Geologic Hazards in Oklahoma

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ABSTRACT.—Natural geologic processes that have caused or might cause hazardous conditions in Oklahoma include earthquakes, landslides, expansive soils, floods, karst/salt dissolution, and radon.

At least four principal areas of seismic activity have been identified in the State: El Reno–Mustang, central Oklahoma; an area in south-central Oklahoma on the eastern margin of the Anadarko Basin; Love and Carter Counties, central southern Oklahoma; and an area north of the Ouachita Mountains in the Arkoma Basin of southeastern Oklahoma.

Most Oklahoma landslides occur in the eastern one-third of the State, owing to a wetter climate and steeper slopes associated with a more mountainous terrain. Many clay-rich shales, or soils derived from the weathering of shales, contain clay minerals, such as montmorillonite, that swell to as much as 1.5 to 2.0 times their original dry volume when they are wetted. More than 75% of Oklahoma contains bedrock units that have the ability to serve as sources of expansive soils.

Although floods can occur in any month in Oklahoma, major floods frequently occur in the spring and fall months. Flood-prone areas in Oklahoma have been identified and mapped by the U.S. Geological Survey, the U.S. Army Corps of Engineers, and private contractors. This mapping program is intended to delineate those areas that have, on average, about 1 chance in 100 of being inundated in any particular year.

Water-soluble rocks, such as limestone, dolomite, gypsum/anhydrite, and/or salt, are prone to the development of karst and dissolution features from the dissolving action of circulating ground waters. The sinkholes and caverns thus developed are potential hazards, owing to possible settlement or collapse of the land surface into the underground openings. Principal areas in Oklahoma where karst features are present in limestone and dolomite are the Ozark Mountains in northeastern Oklahoma, the Arbuckle Mountains in south-central Oklahoma, and the Limestone Hills (north of the Wichita Mountains) of southwestern Oklahoma. Gypsum and shallow salt deposits are present in many areas of western Oklahoma.

Approximately 80% of the State is underlain by formations with uranium contents that are equal to, or less than, the crustal average (2.5 ppm). The U.S. Environmental Protection Agency identified nine Oklahoma counties that have a moderate potential for elevated indoor radon levels.

Some activities of man that have created present, or might create future, geologic hazards in Oklahoma include disposal of industrial wastes, underground mining, and strip mining.

Solid and liquid industrial wastes have been disposed of in some areas of Oklahoma by surface burial in soil or rock units. Rock units in the State most favorable for surface disposal of wastes are impermeable sedimentary rocks, such as shale and clay, that can be excavated and that can prevent loss or migration of wastes from the disposal pit. Rock types in Oklahoma that are most desirable for surface disposal are porous and permeable sedimentary rocks, such as sandstone, limestone, and dolomite, that can store injected liquid wastes. These porous and permeable rock units should be surrounded by impermeable strata to assure containment.

Underground mines associated with the extraction of zinc/lead in Ottawa County in northeastern Oklahoma, and coal in the eastern Oklahoma coal field, along with a small number of underground gypsum, limestone, base-metal, and asphalt mines in other districts, are current and potential hazards because of the following possible problems: (1) collapse of roof rock, causing subsidence or collapse at the land surface; (2) the presence of acidic or toxic ground water; and (3) flooding of a new mine by accidentally breaking into a water-filled abandoned mine.

Lands disturbed through surface mining are potential problem areas because (1) spoil piles and fill material might not be fully compacted, and might still be subsiding or settling; (2) ponds and ground water in the mined areas might be acidic and/or toxic; and (3) highwalls and quarry faces might contain loose rocks or unstable slopes. Of all commodities mined by surface techniques, the extraction of coal has had the greatest impact on the environment in Oklahoma.

INTRODUCTION

Many geologic processes, such as mass wasting, water movements, and volcanic eruptions, become geologic hazards when human life and property are threatened. Furthermore, man's modification of the geologic environment through such activities as mining and waste disposal also can create hazards to life and property.

Data on potential hazards that result from natural geologic processes and from man-made geologic conditions generally are available from the Oklahoma Geological Survey (OGS) and several other State and Federal agencies. Data from geological and engineering reports, field investigations, aerial-photograph and topographic-map studies, industry and public records, and regional subsurface studies typically are compiled on large-scale base maps and aerial photographs. They then may be released as regional maps, generally at scales of 1:250,000 to 1:750,000. The maps and reports generated by these studies enable industry, government, and landowners to identify specific areas that require detailed site investigations and special engineering designs to avoid potential danger to life and property. Some of the data also are used to assist in the establishment of zoning ordinances, insurance rates, and construction codes.

The purpose of this report is to inform readers about geologic hazards, natural and man-made, in Oklahoma. This information should be useful to homeowners, planners, elected officials, contractors, and others for making decisions that will avoid and/or reduce losses from geologic hazards.

Two lists are given at the end of this report as an aid to the reader: a glossary of terms, and a set of acronyms and abbreviations.

NATURAL GEOLOGIC HAZARDS

Natural geologic processes that have caused, or might cause, hazardous conditions in Oklahoma include earthquakes, landslides, expansive soils, flood-prone areas, karst/salt dissolution, and radon.

Earthquakes

Oklahoma is within the stable interior of the United States. Although the State has had almost no significant tectonic activity since Pennsylvanian and Permian time (about 325–245 m.y. ago), an average of about 50 minor earthquakes occur in Oklahoma each year. The New Madrid, Missouri, earthquakes of 1811 and 1812 probably were the earliest historical earthquake tremors felt in what is now southeastern Oklahoma (then part of Arkansas Territory). Before Oklahoma became a state, the earliest documented earthquake epicenter within its current boundaries occurred on October 22, 1882, probably near Fort Gibson, Indian Territory, although it cannot be located precisely (Ross, 1882; Indian Pioneer Papers, date unknown). The *Cherokee Advocate* newspaper reported that at Fort Gibson "the trembling and vibrating were so severe as to cause doors and window shutters to open and shut, hogs in pens to fall and squeal, poultry to run and hide, the tops of weeds to dip, [and] cattle to [low]" (Ross, 1882). The first locatable earthquake in Oklahoma occurred near Jefferson, Grant County, on December 2, 1897 (Stover and others, 1981).

The largest known Oklahoma earthquake (with the possible exception of the Fort Gibson 1882 earthquake) occurred near El Reno, Canadian County, on April 9, 1952 (Table 1). This magnitude-5.5 (m_b) earthquake caused a 50-ft-long crack in the State Capitol Office Building in Oklahoma City. It was felt throughout Oklahoma and in parts of seven other states. The total felt area was ~140,000 mi^2 (Docekal, 1970; Kalb, 1964; von Hake, 1976). Des Moines, Iowa, and Austin, Texas, were at the northern and southern limits, respectively. This major earthquake produced intensity VIII effects near the epicenter on the Modified Mercalli (MM) intensity scale. The MM intensity scale assigns a Roman numeral to each of 12 levels described by effects on humans, man-made constructions, or natural features. For an intensity-level VIII earthquake, damage is slight in specially designed structures, considerable in ordinary substantial buildings, and great in poorly built structures.

A statewide network, consisting of a world-class geophysical observatory and eight satellite seismograph stations, records seismological data in Oklahoma (Fig. 1). The Oklahoma Geophysical Observatory (station TUL), operated by the OGS, began recording earthquake data on January 1, 1962. The statewide network, which became fully operational in 1977, has enabled detection and location of many low-magnitude earthquakes that would otherwise have gone undetected. From 1882 through 2001, 1,655 earthquakes have been located in Oklahoma (Fig. 1). Of these, 158 earthquakes were reported felt. Almost all Oklahoma earthquakes occur at shallow depths, less than 3 mi below ground level. These data were published on a regional-scale (1:750,000) map of the State (Lawson and Luza, 1995), and annual updates are published in *Oklahoma Geology Notes*. Oklahoma earthquake catalogs, earthquake maps, some seismograms, and related information can be accessed on the internet at **http://www.okgeosurvey1.gov**.

The earthquake database can be used to develop numerical estimates of earthquake risk, which give the theoretical frequency of earthquakes of any given size for different regions of Oklahoma. Numerical risk estimates are used in the design of large-scale structures, such as dams, high-rise buildings, and power plants, as well as providing information needed to establish insurance rates. Small-scale, relative-risk maps of the United States are used in various national and international building codes to establish engineering-design standards. For a number of years, the most common risk map used in the United States was based chiefly on historical earthquake activity, with some consideration given to nearby major geologic structures. A version of this type of map for the United States is depicted in Figure 2. This map example has four risk categories, which range from low to high, for damage that might be expected from an earthquake. North-central Oklahoma, east-central Kansas, and southeastern Nebraska are in seismic-risk zone 2, which means that moderate damage might be expected from an earthquake. The higher risk value is given to this region because several moderate-size earthquakes, magnitude 5 or greater, have occurred along (or west of) a major geologic

TABLE 1. — OKLAHOMA EARTHQUAKES WITH MAGNITUDES ≥4.0

Date	Origin time (UTC)[a]	County	Nearest town	Intensity MM[b]	Magnitudes[c] 3Hz	bLg	DUR	Lat. °N	Long. °W
1952 Apr 09	1629 15	Canadian	El Reno	7		5.0[d]		35.4	97.8
1939 Jun 01	0730	Hughes	Spalding	4		4.4		35.0	96.4
1997 Sep 06	2338 01.99	Coal	Stonewall	7		4.4	3.7	34.676	96.499
1926 Jun 20	1420	Sequoyah	W Marble City	5		4.3		35.6	94.9
1959 Jun 17	1027 07	Comanche	NE Faxon	–6		4.2		34.5	98.5
1995 Jan 18	1551 39.90	Garvin	Antioch	6	4.1	4.2		34.712	97.542
1998 Apr 28	1413 01.27	Comanche	NW Richards Spur	6		4.2		34.809	98.402
1956 Oct 30	1036 21	Rogers	Catoosa	7		4.1		36.2	95.8
1961 Apr 27	0730	Latimer	Wilburton	5		4.1		34.9	95.3
1929 Dec 28	0030	Canadian	El Reno	6		4.0		35.5	98.0
1959 Jun 15	1245	Pontotoc	Ada	5		4.0		34.8	96.7
1990 Nov 15	1144 41.63	Garvin	Lindsay	6	4.0	3.9	3.0	34.761	97.550

[a]UTC refers to Coordinated Universal Time, formerly Greenwich Mean Time. The first two digits refer to the hour on a 24-hour clock. The next two digits refer to the minute, and the remaining digits are the second. To convert to local Central Standard Time, subtract 6 hours.

[b]Modified Mercali (MM) earthquake-intensity scale.

[c]Magnitude is a measure of earthquake size, determined by taking the common logarithm (base 10) of the largest ground motion recorded during the arrival of a seismic-wave type and applying a standard correction for distance to the epicenter. Three magnitude types—mbLg (similar to Richter magnitude), m3Hz, and mDUR—are used by the OGS to determine the size of Oklahoma earthquakes (Lawson and Luza, 1995).

[d]The El Reno earthquake had a Gutenberg-Richter magnitude (mb) of 5.5.

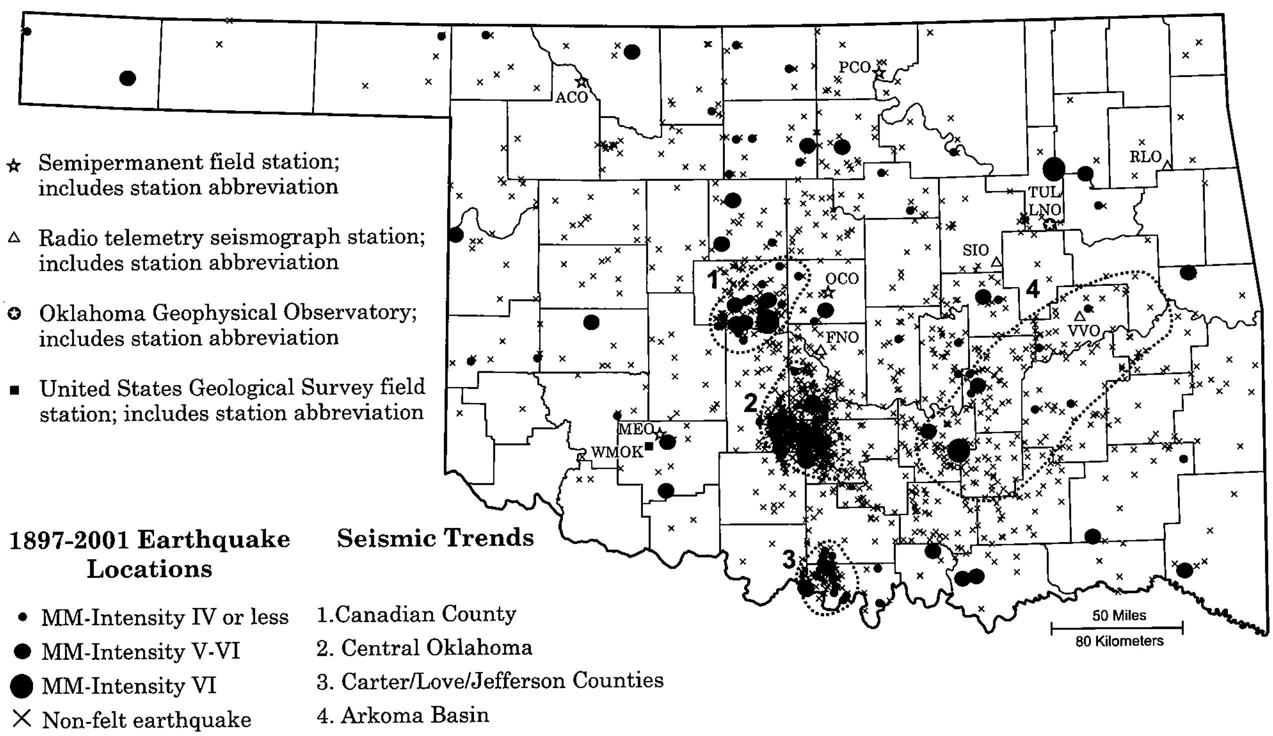

Figure 1. Map of Oklahoma showing felt-earthquake locations, seismic trends, and major tectonic features.

structure, the Nemaha Uplift, common to these three states. The remaining parts of Oklahoma, Kansas, and Nebraska are in seismic-risk zone 1, which means that minor damage might be expected from an earthquake. A second type of risk map, the probabilistic-risk map, is now used for most building-code applications, insurance rates, and disaster-mitigation planning (Fig. 3). This type of map is based on the probability that a certain level of ground motion will occur during an earthquake over a specific time interval. These maps are continually updated and revised as new geological data become available.

An analysis of Oklahoma earthquake data indicates at least four principal seismic areas on the basis of a consistent pattern of earthquake recurrence (Fig. 1). One area, in north-central Oklahoma, is 25 by 90 mi and extends northeastward from El Reno to Perry. The El Reno–Mustang area, near the south end of the zone, has had numerous earthquakes since 1908. The correlation of historical earthquake activity in this trend to known tectonic features remains unclear, inasmuch as the El Reno–Perry trend cuts diagonally across a major structural feature, the Nemaha Uplift.

The second principal area of seismic activity is on the eastern margin of the Anadarko Basin. A majority of these earthquakes are concentrated in a 25-mi-wide and 37-mi-long area that closely parallels the Central Oklahoma fault zone (sometimes referred to as the McClain County fault zone, McClain and Garvin Counties). More than 90% of the earthquakes within this zone have occurred since 1977. The increase in seismic activity is, in part, related to improved earthquake-detection capabilities.

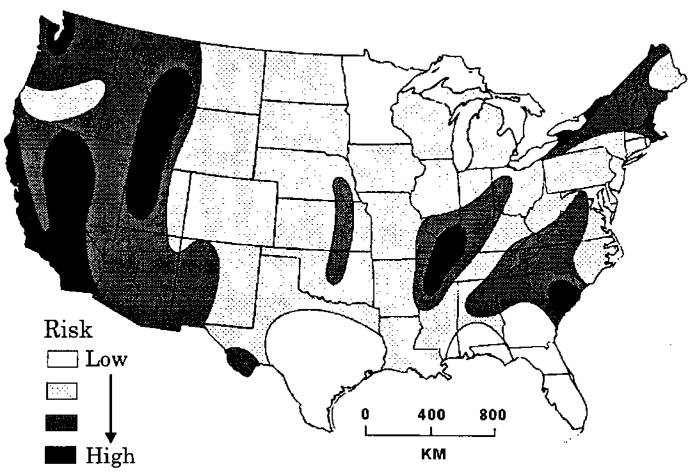

Figure 2. Earthquake-risk map of the United States, which shows relative risk of damage based mostly on known-earthquake history (from Algermissen, 1969).

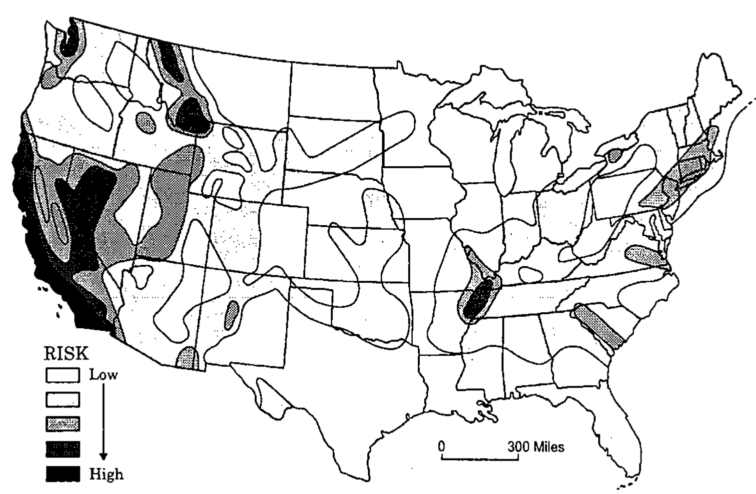

Figure 3. Earthquake-risk map, based on the probability that a certain level of ground motion will occur during an earthquake over a 50-year period (modified from Algermissen and others, 1982, pl. 2).

A third principal area of seismic activity is in central southern Oklahoma, Love and Carter Counties. The first reported earthquake for this area occurred in 1974. Since 1974, a number of small, "felt" earthquakes have occurred within this region.

Another general area of earthquake activity is in the southeastern part of the State. Most of these earthquakes have occurred north of the Ouachita Mountains in the Arkoma Basin. Approximately 90% of all earthquakes in the Arkoma Basin were not felt but were instrumentally located. Typical earthquake-magnitude values range from 1.8 to 2.5, and focal depths are generally shallow (<3 mi).

Landslides

Landslides and smaller slumps are a common highway-construction problem in parts of Oklahoma. Most of the landslides occur in the eastern one-third of the State (Hayes, 1971), owing to a wetter climate (39–59 in. of precipitation per year) and the steeper slopes associated with a more mountainous terrain (Fig. 4). In eastern Oklahoma, thick shale formations (such as the Johns Valley Shale, Savanna Formation, and shale beds within the Jackfork Group, all of Pennsylvanian age) weather quickly and produce large quantities of clayey colluvium. This material usually occurs as a veneer, one to several meters thick, that masks the underlying bedrock on a slope. Generally, the threat of landslides is high where natural slopes exceed a gradient of 2:1.

Rotational slump is the most common type of landslide that occurs in Oklahoma (Figs. 5, 6). Other, less common types include debris slides, block glides, and boulder flows. Rotational slumps can occur on either excavated slopes or embankments. Several construction practices are used to minimize the possibility of landslides. In Oklahoma, highway engineers use a process called *benching*. A bulldozer is used to make several benches or platforms parallel to the roadway alignment. The bases of the benches are cut through any potential unstable material. The embankment is then built upon the benches. Other techniques used to support unstable material include buttress walls and retaining walls.

Moisture from storm runoff and/or seepage is a major contributor to the destabilization of embankments. Perforated underdrain pipe is placed beneath the ditch on the uphill side to intercept water coming down the slope and to convey water away from the embankment. In some cases, underdrains are placed within and/or below the embankment material to reduce and/or eliminate water-related problems.

The Oklahoma Department of Transportation (ODOT) has conducted a landslide-recognition and landslide-stabilization program as it relates to highway construction (Hayes, 1971). Nationwide, small-scale maps (scale 1:7,500,000) have been prepared for Oklahoma and other states, and these maps are updated as new data become available (Radbruch-Hall and others, 1982).

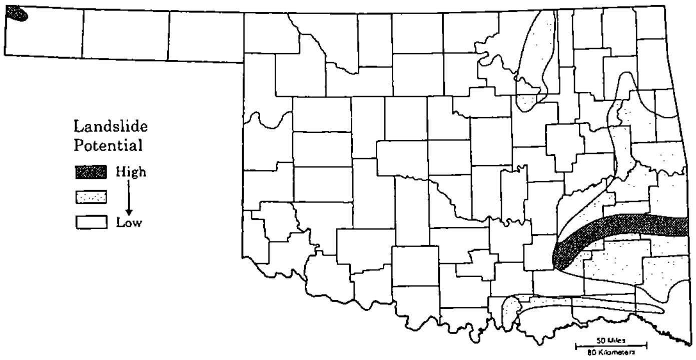

Figure 4. Map of Oklahoma showing landslide susceptibility (modified from Radbruch-Hall and others, 1982).

Figure 5. Landslide in the Pennsylvanian Jackfork Group (mostly shale at this location) along State Highway 1, Talimena Drive, Le Flore County. Photograph by Oklahoma Department of Transportation.

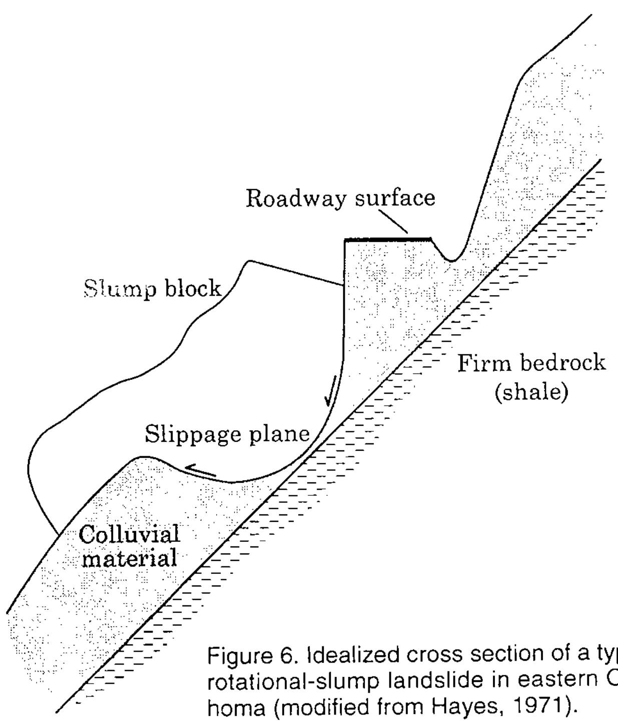

Figure 6. Idealized cross section of a typical rotational-slump landslide in eastern Oklahoma (modified from Hayes, 1971).

Expansive Soils

Clay-rich shales, or soils derived from the weathering of shales, may contain smectite-rich clay minerals, such as montmorillonite, that swell to as much as 1.5 to 2.0 times their original dry volume when they are wetted. More than 75% of Oklahoma contains bedrock units that can serve as sources for expansive soils (Fig. 7). The saturation of soil from rainfall, lawn watering, or sewer leakage can cause major damage through the expansion of soils beneath sidewalks, highways, utility lines, and foundations. If construction takes place on wet materials that have a high clay content, and these materials subsequently dry out, the resulting shrinkage could cause severe cracking in structures (Fig. 8). Creath (1996) reported that uninsured losses to property owners throughout the nation might be as high as $6 billion per year. Repairs to damaged foundations are very expensive—usually several thousands of dollars. In some years, the damage from expansive soils and subsequent repair costs exceed the damage from all other geologic hazards combined in Oklahoma.

Considerable information on soil and/or rock properties is available for building a foundation designed to withstand the effects of the existing soil and/or rock conditions. ODOT and the U.S. Department of Agriculture, National Resources Conservation Service (NRCS), formerly the Soil Conservation Service, have evaluated the expansive properties of soils and shale formations in Oklahoma. ODOT has released a series of district reports containing information on engineering characteristics, such as Atterberg limits and particle-size distribution, for each major geologic unit in Oklahoma (Hartronft and others, 1965, 1966, 1967, 1968, 1969, 1969a, 1969b, 1970). Atterberg limits and indices are empirical tests used to determine some physical properties of materials (Table 2). Each boundary or limit (shrinkage, plastic, and liquid) is defined by the water content for which the material is in a certain stage or state. The limits described are all expressed by their percentages of water content, and normally are shown as a unitless number. The plasticity index, PI, is the difference between the liquid and plastic limits, and represents the range in water content through which a material is in a plastic state. The plasticity index is inversely proportional to the ease with which water passes through a material. Therefore, a material

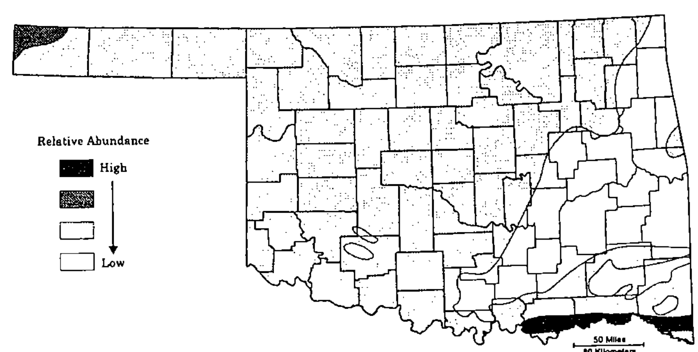

Figure 7. Map showing relative abundance of expansive soils in Oklahoma (modified from Schuster, 1981).

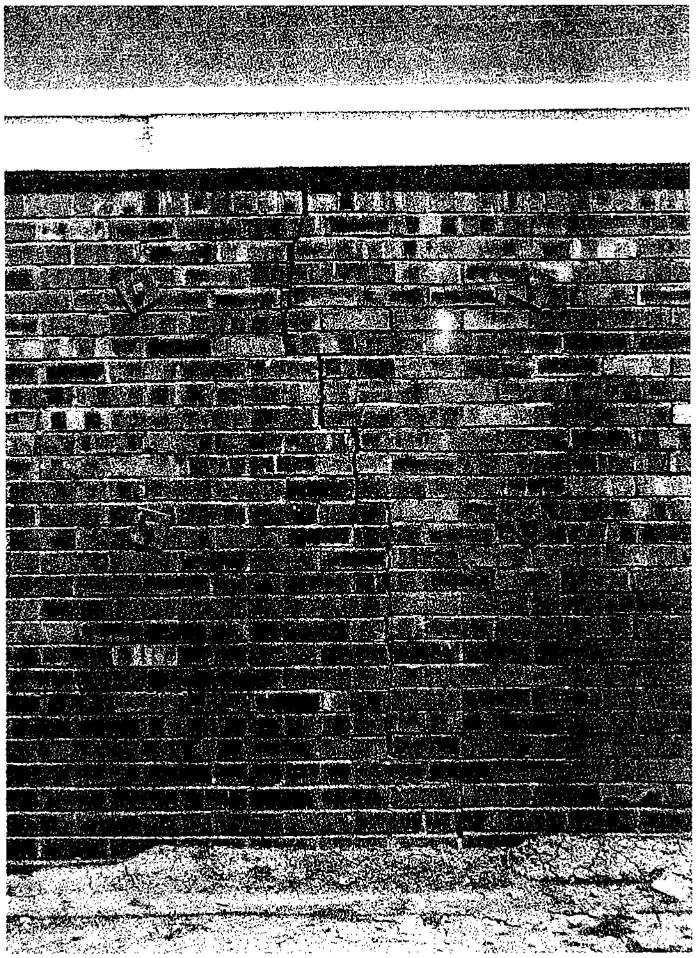

Figure 8. Crack in the wall of a building in Lawton, Oklahoma, caused by expansive soils. Photograph by Oklahoma Department of Transportation.

with a high plasticity index will generally have a low permeability. The plasticity index also can be used to assess clay content. Generally, materials that have high plasticity indices also have high clay-mineral contents (Table 3).

The plasticity index and shrinkage limit can be used to give some indication of the potential volume change that can be expected in a material (Table 4). In general, a high plasticity index and low shrinkage limit indicate a high shrink–swell potential. This is usually the case when clays of the montmorillonite family are present in significant enough quantities to cause large volume changes between swelling and shrinking.

There is considerable variation in properties from location to location. Therefore, descriptive terms, such as *high, moderate,* and *low,* are used to incorporate a range of values that describe some of the physical characteristics of rock and/or soil units.

The ODOT publications, although an excellent source of physical-properties information for the geologic formations in the State, have a limited distribution. However, some of the ODOT physical-property information and engineering data for various shale formations was summarized in various tables by Johnson and others (1980).

TABLE 2. — ATTERBERG LIMITS AND INDICES

State	Limit	Index
Liquid state		
	Liquid limit (LL)	Plasticity index (PI) (PI = LL – PL)
Plastic state		
	Plastic limit (PL)	
Semi-solid state		
	Shrinkage limit (SL)	
Solid state		

Modified from Sowers and Sowers (1961).

TABLE 3. — PLASTICITY TERMINOLOGY IN RELATION TO PLASTICITY INDEX

Term	Plasticity index
Nonplastic	0–3
Slightly plastic	4–8
Medium plastic	9–30
Highly plastic	>30

Modified from Sowers and Sowers (1961).

TABLE 4. — SHRINK–SWELL POTENTIAL

Volume change	Shrinkage limit	Plasticity index
Probably high	0–10	>30
Probably moderate	10–12	15–30
Probably low	>12	0–15

Modified from Sowers and Sowers (1961).

The principal geologic units in the State that have high shrink–swell potential are the Cretaceous shales that crop out in southern Oklahoma. Dominant clay minerals in these shales are montmorillonite, illite, and kaolinite. Other shales that locally have a moderately high shrink–swell potential are several of the Pennsylvanian units in eastern Oklahoma and several of the Permian units in central Oklahoma.

Charts and tables containing data on shrink–swell potential for each major soil type are published by the NRCS in its soil surveys of nearly all the 77 counties in Oklahoma. These surveys can be examined at local NRCS offices, which are usually in the county seats. Office-location information and other related data can be found on the NRCS Oklahoma web site: **http://www.ok.nrcs.usda.gov/**.

The following example from the Cleveland County Soil Survey (Bourlier and others, 1987) is intended to show engineers, developers, builders, and/or home buyers how to use the county soil surveys to do preliminary site evaluation. Each modern soil survey contains a map index to the map sheets that cover the county. For Cleveland County there are 48 map sheets. Each sheet is at a scale of 1:20,000, or 1 in. equals ~1,670 ft. Our example (Fig. 9), which covers mainly secs. 25 and 26, T. 9 N., R. 3 W., is found on their no. 21 map sheet. The area of interest is east of Merkle Creek, north of Main Street, west of Berry Road, and south of Robinson Street. The predominant map-unit symbols are nos. 49 and 59. The index for soil map units lists the name of each map unit and the page where the map unit is described. Map symbol 49 is the Doolin–Urban land–Pawhuska complex, found on 0–3% slopes. A detailed description of this map unit is found on their page 50. Map symbol 59 corresponds to the Bethany–Urban land complex map unit, found on 0–3% slopes. A detailed description of this map unit is given on their page 59. Data on building-site development (their table 14), engineering index properties (their table 18), and physical and chemical properties of soils (their table 19), are useful for a preliminary site evaluation for expansive soils. This information is summarized in Tables 5–7 of this report. The data presented in the tables indicate that both map units have the potential of having moderate to severe shrink–swell problems. These data represent averages and/or ranges of test data taken at several locations and are useful as a general guide. Therefore, detailed on-site testing of a site is needed to confirm the regional test data as well as to provide data for a proper foundation design.

Unfortunately, most of us have purchased an existing house and/or business that did not have a soil analysis done prior to construction. However, some inexpensive ways help to minimize most problems associated with expansive soils. A uniform and constant moisture near the foundation will help minimize shrinkage that can occur in expansive soils during periods of drought. Proper drainage and grading techniques near the foundation will help minimize swelling during periods of high rainfall.

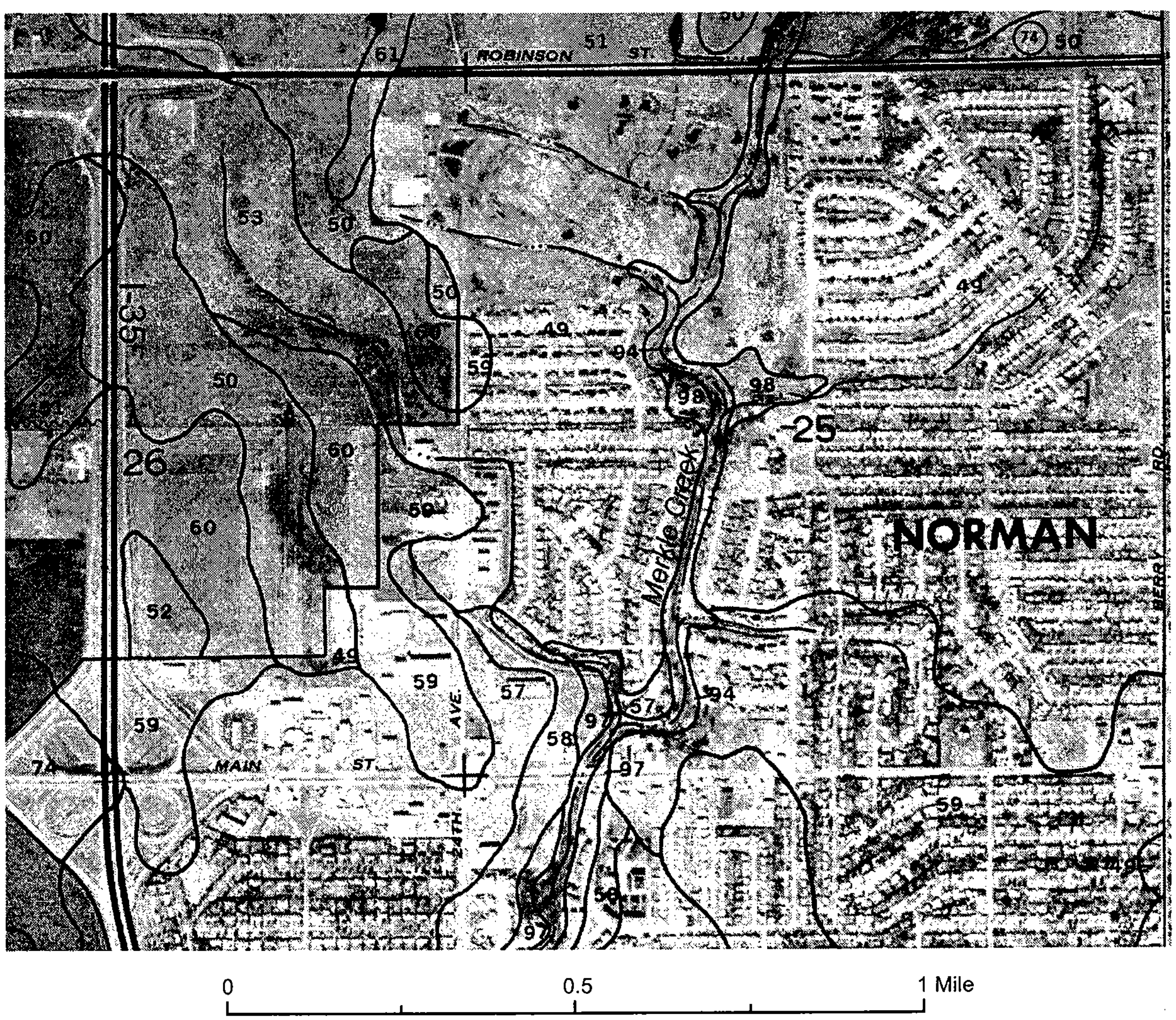

Figure 9. Soil-survey map of parts of secs. 23–26, T. 9 N., R. 3 W., Cleveland County, Oklahoma. The smaller numbers, map-unit symbols, correspond to soil map units in the Cleveland County soil-survey index (modified from Bourlier and others, 1987).

TABLE 5. — Data on Building-Site Development in Cleveland County

Map symbol & soil name	Shallow excavations	Dwellings without basements	Dwellings with basements	Small commercial buildings	Local roads and streets
49:					
Doolin	Moderate: too clayey	Severe: shrink–swell	Moderate: shrink–swell	Severe: shrink–swell	Severe: low strength, shrink–swell
Urban land					
Pawhuska	Moderate: too clayey	Severe: shrink–swell	Severe: shrink–swell	Severe: shrink–swell	Severe: low strength, shrink–swell
Urban land					
59:					
Bethany	Moderate: too clayey	Severe: shrink–swell	Severe: shrink–swell	Severe: shrink–swell	Severe: low strength, shrink–swell

Modified from Bourlier and others (1987, table 14, p. 246–247).

TABLE 6. — Data on Engineering Index Properties

Map symbol & soil name	Depth (inches)	USDA texture	Fragments >3 inches (Pct)	Liquid limit (Pct)	Plasticity index
49:					
Doolin	0–12	Silt loam	0	24–37	5–14
	12–80	Silty clay loam, clay loam, silty clay	0	37–60	15–34
Urban land					
Pawhuska	0–6	Silt loam	0	22–30	2–7
	6–72	Silty clay loam, silty clay, clay	0	41–70	20–40
Urban land					
59:					
Bethany	0–13	Silt loam	0	21–37	2–13
	13–22	Silty clay loam, clay loam	0	33–50	15–26
	22–84	Silty clay, clay, silty clay loam	0	37–60	15–33

Modified from Bourlier and others (1987, table 18, p. 281, 283).

TABLE 7. — Data on Physical and Chemical Properties of Soils

Map symbol & soil name	Depth (inches)	Clay (Pct)	Moist bulk density (g/cm^3)	Permeability (inches per hour)	Soil reaction (pH)	Shrink–swell potential
49:						
Doolin	0–12	10–27	1.30–1.55	0.6–2.0	5.1–7.8	Low
	12–80	35–55	1.35–1.65	<0.06	6.1–8.4	High
Urban land						
Pawhuska	0–6	18–27	1.30–1.50	0.6–2.0	5.6–8.4	Low
	6–72	35–50	1.35–1.65	<0.06	6.1–8.4	High
Urban land						
59:						
Bethany	0–13	15–26	1.30–1.50	0.6–2.0	5.6–7.3	Low
	13–22	27–35	1.45–1.70	0.2–0.6	6.1–7.3	Moderate
	22–84	35–50	1.40–1.70	0.06–0.2	6.1–8.4	High

Modified from Bourlier and others (1987, table 19, p. 294–295).

Flood-Prone Areas

Flood plains are those areas adjacent to rivers and streams that occasionally are flooded but are normally dry, sometimes for many years. During these dry periods, buildings or other structures sometimes are constructed on flood plains. When storms produce more runoff than a stream or river can carry within its normal channel, the water rises and floods the adjacent low-lying lands (Figs. 10, 11). Although floods can occur in any month in Oklahoma, major floods frequently occur in the spring and fall months (Tortorelli and others, 1991).

In the United States, the average annual cost of flood damage is more than $2 billion (Moreland, 1993). In 1968, a nationwide assessment of flood hazards was initiated to support the National Flood Insurance Program (NFIP), administered by the U.S. Department of Housing and Urban Development (HUD) and, after 1979, by the Federal Emergency Management Agency (FEMA). Approximately 100,000 flood-hazard maps or map panels have been produced since the program began. Although these maps originally were produced to evaluate flood risk for the national flood-insurance program, they also are used by flood-plain managers, community planners, surveyors, engineers, and disaster- and emergency-response officials for mitigation, risk assessment, and disaster preparedness, response, and recovery activities.

Flood-prone areas in Oklahoma are identified and mapped by the U.S. Geological Survey (Water Resources Division), the U.S. Army Corps of Engineers, and private contractors. The program is intended to delineate those areas that have, on the average, about 1 chance in 100 of being inundated in any particular year (a 100-year-flood frequency). This delineation is done through the use of readily available information on past floods and, sometimes, through detailed field surveys and inspections. Many of the early flood-prone maps, especially in areas where significant urban development has occurred, are being revised.

The Oklahoma Flood-Plain Management Act, effective May 1980, enabled Oklahoma to participate in the NFIP, as authorized in 1968. In order to participate in the flood-insurance program, communities and/or counties must meet minimum FEMA and Oklahoma flood-plain-management requirements. Eligibility is established by adopting codes which include (1) regulations for platting land for all types of building construction, and for the construction of any barrier in the flood plain that may divert, retard, or obstruct flood water; (2) regulations that establish minimum flood-protection elevations and flood-prevention requirements for structures in the flood plain; and (3) regulations that require coordination with the State Flood-Plain Board, other political subdivisions, and State agencies. The Oklahoma Water Resources Board (OWRB) administers the NFIP in cooperation with FEMA and acts as the State Flood-Plain Board. A list and status of participating communities and/or counties, arranged in alphabetical order, can be found on FEMA's web site at **http://www.fema.gov/fema/csb.htm**. As of June 2002, FEMA identified more than 350 Oklahoma communities and/or counties participating in the national flood-insurance program. A map-panel index is available for every participating community. Some indexes, especially the more recently revised indexes, have a map-repository list. Although repository locations are highly variable, some local places to look for flood-insurance rate maps are as follows: county clerk, city hall, county courthouse, city engineer, and/or city planning department.

Norman, Oklahoma, is covered by 12 maps. An area (the same as the expansive-soils example) is shown on panel 15 (of 85) of FEMA's Flood Insurance Rate Map south of Max Westheimer Airport (Fig. 12). The original map scale is 1 in. = 1,000 ft. Map scales are variable, however. Some of the more common map scales are 1 in. = 500, or 1,000, or 2,000 ft. In this example, two flood boundaries, a 100-year (zone A, in

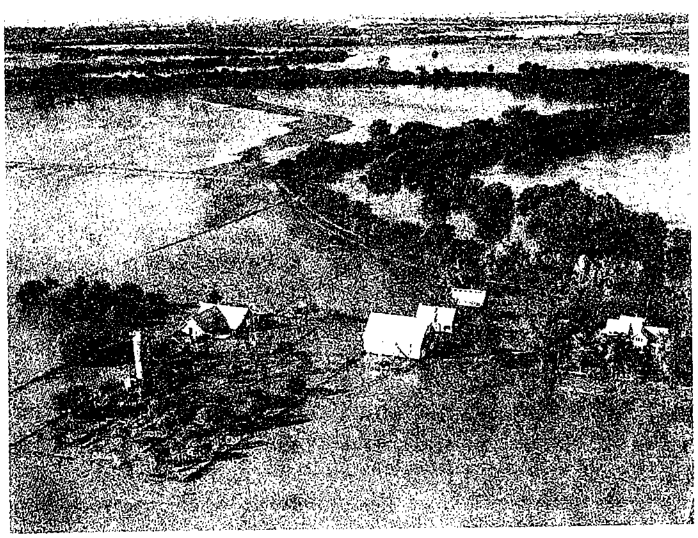

Figure 10. Aerial view of the Chikaskia River looking north toward Blackwell, Oklahoma, during the Enid and vicinity flood of October 1973. The Chikaskia River flows from top to bottom, and the active channel is between the trees that grow on its banks. Photograph by Kenneth Gill, U.S. Army Corps of Engineers.

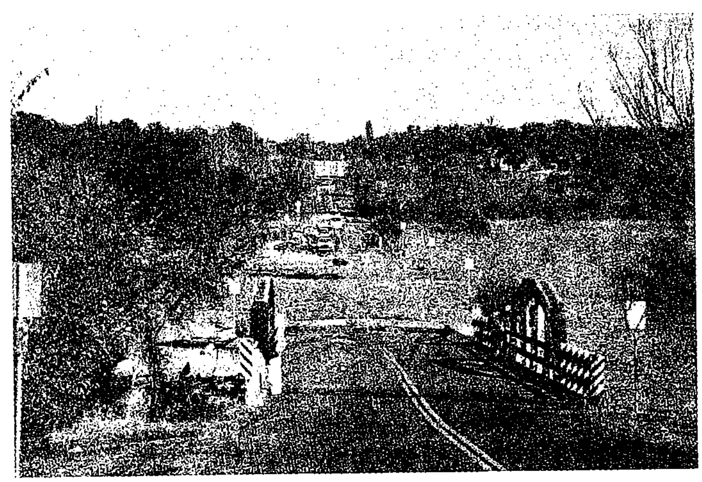

Figure 11. Twin bridges over the Little River at Lake Thunderbird, Cleveland County, were flooded as the result of storms of October 17–23, 1983, from remnants of hurricane Tico. Flooding and damages exceeded $12 million from these storms in an 11-county area in central Oklahoma (Hauth, 1985).

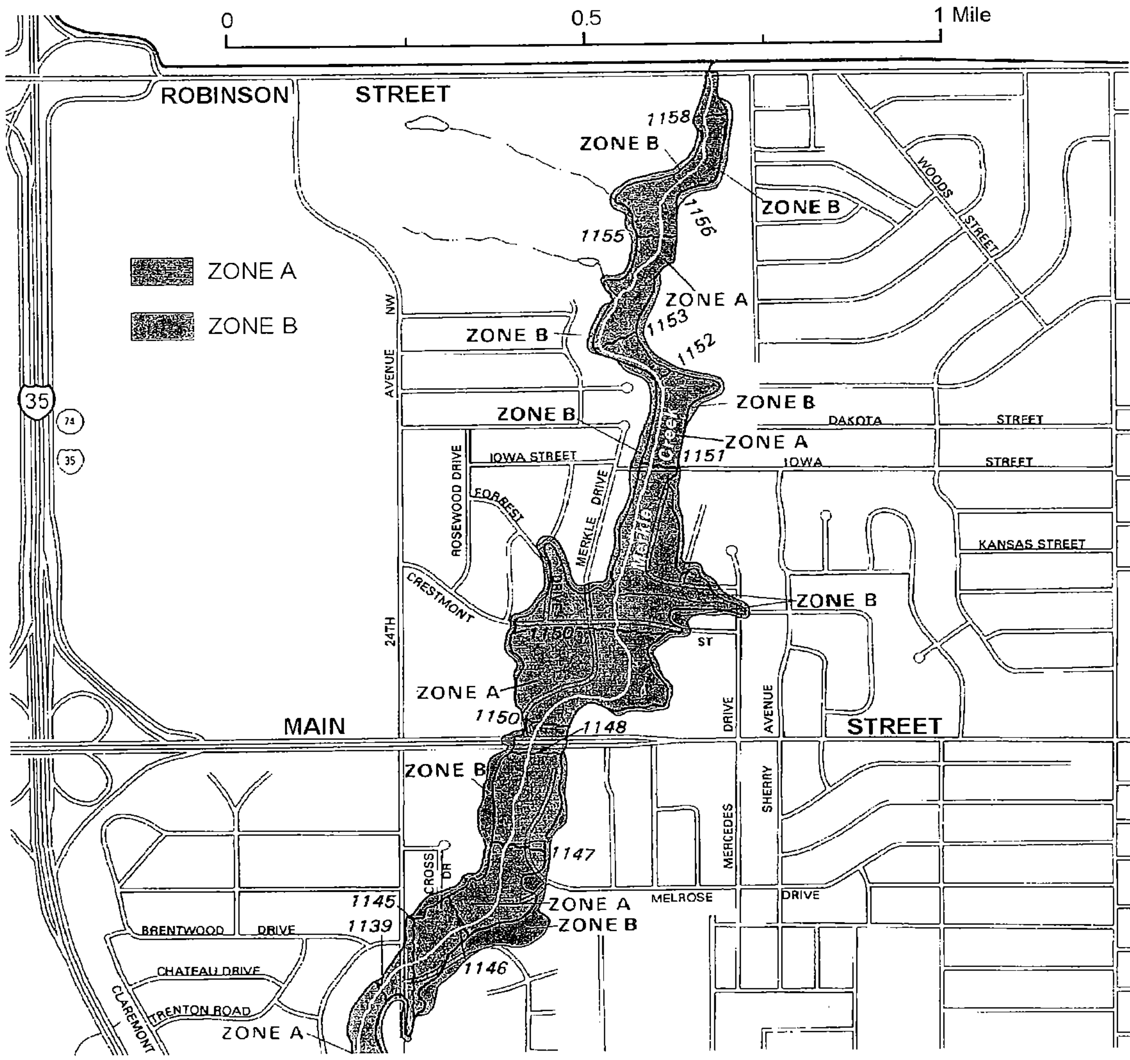

Figure 12. A part of panel 15 (of 85) of FEMA's Flood Insurance Rate Map for the City of Norman, Oklahoma. Merkle Creek is depicted also on the soil-survey map in Figure 9.

black) and a 500-year (zone B, in gray), are shown for Merkle Creek. Base flood-elevation lines, in feet, are shown for the 100-year flood (not all streets are represented on the map).

Areas of Karst and Salt Dissolution

Where water-soluble rocks, such as limestone, dolomite, gypsum/anhydrite, and salt, are at or near the land surface, they are prone to the development of karst and dissolution features from the dissolving action of circulating ground waters (Fig. 13). The sinkholes and caverns thus developed are potential hazards, owing to the possible settlement or collapse of the land surface into the underground openings. Principal areas in Oklahoma where karst features are present in limestone and dolomite are in the Ozark Mountains in northeastern Oklahoma, the Arbuckle Mountains in south-central Oklahoma, and the Limestone Hills (north of the Wichita Mountains) in southwestern Oklahoma (Fig. 14). Gypsum and shallow salt deposits are present in many areas of western Oklahoma.

Caves, cavities, sinkholes, and other karst features can be a hazard when an underground opening becomes large


Figure 13. Cavern developed in the Permian Cloud Chief Formation, Washita County, resulting from the dissolving action of circulating ground water through gypsum beds. Photograph by Rick Andrews.

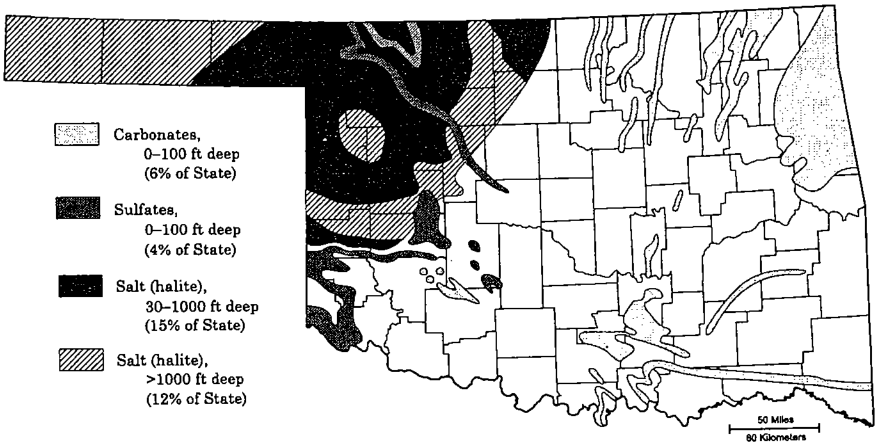

Figure 14. Map showing general distribution of karst terrains in Oklahoma (modified from Johnson and Quinlan, 1995).

Figure 15. A 40-ft-deep sinkhole developed in the Permian Blaine Formation, western Greer County, where large blocks of gypsum, up to 10 ft wide by 20 ft long, collapsed into an underground cavern.

enough to allow the roof (and overlying ground and man-made structures) to collapse into the void (Fig. 15). Man-made structures most likely to be damaged or destroyed include houses, office buildings, dams, pipelines, roads, railroads, and other utilities or infrastructure; and, of course, there is the possibility of human injury or loss of life. By knowing the distribution, depth, and character of karst features before construction, engineers can either relocate the structure or design the construction to prevent or accommodate possible subsidence or collapse. Site-specific studies of the geology and geohydrology are needed when planning to build structures in a karst area.

Limestones, dolomites, and gypsums/anhydrites that crop out, and/or are within 20 ft of the land surface, normally represent the greatest potential for karst development and associated environmental and engineering problems (Fig. 16). Where the top of these karstic rocks is 20–100 ft deep, a somewhat lesser (yet real) potential exists for karst development and associated problems (Fig. 16). Karst also develops in Oklahoma limestones, dolomites, and gypsums/anhydrites at depths greater than 100 ft (perhaps as much as 200–300 ft, locally), but it is much more sporadic, is not well developed, and its potential to cause environmental or engineering problems is probably quite low.

Salt (halite) is a highly soluble rock that is as shallow as 30 ft below the land surface in parts of Oklahoma. Karst features in salt can be a problem locally in drilling for oil and gas and other minerals, and in building dams and/or other structures over cavities in the salt deposits. The dissolution of salt and its consequent collapse, associated

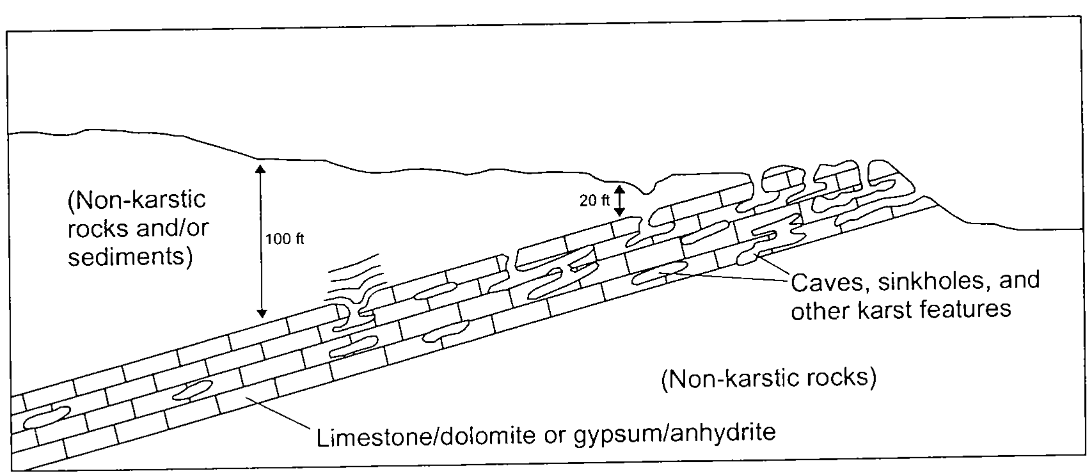

Figure 16. Schematic diagram showing the depth of karstic carbonates (limestone/dolomite) and sulfates (gypsum/anhydrite) in Oklahoma (modified from Johnson and Quinlan, 1995).

with boreholes (owing to salt-cavity development and to petroleum activity), has occurred at several places in the United States where salt beds are as deep as 1,000 ft (Johnson and Quinlan, 1995). In Oklahoma, there are no known natural occurrences of salt dissolution at depths greater than 1,000 ft.

Within Oklahoma's area of nearly 70,000 mi^2, limestone and dolomite crop out, or are no more than 100 ft deep, in about 4,130 mi^2 (6% of the State); gypsum/anhydrite crop out, or are no more than 100 ft deep, in about 2,740 mi^2 (4%); and salt is within 1,000 ft of the land surface in about 10,150 mi^2 (14.5%).

Radon

Radon is a naturally occurring radioactive gas formed by the spontaneous decay of uranium to lead. In the natural, near-surface environment, radon generated from uranium in rocks or soils either decays to a solid while it is still in the ground or escapes to the air, where it is diluted to insignificant levels. In buildings, and particularly in basements, however, radon can accumulate to high concentrations. When radon is inhaled and decays in human lungs, its solid daughter isotopes, which are also radioactive, can lodge in lung tissue. Lung-tissue damage, possibly resulting in cancer, occurs as these isotopes continue to decay and release alpha or beta particles and/or gamma radiation. Health hazards resulting from exposure and inhalation of above-normal levels of indoor radon gas, as well as radon detection, recommended safety levels, and remedial methods, are summarized in publications issued by the U.S. Environmental Protection Agency (1992, 1994, 2000, 2001).

Four fundamental factors determine how much radon in the ground enters a building: (1) radium (the immediate precursor of radon) must be present in the soil and/or bedrock beneath the foundation; higher concentrations of radium result in higher concentrations of radon, where other geological and pedological variables are equal; (2) 90% of radon decays to its solid progeny (polonium) in 13 days; therefore, radon must be able to rapidly enter pore spaces in the rock and/or soil, and subsequently the building; (3) for radon to enter a building, the structure must have openings (such as pore spaces or cracks) in the building materials that are below ground level; (4) a low internal air pressure within a building and a high external pressure within the ground creates a pressure differential across the ground/building interface; this produces a "pumping" effect on the soil/rock gases, including radon, from the ground into the building (Tanner, 1986).

Oklahoma has no known economic uranium deposits. However, the generation of indoor-radon concentrations in excess of the U.S. Environmental Protection Agency (EPA) standard (>4 pCi/L of air) does not require ore-grade uranium (>500 ppm). Under favorable conditions, rocks and residual soils containing much lower uranium contents are capable of generating above-normal radon levels. In Oklahoma, uranium is associated with many different rock types and geologic environments. Uranium occurrences in the State are divided into seven types, based on the mode of uranium enrichment and the size, distribution, and geologic continuity of the occurrence: (1) granitic rocks and their late-stage intrusives (dikes and sills); (2) arkosic sediments (weathered granite detritus); (3) dark, organic-rich shales; (4) phosphatic black shales; (5) lignite and bituminous-coal beds; (6) local point sources; and (7) stratiform bodies (confined to certain Permian stratigraphic units in western and southwestern Oklahoma).

The OGS, in cooperation with the Oklahoma State Department of Health (OSDH), evaluated near-surface geological conditions in Oklahoma for radon potential (Flood and others, 1990). Twenty-six areas in the State were assigned a radon-potential category. The boundary lines are approximate; the map scale is too small to portray individual beds accurately within a formation or show site-specific information. Areas underlain by formations with uranium contents that are equal to, or less than, the crustal average (2.5 ppm) are rated as having *generally very low* or *generally low* radon potential. Approximately 80% of the State is included in these two categories. About 7% of the State's land area has a *locally moderate* or *locally moderate* to *high* radon-potential rating. The rest of the State, 13%, is included in the *locally low* to *moderate* radon-potential category (Fig. 17).

This study was a reconnaissance-level investigation based on existing geological literature. The report and map are intended to serve as a guide for detailed future investigations. The map scale, limited analytical data, time constraints, and lateral lithologic variations in rock units precluded a site-by-site analysis. The study considered only uranium contents in rocks capable of generating above-normal radon levels. The report does not address other significant variables, such as soil characteristics, ground-water hydrology, precipitation and other atmospheric conditions, and types and conditions of building structures. The consideration of these variables is critical for determining site-specific radon potentials.

The OSDH, in cooperation with the EPA, conducted indoor radon surveys throughout Oklahoma. More than 3,150 sites were tested, and the results are available as a link on Oklahoma's Department of Environmental Quality's (DEQ) web site: **http://www.deq.state.ok.us.** Click on "Land Protection Division" and look for "radioactive materials" in small print near the top of the page. The data are accessible by county, city, and/or zip code. This study was part of a nationwide study to identify areas in the United States that have the potential for elevated indoor radon levels.

Indoor radon measurements, geology, aerial radiometric surveys, soil permeability, and building-foundation type were used by the EPA to develop a U.S. Radon Potential Map (**http://www.epa.gov/iaq/radon/zonemap.html**). EPA assigns each of the 3,141 counties in the United States to one of the following three zones: (1) zone 1 counties have a predicted average indoor-radon screening level greater than 4 pCi/L, (2) zone 2 counties have a predicted average indoor-radon screening level between 2 and 4 pCi/L, and (3) zone 3 counties have a predicted average indoor-radon screening level less than 2 pCi/L.

Oklahoma has no zone 1 counties, those with the highest potential, and nine counties were identified in zone 2, the moderate-potential category (Fig. 18).

Although the map does not predict indoor-radon levels, indoor radon can easily be measured by homeowners using a passive detection device and/or kit purchased at a nearby

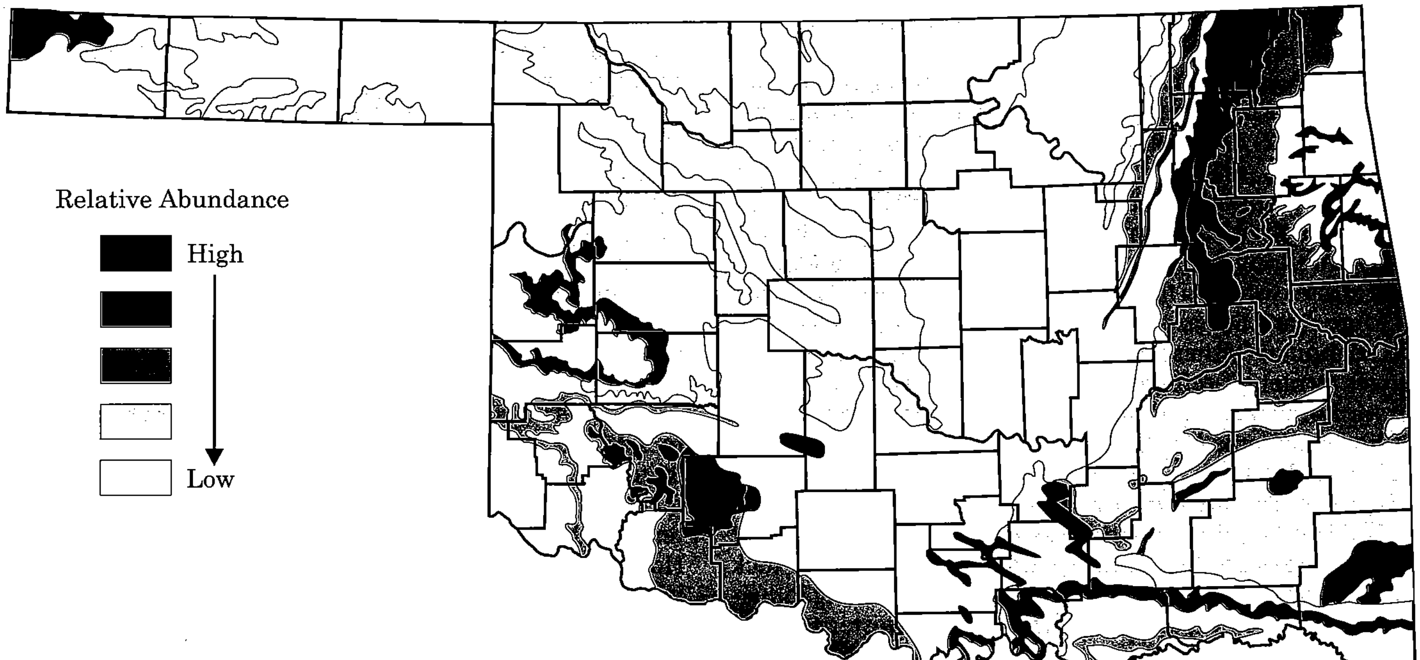

Figure 17. Radon-potential map for Oklahoma (modified from Flood and others, 1990).

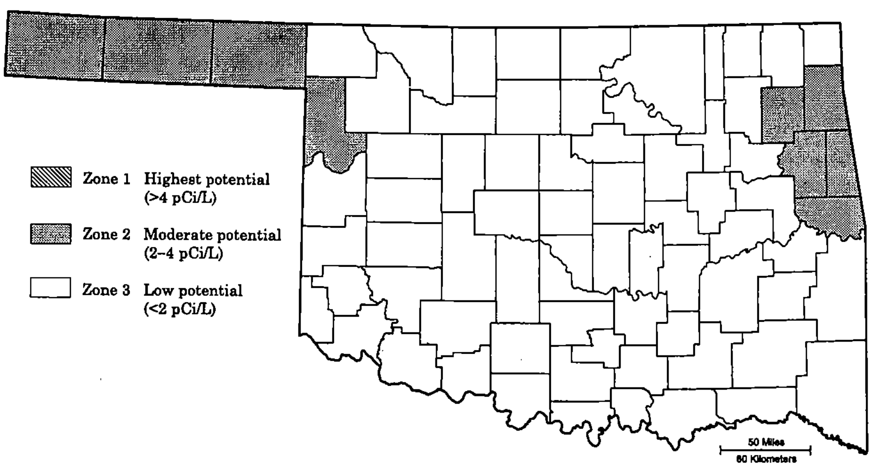

Figure 18. EPA's radon-potential map for Oklahoma. There are no counties in Oklahoma in zone 1.

store. The DEQ has a 48-hour test kit available for about $18. The price includes the kit, postage, and radon analysis.

MAN-MADE GEOLOGIC HAZARDS

Some activities of man that may have created present or future geologic hazards in Oklahoma include disposal of industrial wastes, underground mining, and strip mining.

Industrial-Waste Disposal in Geologic Formations

In the past, many hazardous wastes, such as acids, caustic solutions, flammable liquids, explosives, and liquids containing heavy metals, were disposed of either on the ground and/or in the ground, in streams and rivers, or stored in containers that were subsequently abandoned. These methods of disposal created thousands of uncontrolled or abandoned hazardous-waste sites throughout the United States. To properly regulate industrial-waste disposal, Oklahoma passed the Oklahoma Controlled Industrial Waste Disposal Act in June 1976; it was modified in 1978, and the OSDH established rules and regulations for the storage and disposal of industrial wastes. The rules and regulations subsequently were modified, and the program currently is administered by the DEQ.

In October 1976, Congress passed the Resource Conservation and Recovery Act (RCRA) for the regulation of hazardous and nonhazardous wastes. In December 1980, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as Superfund, was enacted by Congress and reauthorized by the Superfund Amendments and Reauthorization Act (SARA) in 1986. The law created a tax on chemical and petroleum industries and provided broad Federal authority to respond directly to releases or threatened releases of hazardous substances that might endanger public health or the environment. The Superfund program, which is administered by the EPA in cooperation with the states and tribal governments, locates, investigates, and cleans up hazardous-waste sites throughout the country. Kellogg (1990) provides an excellent historical summary of the various state and Federal hazardous-waste laws through 1989.

CERCLA established the following: (1) prohibitions and requirements concerning closed and abandoned hazardous-waste sites, (2) responsibility for releases of hazardous waste at these sites, and (3) a trust fund to provide for cleanup where no responsible party could be established. The law authorizes short-term removals and long-term remedial actions. The long-term remedial actions can be conducted only at sites listed on the EPA's National Priorities List (NPL).

More than 160 hazardous-waste sites have been identified in Oklahoma. Of these, 14 sites are on the NPL. The NPL includes former oil-refinery sites, landfills, a lead/zinc smelter, an Air Force base, and underground zinc/lead mines near Picher, Oklahoma (Tar Creek site). More information on the Oklahoma's CERCLA sites and Superfund sites is found on DEQ's web site: **http://www.deq.state.ok.us/**.

Solid and liquid industrial wastes have been disposed of in some areas of Oklahoma by surface burial in soil or rock units. At present, Oklahoma has only one operating industrial-waste surface-disposal site, in northwestern Major County. Of primary concern in selecting a suitable site for waste disposal is the need for assurance that the waste will be isolated from freshwater zones for as long as the waste is hazardous to man and his environment. Rock units in the State most favorable for surface disposal of wastes are impermeable sedimentary rocks, such as shale and clay, that can be excavated and that can prevent loss or migration of wastes from the disposal pit (Johnson and others, 1980). Most shales and clays consist chiefly of clay minerals, such as illite, montmorillonite, chlorite, and kaolinite, that have the ability to adsorb metal ions as well as to retard the lateral and vertical migration of fluids such as ground water and/or leachate. Areas likely to contain bedrock units suitable for surface disposal of industrial waste are shown in Figure 19.

Many other rock types in Oklahoma generally are not well suited for surface disposal of waste. Rocks such as limestone, dolomite, and gypsum/anhydrite are readily susceptible to dissolution and commonly are cavernous, which makes long-term containment in them unlikely. Granite and metamorphic rocks generally are intensely fractured, which might permit the downward and lateral migration of fluids. Many sandstone units are porous and permeable, which might also permit the infiltration and migration of fluids.

To help protect ground water from waste-disposal activities, maps showing the principal ground-water resources and recharge areas in Oklahoma were prepared by Johnson (1983). These maps, at a scale of 1:500,000 (⅛ in. = 1 mi), show the distribution, character, and recharge areas of bedrock aquifers, alluvium, and terrace deposits throughout the State. The OSDH, and subsequently the DEQ, have adopted these maps as one of the principal preliminary screening criteria for the suitability of a proposed site for waste disposal. However, a final decision concerning suitability should be based on site-specific studies.

The subsurface disposal of liquid industrial wastes has been carried out for many years in Oklahoma. Hazardous-waste products, such as spent acids, caustic solutions, solvents, and other chemicals, were injected into underground reservoirs (porous and permeable rock units that can hold fluids) deep below the land surface and are isolated from freshwater aquifers and the biosphere (Johnson and others, 1980). In 1988, 10 wells were used for disposal of liquid hazardous waste at eight different localities in Oklahoma (Walling, 1990). Nine of the wells are in northeastern Oklahoma, and one well is in central Oklahoma. Permitting and monitoring the operation of these disposal wells was carried out by the OSDH under the authority of the Oklahoma Controlled Industrial Waste Disposal Act of 1976, and later by the DEQ.

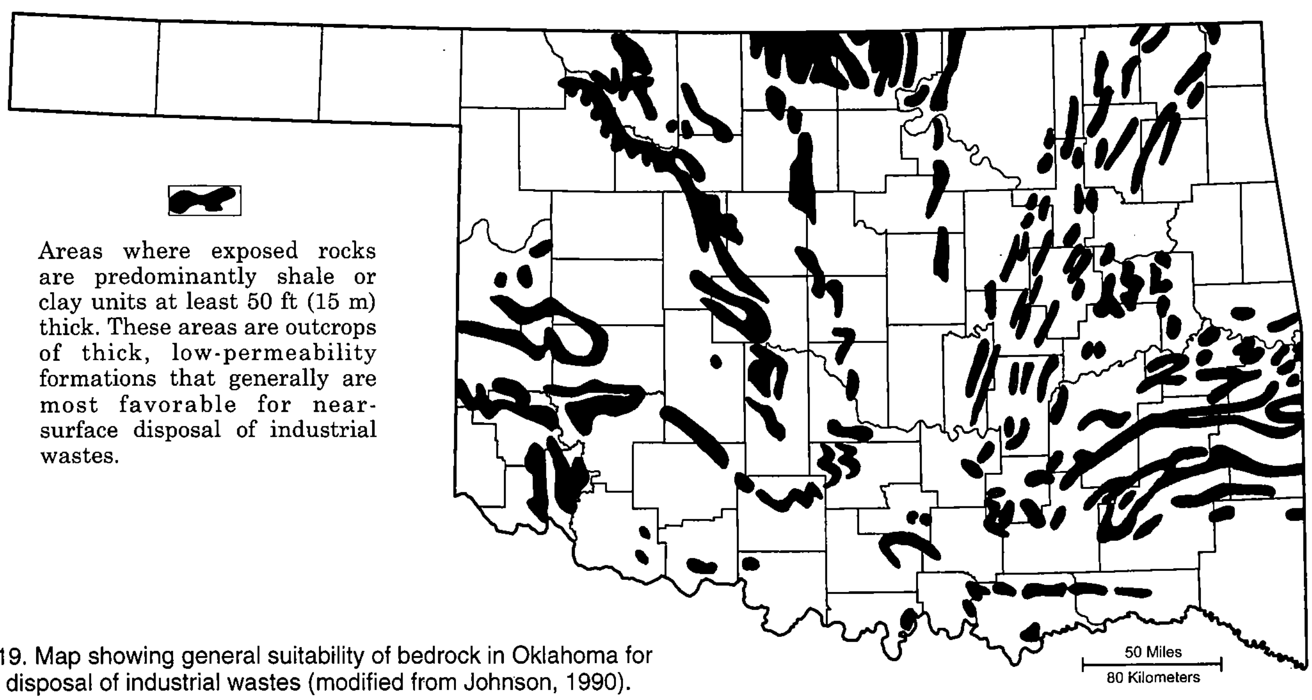

Figure 19. Map showing general suitability of bedrock in Oklahoma for surface disposal of industrial wastes (modified from Johnson, 1990).

In 1983, a Federal underground-injection-control program was established under the provisions of the Safe Drinking Water Act of 1974 to increase ground-water protection. Since then, state and Federal regulatory agencies have modified existing programs and/or developed new strategies to protect ground water by establishing even more effective regulations to control permitting, construction, operation, and closure of injection wells.

The underground-injection-control program divides injection wells into five classes. They are as follows:

Class I: wells used to inject liquid hazardous and nonhazardous wastes beneath the lowermost underground sources of drinking water;

Class II: wells used to dispose of fluids associated with the production of oil and natural gas, enhanced oil recovery, and storage of liquid hydrocarbons;

Class III: wells used to inject fluids for the extraction of minerals;

Class IV: wells used to dispose of hazardous or radioactive wastes into or above underground sources of drinking water (such wells and actions are banned);

Class V: wells not included in the other classes; generally wells used to inject nonhazardous fluids into or above an underground source of drinking water.

The Oklahoma Corporation Commission regulates the following: (1) class II wells; (2) class III wells used for the recovery and injection and/or disposal of mineral brines, such as iodine; and (3) class V wells utilized in the remediation of ground water associated with leaky underground and/or above-ground petroleum-products storage tanks. More than 3,800 class II wells are used to dispose of oil-field brines within the State. There are 11 brine-injection class III wells associated with the production of iodine in northwestern Oklahoma. The remaining well classes are regulated by the DEQ. As of January 2002, no wells were permitted for disposal of hazardous waste, and 12 wells were permitted for the disposal of nonhazardous wastes.

Rock types in Oklahoma that are most desirable for subsurface waste disposal are porous and permeable sedimentary rocks, such as sandstone, limestone, and dolomite, that can store injected liquid wastes (Johnson and others, 1980). Ideally, these porous and permeable rock units should be surrounded by impermeable strata to assure containment.

Johnson and others (1980) identified several geologic factors that need to be studied for a full evaluation of any potential disposal site. Some of these factors include lithology, porosity, permeability, thickness, lateral extent, and depth, as well as structure, geologic framework, confining rocks, hydrology, freshwater aquifers, compatibility of waste with the reservoir, mineral resources, and the presence of boreholes or other excavations. Principal nongeologic factors that need to be assessed include population density, transportation facilities, possible atmospheric degradation (odors, fumes, etc.), and the assured safety of freshwater streams and lakes.

Underground Mines

Underground mining has been conducted intermittently in Oklahoma since the early 1800s, but the major periods of such activity were from 1872 through the present in the eastern Oklahoma coal field, and from 1904 through 1970 in the Picher field, which is part of the world-famous Tri-State lead/zinc mining district that embraces part of northeastern Oklahoma and adjacent areas in Kansas and Missouri (Fig. 20). Underground mines in these two regions, along with a small number of underground gypsum, limestone, basemetal, and asphalt mines in other districts, are potential haz-

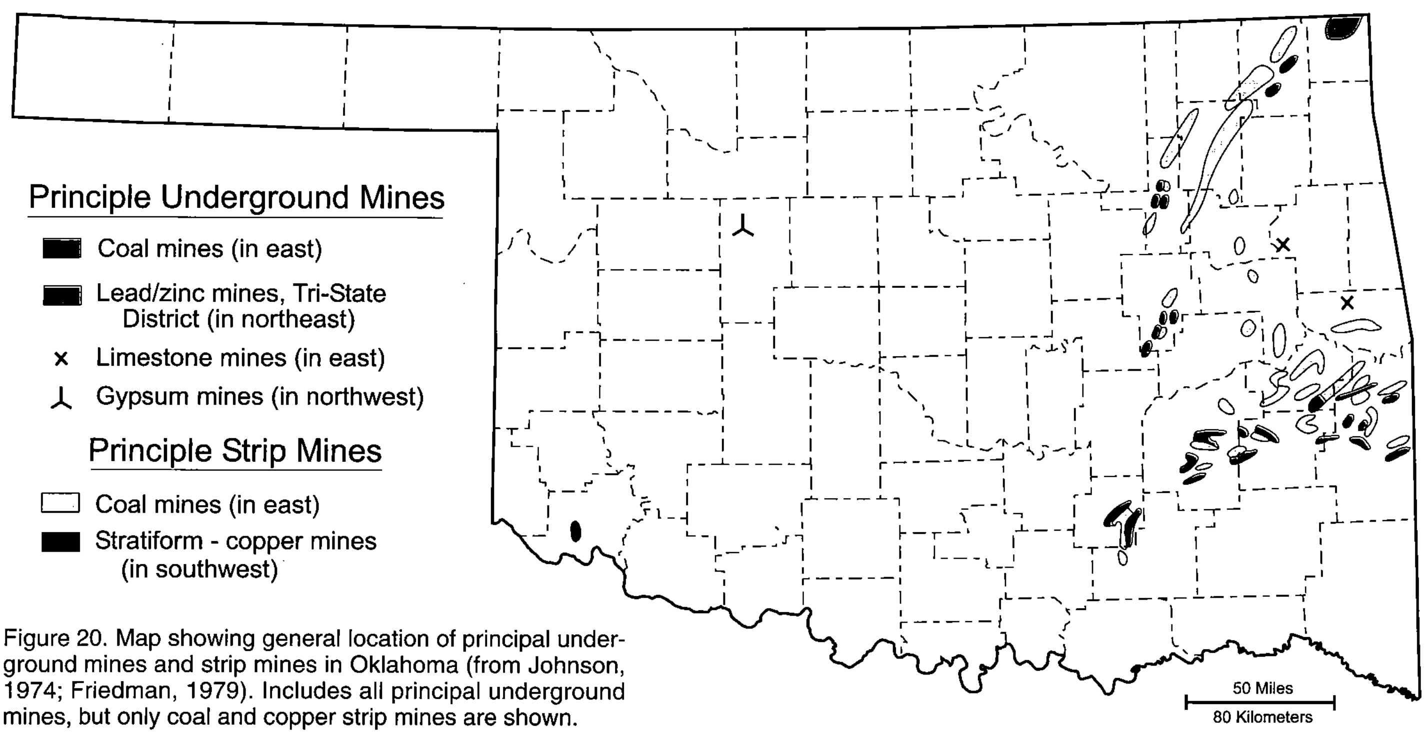

Figure 20. Map showing general location of principal underground mines and strip mines in Oklahoma (from Johnson, 1974; Friedman, 1979). Includes all principal underground mines, but only coal and copper strip mines are shown.

ards because of the following possible problems: (1) collapse of roof rock, causing subsidence or collapse at the land surface; (2) the presence of acidic or toxic ground water; and (3) flooding of a new mine by accidentally breaking into a water-filled abandoned mine.

All mining operations are permitted by the Oklahoma Department of Mines (ODM). As part of the permitting process, the mine operator must post an adequate bond to cover reclamation costs, should it be necessary for a third party to complete the reclamation process. Also, the mining operator's permit application must include the requirements to safeguard environmental resources and an operations and reclamation plan. Mining practices, reclamation, and health and safety procedures are monitored by ODM inspectors.

Large reserves of bituminous coal are distributed over an area of 10,000 mi^2 in eastern Oklahoma. These deposits have been mined continuously since 1872. Early production in Oklahoma was almost entirely from underground mines. Annual production from surface mines began to increase with the development of large earth-moving equipment. In 1943, about 50% of Oklahoma's annual coal production came from surface mines; this increased to 99% in 1964. In fiscal year 2000 (July 1, 1999–June 30, 2000), 244,577 tons of coal were mined from two underground mines, about 15% of the total annual production (Oklahoma Mining Commission and Department of Mines, 2002). About 40,000 acres have been impacted by underground coal mines (Kastl and others, 2001), including scattered gob piles (mine refuse), shaft openings, and subsidence features.

Underground mining for zinc and lead ores in the main part of the Picher field began in 1904, and the last recorded production occurred in 1970. In the main part of the field, an almost continuous underground network of mine workings extended from near Eagle-Picher Mining Company's central mill northward into Kansas. Detailed mine maps were made for each tract of land to ensure proper royalty payments and to provide a guide for future development. The U.S. Bureau of Mines donated their mine-map collection and drill-hole information to the Missouri Southern State College library in Joplin, Missouri. Also, the ODM maintains a collection of maps showing underground workings for coal mines and some lead/zinc mines in northeastern Oklahoma.

More than 2,500 acres are underlain by underground lead/zinc mines in the Oklahoma part of the Picher field. Luza (1986) studied stability problems associated with abandoned underground mines in the Picher field. In 1982, 481 shafts either were open or in some stage of collapse. Approximately 27 surface acres were disturbed as a result of shaft-related collapses. The largest collapse feature, >4 acres, is associated with three shafts at the Domado Mine in Ottawa County (Fig. 21). About 20 surface acres have been disturbed as a result of 55 non-shaft-related collapses. Most of these collapses are west of Commerce and west of Cardin. Apparently most of the non-shaft-related collapses are related to multiple mine levels and/or large stopes and/or incompetent-roof rock.

When the mines were abandoned, they filled with water. In 1979, mine water containing high concentrations of heavy metals began discharging into Tar Creek from natural springs, boreholes, and open mine shafts. In 1980, Oklahoma's Governor, George Nigh, established the Tar Creek Task Force to investigate the drainage of acid mine water into Tar Creek. The site was proposed to be added to the National Priorities List in 1981 and was listed in 1983. Since 1983, a number of studies and remedial actions have taken place, including (1) building dike and diversion structures to stop and/or reduce surface water from entering the abandoned mine workings, and (2) plugging deep, abandoned wells to prevent downward migration of acid mine water into the Roubidoux (Ordovician) aquifer.

Figure 21. Aerial view of a 4-acre-collapse area associated with three mine shafts at the Domado Mine in Ottawa County, sec. 29, T. 29 N., R. 23 E. (from Luza, 1986).

Significant quantities of mill-waste material were generated by the milling of the lead/zinc ores. Luza (1986) reported that approximately 2,900 acres were overlain by mine and/or mill by-products. The discarded mill-waste material, chiefly composed of chert fragments 0.75 in. or less in diameter, was referred to as "chat" by the miners. The chat was transferred away from a mill by a series of conveyors and elevators and heaped into piles. Some piles attained heights greater than 200 ft. The chat has been used for railroad ballast; a base for roads, parking lots, and concrete slabs; and concrete and asphalt aggregate. Datin and Cates (2002) and the University of Oklahoma/Surbec–Art Environmental (2000) reported high concentrations of lead, zinc, and cadmium in the chat. They found most of the lead, zinc, and cadmium concentrated in the smaller particle sizes, <0.0077 in. The chat piles and unwashed chat used as a source of gravel in parking lots and driveways could be a potential source of soil, airborne, and waterborne contaminants. A 1993 study of blood-lead levels by the Indian Health Service found that 34% of Native American children in the area had blood-lead levels above the national standard. Since then, the EPA has provided funds to remove chat from lawns, yards, and recreation areas in the Picher area.

On January 26, 2000, Oklahoma's Governor, Frank Keating, formed the Tar Creek Superfund Task Force. The 10-member task force was charged with developing a comprehensive remediation plan for the Tar Creek Superfund site. Several recommendations were made by the Task Force, including the construction of a wetlands area within the boundaries of the Tar Creek Superfund Site to restore natural resources and reclaim the damaged environment. The final report of the Tar Creek Superfund Task Force is available as a link on the DEQ's web page, **http://www. deq.state.ok.us/.**

Strip Mines and Open-Pit Mines

Strip mining and other forms of open-pit mining have been going on in Oklahoma since pioneer days. The initiation of large-scale quarrying and opencast mining for stone, sand and gravel, asphalt, and other non-coal resources began in the late 1800s, with a great influx of people settling in what was Oklahoma Territory and Indian Territory. The beginning of significant strip-mining activity in the eastern Oklahoma coal field began about 1915. Lands disturbed through surface mining are potential problem areas because (1) spoil piles and fill material might not be fully compacted, and might still be subsiding or settling; (2) ponds and ground water in mined areas might be acidic and/or toxic; and (3) highwalls and quarry faces might contain loose rocks or unstable slopes.

Of all commodities mined by surface techniques, the extraction of coal has had the greatest impact on the environment in Oklahoma. An early study of disturbed coal-mine lands by Johnson (1974) was followed by a comprehensive study by Kastl and others (2001), who showed that the surface mining of coal has produced more than 32,000 acres of unreclaimed land in a 16-county area of eastern Oklahoma. Prior to 1968, surface coal mines typically left behind large areas with elongate ridges of spoil piles, water-filled pits, and steep highwalls (Fig. 22). Oklahoma's Mine Lands Reclamation Acts of 1968 and 1971 required some post-mining restoration of land affected by mining (Fig. 23). In 1977, the U.S. Congress passed Public Law 95-87, known as the Surface Mining Control and Reclamation Act. This established the Abandoned Mine Land (AML) trust fund (funded by taxes on active coal mining) to pay for the reclamation of abandoned coal-mine land that endangered public health and/or safety. The Office of Surface Mining Reclamation and Enforcement, U.S. Department of the Interior, is the Federal agency responsible for allocating the reclamation fees in the AML trust fund. The Oklahoma Conservation Commission is the State agency responsible for reclamation of abandoned coal-mine lands in Oklahoma.

Kastl and others (2001) reported that Oklahoma's AML Program had reclaimed 3,438 acres in 13 counties as of August 2001. The reclaimed acreage included the elimination of 170 hazardous water bodies, the closure of 286 mine openings, and the restoration of 132 subsidence sites. Furthermore, more than 212,000 linear feet of highwall was reclaimed.

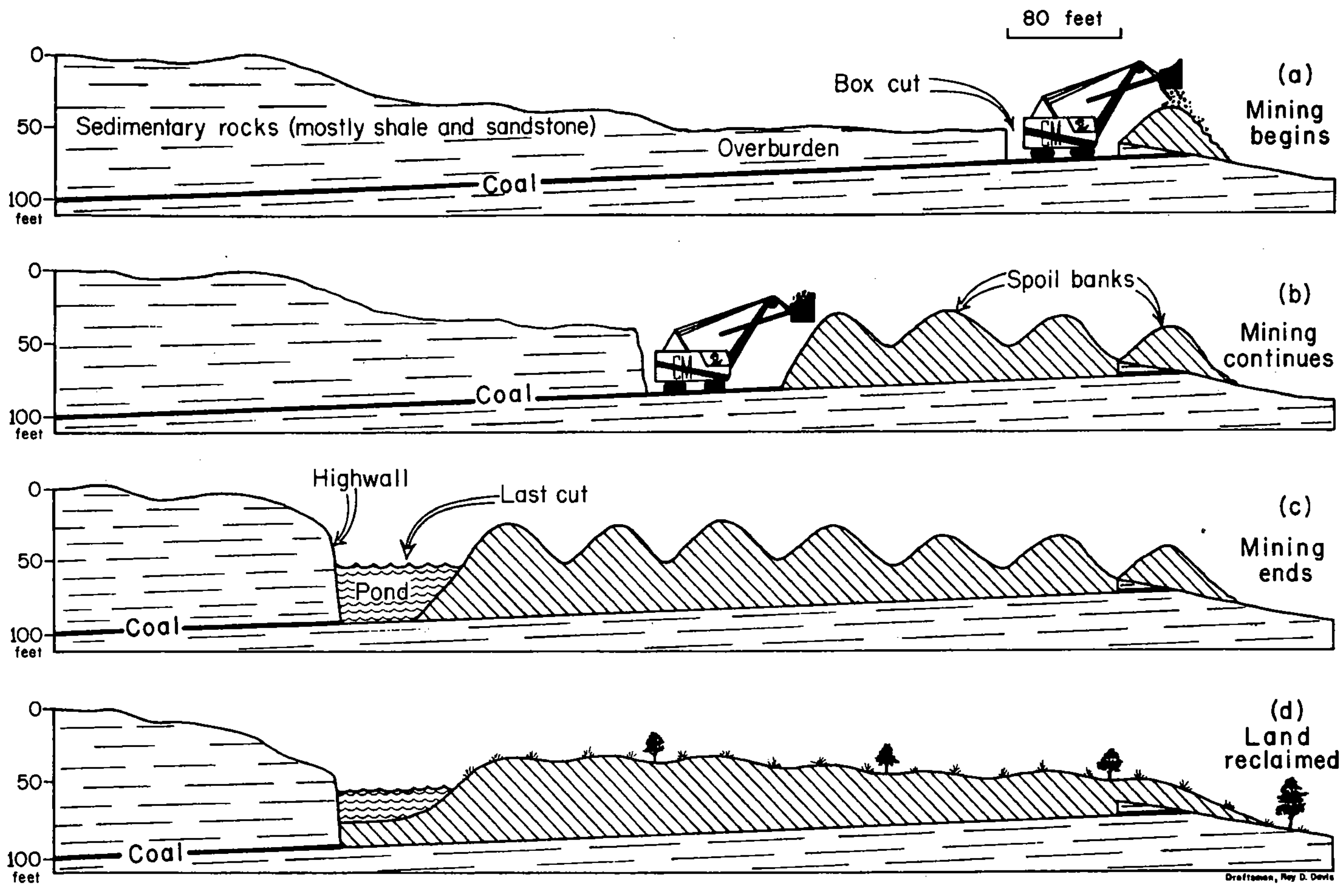

Figure 22. Schematic cross sections showing stages of surface mining for coal. Prior to 1968, most mined lands were left as shown in section c, but Oklahoma laws in 1968, 1971, and 1977 required leveling and land reclamation as in section d (from Johnson, 1974).

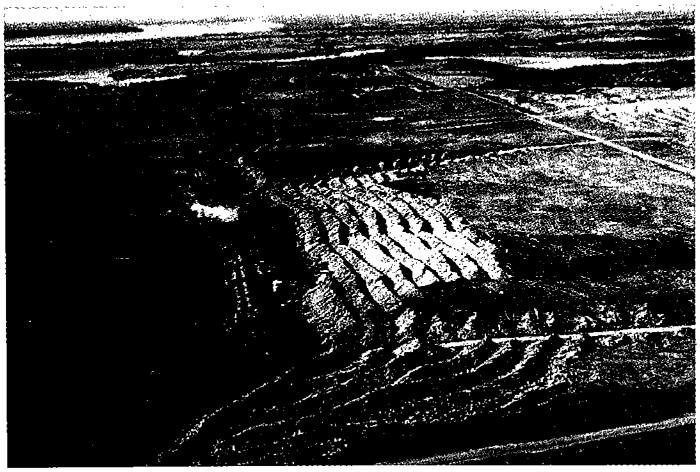

Figure 23. Aerial view of a coal-mining and reclamation operation in Rogers County. Spoil piles in central part of picture are being leveled as mining progresses. Photograph taken in May 1972, looking north across sec. 11, T. 23 N., R. 16 E., Rogers County, toward Oologah Reservoir in the background.

SUMMARY

This report provides a general overview of geologic hazards, both natural and man-made, in Oklahoma. Examples from a soil survey and a FEMA flood map are intended to illustrate how maps and reports can be used to evaluate a site for expansive soils and possible flood hazards, respectively. Other natural geologic processes that might cause hazardous conditions in Oklahoma include earthquakes, landslides, karst, salt dissolution, and radon.

Some activities of man that may have created present or future geologic hazards in Oklahoma include disposal of industrial wastes, underground mining, and strip mining. Some of the major Federal and State hazardous-waste laws that regulate the disposal of industrial and hazardous wastes are presented in the report, and State and Federal agencies that administer these laws are identified. Abandoned underground coal and lead/zinc mines in eastern Oklahoma are responsible for most of the possible problems associated with underground mining in Oklahoma. Of all commodities mined by surface techniques, the mining of coal, especially before 1971, has had the greatest impact on the environment in the State.

The Citizens' Guide to Geologic Hazards (Nuhfer and others, 1993), *Home Buyers' Guide to Geologic Hazards* (Creath, 1996), and *Facing Geologic and Hydrologic Hazards, Earth-Science Considerations* (Hays, 1981) are highly recommended for additional reading.

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Numerous individuals and State agencies provided information for this article. Robert Welch and Jerry Matthews, DEQ, contributed information on injection wells and radon, respectively. The Oklahoma Corporation Commission supplied data on salt-water disposal of mineral brines, such as iodine, and oil-field brines within the State. Robert L. Tortorelli, U.S. Geological Survey, Water Resources Division, furnished information about Oklahoma floods and photographs of the Enid flood. Jim Nevels, Oklahoma Department of Transportation, provided information on expansive soils in Oklahoma.

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APPENDIX 1

Glossary of Terms

(mostly from Jackson, 1997)

anhydrite — A mineral or sedimentary rock composed of calcium sulfate, $CaSO_4$; it alters readily to gypsum.

aquifer — A body of rock permeable enough to yield significant quantities of ground water to wells and springs.

arkose — A sandstone containing 25% or more of feldspars usually derived from the disintegration of rocks similar to granite.

base metal — Any of the more common and more chemically active metals, such as copper, lead, and zinc.

Bethany–Urban land complex — A soil that consists of deep, well drained Bethany soil and Urban land. The soil and Urban land of this complex are so intermingled that they could not be separated. The Bethany soil is on broad, nearly level to very gently sloping uplands.

biosphere — Zone at and adjacent to the earth's surface where all life exists.

bituminous coal — Class of coal having a calorific value of more than 11,500 BTU/lb.

BTU — British Thermal Unit. A unit of heat equal to 252 calories; quantity of heat required to raise the temperature of 1 lb of water from 62°F to 63°F.

calcite — A mineral, calcium carbonate, $CaCO_3$; the principal component of limestone and a common cement of sandstones.

chat — The crushed chert, limestone, and dolomite that is left as a by-product of milling lead-zinc ores.

chert — A hard, extremely dense or compact, dull to semivitreous, microcrystalline or crytocrystalline sedimentary rock, consisting dominantly of quartz; occurs principally as nodules in limestones and dolomites. Syn: *flint* (for dark variety).

colluvium — A general term applied to any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited by rainwater, sheetwash, or slow continuous downslope creep, usually collecting on the sides and at the base of gentle slopes or hillsides.

Cretaceous — A period of geologic time, extending from about 146 to 65 million years ago. Most of the rock outcrops in southeastern and northwestern Oklahoma are of Cretaceous age.

dike — A tabular body of igneous rock that cuts across the structure of adjacent rocks or cuts through massive rocks.

dolomite — A mineral or sedimentary rock composed of calcium magnesium carbonate, $CaMg(CaCO_3)_2$.

Doolin–Urban land–Pawhuska complex — A soil that consists of the deep, moderately well drained Doolin and Pawhuska soils and Urban land. The soils and Urban land of this complex are so intermingled that they could not be separated. The soils of this complex are on nearly level to very gently sloping uplands.

earthquake — A sudden motion or trembling in the Earth caused by the abrupt release of slowly accumulated strain.

earthquake intensity — A measure of the effects of an earthquake at a particular place. Intensity depends not only on the earthquake magnitude, but also on the distance from the origin of the earthquake and on local geology.

earthquake magnitude — A measure of the strength of an earthquake determined by seismographic observations.

flood plain — Land area adjacent of a river channel, constructed by the present river in its existing regimen and covered with water when the river overflows its banks.

granite — An intrusuve igneous rock consisting mostly of potassium-rich feldspar, orthoclase, and quartz, with biotite and/or hornblende as minor constituents.

ground water — That part of subsurface water that is in the zone of saturation, in which all the void spaces are filled with water.

gypsum — A common mineral or sedimentary rock consisting of hydrous calcium sulfate, $CaSO_4{\cdot}2H_2O$.

highwall — The working face of a surface mine or quarry.

igneous — Formed by solidification from a molten or partially molten state.

illite — Group of clay minerals having an intermediate composition between muscovite and montmorillonite.

ion — An electrically charged atom or group of atoms.

kaolinite — A common clay mineral having the general formula $Al_4(OH)_8[Si_4O_{10}]$.

karst — A type of topography that is formed where limestone, gypsum, and other water-soluble rocks are dissolved to produce sinkholes, caves, and underground drainage.

leachate — Water that contains soluble substances in solution after percolating through soil.

lignite — A brownish-black coal with a calorific value less than 8,300 BTU/lb.

limestone — A common sedimentary rock composed mostly of calcite and formed by either organic or inorganic processes; may contain fossils.

lithology — The description of rocks on the basis of such characteristics as color, mineral composition, and grain size.

magnitude — A measure of earthquake size, determined by taking the common logarithm (base 10) of the largest ground motion recorded during the arrival of a seismic-wave type and applying a standard correction for distance to the epicenter. Common types of magnitude are Richter (or local) (M_L), primary (P) body wave (m_b), surface wave (M_s), and duration magnitudes (DUR).

mass wasting — A general term for a variety of processes by which soil and/or rock material are moved by gravity either slowly or quickly from one place to another.

metamorphic rock — Any rock derived from preexisting rocks in response to marked changes in temperature, pressure, and/or chemical environment.

montmorillonite — A group of clay minerals whose formulas may be derived by substitution in the general formula $Al_2Si_4O_{10}(OH)_2$; they swell when wet and shrink when dried.

opencast mining — Surfical mining, in which the valuable rock is exposed by re-moval of overburden. Coal, numerous nonmetals, and metalliferous ores as of iron and copper are worked in this way. Syn: *strip mining; openpit mining; opencut mining.*

pCi/L — Picocurries per liter.

Pennsylvanian — A period of geologic time extending from about 323 to 290 million years ago. Pennsylvanian rocks are the producers of major oil and gas in most of Oklahoma, and they contain bituminous coal resources in eastern Oklahoma.

permeability — The property or capacity of a rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid to flow under unequal pressure.

Permian — A period of geologic time extending from about 290 to 245 million years ago. Most of the rock outcrops in central and western Oklahoma, especially those that are red, are Permian in age.

porosity — The percentage of the bulk volume of a rock or soil that is occupied by voids, whether isolated or connected.

ppm — Parts per million.

quarry — Open workings, usually for the extraction of stone.

scale — The ratio between linear distance on a map and the corresponding distance on the surface being mapped. It may be expressed in the form of a direct or verbal statement using different units (e.g., 1 inch to 1 mile, or 1 inch = 1 mile); a representative fraction or numerical ration (e.g., 1/24,000 or 1:24,000, indicating that one unit of length on the map represents 24,000 identical units on the ground).

seismogram — The record made by a seismograph.

seismograph — An instrument that detects, magnifies, and records vibrations of the Earth, especially earthquakes.

shaft — A vertical or inclined excavation through which a mine is worked.

shale — A sedimentary rock, commonly laminated, composed mostly of clay minerals and formed by the consolidation of clay and mud.

shrink–swell potential — The potential for a soil to shrink when dry and to swell when wet.

sill — A tabular igneous intrusion that parallels the planar structure of the surrounding rock.

sinkhole — A circular depression in a karst area. Its drainage is subterranean, its size is measured in feet or tens of feet, and is commonly funnel-shaped.

stope — An underground excavation formed during the extraction of ore.

stratiform — Refers to a vein or other mineral deposit that follows the bedding plane in a sedimentary rock.

APPENDIX 2

Acronyms and Abbreviations

AML — abandoned mine land

CERCLA — Comprehensive Environmental Response, Compensation, and Liability Act

DEQ — Oklahoma Department of Environmental Quality

EPA — U.S. Environmental Protection Agency

FEMA — Federal Emergency Management Agency

HUD — U.S. Department of Housing and Urban Development

NFIP — National Flood Insurance Program

NPL — National Priorities List

NRCS — National Resources Conservation Service

ODM — Oklahoma Department of Mines

ODOT — Oklahoma Department of Transportation

OGS — Oklahoma Geological Survey

OSDH — Oklahoma State Department of Health

OSM — Office of Surface Mining, Reclamation, and Enforcement

OWRB — Oklahoma Water Resources Board

RCRA — Resource Conservation and Recovery Act

SARA — Superfund Amendments and Reauthorization Act

Cover photos

Front Cover: A cave-in associated with underground lead-zinc mine workings on the Santa Fe mine lease in the Picher Field, Ottawa County, Oklahoma. At this location, a 230- by 200-foot elliptical collapse occurred before 1939. This site was used as a landfill for a number of years. It was almost filled by 1980 and recollapsed between 1981 and 1982, which exposed some of the landfill debris. Photograph taken by Kenneth V. Luza, April 1983. ***Back Cover:*** After reclamation, this is how the same area looks today. The cave-in, which was approximately 20,000 cubic yards in volume, was filled with on-site chat and capped with clay excavated from a pond built on-site. The area was vegetated with fescue/ryegrass/clover in the fall of 2003. In total, the McNeely Tar Creek Abandoned Mine Land Project reclaimed 52 acres and filled two large cave-ins with approximately 80,000 cubic yards of on-site chat. Seven concealed or partially filled shafts were explored and re-sealed while two open shafts were filled and sealed. Photo taken by Mike Sharp, Oklahoma Conservation Commission, April 2004.