FINAL TECHNICAL REPORT

National Earthquake Hazards Reduction Program
Award Number G15AP00009

ISOBATH AND CLAY CAP SURVEY OF THE NEW MADRID SEISMIC ZONE IN SOUTHEAST MISSOURI

Authors
Thomas Herbst, Vicki Voigt and Cheryl M. Seeger (Principal Investigator),
Email: thomas.herbst@dnr.mo.gov; vicki.voigt@dnr.mo.gov; cheryl.seeger@dnr.mo.gov;
Missouri Department of Natural Resources,
Missouri Geological Survey
111 Fairgrounds Road, P.O. Box 250, Rolla, MO 65402
Phone: (573) 368-2100; URL dnr.mo.gov
Fax: 573-368-2111

Award Term
December 1, 2014 to November 30, 2015

Keywords
Static water level, depth to groundwater, alluvial aquifer, liquefaction,
southeast Missouri, Mississippi Embayment, New Madrid Seismic Zone

December 2015

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number G15AP00009. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Award G15AP00009
ISOBATH AND CLAY CAP SURVEY OF THE NEW MADRID SEISMIC ZONE, SOUTHEAST MISSOURI

Thomas G. Herbst, Vicki Voigt and Cheryl M. Seeger

Missouri Department of Natural Resources, Missouri Geological Survey
111 Fairgrounds Road, P.O. Box 250, Rolla, MO 65402
thomas.herbst@dnr.mo.gov; vicki.voigt@dnr.mo.gov; cheryl.seeger@dnr.mo.gov;
Phone: (573) 368-2184

ABSTRACT

The Missouri portion of the Mississippi Embayment (study area) lies within the New Madrid Seismic Zone. Historically and prehistorically, the area has produced large magnitude seismic events (Tuttle et al., 1999, 2002, 2005; Tuttle, 2001; Guccione, 2005). An alluvial aquifer defines the water table, causing the region to be susceptible to liquefaction during a magnitude (M) 5.5 or greater event (Obermeier, 1994, 2009). Published earthquake hazard maps of the region presented only broad-brush views of potential liquefaction criteria for the study area (Obermeier, 1989; Marcus, 1993; Hoffman, 1997, 1999; Haselwander, 2013).

Liquefaction susceptibility hinges on two key criteria – a shallow water table and the presence of a fine-grained confining unit, or cap, over cohesionless sand deposits, both found in the study area. During the 1811 and 1812 events, substantial liquefaction occurred throughout the study area, which, if occurring today, would result in extensive damage. Swamplands present during the 1811 and 1812 events have been drained extensively due to agricultural development. Modern agriculture practices associated with prolific rice cultivation have increased the utilization of irrigation wells since the 1970s, potentially altering liquefaction risk related to depth to groundwater from the 1811 and 1812 susceptibility levels.

This multi-part Geographic Information System (GIS)-based mapping project used internal Missouri Geological Survey (MGS) and Missouri Department of Natural Resources (MDNR) water well record databases and files along with other appropriate external data sources to delineate potential liquefaction risk by spatially defining regions whose characteristics match criteria for liquefaction susceptibility based on static water levels (SWLs) and the presence and thickness of a clay-rich cap overlying alluvial sand deposits. Isobath maps and GIS files for pre-1971 and post-2000 water levels established baselines for determination of potential changes in groundwater depth related to agricultural pumping; a derivative map and GIS file created from those data shows pumping-induced water level changes. An isochore map and GIS file of the clay-rich cap helped define liquefaction hazard risk. These maps and GIS-based data will aid in disaster response, emergency management, preventative planning measures and regional earthquake hazards assessments, as well as provide data for future liquefaction susceptibility studies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

The New Madrid Seismic Zone (NMSZ) is an active intraplate right-lateral strike-slip fault system that has produced multiple large magnitude seismic events, including the historic 1811 and 1812 earthquakes (Tuttle and others, 1999, 2002, 2005; Tuttle, 2001; Guccione, 2005). The NMSZ includes the Missouri portion of the Mississippi Embayment (study area) (fig. 1), located in the extreme southeastern part of the state. The study area contains Interstate and federal highways, rail routes, pipelines, electric transmission lines, regulated and non-regulated dams and power plants (Marcus, 1993; Hoffman, 1997, 1999). An earthquake of M5.5 or greater could cause extensive liquefaction in the region (Obermeier, 1994, 2009) and major disruption of infrastructure. Existing small-scale hazard maps quantify the entire study area at the same level of liquefaction risk (Marcus, 1993; Hoffman, 1997, 1999; Haselwander, 2013) or only have general risk differentiation (Obermeier, 1989).

Figure 1. The Missouri portion of the Mississippi Embayment in southeast Missouri (study area). Extent of the Alluvial Aquifer is shown in tan. Excluded areas (Crowley's Ridge, other highlands and Birds Point New Madrid Floodway) are indicated. Black dot marks the hydrologic connection of the alluvial aquifer between the Eastern and Western lowlands (Luckey, 1985).

Obermeier (2009) notes that, within the NMSZ, the geology and topography tend to have greater control on formation of liquefaction features than does the direction of shaking. In addition, work by Obermeier (1989) on general distributions of sand blows and fissures shows that this region had variable liquefaction susceptibility in the historic 1811 and 1812 earthquake events, and suggests that similar variability would occur today in a large magnitude seismic event. Recent studies in the region primarily have focused on paleoseismic liquefaction features for determination of earthquake magnitude and recurrence cycles, and include Obermeier (1988, 2009), Tuttle and Schweig (1996), Li and others (1998), Tuttle and others (1999, 2002, 2005), Tuttle (2001), Obermeier and others (2001) and Guccione (2005), to note a few. Factors that increase liquefaction susceptibility, such as a shallow water table and the presence of a fine-grained confining unit, or cap, over cohesionless sand deposits, have not been evaluated for current geologic and hydrologic conditions in the study area. Extensive historic draining of lowland areas and recent expansions in rice cultivation using high-yield agricultural pumping of groundwater for flooded field methods are both factors that potentially have altered the depth to the water table throughout the region, possibly impacting the liquefaction susceptibility in the study area.

The Missouri Department of Natural Resources' (MDNR) Missouri Geological Survey (MGS) completed a multi-part project to address earthquake hazards and reduction in losses related to liquefaction through development of isobath maps and GIS files and collection of required surficial material data that can be used in construction of predictive models for liquefaction susceptibility in the Missouri portion of the Mississippi Embayment. The intent is to highlight several key liquefaction susceptibility criteria and define their current geologic and hydrologic conditions in the study area by spatial delineation of the depth to the water table and the presence and thickness of a clay-rich cap overlying alluvial sands.

2.0 GEOLOGIC AND HYDROLOGIC SETTING

The Missouri Bootheel, composing the Missouri portion of the Mississippi Embayment, currently is Missouri's highest producing agricultural district (Miller and Vandike, 1997). Characterized by a shallow water table and thick Quaternary alluvial deposits, the Alluvial Aquifer, originally deposited by the ancestral Mississippi and Ohio rivers, can attain thicknesses of more than 300 feet and forms the region's most widely-used aquifer. A fine-grained layer consisting of clay and silt resides primarily near the surface, overlying thicker sand deposits and isolated thin units of gravel. Consolidated bedrock crops out in Crowley's Ridge, located in the northwest region of the Embayment (figure 1). The lowlands composing the study area are divided into Eastern and Western sections by Crowley's Ridge, which separates the Alluvial Aquifer hydrologically. The study area is bounded by the Mississippi River to the east, bedrock formations that make up the Ozark Escarpment to the north and west, and the Arkansas-Missouri state boundary on the south and west.

Earthquake Hazards

The Mississippi Embayment lies within the New Madrid Seismic Zone (NMSZ) and therefore is at risk during an earthquake in the NMSZ. Historically and prehistorically, the area has produced large magnitude seismic events (Tuttle and others, 1999, 2002, 2005; Tuttle, 2001;

Guccione, 2005) as well as numerous smaller events (figure 2). This area is particularly at risk of subsequent liquefaction occurring from a M5.5 or greater seismic event (Obermeier, 1994, 2009). If such an event were to occur today, damage from liquefaction features, such as sand blows and fissures, could be significant.

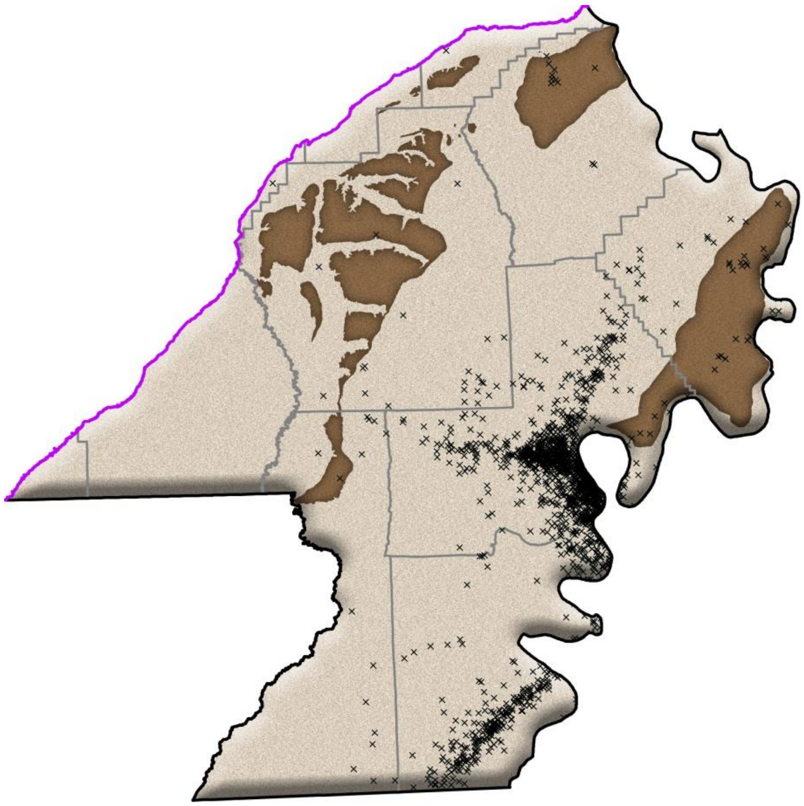

Figure 2. Earthquake epicenters in the study area recorded from 1973 to 1999. Earthquakes occur along active faults at depths ranging from 1 to 20 km. The faults are not expressed at the surface. Areas excluded from the study are shown in brown. Purple line represents boundary of the Ozark highlands.

Liquefaction susceptibility hinges on two key criteria—a shallow water table and the presence of a fine-grained confining unit, or cap, over cohesionless sand deposits as seen in the study area. Liquefaction is most likely to occur when the thickness of this clay-rich cap is five meters (16.4 feet) or less. For thicknesses greater than five meters but less than 10 meters (32.8 feet) the susceptibility drops from high to moderate. At thicknesses greater than 10 meters, susceptibility approaches zero (Obermeier, 2009). Low topographic relief also can be a contributing factor for liquefaction (Obermeier, 1994, 2009; Obermeier and Pond, 1999; Obermeier and others, 2005). Excluding Crowley's Ridge, Missouri's Bootheel has notably low local relief, often varying by three meters (~10 feet) or less. Elevations vary from 70 to 120 meters at the lowest and highest points of the lowlands.

3.0 METHODOLOGY

All map and GIS file development involved use of existing MGS and other MDNR water well data sources, major and public water users, certified wells and external archived groundwater data, including U.S. Geological Survey sources. Study area boundaries were used to select the potential data. Well data was evaluated for completeness and accuracy of information. Required data, dependent on each project deliverable, included location, static water level, lithology and date drilled. Wells with incomplete or suspect data or that had locational issues were eliminated. In some cases, well data were used for one type of map and GIS file but not for another; i.e. a well may have been missing static water level information but contained lithologic information for the clay cap map and GIS file. Anomalous data points were examined specifically for potential data issues and underwent greater verification before use.

Data within Crowley's Ridge and other highlands (figure 1) were excluded due to absence of the Alluvial Aquifer and owing to the greater relief of the highlands, which limits liquefaction potential. The Birds Point New Madrid Floodway was also excluded due to activation of the floodway by the Corps of Engineers in 1937 and 2011, which caused extensive geomorphological alteration of the landscape (Londono and Hart, 2013) and altered water levels and sediment thicknesses.

Data were evaluated and processed using ArcGIS (version 10.1) software. Editing functions included smoothing of the contours to remove contouring relics, removal of the excluded areas (Crowley's Ridge and Birds Point-New Madrid Floodway) and clipping of the contours to the study area boundaries. A raster image depicting shaded relief of the region was developed using a topo to raster function with hypsographic data to generate line coverages representing continuous contours. The shaded relief was used to accentuate contour-related features. Methodologies and data processing specific to each map and GIS file follow. Results are discussed in section 5.0.

3.1 Pre-1971 and Post-2000 Depth to Groundwater (Isobath) Maps and GIS Files

3.1.1 Data Selection

Well records used for the pre-1971 depth to groundwater map and GIS file were considered appropriate if they met the above noted criteria, contained measured static water level (SWL) data and were drilled prior to 1971, thereby predating significant increases in high-yield agricultural pumping. Wells whose casing depth exceeded the depth to bedrock (i.e. were cased through the Alluvial Aquifer) were omitted. Data totaled 866 wells (figure 3A).

The post-2000 depth to groundwater map and GIS file used data that met the above noted criteria, contained a measured static water level data and were drilled after the year 2000, postdating the major expansion in high-yield agricultural pumping. Wells in which casing depth exceeded the depth to bedrock were eliminated. Data totaled 7,757 wells (figure 3B).

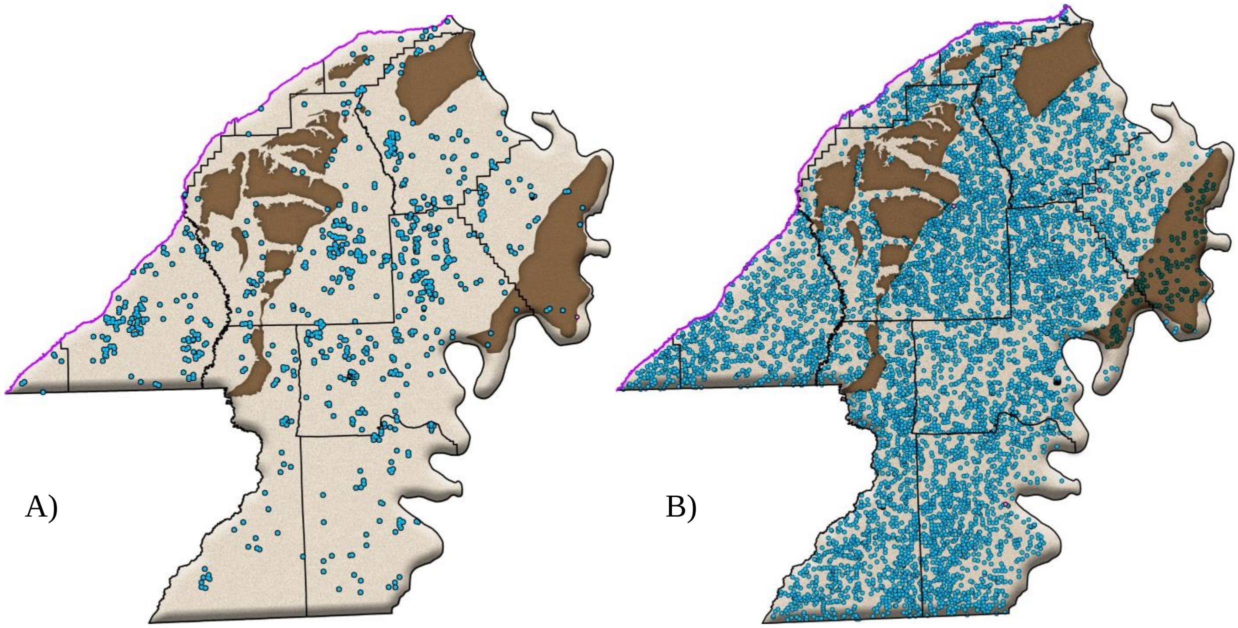

Figure 3. Distribution of well information used for isobath maps and GIS files of the Alluvial Aquifer. Purple line represents boundary of the Ozark highlands; excluded areas are shown in brown. A) Pre-1971 isobath data distribution. B) Post-2000 isobath data distribution.

3.1.2 Isobathic Mapping and GIS File Generation

Point data for the isobath maps and GIS files (figures 4A and 4B) were interpolated using inverse distance weighting to create a model of SWL across the study area. Multiple raster data sets were created, each varying the parameters until the best representation of the point data was determined. A set of isobathic contours was generated from this raster data set. The contours were then evaluated and edited in accordance with the individual data points. A color index was drawn, filling areas between contours (see sections 4.1.1 and 4.1.2). Each color represents a range in depths to groundwater to aid in data interpretation.

Positively numbered depth to groundwater annotations and associated contours represent depth (in feet) below ground surface to the SWL. Due to the actions of Crowley's Ridge as a hydrologic divide, contours for the Eastern and Western lowlands (figure 1) were generated separately for greater accuracy and were merged in the final GIS products.

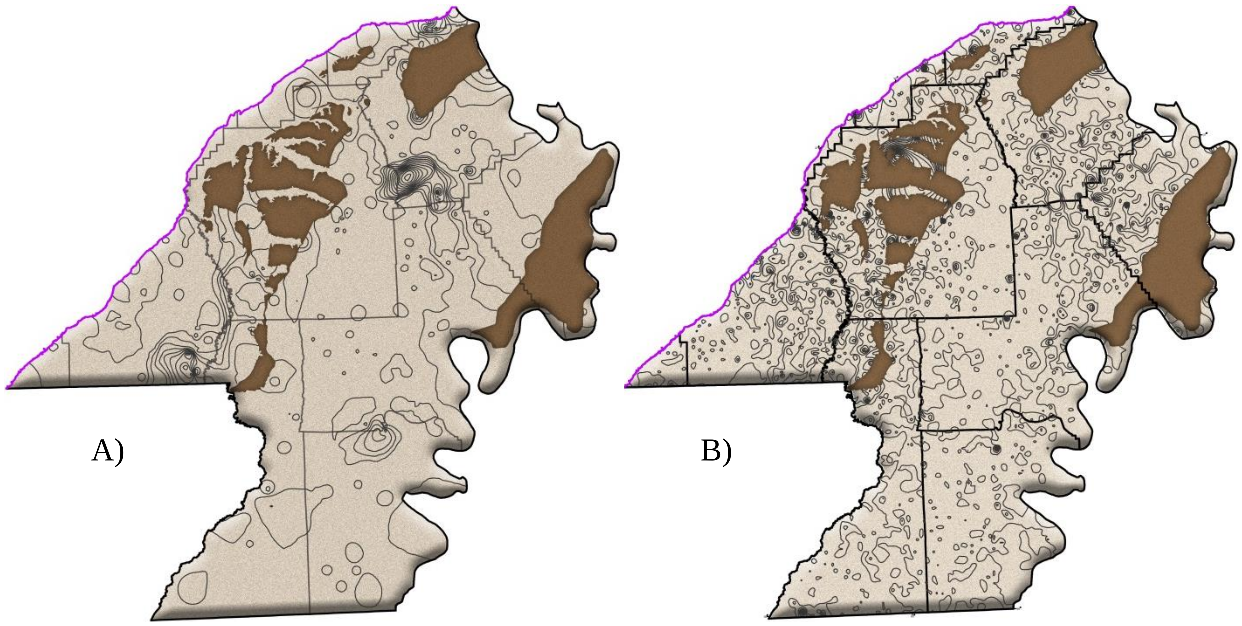

Figure 4. Depth to groundwater contours. Purple line represents boundary of the Ozark highlands; excluded areas shown in brown. A) Pre-1971 isobath (after Herbst, 2015d). B) Post-2000 isobath (after Herbst, 2015c).

3.2 Change in Depth to Groundwater from 1970-2000 Map and GIS File

Agricultural irrigation from the Alluvial Aquifer has increased extensively in the study area over the past 40 years. Previous studies of the aquifer in Arkansas (Reed, 2003, 2004; Czarnekci and others, 2003; Clark and others, 2011) suggested that water withdrawals are lowering the water table in that state. However, Clark and others (2011) posed that water levels within the Missouri portion of the alluvial aquifer are both lowering and rising, dependent upon location.

While it generally is accepted that changes in high-yield agricultural pumping related to rice cultivation and other agricultural usage have affected the depth to groundwater in the study area, the extent and variability of these changes, and their potential to alter the risk of earthquake-induced liquefaction, currently are unknown. The Change in Depth to Groundwater Map (figure 5) and GIS files marked noted changes that occurred after the onset of high-yield pumping (discussed in section 5.0).

3.2.1 Derivative Contour Mapping and GIS File Generation

ArcGIS models of SWL generated from the pre-1971 and post-2000 data were used to create a derivative model of the change in depth to groundwater. Using a raster math function, the pre-1971 raster data set was subtracted from the post-2000 data set to reflect changes in depth to groundwater. A set of contours, created from the resulting data set, were evaluated and edited. A topo to raster function was used to create a raster image, or data set. Negatively numbered changes in depth to groundwater annotations and associated contours represent rising of the water table. Positive changes in depth to groundwater represent deepening of the water table.

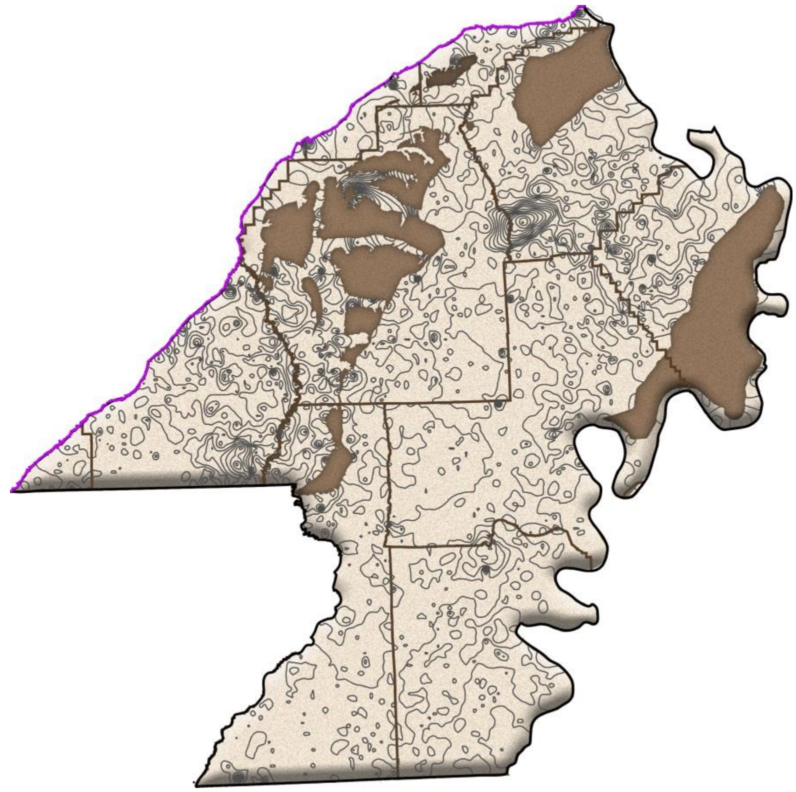

Figure 5. Change in depth to groundwater contours (after Herbst 2015a). Purple line represents boundary of the Ozark highlands; excluded areas are marked by dark brown.

3.3 Clay Cap Thickness (Isochore) Map and GIS File

3.3.1 Data Acquisition and Processing

The clay cap thickness map and GIS file was developed using 9,541 well records (figure 6A). Specific criteria included a lithologic description of each alluvial horizon (clay, sand, gravel, topsoil, etc.). It was determined that in order to be labelled as a *cap*, the top of the clay horizon must be three feet or less below surface in order for the clay thickness to be considered relevant to liquefaction potential. If near surface clay tops were deeper than three feet, their thickness was assigned a zero value, the same value assigned to those wells entirely absent of clay (figure 6B). Well records revealed a lack of a universal application for the term “clay.” Therefore, alternate terms considered equivalent to clay were *gumbo* and *hard pan*. Records showing ambiguous surficial formations, such as topsoil or mud, and anthropogenic materials (concrete, asphalt, construction debris) greater than three feet in thickness were excluded.

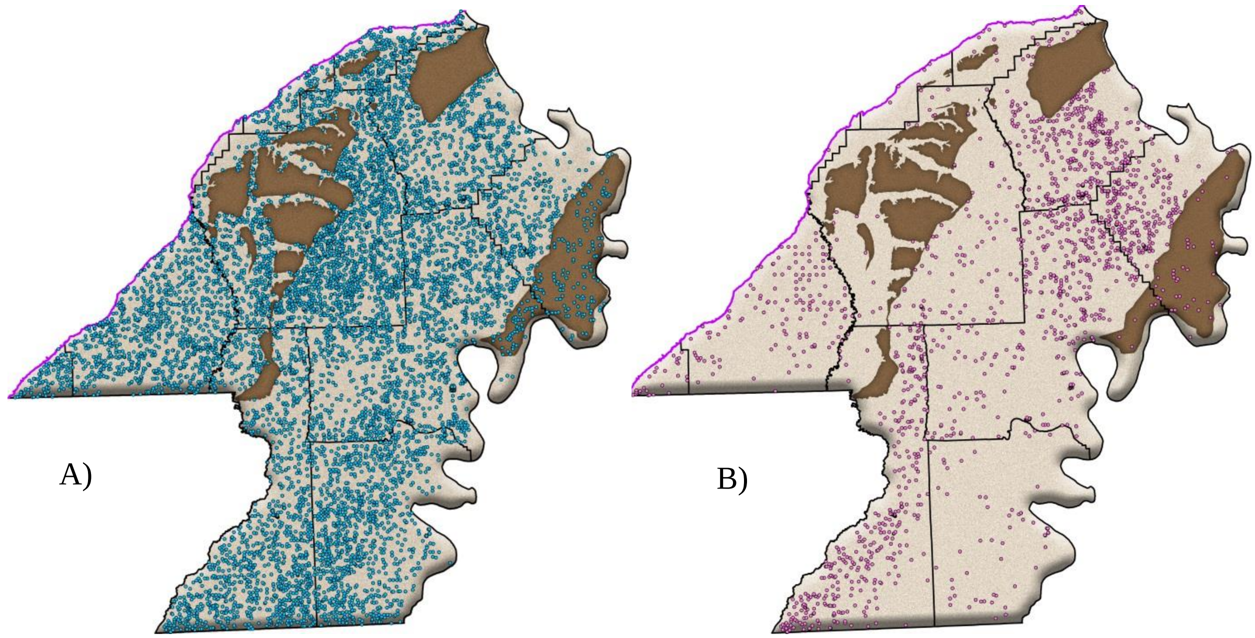

Figure 6. Distribution of MGS well information used for clay-rich cap isochore map and GIS file. Purple line represents boundary of the Ozark highlands; excluded areas are shown in brown. A) Total isochore data distribution. B) Isochore data distribution where alluvial clay thickness equals zero.

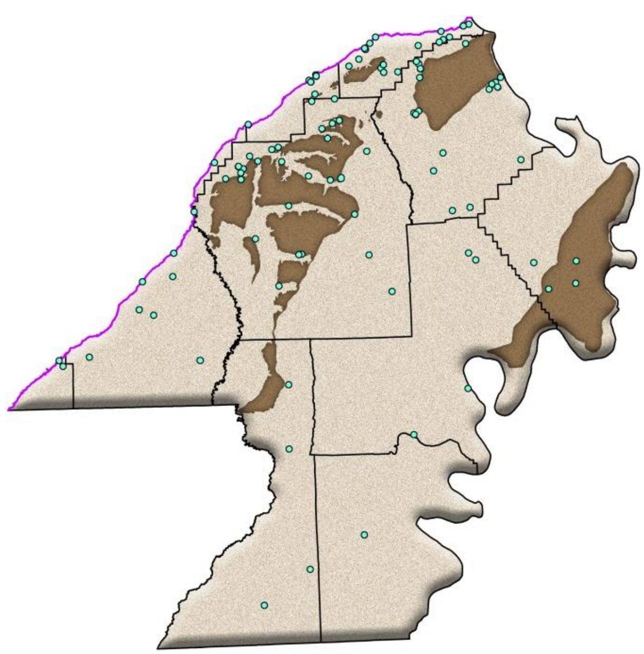

Figure 7. Distribution of well data showing clay-rich cap without underlying sand. Purple line represents boundary of the Ozark highlands; excluded areas are shown in brown.

Additionally, the presence or absence of thick unconsolidated sand deposits is considered a significant factor in forming liquefaction features, such as sand blows, gravel blows and fissures. Records that showed a lack of these materials underlying the clay-rich cap were labelled as such (figure 7).

3.3.2 Isochoric Mapping and GIS File Generation

Data was interpolated using inverse distance weighting to create a model of alluvial clay thickness across the study area. Multiple raster data sets were created, each varying parameters until the best data representation was found. Contours generated from the data set represent the drilled vertical clay thickness (isochore), and were evaluated and edited in accordance with the data. Colors were added to the contours to aid in visual interpretation (see section 4.3).

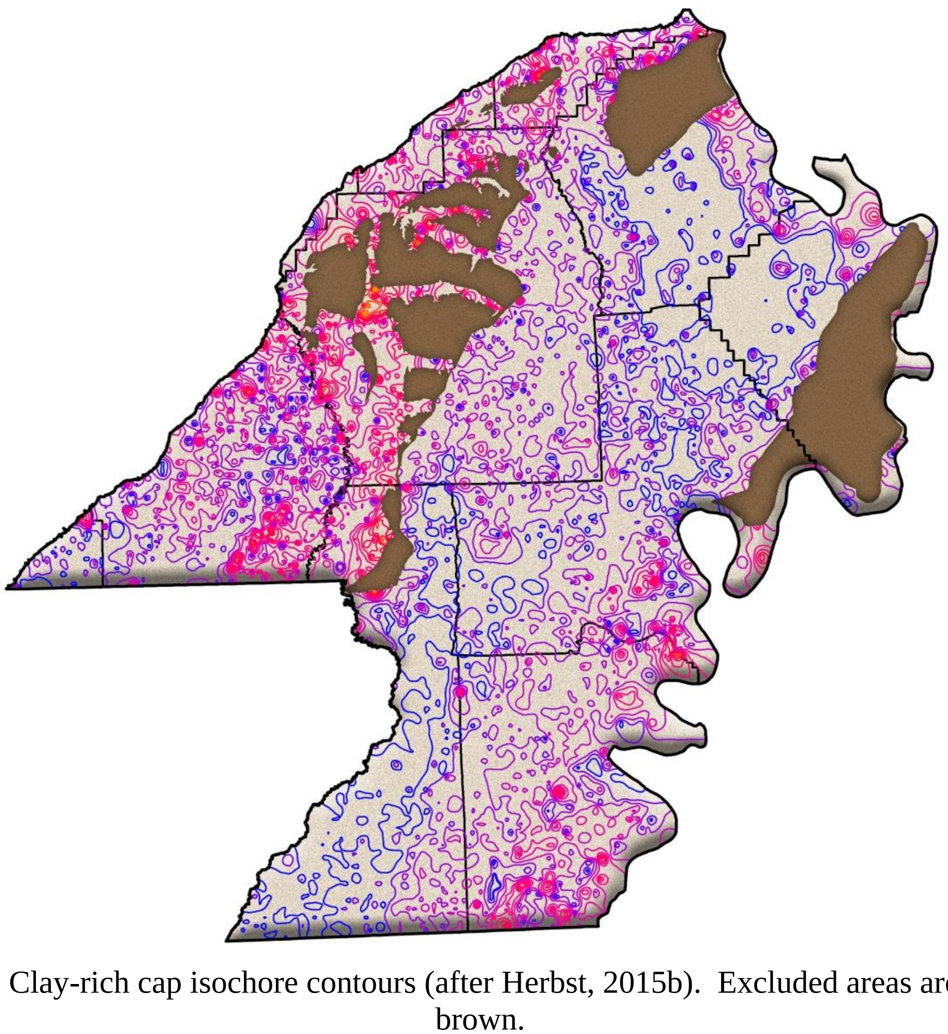

Figure 8. Clay-rich cap isochore contours (after Herbst, 2015b). Excluded areas are shown in brown.

4.0 RESULTS

4.1 Pre-1971 and Post-2000 Depth to Groundwater

4.1.1 Pre-1971 Depth to Groundwater Map and GIS File

Mapping clearly identifies that pre-1971 the majority of the project area had a shallow water table, located within 15 feet of the ground surface. Deeper SWLs predominantly coincided with areas immediately adjacent to Crowley's Ridge, which is characterized by bedrock aquifers. Uneven distribution of the data set (figure 3A) undoubtedly caused much of the heterogeneity on the map.

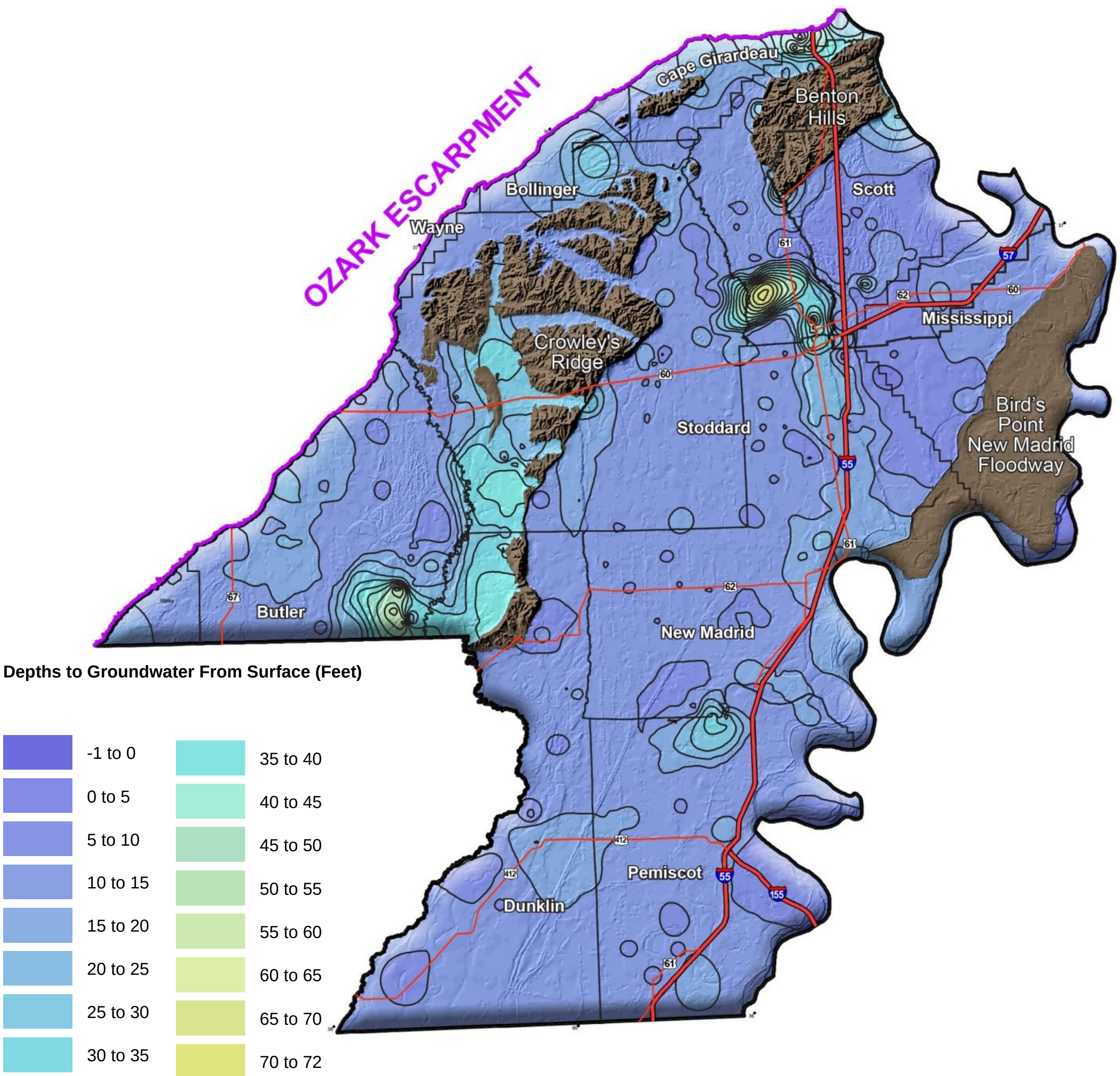

Figure 9. Pre-1971 depth to groundwater map (after Herbst, 2015d). Excluded areas shown in brown.

There are several noteworthy areas with deeper water levels or an abrupt change from nearby SWLs. Deep SWLs in southeastern Butler County are likely related to a rise in topographic relief known as the Melville Ridge, rather than changes in subsurface geology or aquifer characteristics. This area is marked by sand dune formation, resulting in greater relief and higher elevations. The deepest observed alluvial SWLs are in southern Scott County and possibly are related to the Sikeston Power Plant. Nearby, another abrupt change in SWL also likely is related to the Sikeston Power Plant. A curved SWL depression north of the Benton Hills likely is the result of dewatering associated with nearby limestone quarry operations. One location (southeast edge of the Birds Point New Madrid Floodway) was noted to have a negative SWL (above ground surface) due to the presence of an artesian well.

4.1.2 Post-2000 Depth to Groundwater Map and GIS File

Significant SWL data is available for the post-2000 map and GIS file, allowing for a more accurate rendering of the depth to groundwater across the study area. Based on Obermeier (2009), the majority of the SWLs in the study area fall within the high liquefaction susceptibility bracket (zero to five meters) (figure 10). The deepest SWLs coincide with areas immediately adjacent to Crowley's Ridge. A noticeable change in SWL also occurs between the Western and Eastern lowlands, with Crowley's Ridge acting as a hydrologic divide. West of the ridge to approximately central and eastern Butler County, SWLs are deeper and subsequent liquefaction potential falls to moderate and low levels in places. Across Crowley's Ridge, the Eastern Lowlands show shallower SWLs with greater potential for liquefaction. The north to northwestern trending region of moderate groundwater depths observed in northern New Madrid and southern Scott counties coincides with an alluvial feature known as the Sikeston Ridge and likely is the result of a rise in topographic relief rather than a change in aquifer characteristics. Only three locations were noted to have a SWL of zero feet, indicating the water table being at or above the surface as a result of a flowing artesian well.

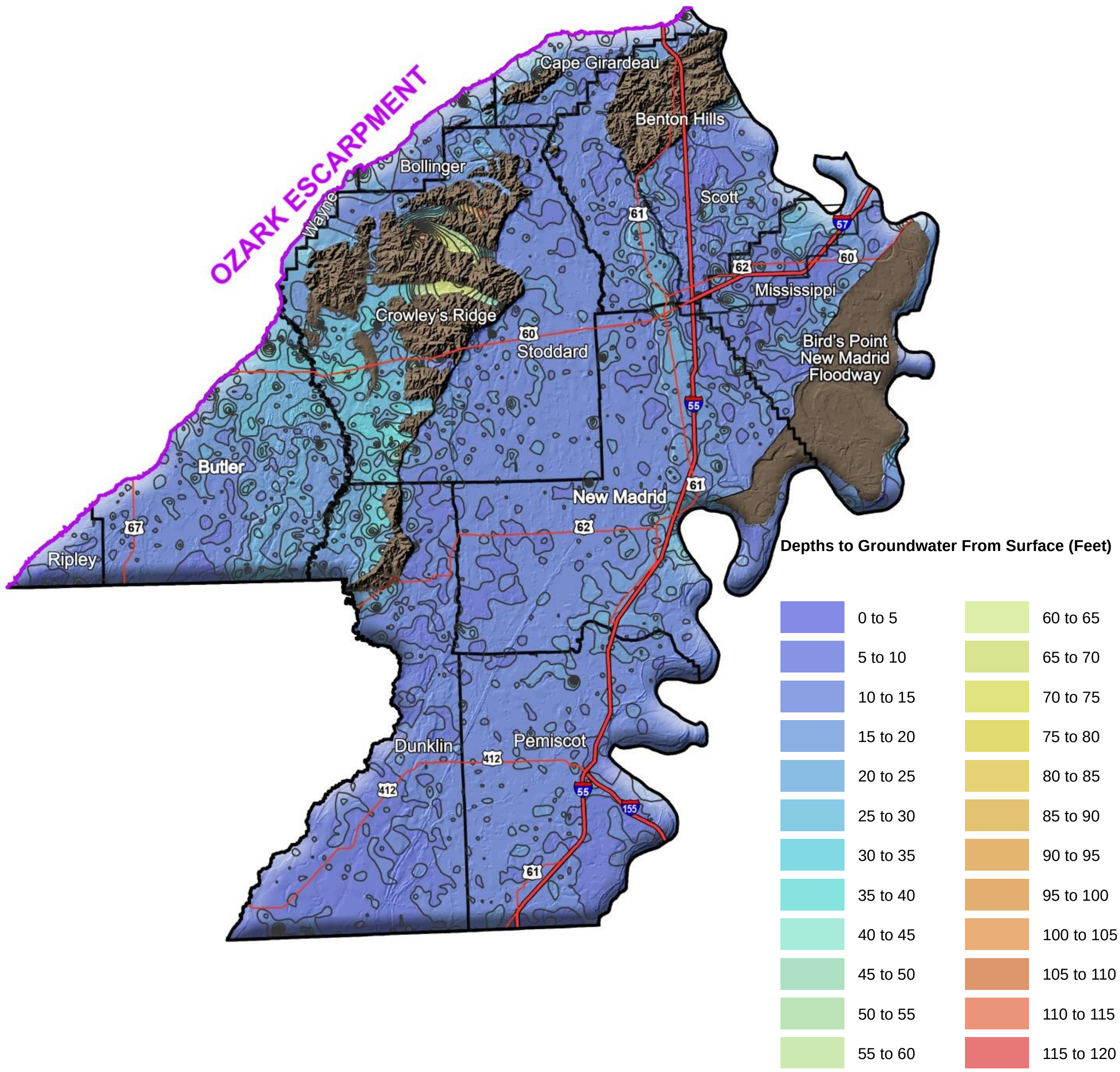

Figure 10. Post-2000 depth to groundwater map (after Herbst, 2015c). Excluded areas shown in brown.

4.1.3 Seasonal Comparison

One of the purposes to the pre-1971 and post-2000 SWL data sets was to establish baselines for determination of potential changes in groundwater depth related to high-yield agricultural pumping. A derivative data set created by comparing pre-1971 and post-2000 data (figures 4 and 5) would prove less valid if seasonal variations led to significant changes in SWLs or if there were a greater number of wells drilled in a season for one data set versus the other. Both pre-1971 and post-2000 data sets had more wells drilled during the wet season (March–May) than the dry season (July–September). Wet and Dry seasons were selected based on meteorological records for Cape Girardeau, Missouri, located near the northernmost extent of the embayment

(U.S. Climate Data, 2015). The percentages of wells drilled in the wet season were also comparable (table 1). The percent of seasonal wells drilled post-2000 show less than a 5% difference compared to pre-1971 wells (table 1, highlighted). The ratio of wells drilled during the post-2000 wet season (67.1%) versus pre-1971 (62.6%) comes to ~1.07, affirming the reliability of comparing data sets and subsequently the change in depth to groundwater data set. The changes in SWL between wet and dry season within each individual dataset were not significant in terms of contouring of the data or for liquefaction potential (Obermeier, 2009).

Average SWLs for both data sets during the dry season were shown to be equivalent (16 feet). Average SWL during the wet season was approximately two feet lower for post-2000 data (13.0 feet) than for pre-1971 (11.1 feet). This suggests that the expansion of irrigation wells between 1971 and 2000 may be impacting local SWLs.

Table 1. Pre-1971 vs. Post-2000 Seasonal Comparison

Data Set	Total Wells Drilled in Season	Season	Seasonal Wells Drilled	Percent of Total Wells (%)	Average SWL (feet)	ΔSWL Dry vs. Wet Season (feet)
Pre-1971	115	Dry*	43	37.4	16.2	5.1
		Wet†	72	62.6	11.1	
Post-2000	4,915	Dry	1,616	32.9	16.0	3.0
		Wet	3,299	67.1	13.0	

*Based on three month span having the lowest average precipitation (July–September) (U.S. Climate Data, 2015)

†Based on three month span having the highest average precipitation (March–May) (U.S. Climate Data, 2015).

4.2 Change in Depth to Groundwater from 1970-2000

Due to the data distribution and manner in which the contours were interpolated, minor to moderate changes in depth to groundwater can appear as sharp color deviations. Much of the study area was shown to have minimal changes in depth to groundwater (figure 11), varying by 5 feet or less. Of note, however, is that throughout the majority of the study area the changes appear to be nearly equal in terms of the SWL being either raised or lowered by that amount. These changes also are not restricted in areal extent, but are dispersed equally throughout the study area, suggesting numerous local variations in agricultural water usage. The marked low SWL areas on the pre-1971 data set appear to have a marked effect on the derivative data set. The areas of negative change (shallowing of the water table) north of the Benton Hills, near the Sikeston power plant in southern Scott County, and in the Melville Ridge area in southeastern Butler County, all mimic the pre-1971 isobath data set. In addition, discernible areas of positive change in depth to groundwater (deepening of the water table) are most concentrated in the Western Lowlands. These moderate to high changes in depth to groundwater, appearing as bullseye patterns in the contour lines (figure 11), appear to be related to locations of irrigation wells with pump rates of greater than 1,000 gpm.

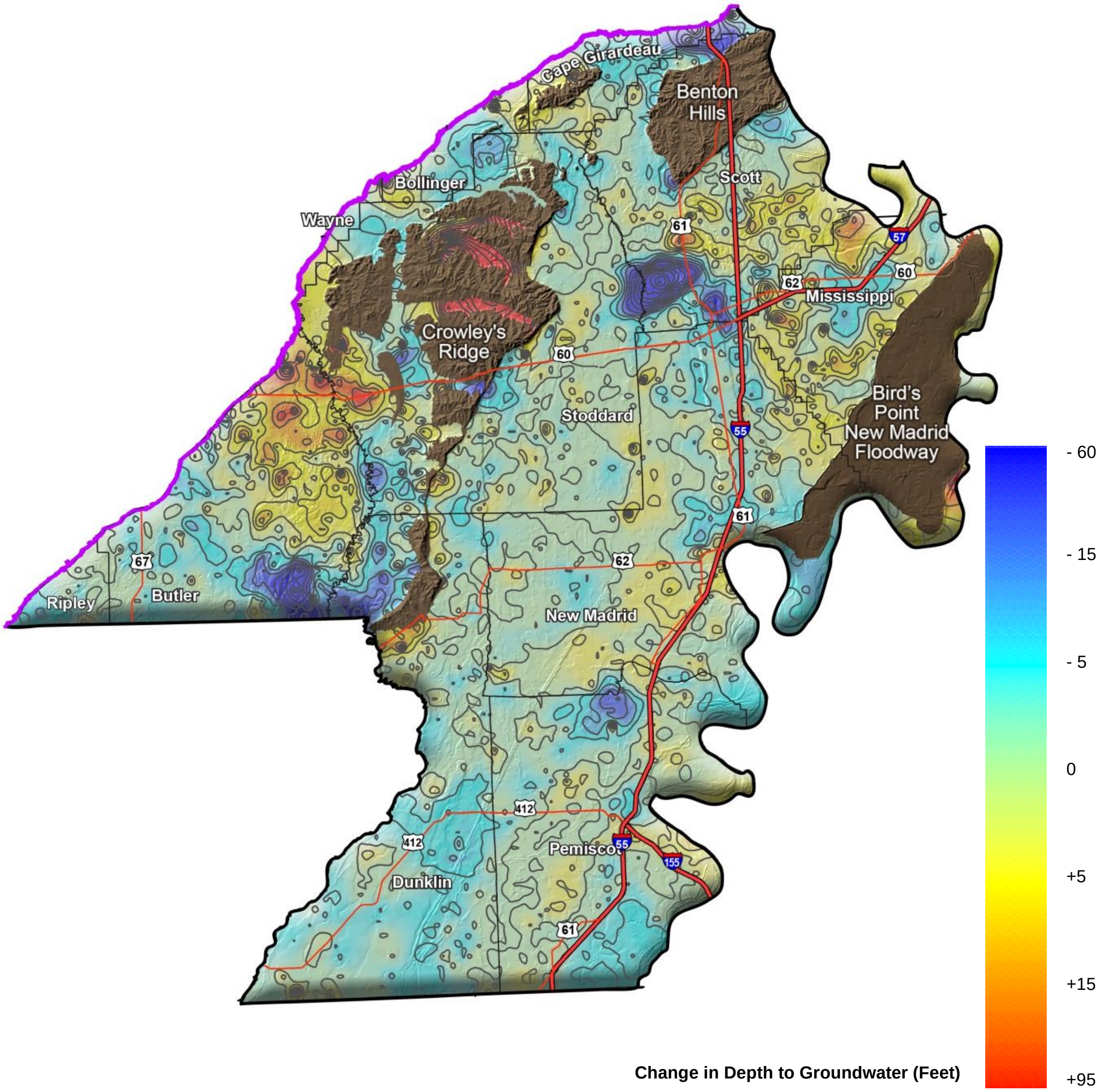

Figure 11. Change in depth to groundwater from 1970-2000 map (after Herbst, 2015a). Excluded areas shown in brown.

4.3 Clay Cap Thickness Map

The majority of the study area has an alluvial clay cap less than 10 meters (32.8 feet) in thickness that is underlain by alluvial sand deposits (figure 12). Locations of wells with a clay cap but without underlying sand deposits are depicted as points on the map rather than areas given their isolated nature (figure 12). Clay thickness increases from west to east in the southern half of the study area from Dunklin County to the easternmost portions of Pemiscot and southeast New Madrid counties. Similar to the static water levels depicted in the depth to groundwater maps (Herbst, 2015c, 2015d), a noticeable change occurs between the Western and Eastern lowlands adjacent to Crowley's Ridge. The clay cap is much thicker on the western side of Crowley's Ridge and remains thick (30 feet or greater) tracking north, parallel to the ridge. The Melville

Ridge area in southeastern Butler County shows a discernible increase in clay thickness of up to 75 feet in places.

Figure 13 depicts areas where either no clay cap is present, or near-surface clays did not meet the criteria to be labelled as a *cap* (i.e. the top of the clay horizon is greater than three feet below surface). There are two distinct regions without a clay cap. The first is nearly entirely within Dunklin County along a north-south trend from the southwest to northeast county boundaries. The second resides along a northwest-southeast trend making up much of central and southeast Scott County, northeast New Madrid County, and western to central Mississippi County. The eastern boundary of this area coincides with a lowering of the topographic elevation, denoting the transition into the Mississippi floodplain.

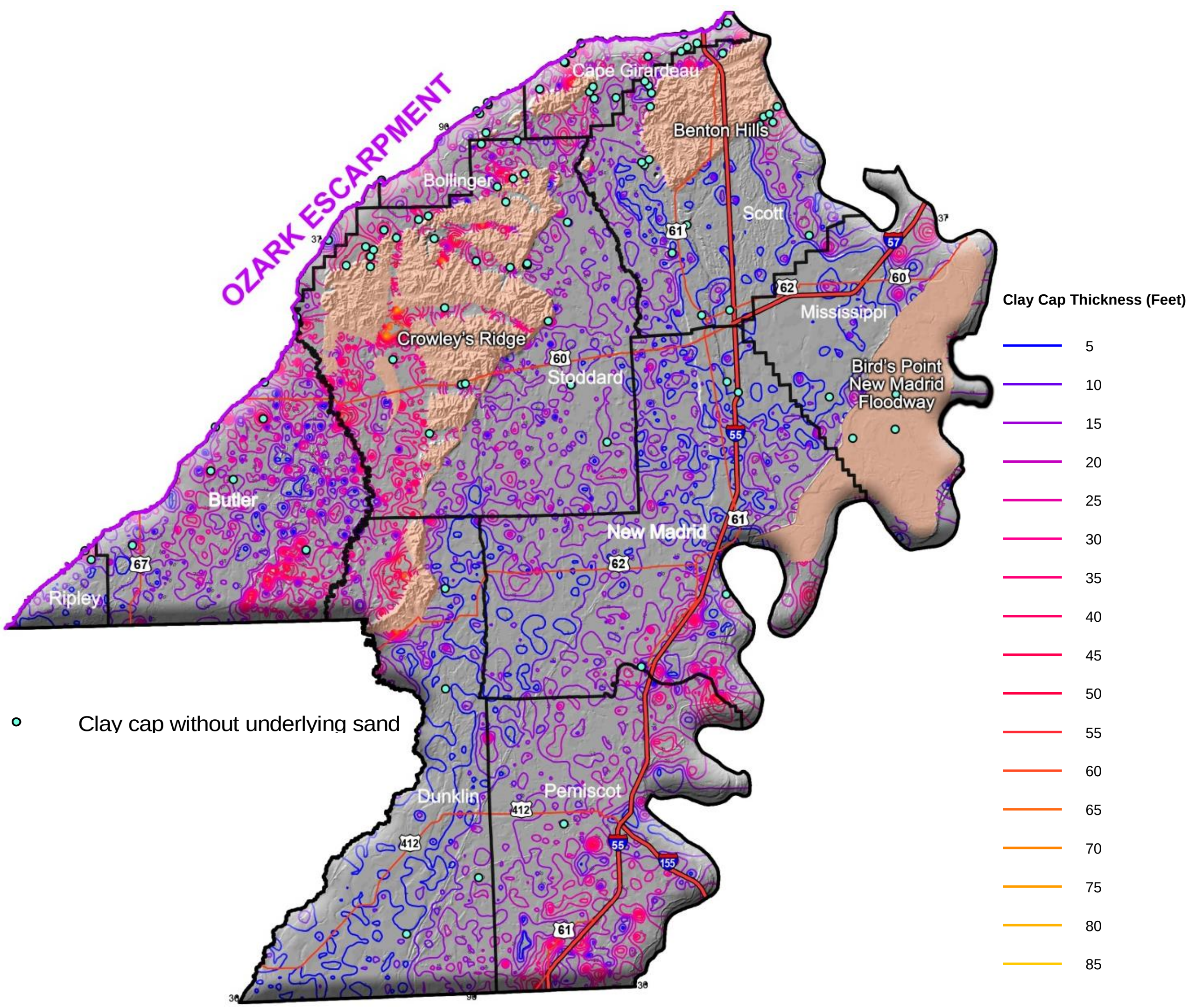

Figure 12. Clay cap thickness map (after Herbst, 2015b). Excluded areas shown in orange.

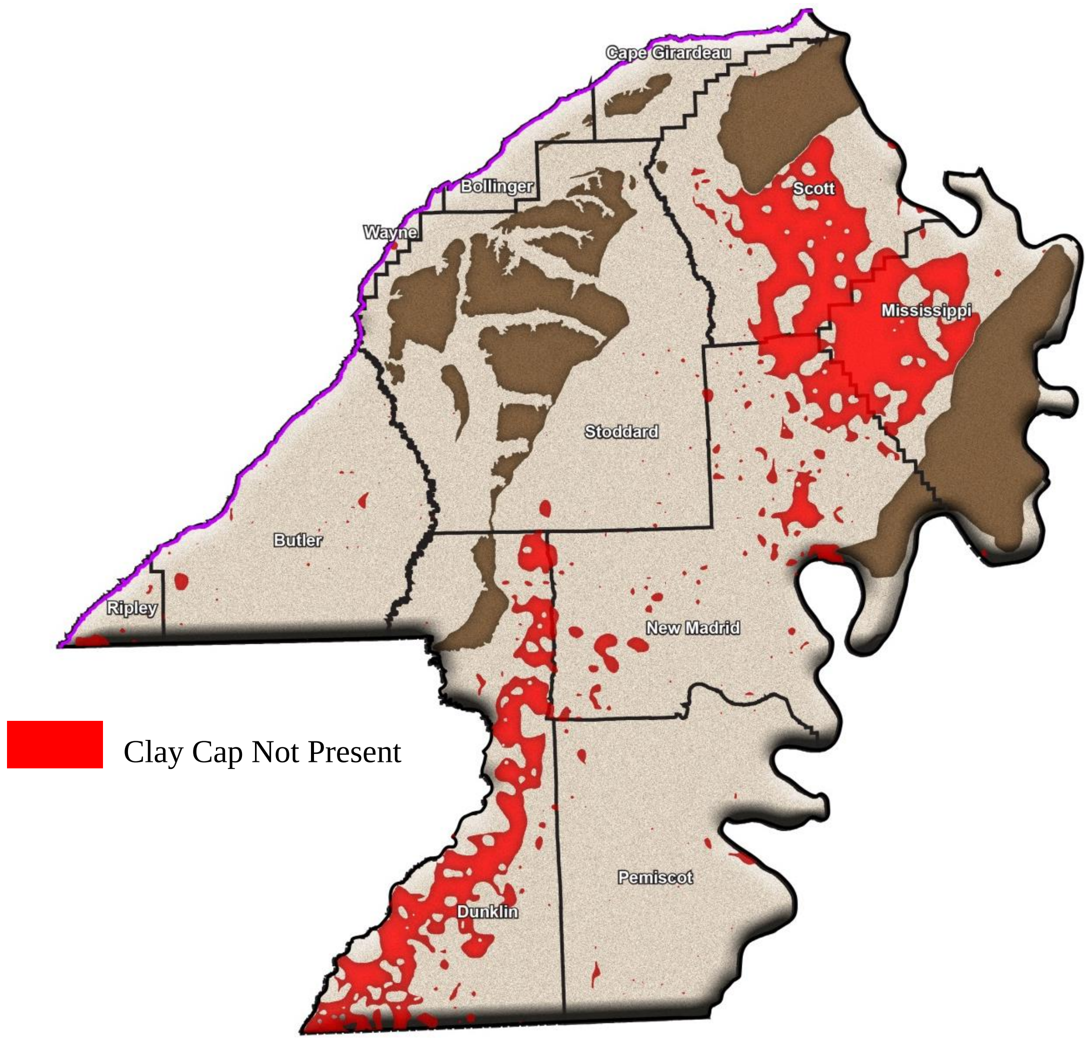

Figure 13. Areas without an alluvial clay cap within the study area (after Herbst, 2015b). Excluded areas shown in brown.

5.0 CONCLUSIONS

Spatial definition of potential liquefaction criteria in the Missouri portion of the Mississippi Embayment (study area) helps improve our understanding of liquefaction hazard risk and will aid in disaster response, emergency management preventative planning measures and regional earthquake hazards assessments.

Based on SWLs from the pre-1971 data set, the majority of the study area had a shallow water table that was 15 feet or less in depth from the ground surface. This data set established a baseline for determination of potential changes in depth to groundwater related to high-yield agricultural pumping. Post-2000 data acted as the second baseline to produce a derivative data set and also provided a current isobath data set for the study area. Due to the numerous data points available for this data set, the post-2000 data set contains a more accurate representation of modern SWLs. Based on Obermeier (2009), the majority of the SWLs in the study area fall within the high liquefaction susceptibility bracket (zero to five meters), with the greatest concentration of these values being in the Eastern Lowlands. The deepest groundwater depths coincide with areas immediately adjacent to Crowley's Ridge, an area characterized by bedrock aquifers. Seasonal variations (wet vs. dry) were not noted to affect the SWLs and thereby the potential liquefaction hazard in the area.

The change in depth to groundwater data set and derivative map (figure 11) shows much of the study area experienced SWL changes of 5 feet or less from local agricultural pumping. However, changes in both lowering and raising of the SWL by this amount appear to have occurred over the majority of the study area, without specific areal trends noted in the location of either type of change. The most marked areas with lowering of the SWL are in the Western Lowlands with changes of up to 25 feet. Other areas with marked lowering include southern Scott County and northern New Madrid County. These moderate to high changes in groundwater depth appear to be related to locations of irrigation wells with very high pump rates of greater than 1,000 gpm.

Most of the study area has an alluvial clay cap less than 10 meters (32.8 feet) and greater than 1.5 meters (5 feet) in thickness, placing it within the high to moderate liquefaction susceptibility bracket (Obermeier, 2009). The clay cap in the entire study area is underlain by alluvial sand deposits. Given their isolated nature, locations lacking underlying alluvial sand are noted as singular points. Similar to patterns observed in the isobath data sets, a discernible change in clay thickness occurs from east to west, with Crowley's Ridge as the divide. Topographically, the study area maintains a shallow, but continuous, increase in elevation west to east. As a result, the clay cap is much thicker along the western edge of Crowley's Ridge. Finally, there are two distinct regions without a clay cap (figure 13). While the threat of earthquake-induced liquefaction, subsidence or lateral spreading would still remain, the lack of an impermeable confining unit over cohesionless sand reduces the chances for formation of features such as sand blows and fissures.

6.0 ACKNOWLEDGEMENTS

This project was supported by the U.S. Geological Survey's National Earthquake Hazards Reduction Program under Federal Aid Number G15AP00009.

7.0 REFERENCES

Clark, B.R., R.M. Hart, and J.J. Gurdak, 2011, Groundwater availability of the Mississippi embayment; U.S. Geological Survey Professional Paper 1785, 62 p.

Czarnekci, J.B., B.R. Clark and T.B. Reed, 2003, Conjunctive-use optimization model of the Mississippi River Valley Alluvial Aquifer of northeastern Arkansas; U.S. Geological Survey Water–Resources Investigations Report 03-4230, 29 p.

Guccione, M.J., 2005, Late Pleistocene and Holocene paleoseismology of an intraplate seismic zone in a large alluvial valley, the New Madrid seismic zone, Central USA; Tectonophysics, v. 408, p. 237-264.

Haselwander, A., 2013, Geologic hazards map for Region E Missouri State Emergency Management Agency; Missouri Department of Natural Resources Division of Geology and Land Survey Open-File Map OFM-13-620-GS, 1 sheet, 1:250,000.

Herbst, T.G., 2015a, Change in depth to groundwater from 1970-2000 for the Mississippi Embayment Alluvial Aquifer, Southeast Missouri; Missouri Department of Natural Resources Missouri Geological Survey Open File Map OFM-2015-666-GS, 1 sheet, 1:250,000.

Herbst, T.G., 2015b, Clay cap thickness for the Mississippi Embayment Alluvial Aquifer, Southeast Missouri; Missouri Department of Natural Resources Missouri Geological Survey Open File Map OFM-2015-667-GS, 1 sheet, 1:250,000.

Herbst, T.G., 2015c, Post-2000 depth to groundwater for the Mississippi Embayment Alluvial Aquifer, Southeast Missouri; Missouri Department of Natural Resources Missouri Geological Survey Open File Map OFM-2015-665-GS, 1 sheet, 1:250,000.

Herbst, T.G., 2015d, Pre-1971 depth to groundwater for the Mississippi Embayment Alluvial Aquifer, Southeast Missouri; Missouri Department of Natural Resources Missouri Geological Survey Open File Map OFM-2015-664-GS, 1 sheet, 1:250,000.

Hoffman, D., 1997, Earthquake hazards map of the Cape Girardeau-Perryville area, Missouri; Missouri Department of Natural Resources Division of Geology and Land Survey map, 1 sheet, 1:100,000.

Hoffman, D., 1999, Earthquake hazards map of the Sikeston – Caruthersville area, Missouri; Missouri Department of Natural Resources Division of Geology and Land Survey map, 1 sheet, 1:100,000.

Li, Yong, E.S. Schweig, M.P. Tuttle and M.A. Ellis, 1998, Evidence for large prehistoric earthquakes in the northern New Madrid Seismic Zone, Central United States; Seismological Research Letters, v. 69, p. 270-276.

Londono, A.C. and M.L. Hart, 2013, Landscape response to the intentional use of the Birds Point New Madrid Floodway on May 3, 2011; Journal of Hydrology, v. 489, p. 135-147.

Luckey, R.R., 1985, Water resources of the Southeast Lowlands, Missouri; U.S. Geological Survey Water-Resources Investigations Report 84-4277, 78 p.

Marcus, M., 1993, Earthquake hazards map of southeast Missouri; Missouri Department of Natural Resources Division of Geology and Land Survey map, 1 sheet, 1:300,000.

Miller, D.E. and J.E. Vandike, 1997, Groundwater resources of Missouri; Missouri Department of Natural Resources Division of Geology and Land Survey Water Resources Report Number 46, 211 p.

Obermeier, S.F., 1988, Liquefaction potential in the central Mississippi Valley; U.S. Geological Survey Bulletin 1832, 21 p.

Obermeier, S.F., 1989, The New Madrid earthquakes: an engineering-geologic interpretation of relict liquefaction features. U.S. Geological Survey Professional Paper 1336-B, p. 1–114, 11 pl.

Obermeier, S.F., 1994, Using liquefaction-induced features for paleoseismic analysis; in Obermeier, S.F. and R.W. Jibson, eds., Using ground-failure features for paleoseismic analysis, U.S. Geological Survey Open File Report 94-663 Chapter A, p. 1–58.

Obermeier, S.F., 2009, Using liquefaction-induced and other soft-sediment features for paleoseismic analysis; in Paleoseismology, J.P. McCalpin ed., Academic Press, p. 497-564.

Obermeier, S.F. and E.C. Pond, 1999, Issues in using liquefaction features for paleoseismic analysis; Seismological Research Letters, v. 70, p. 34-58

Obermeier, S.F., E.C. Pond and S.M. Olson, 2001, Paleoseismic studies in continental settings – geologic and geotechnical factors in interpretations and back-analysis; U.S. Geological Survey Open-File Report 01-29, 53 p., http://pubs.usgs.gov/openfile/of01-029.

Obermeier, S.F., S.M. Olson and R.A. Green, 2005, Field occurrences of liquefaction-induced features: a primer for engineering geologic analysis of paleoseismic shaking; Engineering Geology, v. 76, p. 209–234.

Reed, T.B., 2003, Recalibration of a ground-water flow model of the Mississippi River Valley Alluvial Aquifer of northeastern Arkansas, 1918-1998, with simulations of water levels caused by projected ground-water withdrawals through 2049; U.S. Geological Survey Water-Resources Investigations Report 03-4109, 58 p.

Reed, T.B., 2004, Status of water levels and selected water-quality conditions in the Mississippi River Valley Alluvial Aquifer in eastern Arkansas, 2002; U.S. Geological Survey Scientific Investigations Report 2004-5129, 53 p., 2 pl.

Tuttle, M., 2001, The use of liquefaction features in paleoseismology: lessons learned in the New Madrid seismic zone, central United States; Journal of Seismology, v. 5, p. 361-380.

Tuttle, M.P., J. Collier, L.W. Wolf and R.H. Lafferty III, 1999, New evidence for a large earthquake in the New Madrid seismic zone between A.D. 1400 and 1670; Geology, v. 27, p. 771-774.

Tuttle, M.P. and E.S. Schweig, 1996, Recognizing and dating prehistoric liquefaction features: Lessons learned in the New Madrid seismic zone, central United States, Journal of Geophysical Research, v. 101, p. 6171–6178.

Tuttle, M.P., E.S. Schweig, J.D. Sims, R.H. Lafferty, L.W. Wolf and M.L. Haynes, 2002, The earthquake potential of the New Madrid Seismic Zone; Bulletin of the Seismological Society of America, v. 92, p. 2080-2089.

Tuttle, M.P., E.S. Schweig III, J. Campbell, P.M. Thomas, J.D. Sims and R.H. Lafferty III, 2005, Evidence for New Madrid Earthquakes in A.D. 300 and 2350 B.C.; Seismological Research Letters, v. 76, p. 489-501.

U.S. Climate Data, 2015, [Cape Girardeau, Missouri], www.usclimatedata.com.