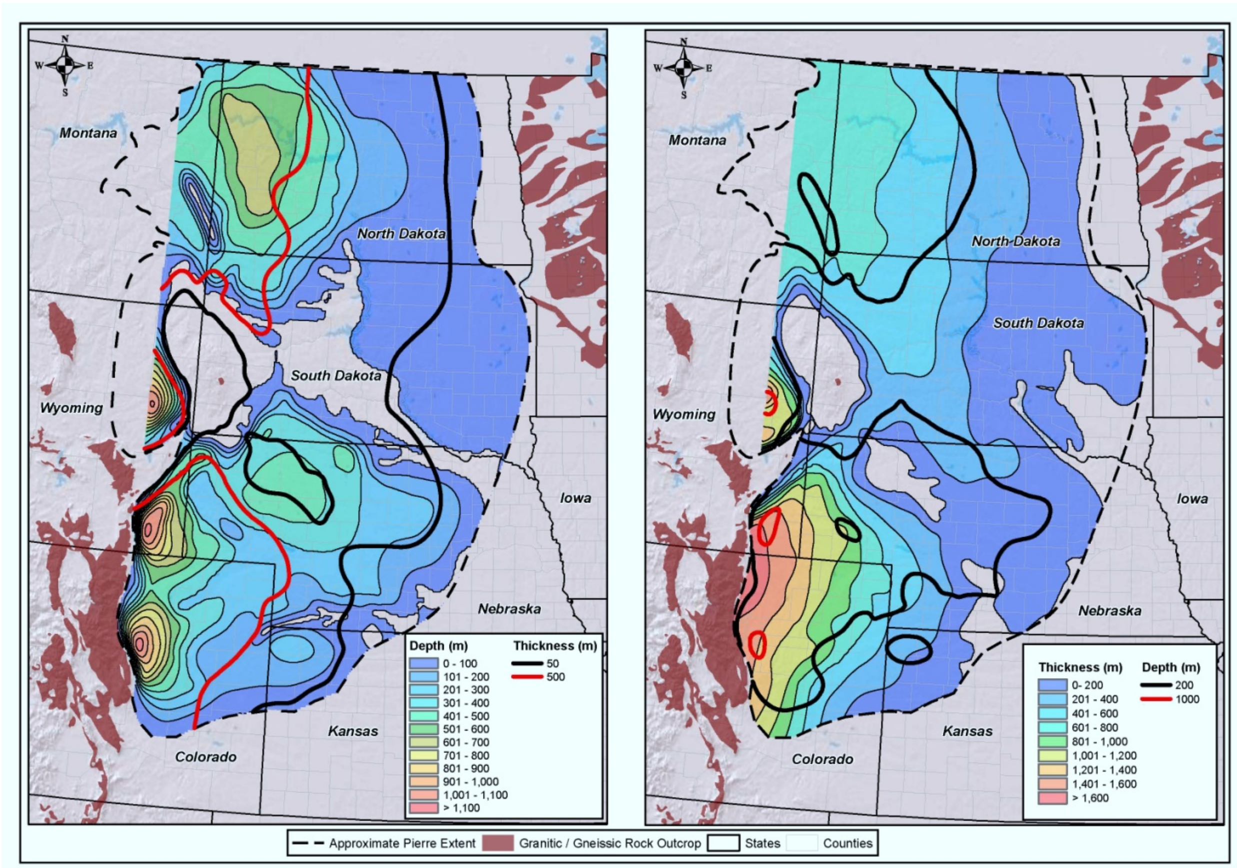


Figure 13. Depth and isopach maps of the Woodford Shale, Permian Basin. Figure produced by LANL from shale data populated into the GIS database.

3.9 Williston Basin

The Williston Basin is an intercratonic basin centered in North Dakota with sedimentary rocks consisting of carbonates, evaporites, sandstones, and shales. These rocks range in age from Precambrian to Tertiary (Gerhard et al., 1982). Shale-bearing units within the Paleozoic section include the Ordovician Ice Box Formation and the Mississippian Bakken and Otter Formations. The Bakken Formation has upper and lower shale members and a middle sandstone member (Pollastro et al., 2008) and contains significant (3.59 billion barrel) reserves of oil shale (EIA, 2011). The basin also contains a sequence of Cretaceous shales, including the Skull Creek, Mowry, Belle Fourche, Carlile, and Pierre Shales. Shurr (1977) conducted an extensive study of the Pierre Shale as a possible host formation for radioactive waste. Isopach and structural maps from Shurr (1977) were used to generate GIS data (Figure 14).



Depth and Isopach maps of the Pierre Shale in the nothern Great Plains.

Figure 14. Depth and isopach maps of the Pierre Shale Williston, Powder River, and Denver Basins. Figure produced by LANL from shale data populated into the GIS database.

3.10 Powder River Basin

The Powder River Basin contains vast coal resources, consisting of thick deposits of subbituminous or lignite coal occurring at shallow depths. As part of a hydrogeologic study of this basin, Lewis and Hotchkiss (1981) generated isopach and structure maps for the Lebo Shale member of the Ft. Union Formation (Figure 15) and the Upper Hell Creek (or Lance) Formation.

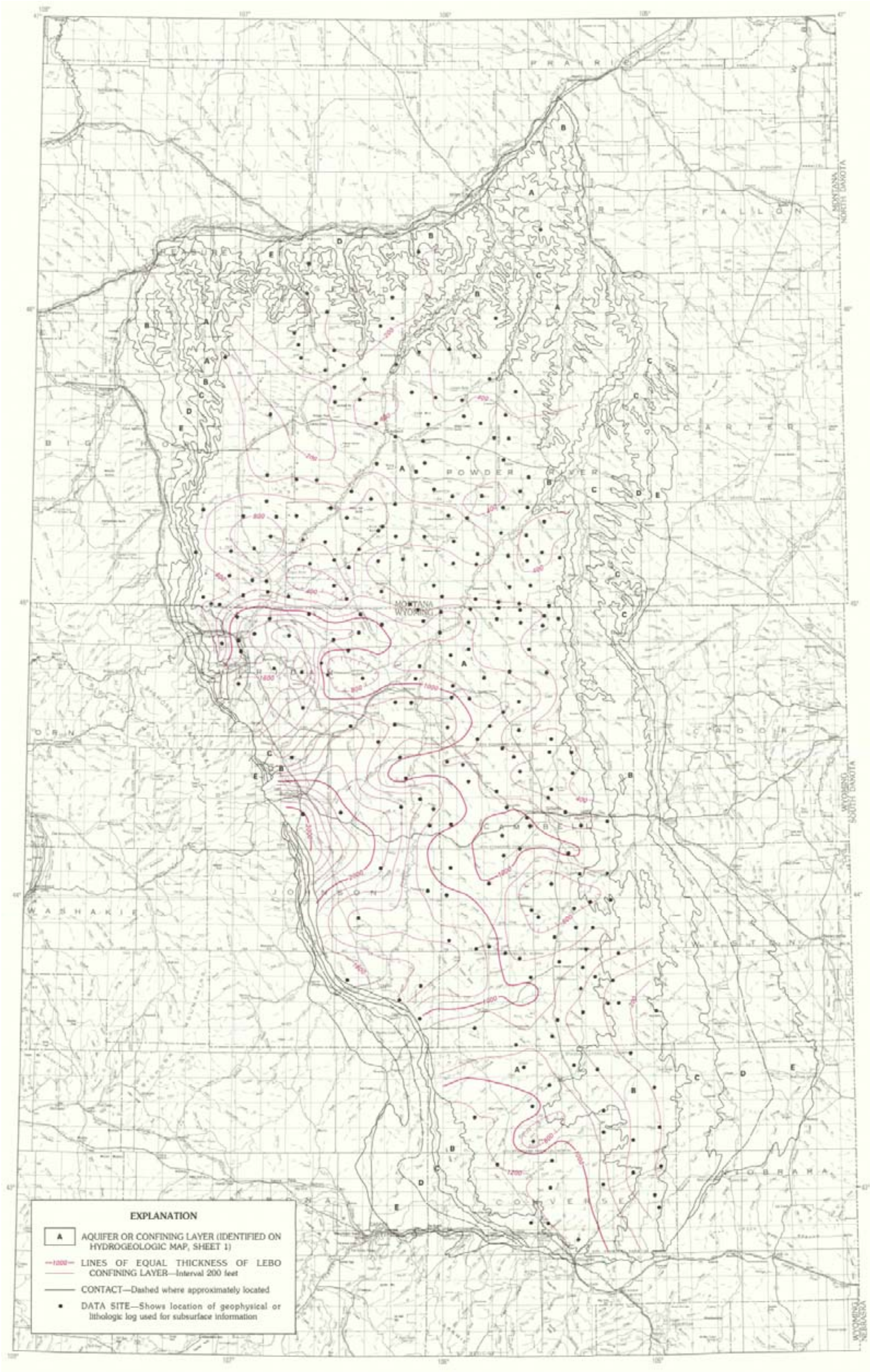


Figure 15. Isopach map of the Lebo Shale member of the Ft. Union Formation, Powder River Basin (Lewis and Hotchkiss, 1981)

3.11 Denver Basin

The Denver Basin is a foreland structural basin bounded to the west by the Rocky Mountains. Most of the sediments in the basin are Cretaceous sandstones, shales, and carbonates (Higley and Cox, 2007); the shale units include the Skull Creek, Mowry, Graneros, Carlile, Niobrara (Smoky Hills Shale Member), and Pierre. The Pierre Shale is the most prominent of these units, and its distribution and thickness (Figure 14) has been characterized by Shurr (1977).

3.12 Green River, Piceance, and Uinta Basins

The Green River, Piceance, and Uinta Basins are located in Wyoming, Utah and Colorado. These basins contain major shale-bearing intervals (USGS Southwestern Wyoming Province Assessment Team, 2005; Dubiel, 2003; Johnson, 2003; Kirshbaum, 2003; USGS Uinta-Piceance Assessment Team, 2003; Johnson et al., 2010). The oldest of these units is the Permian Phosphoria Formation, which contains organic-rich mudstones. These basins also contain a number of shales that are Cretaceous in age, including the Baxter, Hillard, Steele, and Lewis Mancos and Mowry Shales. Present in all three of these basins is the Eocene Green River Formation, which contains the world's largest oil-shale deposit, with about 1.2 trillion barrels of oil in place (Dubiel, 2003). The Green River Formation consists of interbedded oil shales (such as the Parachute Creek Member), organic shales, evaporites, siltstones, sandstones, and mudstones. The USGS has generated GIS data that maps the thickness and structure of different members of the Green River Formation in these three basins as part of an oil shale resource assessment (Mercier et al., 2010a, b, c; Mercier and Johnson, 2012). Figure 16 illustrates the thickness of the Green River Formation in the Piceance and Uinta Basins.

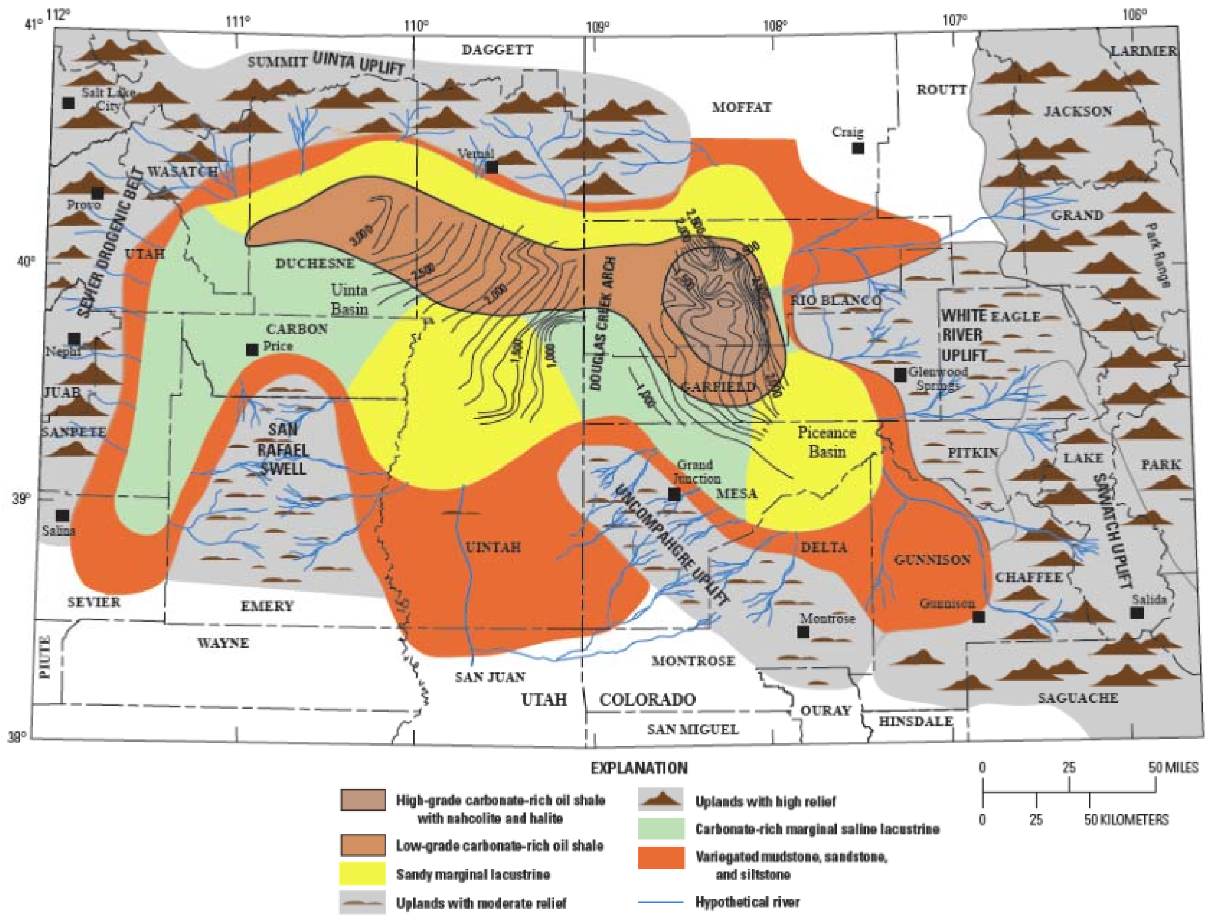


Figure 16. Paleogeographic map of the Piceance and Uinta Basins, with isopachs depicting the thickness of the Green River Formation from the base of the Long Point bed to the top of the Mahogany oil shale zone (Mercier and Johnson, 2012)

4. CONCLUSIONS

This report serves as an update report relating to the progress of obtaining shale formation extent, thickness and depth data for the LANL geologic database. GIS data have been obtained for many shale formations associated with shale gas, such as the Marcellus, Utica, Barnett, New Albany and Woodford Shales. Additional GIS data are in the process of being generated through the digitization of published isopach and structure maps. Continued efforts are being made to obtain additional GIS and map data for other shale formations that can be used to augment the GIS database.

5. ACKNOWLEDGMENTS

This report represents a collaborative effort with Frank Perry and Rick Kelley of Los Alamos National Laboratory. They have scanned and generated GIS data from pdf versions of isopach and structure maps, and have uploaded existing GIS data into their database.

Many individuals generously shared their knowledge and data to help populate the GIS database. Steve Ruppel and Cari Breton of the University of Texas, Bureau of Economic Geology, provided us with their GIS dataset for the Permian Basin. John Bocan, with the West Virginia Geological and Economic Survey, provided us with GIS data for the Utica Shale that had been developed by the Trenton-Black River Research Consortium. Jim McDonald of the Ohio Department of Natural Resources shared with us a regional GIS dataset for the Marcellus Shale. Christopher Korose of the Illinois State Geological Survey provided us with GIS data for the New Albany Shale that was developed by the Illinois Basin Consortium. Jeff Zimmerman of the Susquehanna River Basin Commission provided us with some USGS GIS data for the Utica and Marcellus Shales. David Effert of the Louisiana Department of Natural Resources gave us access to GIS data for the Haynesville Shale. Brian Cardott of the Oklahoma Geological Survey provided us with additional references on the Woodford Shale and Sue Palmer (also of the Oklahoma Geological Survey) provided us with pdf copies of plates depicting the thickness and depth of the Woodford Shale in the Anadarko Basin. Sue Hovorka of the University of Texas, Bureau of Economic Geology, pointed us towards a study conducted by the Gulf Coast Carbon Center, which contains abundant information regarding seals (i.e., shales) in many sedimentary basins in the US. Jim Houseworth, Peter Persoff, and Frank Perry reviewed this report and their feedback was greatly appreciated. Editorial assistance was also provided by Helen Prieto.

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