REPORT

Location Restrictions Demonstration - Upstream Raise 92

Great River Energy - Coal Creek Station

Submitted to:

Great River Energy

Coal Creek Station
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October 16, 2018

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FIGURES

1.0 INTRODUCTION

This report presents documentation and certification of the Location Restrictions Demonstration for the Upstream Raise 92 CCR Surface Impoundment (Upstream Raise 92) at Great River Energy's (GRE) Coal Creek Station (CCS). Upstream Raise 92 is an existing coal combustion residuals (CCR) surface impoundment. This report addresses the requirements of the United States Environmental Protection Agency's (EPA's) CCR rule (40 CFR 257.60 through 257.64, (EPA, 2015)). The location restrictions as defined in the CCR rule are summarized in the following sections.

1.1 Site Background

CCS is a coal-fired electric generation facility located in McLean County, North Dakota, approximately 10 miles northwest of Washburn, North Dakota. CCRs are managed in composite-lined surface impoundments and dry waste landfill facilities regulated and permitted by the North Dakota Department of Health (NDDH) in accordance with North Dakota Administrative Code (NDAC) Article 33-20, Solid Waste Management and Land Protection.

CCS has four CCR facilities that are within the purview of the EPA CCR rule (Figure 1):

- Drains Pond System CCR Surface Impoundment (Drains Pond System) is located in the south-central portion of the plant site, northeast of the plant buildings.
- Upstream Raise 91 CCR Surface Impoundment (Upstream Raise 91) is located in the south-central portion of the plant site, east of the plant buildings.
- Upstream Raise 92 CCR Surface Impoundment (Upstream Raise 92) is located in the southeast portion of the plant site, between Upstream Raise 91 and Southeast Section 16 CCR Landfill.
- Southeast Section 16 CCR Landfill (Southeast 16) is located in the southeast portion of the plant site, east of Upstream Raise 92.

2.0 LOCATION RESTRICTIONS

The location restrictions are found within the following sections of the Code of Federal Regulations:

- 40 CFR 257.60 – Placement above the uppermost aquifer
- 40 CFR 257.61 – Wetlands
- 40 CFR 257.62 – Fault areas
- 40 CFR 257.63 – Seismic impact zones
- 40 CFR 257.64 – Unstable areas

Per the CCR rule definitions, Upstream Raise 92 is considered an existing CCR surface impoundment and is subject to each of the location restriction requirements above.

3.0 PLACEMENT ABOVE THE UPPERMOST AQUIFER

Per 40 CFR 257.60, the base of existing and new CCR surface impoundments, new CCR landfills, and all lateral expansions must be no less than five feet (1.52 meters) above the uppermost aquifer, or a demonstration must be made that there will not be an intermittent, recurring, or sustained hydraulic connection between any portion of the base of the CCR unit and the uppermost aquifer due to normal fluctuations in groundwater elevations, including fluctuations due to the seasonal high water table. The CCR rule defines the uppermost aquifer as the geologic formation nearest the natural ground surface that is an aquifer, as well as lower aquifers that are hydraulically interconnected with this aquifer within the facility's property boundary.

To provide support for the groundwater separation demonstration, groundwater levels were measured in the monitoring wells and piezometers surrounding Upstream Raise 92 from June 2017 through June 2018 (Figure 2). This was done to evaluate the normal fluctuations (including seasonal high water table) of groundwater elevation in the area of Upstream Raise 92.

Based on this measured data, the groundwater level fluctuated up to approximately 1.7 feet at individual wells/piezometers between June 2017 and June 2018. Groundwater contours were drawn based on the measured groundwater levels from October 2017 since groundwater levels were measured at additional site piezometers during this period, providing more detailed information for the development of groundwater contours. These groundwater contours were then compared to the as-built bottom of composite liner grades (Swenson, Hagen & Co. P.C. Consulting Engineers, 1990) (Kadrmas, Lee, & Jackson, 2006a) (Kadrmas, Lee, & Jackson, 2006b) (Kadrmas, Lee, & Jackson, 2008). Figure 3 provides a visualization of the separation between the bottom of the composite liner (bottom of mechanically compacted clay liner) and the October 2017 groundwater contours. Most of the Upstream Raise 92 footprint has a separation between the bottom of the composite liner and groundwater greater than 5 feet. A small area on the north side of the west half of Upstream Raise 92 indicates a minimum separation of approximately 3.5 feet. From June 2017 through June 2018, the wells/piezometers near this corner of Upstream Raise 92 (MW-51, MW-10) showed groundwater elevations up to 1.5 feet higher than the October 2017 readings. Therefore, the separation between the bottom of the composite liner and groundwater is anticipated to be greater than approximately 2.0 feet after considering potential site variations, including anticipated site seasonality based on the information collected.

Based on information acquired between June 2017 and June 2018, the base of the liner system at Upstream Raise 92 is above the upper limits of the uppermost aquifer and no intermittent, recurring, or sustained hydraulic connection between any portion of the base of the CCR unit and the uppermost aquifer exists.

4.0 WETLANDS

Per 40 CFR 257.61, existing and new CCR surface impoundments, new CCR landfills, and all lateral expansions must not be located in wetlands, unless a specific demonstration has been made by the owner or operator of a CCR unit ensuring that the unit will not degrade sensitive wetland ecosystems. Wetlands are areas that are inundated or saturated by surface or groundwater at a frequency and over a duration sufficient to support a prevalence of vegetation typically adapted for life in saturated soil conditions, and may include marshes, swamps, bogs, or other similar areas.

Upstream Raise 92 was constructed as an above-grade impoundment with grass covered perimeter earthen embankments and is located several hundred feet uphill of Samuelson Slough (closest surface water body). There are no visual indications suggesting the impoundment is located in wetlands. In addition, the NDDH, as part of the permit requirements of each facility, has previously accepted that Upstream Raise 92 is not located in wetlands (Golder, 2004a).

Upstream Raise 92 is not located in wetlands.

5.0 FAULT AREAS

Per 40 CFR 257.62, new CCR landfills, new and existing CCR surface impoundments, and all lateral expansions must not be located within 200 feet of a fault (or the outermost damage zone of a fault) that has had displacement in Holocene time, unless a demonstration can be made that an alternative setback distance of less than 200 feet will not result in damage to the structural integrity of the unit. Holocene time is defined as the geological epoch which began at the end of the Pleistocene, roughly 11,700 years before the present, and continues to present time.

As evidence of being outside of fault areas, Figures 4 through 6 contain images derived from the United States Geological Survey's (USGS) Earthquake Hazards Program's U.S. Quaternary Faults and Folds Database. An overall map of the known faults in the contiguous United States is shown in Figure 4, while Figure 5 focuses on North Dakota. No known quaternary faults are located in the state of North Dakota. Further, Figure 6 provides the 2018 national earthquake probability map. North Dakota as a whole is predicted to have a less than 1% chance of potentially minor-damage ground shaking in 2018 (Petersen, et al., 2018).

Upstream Raise 92 is not located within 200 feet of a fault (or the outermost damage zone of a fault) that has had displacement in Holocene time.

6.0 SEISMIC IMPACT ZONES

Per 40 CFR 257.63, new CCR landfills, new and existing CCR surface impoundments, and all lateral expansions must not be located in seismic impact zones, unless a demonstration is made that shows all structural components, including liner, leachate collection systems, and surface water control systems are designed to resist the maximum horizontal acceleration in lithified earth material from a probable earthquake at the site. A seismic impact zone is defined as an area having a 2% or greater probability that the maximum expected horizontal acceleration, expressed as a percentage of the earth's gravitational pull (g), will exceed 0.10 g in 50 years. Maximum horizontal acceleration in lithified earthen materials is defined as the maximum expected horizontal acceleration at the ground surface as depicted on a seismic hazard map, with a 98% or greater probability that the acceleration will not be exceeded in 50 years.

Figure 7 is a map prepared by the USGS (Petersen, et al., 2014) showing the nationwide 2% probability in 50 years of exceedance of peak ground acceleration. On the map, the majority of North Dakota, including CCS, is given a 2% probability of exceeding 0.02 g in 50 years, below the 0.10 g threshold for defining a seismic impact zone.

Upstream Raise 92 is not located in a seismic impact zone.

7.0 UNSTABLE AREAS

Per 40 CFR 257.64, new and existing CCR landfills, new and existing CCR surface impoundments, and all lateral expansions must not be located in unstable areas, unless a demonstration can be made that shows the structural components of the unit will not be disrupted. The rule defines an unstable area as a location that is susceptible to natural or human-induced events or forces capable of impairing the integrity of some or all of the structural components responsible for preventing releases from a CCR unit. Unstable areas can include poor foundation conditions, areas susceptible to mass movements, and karst terrains. Per the rule, structural components are any component used in the construction and operation of the unit that are necessary to ensure the integrity of the unit and to prevent a release, and can include liners, leachate collection systems, embankments, spillways, outlets, final covers, and inflow design flood control systems.

Per the rule, the following factors were considered in determining whether the facilities have been located within unstable areas:

- On-site or local soil conditions that may result in significant differential settlement;
- On-site or local geologic or geomorphologic features; and
- On-site or local human-made features or events (both surface and subsurface).

Potential indications of unstable areas are evaluated during the annual visual inspections required to satisfy 40 CFR Part 257.83. These inspections are specifically meant to assess hydraulic structures, upstream and downstream slopes, berm crests, and the toe of the facility to look for signs of structural weakness, differential settlement, or other conditions that could affect stability. No evidence of differential settlement or other indications of unstable areas has been observed at the facility during the annual inspections performed in 2015, 2016, 2017, and 2018 (Golder, 2016a) (Golder, 2017) (Golder, 2018) (2018 inspection report not yet issued).

An assessment of structural stability and slope stability was completed for Upstream Raise 92 in 2016 (Golder, 2016b). This assessment evaluated foundation conditions as well as overall mass movement of the facility and indicated that no structural stability deficiencies were identified.

7.1 Soil Conditions

Upstream Raise 92 is generally constructed over a glacial till layer consisting of sand and silty-clay soils. Glacial till varies in thickness from 20 feet to several hundred feet in the area of CCS. Silty-sand and sand lenses are present throughout the glacial till formation, which is underlain by poorly consolidated siltstone/sandstone bedrock (Barr, 1982) (CPA and UPA, 1989).

The location of Upstream Raise 92 was originally characterized in 1973 (Burns & McDonnell, 1973). A hydrogeologic study was performed in 1982 (Barr, 1982) and an evaluation of the pond bottom conditions of the southwest portion of Section 16 was completed in 1986 (Eugene A. Hickok & Associates, 1986). Site geology, soils, and hydrology, including drainage and surface water flow, were examined during these prior studies to determine site suitability for disposal of CCRs. Additional subsurface field investigations were performed by Golder in 2001 and 2003 with the drilling of 29 boreholes (Golder, 2004b).

The foundation soils of the west side of Upstream Raise 92 consist of native soils (lean clay, fat clay, and sandy clay) and embankment fill materials sourced from nearby native soils (lean clay, fat clay, and sandy clay). The west side of Upstream Raise 92 was cleaned out and relined in 1989 (Foth & Van Dyke, 1990). According to construction documents, the foundation materials were compacted to 90% standard Proctor density. The east side of Upstream Raise 92 was also excavated into clay-rich material (Eugene A. Hickok & Associates, 1986). The clay-rich zone is approximately 15 to 30 feet thick and is underlain by sandstone bedrock. Based on historic information, Upstream Raise 92 appears to be underlain by relatively homogenous soils unlikely to be susceptible to large differential settlement.

Foundation site soil conditions do not indicate that the facility is located in an unstable area susceptible to significant differential settlement due to consolidation of underlying native soils. Additionally, the site facilities are routinely inspected for both state and federal regulatory requirements. The facility will continue to be inspected per state and federal regulatory requirements, and signs of significant differential settlement will be documented and corrected as needed.

7.2 Geologic and Geomorphologic Features

CCS and McLean County are situated at the eastern-most extent of the Williston Basin, a structural and sedimentary basin (USGS, 1999). The region is characterized by the presence of glacial drift, reaching thicknesses of several hundred feet, and overlying the Sentinel Butte Member, the source of commercially mined coal in the direct vicinity of CCS (Falkirk Mining Company, 1979). The Sentinel Butte Member is the highest strata of the Paleocene Fort Union Formation, overlying the Tongue River, Ludlow, and Cannonball Members (USGS, 1999). The Sentinel Butte Member is marked by drab-gray units, separating it from the lower Tongue River Member.

The site geology of CCS includes unconsolidated surficial deposits of the Coleharbor formation consisting of stratified and unstratified glacial drift. The near-surface materials are silty clay and sandy clay till with interbedded sand lenses (CPA and UPA, 1989). Karst is not known to exist at CCS based on USGS information (USGS, 2004) or site historical information from site borings and test pits (see Figure 8).

7.3 Human-Made Features

7.3.1 Historically Placed Fill (East Side Upstream Raise 92)

The east side of Upstream Raise 92 was originally constructed with a natural clay liner. In 1989, the west side of Upstream Raise 92 was cleaned out and lined while the east side of Upstream Raise 92 was reclassified as a solid waste disposal area. CCRs from other site containment areas were excavated and placed on the east side of Upstream Raise 92 prior to these materials being re-graded and a new composite liner installed over the existing CCRs between 2005 and 2008. The composite liners from the west and east sides of Upstream Raise 92 were connected and the facility began operating as a single CCR surface impoundment in 2005 (Golder, 2006) (Golder, 2007) (Golder, 2009).

The materials placed between the original natural clay liner and the new composite liner consisted of a combination of hardened fly ash, flue gas desulfurization (FGD) material, bottom ash, and native soil. Prior to construction of the new composite liner, subgrade and embankment grades were constructed by:

- Over-excavating unsuitable materials and replacing those materials with competent embankment fill and
- Placing and compacting competent embankment fill over the east side of Upstream Raise 92 to reach subgrade and/or embankment grades in preparation for construction of the composite liner system.

Construction of the east side of Upstream Raise 92 was completed in 2008. Embankment fill was placed to a maximum thickness of up to approximately 40 feet at locations where berms were constructed. The as-built elevation of the top of this berm was approximately 1950 feet in 2008. Subsequent inspections and surveys of the facility between 2008 and 2017 have not identified signs of differential settlement and indicate that the berm remains at an approximate elevation of 1950 feet, an indication that minimal settlement has occurred of the historically placed materials between the original natural clay liner and the new composite liner.

7.3.2 Other Human-Made Features

Although commercial mining occurs in the vicinity of CCS, no prior mining has occurred within the footprint of the facility, or adjacent to the facility, that would undermine the stability of the facility.

No significant fills, excavations, or structures are present adjacent to the facilities.

Upstream Raise 92 is not located in an unstable area caused by human-made features.

8.0 CERTIFICATION

The undersigned attest to the completeness and accuracy of the above written Location Restrictions Demonstration, and certify that the location of Upstream Raise 92 meets the requirements detailed in 40 CFR 257.60 through 257.64, summarized as follows:

- 40 CFR 257.60 – Placement above the uppermost aquifer
  - Based on information acquired between June 2017 and June 2018, the base of the liner system for Upstream Raise 92 is above the upper limits of the uppermost aquifer and no intermittent, recurring, or sustained hydraulic connection between any portion of the base of the CCR unit and the uppermost aquifer exists.
- 40 CFR 257.61 – Wetlands
  - Upstream Raise 92 is not located in wetlands.
- 40 CFR 257.62 – Fault areas
  - Upstream Raise 92 is not located within 200 feet of a fault (or the outermost damage zone of a fault) that has had displacement in Holocene time.
- 40 CFR 257.63 – Seismic impact zones
  - Upstream Raise 92 is not located in a seismic impact zone.
- 40 CFR 257.64 – Unstable areas
  - Upstream Raise 92 is not located in an unstable area.

Golder Associates Inc.

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Senior Project Engineer

Todd Stong, PE
Associate and Senior Consultant

CCS/TJS/ds

https://golderassociates.sharepoint.com/sites/22722g/deliverables/report/ccs_ur92_locationdemorpt_fnl_16oct18/18939823_ur92_location_demo_fnl_16oct18.docx

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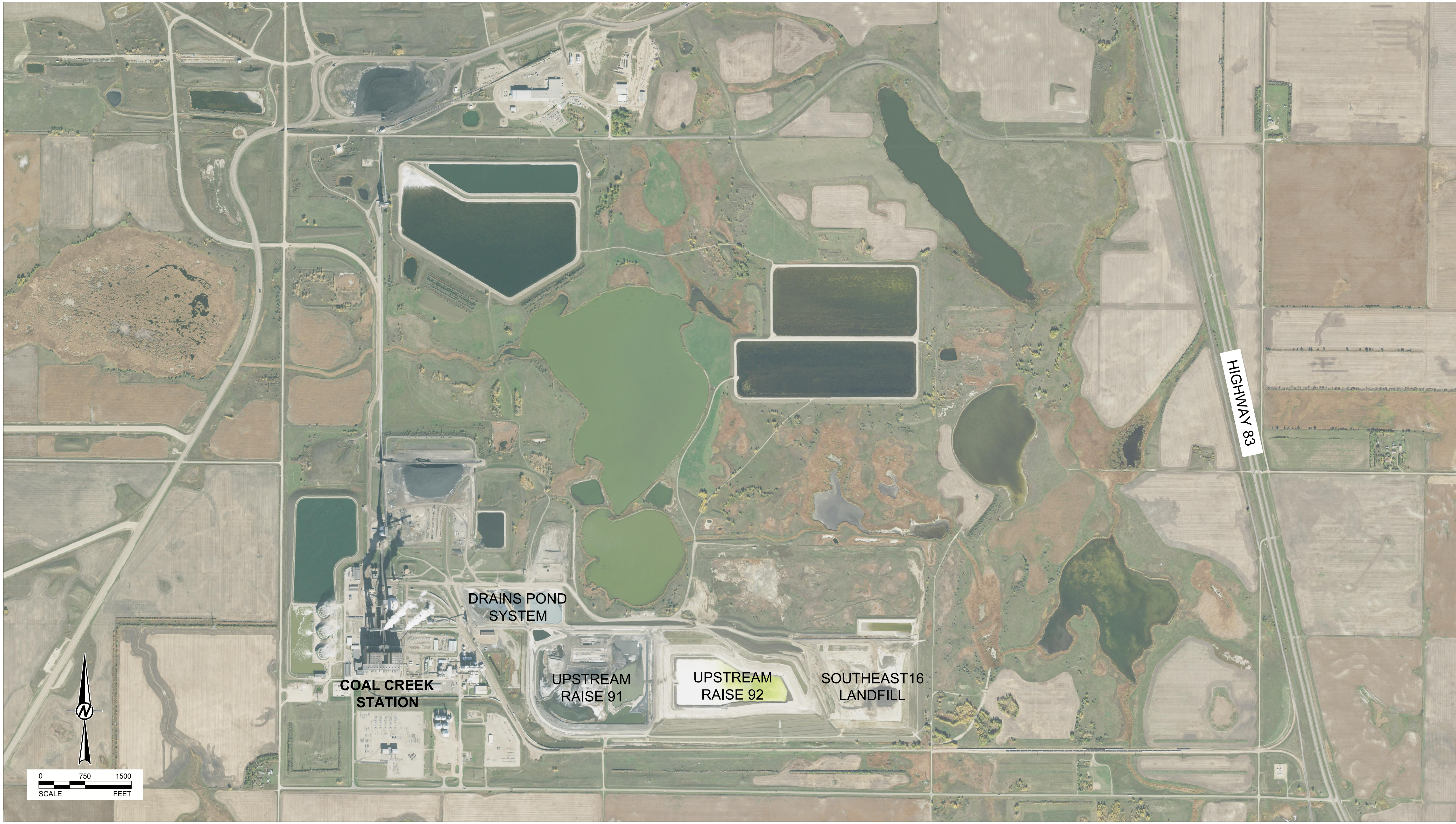
FIGURE 1

Coal Creek Station CCR Facilities



REFERENCES

1. AERIAL IMAGE FROM UNITED STATES DEPARTMENT OF AGRICULTURE NATIONAL AERIAL IMAGERY PROGRAM, PUBLISHED 2017.

CLIENT
GREAT RIVER ENERGY
COAL CREEK STATION
UNDERWOOD, NORTH DAKOTA

PROJECT
LOCATION RESTRICTION DEMONSTRATION

CONSULTANT
GOLDER

YYYY-MM-DD	2018-09-12
DESIGNED	RFS
PREPARED	KAC
REVIEWED	CCS
APPROVED	TJS

TITLE
COAL CREEK STATION CCR FACILITIES

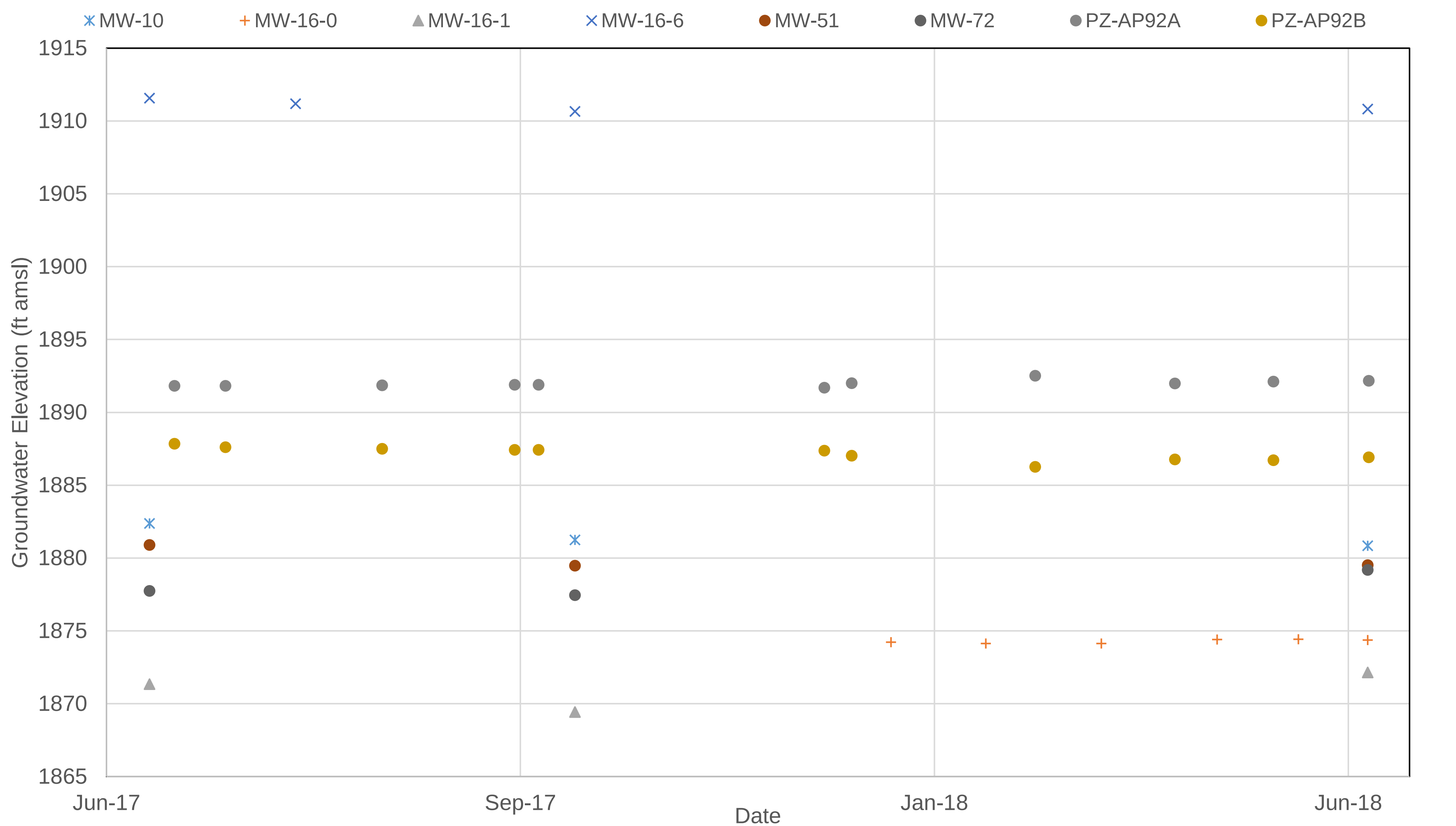
PROJECT NO.	REV.	FIGURE
1893823	A	1

Path: \\Denver\acad\GREAT RIVER ENERGY\COAL CREEK\99_PROJECTS\1893823\Groundwater Separation\ | File Name: Figure1.dwg

IF THIS MEASUREMENT DOES NOT MATCH WHAT IS SHOWN, THE SHEET SIZE HAS BEEN MODIFIED FROM: ANSI B

FIGURE 2

Groundwater Level Measurements (June 2017 through June 2018)



GOLDER

DENVER, COLORADO

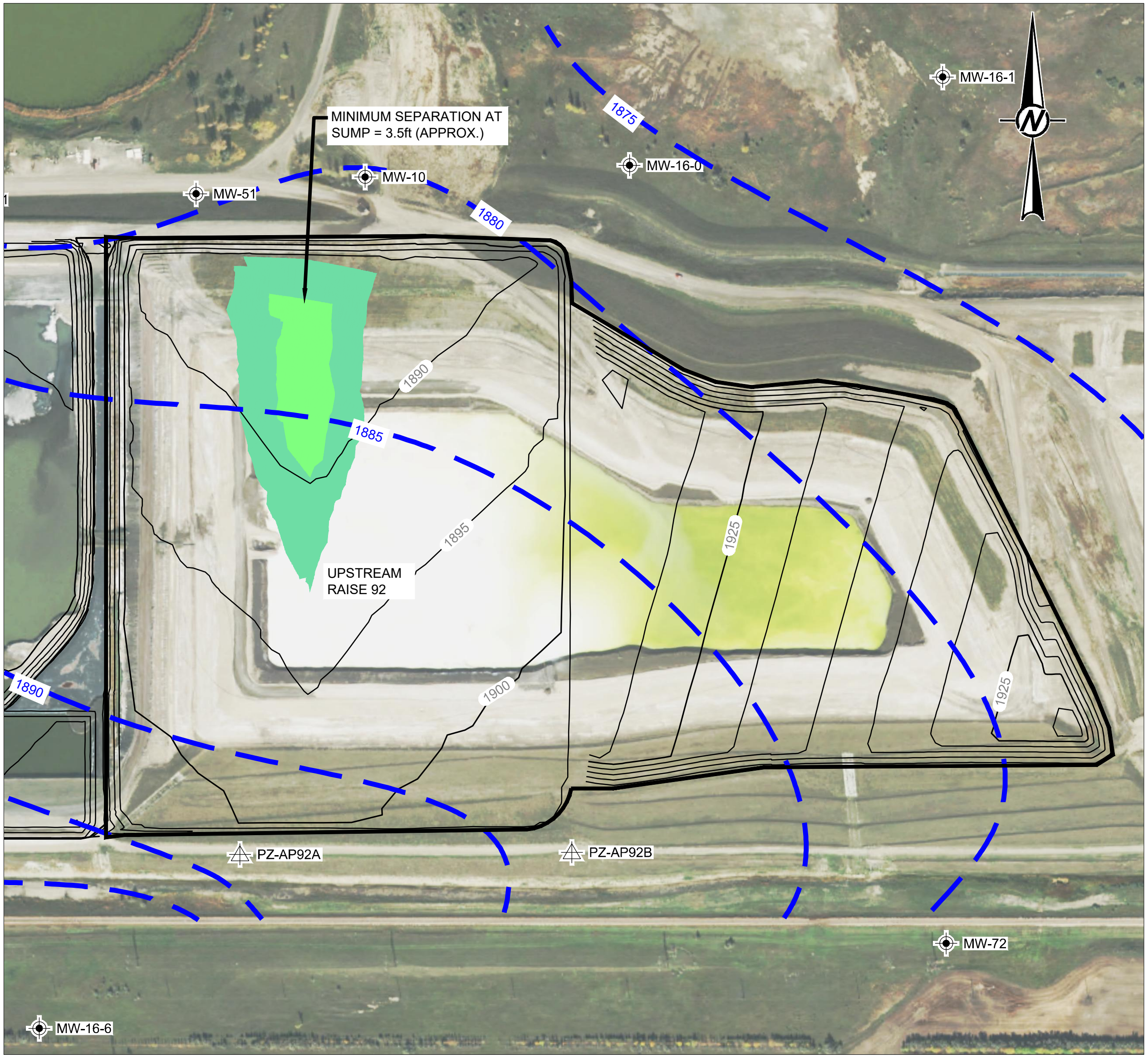
Groundwater Level Measurements (June 2017 through June 2018) Upstream Raise 92

GREAT RIVER ENERGY
COAL CREEK STATION

9/17/2018	Job No. 1893823
1893823_CCS_GWElev_All.xlsx	**Figure 2**

FIGURE 3

Groundwater Separation
October 2017 Water Levels



LEGEND

- 1908 — BOTTOM OF LINER GRADES (REFERENCE 2)
- 1900 — GROUNDWATER ELEVATION CONTOUR - OCTOBER 2017 (NOTE 1)
- APPROXIMATE EXTENTS OF LINED SURFACE IMPOUNDMENT
- MONITORING WELL
- PIEZOMETER

NOTE(S)

1. GROUNDWATER ELEVATION CONTOURS WERE INTERPRETED FROM WATER LEVELS MEASURED IN MONITORING WELLS AND PIEZOMETERS ON OCTOBER 2017.
2. GROUNDWATER ELEVATION CONTOUR INTERVALS ARE FIVE FEET.
3. BOTTOM OF LINER CONTOUR INTERVALS ARE FIVE FEET.
4. ADDITIONAL INFORMATION (SURFACE WATER BODIES AND ADDITIONAL MONITORING WELLS/PIEZOMETERS) NOT SHOWN WAS CONSIDERED WHEN CREATING GROUNDWATER ELEVATION CONTOURS.

REFERENCE(S)

1. AERIAL IMAGE FROM THE UNITED STATES DEPARTMENT OF AGRICULTURE NATIONAL IMAGERY PROGRAM ACQUIRED IN 2017. THE LOCATION OF THE AERIAL IMAGE IS APPROXIMATE.
2. BOTTOM OF LINER GRADES REPRESENT THE BOTTOM OF THE COMPOSITE LINER SYSTEMS (BOTTOM OF CLAY AND/OR GEOSYNTHETIC CLAY LINER) AND ARE BASED ON AS-BUILT INFORMATION PROVIDED BY GRE.

GROUNDWATER SEPARATION (GROUNDWATER TO BOTTOM OF LINER IN FEET)

NUMBER	MINIMUM	MAXIMUM	COLOR
1	0.0	1.0	
2	1.0	2.0	
3	2.0	3.0	
4	3.0	4.0	
5	4.0	5.0	

*THE LACK OF SHADING INDICATES GROUNDWATER SEPARATION IS GREATER THAN FIVE FEET.

0 250 500
1" = 500' FEET

CLIENT
GREAT RIVER ENERGY
COAL CREEK STATION
UNDERWOOD, NORTH DAKOTA

CONSULTANT
GOLDER

YYYY-MM-DD	2018-09-06
DESIGNED	KAC
PREPARED	KAC
REVIEWED	CCS
APPROVED	TJS

PROJECT
COAL CREEK STATION
CCR SITING DEMONSTRATION
PLACEMENT ABOVE THE UPPERMOST AQUIFER

TITLE
GROUNDWATER SEPARATION
OCTOBER 2017 WATER LEVELS
UPSTREAM RAISE 92

PROJECT NO. 1893823
REV. A
FIGURE 3

FIGURE 4

USGS Quaternary Faults and Folds Database Map – United States

USGS Quaternary Faults and Folds Database

May 30, 2018

Quaternary Faults

historical (<150 years), well constrained location

historical (<150 years), moderately constrained location

historical (<150 years), inferred location

latest Quaternary (<15,000 years), well constrained location

latest Quaternary (<15,000 years), moderately constrained location

1:29,007,920

0 250 500 1,000 mi

0 387.5 775 1,550 km

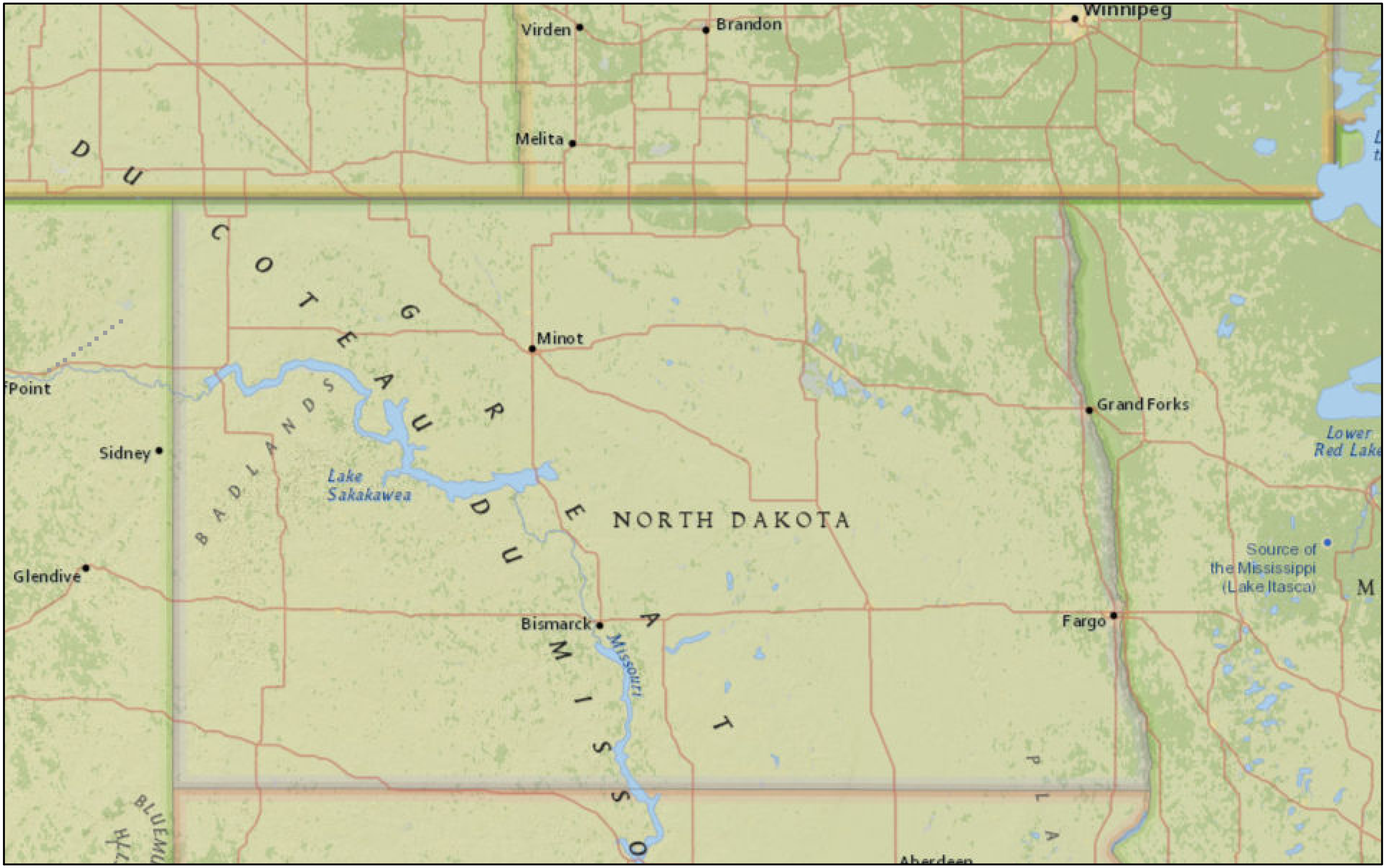
Content may not reflect National Geographic's current map policy. Sources: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, U.S. Geological Survey

Content may not reflect National Geographic's current map policy. Sources: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp. |

FIGURE 5

USGS Quaternary Faults and Folds Database Map – North Dakota

USGS Quaternary Faults and Folds Database - North Dakota



May 30, 2018

Site Investigations

Quaternary Faults

historical (<150 years), well constrained location

historical (<150 years), moderately constrained location

historical (<150 years), inferred location

latest Quaternary (<15,000 years), well constrained location

1:4,622,324

0 25 50 100 mi

0 40 80 160 km

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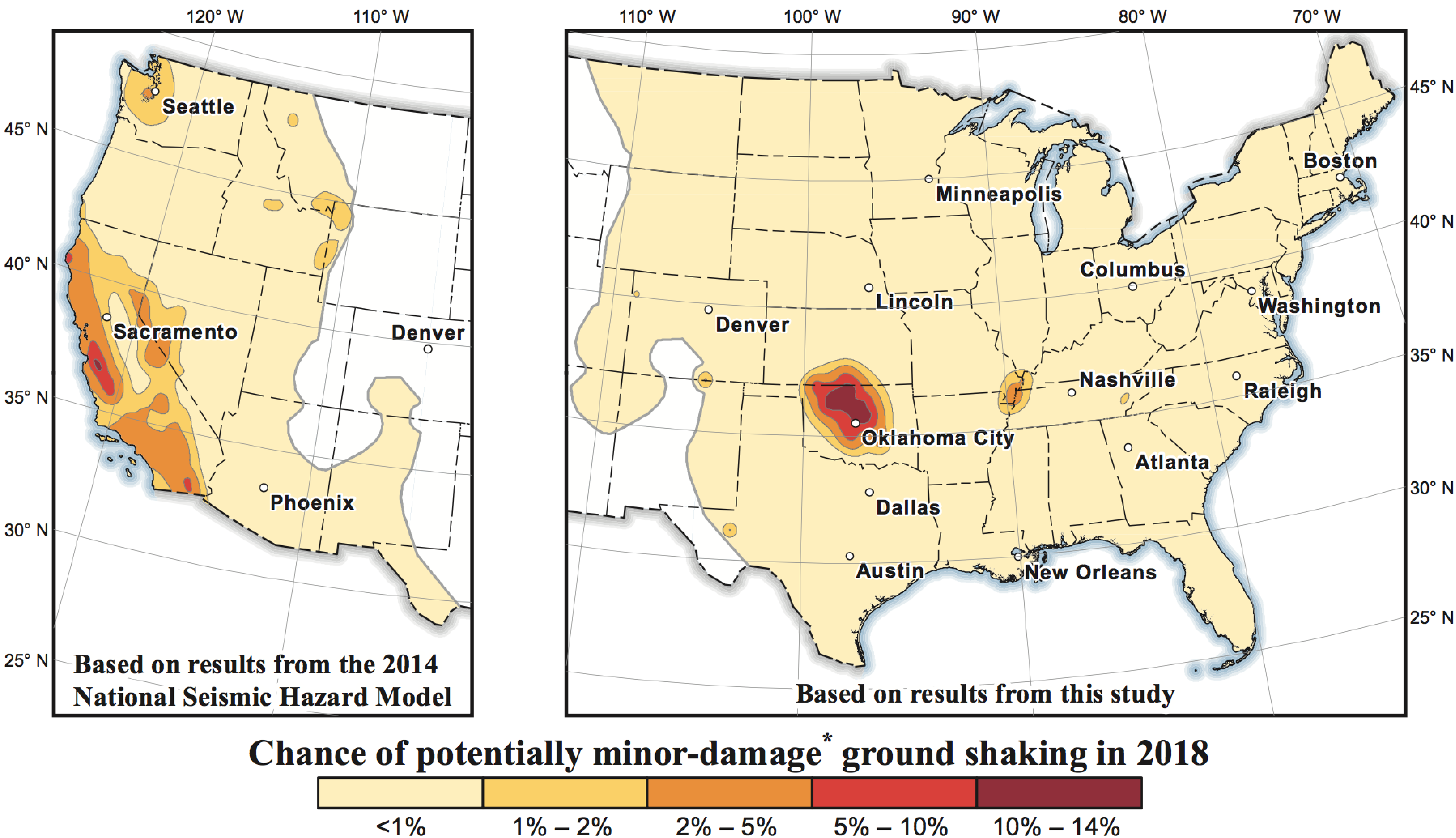
Content may not reflect National Geographic's current map policy. Sources: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp. |

FIGURE 6

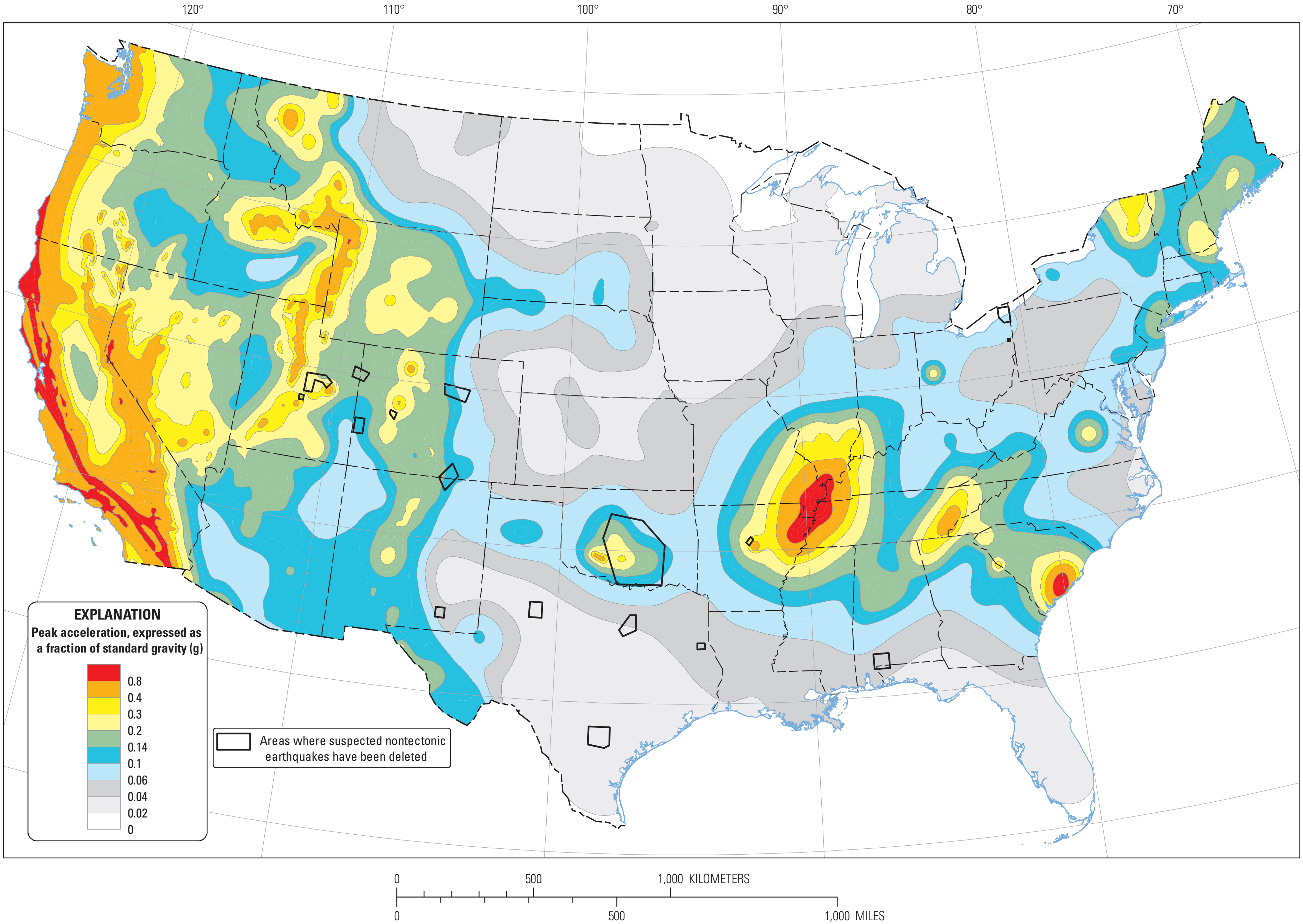
Chance of Potentially Minor Damage Ground Shaking in 2018 Map



* equivalent to Modified Mercalli Intensity VI, which is defined as: "Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight."

FIGURE 7

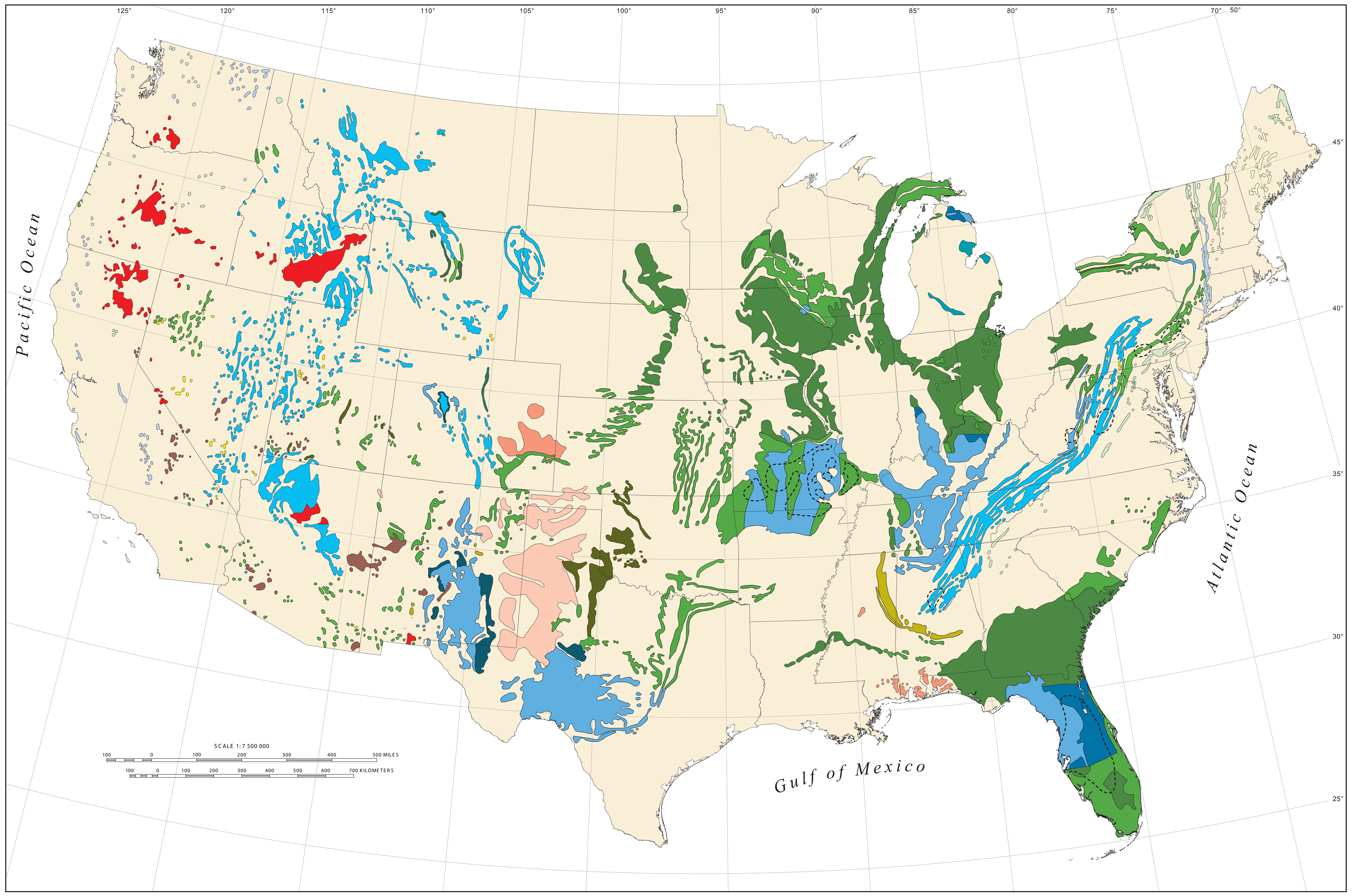
Two-percent Probability of Exceedance in 50 Years Map or Peak Ground Acceleration



Two-percent probability of exceedance in 50 years map of peak ground acceleration

FIGURE 8

Digital Engineering Aspects of Karst Map



FISSURES, TUBES, AND CAVES OVER 1,000 FT (300 M) LONG; 50 FT (15 M) TO OVER 250 FT (75 M) VERTICAL EXTENT

- In metamorphosed limestone, dolostone, and marble
- In moderately to steeply dipping beds of carbonate rock
- In gently dipping to flat-lying beds of carbonate rock
- In gently dipping to flat-lying beds of carbonate rock beneath an overburden of noncarbonate material 10 ft (3 m) to 200 ft (60 m) thick
- In moderately to steeply dipping beds of gypsum
- In gently dipping to flat-lying beds of gypsum

FISSURES, TUBES, AND CAVES GENERALLY LESS THAN 1,000 FT (300 M) LONG; 50 FT (15 M) OR LESS VERTICAL EXTENT

- In metamorphosed limestone, dolostone, and marble
- In crystalline, highly siliceous intensely folded cabonate rock
- In moderately to steeply dipping carbonate rock
- In gently dipping to flat-lying carbonate rock
- In gently dipping to flat-lying beds of carbonate rock beneath an overburden of noncarbonate material 10 ft (3 m) to 200 ft (60 m) thick
- In moderately to steeply dipping beds of gypsum
- In gently dipping to flat-lying beds of gypsum
- In gently dipping to flat-lying beds of gypsum beneath and overburden of nongypsiferous material 10 ft (3 m) to 200 ft (60 m) thick
- In carbonate zones in highly calcic granite (Alaska only)
- In moderately to steeply dipping beds of carbonate rock with a thin cover of glacial till and frost-derived residual soil (Alaska only)

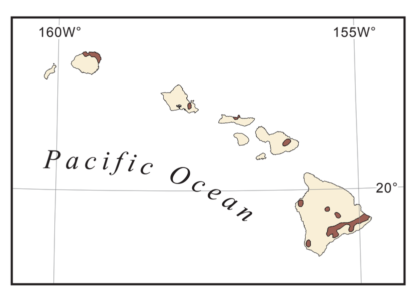
FISSURES, TUBES, AND CAVES GENERALLY ABSENT; WHERE PRESENT IN SMALL ISOLATED AREAS, LESS THAN 50 FT (15 M) LONG; LESS THAN 10 FT (3 M) VERTICAL EXTENT

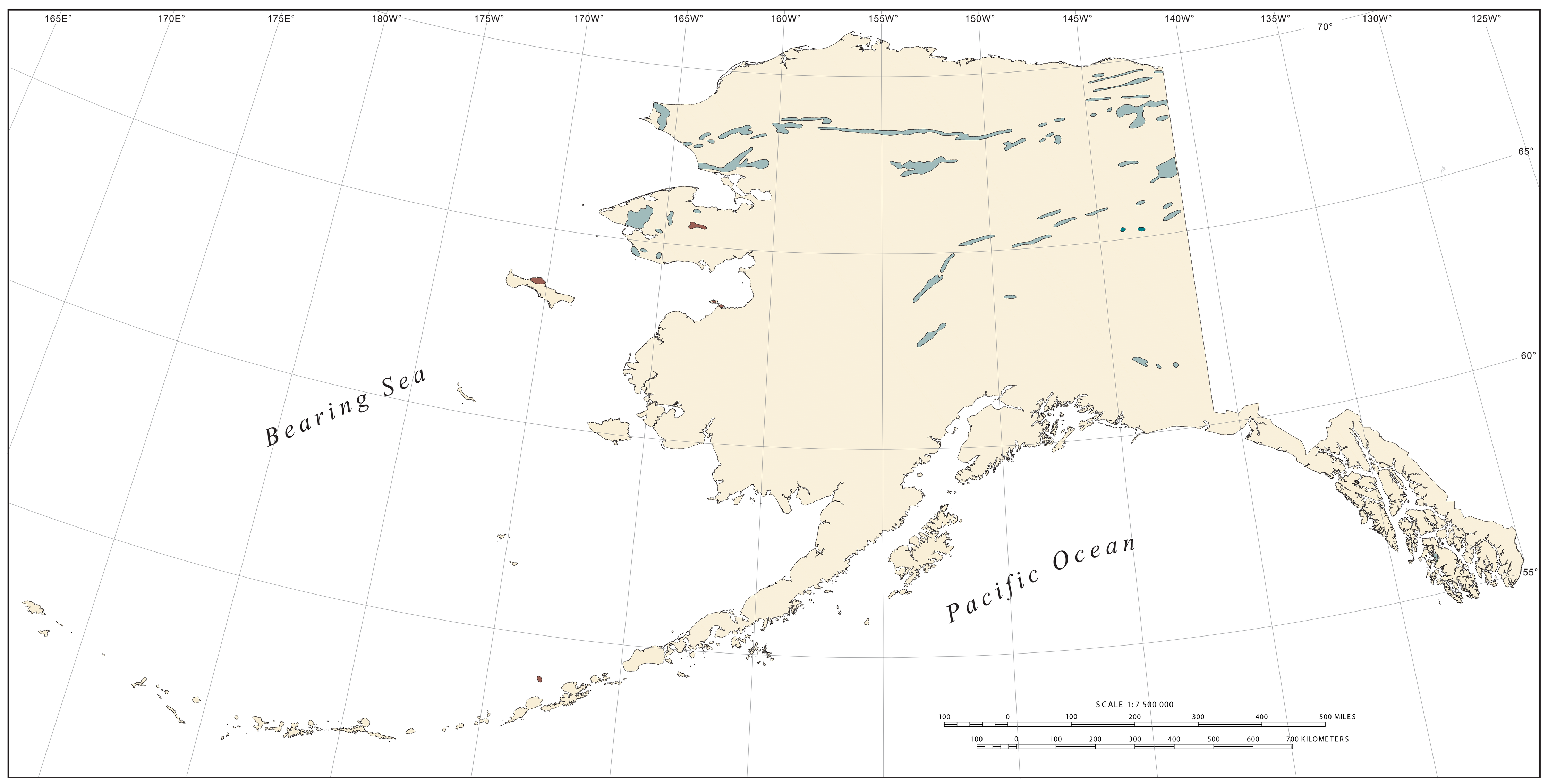
- In crystalline, highly siliceous intensely folded carbonate rock
- In moderately to steeply dipping beds of carbonate rock
- In gently dipping to flat-lying beds of carbonate rock

FEATURES ANALOGOUS TO KARST

- Fissures and voids present to a depth of 250 ft (75 m) or more in areas of subsidence from piping in thick unconsolidated material
- Fissures and voids present to a depth of 50 ft (15 m) in areas of subsidence from piping in thick, unconsolidated material
- Fissures, tubes, and tunnels present to a depth of 250 ft (75 m) or more in lava
- Fissures, tubes, and tunnels present to a depth of 50 ft (15 m) in lava

Areas in which extensive historical susidence has occurred





Albers equal area projection
North American Datum 1983
standard parallels 25°N and 50°N
longitude of central meridian 96°W
latitude of projection origin 37°N

Digital Engineering Aspects of Karst Map : A GIS version of Davies, W.E., Simpson, J.H., Ohlmacher, G.C., Kirk, W.S., and Newton, E.G., 1984, Engineering aspects of karst: U.S. Geological Survey, National Atlas of the United States of America, scale 1:7,500,000

by Bret D. Tobin and David J. Weary

U.S. Geological Survey Open-File Report 2004-1352

Introduction

This data set was converted from a printed map to a digital GIS coverage to provide users with a citable national-scale karst data set to use for graphic and demonstration purposes until new, improved data are developed. These data may be served on the internet or distributed freely with proper citation. Because it has been converted to GIS format, this data can be easily projected, displayed and queried for multiple uses in GIS. The karst polygons of the original map were scanned from the stable base negatives of the original, vectorized, edited, and then attributed with unit descriptions. All of these processes potentially introduce small errors and distortions to the geography. The original map was produced at a scale of 1:7,500,000; this coverage is not as accurate and should be used for broad scale purposes only. It is not intended for any site-specific studies.

The following text is taken verbatim from the original map, which was printed front and back on a single sheet.

ENGINEERING ASPECTS OF KARST

By
William E. Davies

Distinctive surficial and subterranean features developed by solution of carbonate and other rocks and characterized by closed depressions, sinking streams, and cavern openings are commonly referred to as karst. The term was used first to describe the region of Carso in northeastern Italy and northern Yugoslavia, where solution landscape was studied in the 19th century. Originally the term defined surface features derived by solution of carbonate rocks, but subsequent use has broadened the definition to include sulfates, halides, and other soluble rocks. The term has been expanded also to cover interrelated forms derived by solution on the surface in the subsurface. A further expansion of the concept of karst was the introduction of the term "pseudokarst" to designate karstlike terrain produced by processes other than the dissolution of rocks (Burger and Dubertret, 1975). When used in its broadest sense, the term encompasses many surface and subsurface conditions that give rise to problems in engineering geology. Most of these problems pertain to subterranean karst and pseudokarst features that affect foundations, tunnels, reservoir tightness, and diversion of surface drainage. Environmental aspects of karst lead to additional problems in engineering geology, especially in site selection. Subterranean openings may be the habitat of unique and, in some cases, endangered fauna. The openings are also conduits for water and refuse disposal from the surface or, in caves, for pollutants that can be carried for great distances. Many caves contain features of beauty and scientific interest that can be important esthetic factors in site selection for structures, transportation routes, and impoundments.

Although surface features of karst terrain (primarily sinkholes, solution valleys, and solution-sculptured rock ledges) are significant in engineering geology, they have not been included on this map because of the additional complexity that would occur in classification and portrayal.

The systematic study of karst in the United States started with W. M. Davis' (1930) theory on the origin of caves by deep-seated solution. Bretz (1942) obtained data, from studies in flat-lying carbonate rocks in the Midwestern States that supported Davis' theory. After World War II, studies of karst in the United States became widespread beginning with investigations in the Appalachian Mountains. Based on these studies, many of which were in areas of folded rock, older theories were modified with emphasis on maximum solution activity in a zone directly beneath a uniform water table (Davies, 1960). Since 1948, the exploration of caves and studies of landforms in carbonate terrains have produced a vast amount of data on karst. Reports of these explorations and studies have been primary sources in compiling this map on the subterranean aspects of engineering geology of karst and pseudokarst. In addition, published logs of borings were used. Much of the information on the Eastern United States, principally for the Appalachian Mountains and Plateau, is from field observations.

The small scale of the map and the limited data on openings, other than caves, in soluble rocks restrict the use of the map to the most general types of planning and as a guide to areas where subterranean karst and pseudokarst features occur. The map cannot be used either for specific site selection or as a substitute for field examination in planning and site development. Because cartographic license was taken to portray the features at the small scale of this map, enlargement can lead to gross errors in location of the data presented.

Subterranean openings in karst range in size from minute voids to large caverns. Most of the openings are formed by solution processes along fractures, joints, and bedding planes. Caves and related solution features are common in most carbonate and gypsum terrains in the United States, except in the area formerly covered by Pleistocene ice sheets (Davies and LeGrand, 1972). The southward advance of these ice sheets covered New England, New York, northeastern and northwestern Pennsylvania, most of the States bordering the Great Lakes, and much of the area north of the Missouri River. Karst features in the formerly glaciated area are covered by glacial drift, and most caves and fissure openings have been eroded away or filled. The caves and open fissures that remain generally have less than 1,000 ft (300 m) each of passages large enough to be traversed by humans.

South of the formerly glaciated area, caves, open joints, fissures, and other subterranean karst features are present in most soluble rocks. In general, both the number and size of solution features increase inversely with latitude. In addition, the number and size also vary according to the age and structure of the soluble rock in which solution features develop. Solution features in folded rocks are subordinate to those in nondeformed rocks; those in rocks older than Mississippian are subordinate to those in Mississippian and younger rocks. These are broad generalizations, and local exceptions exist. However, these generalizations can be used as a hasty estimate of karst conditions.

Most caves consist of a series of passages on one level. Some caves have multiple levels of passages that extend vertically as much as 300 ft (90 m). The levels are generally connected by shafts or large galleries. Most passages are less than 10 ft (3 m) high and less than 10 ft (3 m) wide. Maximum size of passages is about 100 ft (30 m) in height and width. In many caves, passages expand into galleries or rooms that are 30 to 200 ft (9 to 60 m) long and wide and up to 150 ft (45 m) high. The largest known solution opening in the United States is in Carlsbad Caverns, New Mexico, where a T-shaped room is 1,800 ft (550 m) long in one section, 1,100 ft (330 m) long in the other section, 255 ft (77 m) high, and up to 300 ft (90 m) wide.

Shafts are present in multiple-level caves and in some single-level caves. The deepest shafts are about 1,000 ft (300 m) deep, but in most caves they are less than 300 ft (90 m) deep. Most shafts are 30 ft (10 m) or less wide. In multiple-level caves, shafts connect levels; in other caves, the shafts are pits with no apparent connection at the base. Shafts are irregular in shape; some resemble funnels, and others are shaped like cylinders. Dome pits are cylindrical shafts that develop upward from a passage towards the surface of the Earth. Dome pits are up to 50 ft (15 m) wide and extend upward for as much as 150 ft (45 m). Their walls are uniform. Dome pits are capped by a cover of carbonate rocks 10 to 50 ft (3 to 15 m) thick. In many domes, the caps have collapsed and left vertical-sided open pits.

Virginia, West Virginia, Kentucky, Tennessee, Alabama, Missouri, Texas, and New Mexico contain hundreds of caves, each of which has over a mile of passages. At least one cavern system in each of these States has 10 to more than 100 mi (16 to 160 km) of passages. The largest known system is Flint Ridge-Mammoth Cave in Kentucky (Brucker, 1979), with over 200 mi (320 km) of passageways in an area of 362 mi (902 km).

Solution tubes with openings as much as 1 ft (0.3 m) wide and irregular alignment occupy portions of the carbonate bedrock. In some cases, the tubes connect with caves. However, the tubes generally lack the systematic patterns that are common in development of cavern passages. These tubes apparently predate cavern development. Although most tubes are seldom longer than a few hundred feet, they are interconnected and commonly act as conduits for subsurface drainage. During freezing weather, water from tubes can cause large buildups of ice where excavations intersect the tubes. At other times, the tubes lead to flooding of excavations and leaks in reservoirs and contribute to weakening of retaining walls.

Fissures (also referred to as open joints) up to 1 ft (0.3 m) wide result from limited solution along joints, fractures, and bedding planes. Fissures occur in various attitudes from vertical to gently inclined and generally are in repetitive geometrical patterns or sets. Fissures form systems that may extend for several thousand feet horizontally and over 300 ft (90 m) vertically. Some fissures or parts of fissures are filled with consolidated clay-silt and clay-gravel that seal them. The seals, however, are altered in contact with water and can be removed by running water. Fissures are commonly conduits for subterranean streams. In addition, they can cause serious engineering problems, such as reservoir leakage and instability of cuts, bridge abutments, piers, and dam foundations and abutments.

The depth to which solution openings occur depends on relief in an area, thickness of soluble rock, and geologic structure. The configuration and depth of the water table, in some cases, are controlling factors. Ground water in karst terrain generally is found in existing openings that extend tens to hundreds of feet below the water table. In the mountainous areas of the Western United States, the known vertical extent of solution openings is as much as 1,100 ft (330 m). In the Eastern United States, where relief is less, the vertical extent is generally less than 400 ft (120 m), with a maximum of 650 ft (200 m). Beneath many broad river valleys, solution features in carbonate rocks are present to a depth of about 100 ft (30 m) in both the Eastern and Western United States.

Surface subsidence (sinkhole development) occurs most commonly in areas where ground-water conditions are altered by excessive pumping or by diversion of surface drainage. Subsidence generally involves weathered bedrock and soil that bridge caverns, subterranean galleries, and dome pits. The collapse is caused by loss of support resulting from the reduction of hydrostatic pressure of ground water, by sapping, and by piping. Most subsidence forms shallow, steep-sided depressions up to 100 ft (30 m) wide and up to 20 ft (6 m) deep. However, in Florida and central Alabama, recent subsidence has resulted in nearly vertical sided sinkholes up to 425 ft (130 m) wide and 150 ft (45 m) deep.

Areas of local subsidence caused by mining operations and regional subsidence caused by withdrawal of ground water and petroleum in thick, unconsolidated sediments have not been included on the map of subterranean aspects of engineering geology of karst and pseudokarst because natural processes are involved only in a subordinate way in development of these phenomena. The problems of these types of subsidence are complex, and the areas involved are so extensive that they are best treated as subjects for another map.

In the New England States, solution terrain is confined to crystalline limestones and marbles mainly in northeastern Maine, western Vermont, and western Massachusetts. Solution features in these areas are primarily narrow fissures generally less than 200 ft (60 m) long and less than 30 ft (10 m) deep. A few small caves are known in western Vermont and in the Berkshire Mountains of western Massachusetts. In eastern Vermont and much of Maine, carbonate rocks high in silica and other impurities' are commonly, yet incorrectly, referred to as limestone. Solution features are generally absent in these rocks.

In the Appalachian Highlands, three major groups of carbonate rocks are in the karst regions. The Great Valley, in the eastern part of the Highlands, from southeastern New York to central Alabama, is a lowland up to 26 mi (42 km) wide eroded across dolomite, limestone, and shale of Cambrian and Ordovician age, Regionally, and to some extend reflecting differences in degree of karst development, the Great Valley is designated from north to south as the Kittatinny, Lehigh, Lebanon, Cumberland, Hagerstown, Shenandoah, and Tennessee Valleys. All types of solution features are present in the Great Valley, with small caves and fissures in southeastern New York and like features increasing in size and numbers southward. From central Virginia southward, large caves with over 1 mi (1.6 km) of passages in each are common, and fissures extend hundreds of feet in length and over 100 ft (30 m) in depth. The major geologic units involved in karst development in the Great Valley are the Elbrook (Cambrian), Conococheague (Cambrian-Ordovician), Beekmantown (Ordovician), and their equivalents. All are folded with steep dips, and overturning is common along the east half of the lowland. Faults are numerous and some major fault zones extend over 200 mi (320 km). Active subsidence is prevalent throughout the Great Valley and is a result primarily of alteration of the water table. Generally, the subsidence involves the opening of shallow fissures and shafts up to 10 ft (3 m) in diameter in farmland through removal of soil and thin rock cover over fissures, shallow cavern passages, and small dome pits. More extensive subsidence is in progress in the vicinity of Allentown and Harrisburg, Pennsylvania, where numerous subsidence depressions up to 100 ft (30 m) in diameter have developed. In Staunton, Virginia, active subsidence from collapse of rocks and soil covering shallow caves and fissures was recorded as early as 1911. Subsidence in the Staunton area resulted from large-scale piping of sinkhole soils by leakage from settling basins and from drawdown of the water table. In central Alabama, steep-sided, water-filled sinks, up to 425 ft (130 m) wide and 150 ft (45 m) deep, have formed recently by collapse of weathered limestone and thick soils covering limestone.

In the area west of the Great Valley, a sequence of limestones in the Upper Silurian (Tonoloway) and the Lower Devonian (Helderberg Group) forms subordinate ridges in southeastem New York, central Pennsylvania, eastern West Virginia, and western Virginia. The rock is folded, and dips are steep. Karst features include fissures extending several hundred feet vertically and caves with up to 1 mi (1.6 km) of large passageways. Subsidence is uncommon, but the fissures and caves have caused problems in foundations and abutments of dams, in cuts because of unstable wedges, and in tunnels that encounter earth fills in solution cavities.

Along the western edge of the Valley and Ridge province of the Appalachian Highlands, several large basinlike lowlands underlain by Cambrian and Ordovician carbonate rocks occur. The lowlands are eroded across large anticlines with steep dips on the flanks and moderate to steep plunges along the axes of the anticlines. In the Nittany and Kishacoquillas Valleys of Pennsylvania, and some smaller valleys designated as "coves," numerous caves occur, each with passageways 1,000 to 5,000 ft (300 to 1,5!)0 m) long The passages generally are 100 ft (30 m) or less below the surface. Many act as subterranean feeders that carry runoff from adjacent ridges to a few points of resurgence. The resurgent points are large springs with a daily flow of up to 1 million gallons or more (4 million or more). Fissures are present but seldom exceed 200 ft (60 m) in depth. Subsidence is not common, but deep cuts and excavations are subject to uncontrollable flooding if major subterranean conduits are encountered. In Germany Valley, West Virginia, solution features, primarily multiple-level caves and fissures, extend to depths of 350 ft (105 m) or more. Drainage of most of this valley is by way of one large spring. Subsidence from collapse of sinkholes is common, and potential for subsidence exists over numerous dome pits above caves.

The Appalachian Plateau's province and adjacent parts of the Interior Plains in West Virginia, Kentucky, Tennessee, northern Alabama, and southern Indiana contain the most intensely developed karst areas in the United States. The karstic carbonate rocks are Mississippian in age and include the Greenbrier limestone (West Virginia) and the Golconda, Ste. Genevieve. St. Louis, and Warsaw limestones and their equivalents elsewhere. Caves generally contain 3,000 ft (900 m) or more of passageways. Multiple-level caves are not common, but some large cave systems, such as Flint Ridge-Mammoth Cave in Kentucky and Organ Cave in West Virginia, have a multitude of complex passageways at various elevations that extend in aggregate from 30 to over 200 miles (48 to over 320 km). Dome pits, common in many caves, are areas of potential collapse. Many of the caves are large subterranean drainageways that receive streams flowing from adjacent highlands. Cuts and excavations intersecting these caves are subject to inundation from over 1 million cubic ft (40,000 m^3) of water stored in the subterranean reservoirs. Large sinkholes, up to 1 mi (1.6 km) wide and several hundred feet deep, are so numerous that the rims of many sinkholes intersect the rims of their neighbors. Suitable foundations for large structures are difficult to site. Deep cuts, mines, tunnels, and excavations commonly encounter deeply weathered rock and large volumes of weak soil filling cavern passages and fissures. Seasonal flooding is common from snow melt and from heavy rainfall that exceeds the infiltration capacity of sinkholes and the capacity of subterranean channels to carry the runoff. Subsidence in most of the area is not extensive except above the dome pits and along karst valleys in southern Indiana and in the Mammoth Cave plateau in Kentucky.

In the Southeastern United States, karst is extensive on the Coastal Plain in southern Alabama, Georgia, and Florida. The limestones in the karst area are primarily the Ocala Limestone and Jackson Formation of Eocene age and their equivalents. In the Dougherty Plain of southeastern Alabama and southern Georgia, the limestone has been weathered deeply, and in the southern part of the plain the limestone is covered by a residuum of sandy clay. In the northern part of the plain, only small areas of the limestone remain within the residuum. Subsidence occurs as broad, slowly developing, shallow sinkholes in the residuum. In Florida, subsidence is more extensive. In the northern half of the State, the limestone is covered by younger sand deposits that are locally over 100 ft (30 m) thick. In Polk County, subsidence has resulted in vertical-sided sinkholes up to 150 ft (45 m) deep and 425 ft (130 m) wide. The subsidence has engulfed several houses and resulted in large property losses to homeowners. The subsidence is related to alteration of ground-water levels in caverns and to collapse of the weathered carbonate rock that supports the surface deposits.

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Cretaceous carbonate rocks of the Selma Group are extensive in central and western Alabama and northeastern Mississippi. These rocks show little alteration by solution, and open fissures, open joints, and caves are generally not present.

The Silurian limestones and dolomites (Niagaran) of northwestern Ohio and adjacent Indiana are buried beneath glacial drift. Only in northwestern Ohio, where the glacial deposits are less than 20 ft (6 m) thick, are there karst features large enough to cause problems in engineering geology. Caves, each generally with less than 1,000 ft (300 m) of passages, are present but not numerous. Fissures less than 100 ft (30 m) wide extend for hundreds of feet. Small areas of subsidence have been attributed to alteration of the water table by pumping processes in quarries several miles from the site of subsidence. Because of the flat terrain, excavations and cuts seldom are deep enough to encounter major karst features. In the vicinity of Sandusky, Ohio, and on some of the nearby islands in Lake Erie, beds of calcium sulfate expand and change because of weathering and may cause local problems in heaving.

Broad anticlines with gentle dips bring Ordovician limestones and dolomite to the surface in southwestern Ohio and north-central Kentucky. Small caves and numerous joint-controlled fissures occur. Subsidence is not common or extensive, but the fissures and caves that result contain a large volume of water that may flood excavations. Ordovician and Silurian carbonate rocks also are brought to the surface in a broad anticline in central Tennessee around Nashville. Karst conditions are similar to those in north-central Kentucky.

In the Lower Peninsula of Michigan, carbonate rocks are extensive but are buried deeply beneath glacial deposits. Silurian limestones along Lake Huron between Alpena and the Straits of Mackinac contain several large sinkholes up to 1 mi (1.6 km) long and 200 ft (60 m) deep. The sinkholes are interconnected by an extensive fissure system. Normally, the sinkholes are filled with water, but, over time, plugs in the fissure system fail and the lakes drain through the subterranean openings. Subsidence generally does not occur in the Lower Peninsula.

Ordovician limestones cover the south half of the Upper Peninsula of Michigan and extend through eastern and southern Wisconsin, eastern Iowa, and parts of southeastern Minnesota. Karstic features are poorly developed and consist of simple caves, each with less than 1,000 ft (300 m) of passageways and less than 50 ft (15 m) of vertical extent. Fissures developed along joint lines are in about the same size range as the caves. In the vicinity of Dubuque, Iowa, and extending into adjacent Wisconsin and Illinois, fissures several hundred feet long and more than 300 ft (90 m) deep have been encountered in lead-zinc mines. The fissures possibly are relict from older buried karst. Subsidence from karst features is rare, although subsidence over mines is extensive.

The Ozark Plateaus province and adjacent plains in Missouri and northern Arkansas have extensive karst areas. The Ozarks are a large regional structural dome with steep dips along the southern flank. The dome brings Cambrian and Ordovician limestones and dolomites to the surface. North and west of the dome are plains underlain by Mississippian carbonate rocks (Warsaw, St Louis, Ste. Genevieve, and equivalents). Within the Ozarks, caves, each with passages 1,000 ft (300 m) or more long, are common. The passages in most caves extend to a depth of less than 100 ft (30 m). Pits, formed by collapse into cavern shafts and dome pits, are common, and, in southern Missouri, active subsidence is extensive. Most of the pits are water filled. Fissures over 1,000 ft (300 m) long and more than 300 ft (90 m) deep are present in much of the area. Similar fissures are numerous in the lead-zinc mining region in southwestern Missouri and adjacent Oklahoma and Arkansas. Throughout the Ozarks, the caves and fissures give rise to serious problems in foundations and abutments of dams and with reservoir tightness, stability of bridge piers, and stability of cut slopes. The presence of large quantities of subterranean water is a problem in deep foundations.

The Niobrara Formation (Upper Cretaceous) and its equivalents are the most widespread carbonate rocks in western Kansas, eastern Nebraska, and southeastern South Dakota. The Niobrara is generally covered by more than 50 ft (15 m) of younger sediments. Small fissures, less than 1,000 ft (300 m) long and up to 100 ft (30 m) deep, are present, but they are not common and are generally irregularly spaced with 1,000 ft (300 m) or more of solid rock between fissures.

Salt beds in south-central and southwestern Kansas form karst areas. Fissures are extensive, with openings more than 1,000 ft (300 m) long and over 300 ft (90 m) deep. Throughout the saline rock, recent subsidence has resulted from natural causes, as well as from alteration of the water table by solution mining and open pit mining.

In western South Dakota and adjacent parts of Wyoming and Montana, Paleozoic and Cretaceous carbonate rocks, arched steeply upwards, encircle the structural dome that forms the Black Hills. Caves and open fissures are common in the Paleozoic carbonate rocks. A few caves contain many miles of passages but most of the cave passages and fissures in the Black Hills area only extend up to 3,000 ft (900 m) in length and are generally less than 150 ft (45 m) in depth. Closely spaced solution joints also are prevalent.

In western Oklahoma and in the eastern part of the Texas Panhandle, extensive areas of karstic gypsum occur. Small open fissures up to 50 ft (15 m) deep and 1,000 ft (300 m) long are present. Passages in caves in gypsum are generally of similar length and depth.

The Edwards Limestone (Cretaceous) in west-central Texas forms an extensive plateau. Large caves and fissures are present to a depth of 600 ft (180 m), and both fissure systems and passages of single caves commonly extend for more than 1 mi (1.6 km). Both the caves and fissures contain large quantities of water in their deeper parts.

Permian carbonate rocks in central and southern New Mexico contain numerous well-developed karst features. Caves are generally very large and contain miles of passages with a vertical extent of 1,000 ft (300 m) or more. Fissures are of similar size and are interconnected, forming networks that extend for several miles. Closely spaced open joints, enlarged by solution, and numerous small, near-surface solution tubes cause extensive trouble in reservoir tightness throughout this karst area.

In northern and central Arizona, the Kaibab Limestone (Lower Permian) and its equivalents are karstic. North of the Grand Canyon, subterranean openings are primarily widely spaced fissures up to 1,000 ft (300 m) long and 250 ft (75 m) or more deep. South of the Grand Canyon, the fissures are more closely spaced and a few shallow caves are present. East of Flagstaff, there is an area of open fissures. These fissures are over 300 ft (90 m) deep, up to 1,000 ft (300 m) long, and up to 3 ft (1 m) wide. They cut the Coconino Sandstone, as well as the Kaibab Limestone (Colton, 1938).

The Madison Limestone (Mississippian) lies under karst areas in western Montana and adjacent parts of Idaho and Wyoming. Passages in a single cave are commonly up to 2 mi (3.2 km) long. Open fissures up to 1,000 ft (300 m) long and shallow, open joint systems are also common. Fissures and cavern passages extend as much as 1,000 ft (300 m) deep. Large quantities of water are present in the lower parts of the fissures and in some of the deeper cavern passages. Relict karst features developed during times of disconformity at the end of the Mississippian are common in the Madison Limestone. Most of the relict features are solution tubes, caves, and small fissures that have been filled with younger deposits that are now lithified. Because of differences in materials, residual openings, and secondary solution, these features can give rise to foundation problems and leakage.

Karst features in Alaska are not well known. Most of these features are shallow, swalelike depressions developed in a thin cover of residual soil and glacial till that lies over intensely folded limestone. A few cave openings are in limestone bluffs, but most cave entrances are hidden by a cover of spalled rock fragments. Streams crossing limestone terrains commonly disappear into the soil mantle and resurge at contact with insoluble rocks bordering the limestone. No subsidence features have been reported in Alaska.

Pseudokarst conditions in the United States develop in areas of thick, unconsolidated sediments and are primary features in basalt lava. In addition, in Mississippi and Alabama. numerous subsidence features occur in unconsolidated silt, sand and gravel of the Coastal Plain; these subsidence features are analogous to karst features. The subsidence occurs as numerous shallow depressions that are generally less than 50 ft (15 m) deep and up to 1 mi (1.6 km) or more wide. The depressions occur in Miocene and Pliocene sediments 800 to 1,000 ft (240 to 300 m) or more thick. Oligocene carbonate rocks are present beneath these sediments. The origin of the depressions is not understood The depressions appear to be associated with poorly drained areas such as flat lowlands and elevated, dissected, higher erosion surfaces. The depressions apparently are confined to flat surfaces and are not present on slopes that bound the flat surfaces. Excavations in the depressions probably would encounter weak and unstable soil and would be subject to flooding.

The High Plains of western Texas and adjacent States contain numerous depressions, some of which are as much as 3 mi (4.8 km) long and up to 1 mi (1.6 km) wide. They vary from "buffalo wallows," 3 to 10 ft (1 to 3 m) deep, to steep-sided features as much as 250 ft (75 m) deep. The depressions are aligned along a series of major joints and apparently formed by piping and removal of fine-grained material along joint planes at depths greater than 250 ft (75 m). Deep excavations in the depressions encounter weak, unstable soils and are subject to flooding from ground water during occasional periods of high rainfall.

Pseudokarst features in late Cenozoic basalt lava fields are extensive in some regions of the west. The largest regions with this type of pseudokarst are in the Snake River area of Idaho, in part of the Columbia Basalt Plateau in Washington and Oregon, and in the lava fields of northeastern California. Smaller areas are in New Mexico, Arizona, Utah, Nevada, southern California and on the Seward Peninsula in Alaska. The pseudokarst features include lava tubes, fissures, open sinkholes, and caves formed by extrusion of the still-liquid portion of the lava. Subsurface solution of the bedrock and subsequent collapse are not involved in the formation of these features. Lava tubes, in the form of tunnels, are up to 20 ft (6 m) in diameter, and some extend for several miles. Fissures are common but seldom extend for more than 1,000 ft (300 m). The fissures and lava tubes, in contrast to solution features, are not in geometrical sets but are generally parallel and extend in the direction of the flow of the lava. Fissures and lava tubes are generally near-surface features, but some are as much as 250 ft (75 m) deep. "Sinkholes" in lava generally lack the symmetry of those developed in solution terrain. The lava sinks are commonly less than 100 ft (30 m) wide, but a few large sinks, notably in the Snake River area of Idaho, are as much as 1 mi (1.6 km) or more wide. Most of the lava sinks are irregular in shape and generally are shallow features (less than 30 ft (10 m) deep), although some are 150 ft (45 m) or more deep. Many of the sinks have near-vertical sides or overhangs. Lava pseudokarst features present problems in foundations, abutments, and reservoir tightness. In addition, the tubes and related permeable lava often contain large quantities of water that may lead to flooding and slope-stability problems in cuts and excavations.

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