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## Stratigraphic Investigations of a Possible Late-Quaternary Fault System at the Bone Cove Site on Harlan County Lake, Harlan County, Nebraska

by

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## Introduction

Recent geoarchaeological and geomorphological research with C.W. Martin in the vicinity of Harlan County Lake, south-central Nebraska (e.g., Johnson, 1989; Martin, 1993), led to the discovery of a fault-like fracture developed in late-Quaternary loess. No other potential faults are known to have been reported for loess deposits of the region, making this locality unique. Stratigraphic data indicate that the feature is relatively young, dating anywhere from the latest Pleistocene to at least the early Holocene. Further indication of a tectonic source for faulting is the direction of movement which is southward away from the adjacent Republican River valley. Also, given the location of this feature in a seismically active zone on the eastern flank of the Charon-Cambridge Arch of Kansas and Nebraska, its situation between the Meers fault of southwestern Oklahoma and the New Madrid seismic zone of Missouri, and the many faults exposed in bedrock during construction of the Harlan County Dam, it appeared that the origin of the feature could be tectonic. In many years of viewing loess exposures within the central Great Plains, I have not seen any other localities with such a feature, and, to my knowledge, none have been reported in the literature. Since loess mantles much of the region, investigation of possible geologically recent faulting is very important and needs to be investigated.

In order to fully characterize the fracture system and to determine if it was tectonically or mass movement-induced, on-site investigations included seismic reflection survey and surface stratigraphic study. Toward the latter, invaluable expertise was made available from the U.S. Geological Survey in Denver.

## Regional Geology

Direct study of the exposure dealt with the nonindurated late-Quaternary sediments, whereas a companion seismic investigation (Miller and Steeples, 1996) focused on the subsurface bedrock geology. Types and ages of sediments found in the study are described below, with an emphasis on the late-Quaternary units studies in this research.

### Late-Quaternary Stratigraphy

Deposits of late-Quaternary age that are exposed in the study area include Illinoian alluvium and soils, and Wisconsinan loess and soils, capped by the modern surface soil. Late-Quaternary stratigraphic succession of the region is represented in Figure 1.

**Illinoian age deposits**. Although the study area was not glaciated during the Illinoian glacial age, the alluvial and eolian deposits of this era are well represented in the region, including the Harlan County Lake, Nebraska, study site.

*Crete Formation.* Consisting of sand and gravel, the Crete Formation is an alluvial deposit, probably reflecting several cut and fill sequences, that is presumably of Illinoian age. Originally, the Loveland unit included both eolian and alluvial sediments (Lugn, 1935), but Condra et al. (1947) introduced the name Crete Formation in Nebraska in order to differentiate the alluvium from the loess. Based on recent data from Nebraska, Wayne and Aber (1991) suggested that the names *Crete* and *Grand Island* may reference the same sedimentary unit. As a result, they favored discontinuing use of the name *Crete Formation*. Until better age control is established, however, the continued use of the formational name is appropriate.

The Crete Formation, as it is defined in Kansas, is widely recognized in the north-central part of the state, where it consists locally of gully fills and as terrace deposits on the north side of major river valleys (Frye and Leonard, 1952 p. 112). Typically, Crete lithology is consistent with that of the drainage basin within which the deposits occur. In the vicinity of Harlan County Lake, the Crete Formation contains a mixed local and Rocky Mountain lithology and rests on the Pierre Shale, Niobrara Formation, or Ogallala Formation, whichever is at the discontinuity with the overlying Quaternary deposits.

*Loveland Loess.* Loveland Loess is the most pervasive pre-Wisconsin loess in the central United States. Shimek (1909) first identified the Loveland in exposures along the east bluff of the Missouri River northeast of Loveland, Iowa. Recently, the Loveland Loess has been described throughout the Missouri, Mississippi, and Ohio River basins (e.g., Reed and Dreeszen, 1965; Ruhe, 1969; Willman and Frye, 1970; Ruhe and Olson, 1980) and has been recognized as far south as Arkansas and Mississippi (e.g., McCraw and Autin, 1989). Loveland Loess consists of carbonate enriched eolian silt that accumulated during the Illinoian Stage between about 300 and 130 ka. The Loveland Loess is yellowish-brown or reddish-brown in color, with increased red hues toward the top of the formation due to development of the Sangamon Soil. Several paleosols of variable development, including the Sangamon Soil, have been recognized in the Loveland (Frye and Leonard, 1954; Feng, 1991; Feng et al. 1994 a, b). In the study area, Loveland loess occurs only on the drainage divides.

*Sangamon Soil.* The Sangamon Soil is a strongly developed paleosol or complex of paleosols distributed throughout the midcontinent, including the states of Indiana (Hall, 1973; Ruhe et al., 1974; Ruhe and Olson, 1980), Illinois (Bushue et al., 1974; Follmer, 1979), Iowa (Simonson, 1941, Ruhe, 1956, 1969), Nebraska (Schultz and Stout, 1945; Thorpe et al., 1951), and Kansas (Frye and Leonard, 1952). Initially recognized by Leverett (1899) to differentiate Illinoian and Wisconsin deposits, the Sangamon is characterized by intense oxidation (vivid to pale reddish brown colors), deep leaching, and high clay accumulation. Because of apparent time transgressiveness and the diachronous nature of the Sangamon Soil, the age of the soil is not precisely known. Age estimates indicate, however, that it ranges from approximately 135 ka to 75 ka in age (e.g., Forman 1990; Forman et al. 1992; Johnson et al., 1990; Maat and Johnson, 1995).

The Sangamon Soil probably should be considered a pedocomplex, with several soils representing significant temporal and environmental variability welded together, rather than a single soil that developed under unique environmental conditions (Schultz and Tanner, 1957; Fredlund et al., 1985; Morrison, 1987). From his research in Brown County, Kansas, Schaetzl (1986) observed that the Sangamon appears to be a strongly developed Ultisol or Mollisol.

Originally known in Kansas as the "soil in the Sanborn formation" (Hibbard et al., 1944) and the Loveland soil (Frye and Fent, 1947), the Sangamon has been extensively studied in the northeastern part of the state (e.g., Frye and A.B. Leonard, 1949, 1952, Caspell, 1970, Schaetzl, 1986), but has been recognized elsewhere (Bayne and O'Connor, 1968). Recently, in a study of the Sangamon Soil at Barton County, Kansas, Feng et al. (1994a, b) concluded from chemical and physical characteristics that the soil formed in a warm, moist climate, resulting in strong chemical weathering.

In the Harlan County Lake area, the Sangamon Soil is developed both in the Loveland Loess and in the Crete Formation, the latter of which occurs at the Bone Cove study locality.

**Wisconsinan age deposits**. Subsequent research in type areas of Illinois and Wisconsin has placed the age of the Sangamon-Wisconsinan boundary at about 50 ka (McKay, 1979a, b; Leigh, 1991, 1994; Curry and Folmer, 1992). The boundary appears, however, to be time transgressive (Johnson et al., 1991), which accounts for the lack of consistency in the limited chronologic data. The Wisconsinan chronology has been subdivided so as to include early, middle, and late-Wisconsin divisions, with the stage extending from about 116 ka to 10 ka (marine isotope stages 5d through 2; Clark et al., 1993). Wisconsinan rock-stratigraphic units recognized in Harlan County consist of the Gilman Canyon Formation and the Peoria Loess.

*Gilman Canyon Formation.* The Gilman Canyon Formation, a middle Wisconsinan loess and valley fill, was first recognized in Nebraska by Reed and Dreeszen (1965). It is the apparent chronostratigraphic equivalent to the Pisgah Formation in western Iowa (Bettis, 1990, Forman et al., 1991), and the Roxana Silt (Leigh and Knox, 1993, Leigh, 1994), which has been recognized in an area extending from Minnesota and Wisconsin to Arkansas. In Kansas and Nebraska, the upper part or all of the Gilman Canyon Loess is usually silty, leached of calcium carbonate, commonly bioturbated, and dark colored as a consequence of heavy enrichment of pedogenic organic carbon. Once thought to be the attenuated A horizon of the Sangamon Soil (Thorpe et al., 1951; Reed and Dreeszen, 1965), radiocarbon time control and stratigraphic information indicate that the Gilman Canyon Formation is a *geosol* or a *composite geosol* (Johnson, 1993) because it is a laterally traceable, mappable, pedostratigraphic unit with a consistent time-stratigraphic position (Morrison, 1965; North American Commission on Stratigraphic Nomenclature, 1983, p. 865).

In Illinois, radiocarbon ages on organic materials from within early Wisconsinan loess range from 40,000 to 31,000 yr B.P. Based on these ages, McKay (1979a, b) extrapolated that loess deposition began about 45,000 yr B.P. TL and radiocarbon ages from loess lying directly above the Sangamon Soil in Iowa range from 35 - 30 ka (Forman, 1990; Forman et al., 1992). Radiocarbon ages from the middle Wisconsinan Roxana silt in the Upper Mississippi River valley indicate that the loess unit was deposited between 50 and 27 ka (Leigh, 1991, 1994; Leigh and Knox, 1993).

Radiocarbon ages from the Gilman Canyon Formation range from about 38,000 yr B.P. near the base to about 20,000 yr B.P. at the top (May and Souders, 1988; Johnson et al., 1990; Johnson, 1993). The age of 38 ka is derived from a sample taken from the base of the Gilman Canyon geosol, but not the base of the formation; consequently, age of the basal part of the formation is perhaps close to 50 ka which would agree with that of the Roxana silt (Leigh, 1991; Leigh and Knox, 1993). In Nebraska and Kansas, the Gilman Canyon Formation has been dated at 54 localities (Johnson and May, 1996).

Limited textural data and description of the Gilman Canyon Loess at the Buzzard's Roost type section was provided by Reed and Dreeszen (1965). Their description states (p. 62): "Upper 12 inches (31 cm) is medium dark gray, slightly humic, silt; middle 1 inches (1.1 m) is dark brownish-gray, humic, soil-like silt; entire thickness is noncalcareous...5 feet 9 inches (1.8 m)." The bimodal distribution of the humus indicates that two periods of relative stability and low accumulation are separated by a period of increased accumulation. As a result, the Gilman Canyon is often expressed as two or more cumulic A horizons. May and Souders (1988) recognized three distinct organic zones in an expanded valley-fill section in Nebraska, and two organic zones have been recognized at the Eustis Ash Pit in south-central Nebraska by Johnson et al. (1993). These observations indicate that the Gilman Canyon accumulated at an average rate (<0.08mm/yr) sufficient for continuous pedogenesis, but did exhibit a variable depositional rate. Texturally, the Gilman Canyon Loess consists largely of silt, with lesser, but approximately equal, percentages of sand and clay. Two magnetic parameters, susceptibility and frequency dependence, have been employed as surrogates of weathering and soil formation. The bimodal organic matter distribution is corroborated by frequency dependence, an indicator of pedogenically produced fine sediments. These observations are consistent with data previously noted from the type locality (Reed and Dreeszen, 1965) and the Eustis Ash Pit of southwestern Nebraska (Johnson et al., 1993). The Gilman Canyon loess and soil are well expressed in the Harlan County Lake area, and at the Bone Cove study locality.

*Peoria Loess.* The name *Peoria* was first proposed by Leverett (1899) for deposits of an interglacial period that separates the Iowan and Wisconsinan glacial stages. When Alden and Leighton (1917) demonstrated that the Peoria is younger than the Iowan, the name *Peoria* became associated with a loess rather than a weathering interval. Several names have, however, been used for post-Farmdalian loess in the central United States. Ruhe (1983), for example, preferred the term "late Wisconsin loess" because of correlation uncertainties from one region to another.

The Peoria Loess is typically calcareous, massive, light yellowish-tan to buff silt that usually overlies the Loveland Loess or an approximate equivalent of the Gilman Canyon Formation. Ruhe (1983) noted three major characteristics of the Peoria, i.e., that it thins downwind of the source area, systematically fines in particle size downwind from the source area, and is time transgressive. Regarding the latter, Ruhe (1969) found that the age of the soil beneath the Peoria Loess decreases from 24,500 yr B.P. near the Missouri River to about 19,000 yr B.P. eastward across southwestern Iowa. Similarly, the base of the loess decreases in age from 25,000 to 21,000 yr B.P. along a transect in Illinois (Kleiss and Fehrenbacher, 1973). Ages from the top of the loess range from 12,500 yr B.P. in Illinois (McKay, 1979a) to 14,000 yr B.P. in central Iowa (Ruhe, 1969). Deposition of Peoria Loess was not continuous, as evidenced by stratigraphic breaks such as that marked by the Jules soil in Illinois (Frye and Willman, 1973; Frye et al., 1974, Ruhe, 1976; McKay, 1979) and the soil zones recognized in Iowa (Daniels et al., 1960; Ruhe et al., 1971).

In Kansas, the Peoria Loess is a reddish, yellowish, or tan-buff homogeneous, massive, locally fossiliferous, variably calcareous coarse silt to very fine sand to medium to fine silt and clay (Frye and Leonard, 1952). The source of the silt is not certain. In a review of available data, Welch and Hale (1987) concluded that loess deposits in Kansas were not derived from a single source, but rather from a combination of three sources: glacial outwash river flood plains, present sand dune fields, and erosion of the Ogallala Formation. In Phillips County, Kansas, which is adjacent to Harlan County, the Peoria contains moderate but variable amounts of sand with a general increase upward in clay. According to Johnson (1993), this trend may have resulted from increased clay influx from the southwest when atmospheric circulation patterns shifted as the Laurentide ice sheet diminished (COHMAP members, 1988). Thickness of the Peoria ranges from 30.5 m along the Missouri River valley to 0.6 m in isolated patches elsewhere. Where accumulation is less than 0.6 m, the Peoria is considered to be unrecognizable because it is incorporated into the existing surface soil.

Although visible soil zones such as those recognized in Illinois (Frye and Willman, 1973; Frye et al., 1974; Ruhe, 1976; McKay, 1979) and Iowa (Daniels et al., 1960; Ruhe et al., 1971) have not been recognized in Kansas, lenses of plant remains, reflecting former stable surfaces, suggest that Peoria Loess deposition was discontinuous in the region. *Picea* (cf. *glauca*) remains, which indicate a cool, moist environment, are common. Radiocarbon ages from these materials document their burial and suggest up to three discrete periods of surface stability: 21-21ka, 18-17 ka, and 14-13 ka. The earliest intervals occurred during the last glacial maximum, while the latter represents major deglaciation (Ruddiman, 1987). Magnetic analyses have indicated weathering zones or weakly developed soils within the Peoria Loess (Johnson and Park, 1996). Atmospheric data obtained from Greenland ice-cores indicates a significant decrease in dust at about 13 ka (Paterson and Hammer, 1987) which may have resulted in relative surface stability, soil formation, and tree establishment in the central Great Plains (Johnson, 1993). The Peoria Loess forms the bulk of the exposures along the perimeter of Harlan County Lake, including the study locality.

## Bedrock stratigraphy and structure

Although no core data exist for the Bone Cove site, extensive data were acquired by the Army Corps of Engineers prior to and during excavation for construction of the earthfill dam, located less than three miles to the east. Profiles of excavation along the right abutment of the dam exposed the Cretaceous Pierre Shale and Niobrara chalk (U.S. Army Corps of Engineers, 1977). The Niobrara Formation, Pierre Shale, and Ogallala Group are exposed at low-water levels along the shoreline; the particular unit exposed is a function of local fault patterns. At the Bone Cove site, the Ogallala Group and Niobrara Formation are exposed at low water; it appears that the Pierre shale was removed locally prior to deposition of the Ogallala. The Cretaceous units are presumable underlain by Permian deposits.

**Stratigraphy**. The Ogallala Group is Miocene age alluvium derived from the Rocky Mountains. The sediments were deposited in paleovalleys and other alluvial environments and consist primarily of sand-sized material with intercalated, discontinuous volcanic ash beds. Formations comprising the Ogallala Group are, in descending order, the Ash Hollow, Valentine, and Runningwater (Swinehart and Diffendal, 1989). In adjacent Kansas, the Ogallala has formational status and consists of the Kimball, Ash Hollow, and Valentine members (Zeller, 1969). In Harlan County, Nebraska, the Ogallala is occurring at its easternmost limit. As expressed in the vicinity of Harlan County Lake, the Ogallala is a light gray, generally fine-grained, calcareous, and poorly cemented unit, with a thickness of about 6m.

As the uppermost Cretaceous formation, the Pierre Shale consist of several members and is generally composed of black to dark gray-brown fissile platy, noncalcareous shale with several zones of chalky shale and occasional layers of bentonite and thin veins and isolated crystals of gypsum and limonite concretions. In adjacent Phillips County, Kansas, only the lowermost Sharon Springs Shale Member is exposed at the surface (Johnson, 1993). In the Harlan County Dam project area, the Pierre Shale was described as a dark gray, soft, waxy, clay shale containing numerous thin bentonite clay layers up to 15cm thick, irregular calcite seams, and small crystals of pyrite. Basal beds are increasingly limey as the formation grades into the underlying Niobrara Formation (U.S. Army Corps of Engineers, 1977). Thickness as exposed in the right abutment of the dam is about 15m.

The Niobrara Formation was named by Meek and Hayden in 1862 to characterize exposures of calcareous marl and chalky limestone in the Niobrara River valley of northeastern Nebraska. The formation was later subdivided into the Fort Hays Limestone and Smoky Hill Chalk (Logan, 1897). The Smoky Hill Chalk has recently received intensive and extensive study by Hattin (1982). The type area, western Kansas, consists of twelve sections that form a composite section over 182 m thick. In Kansas, the outcrop of the Smoky Hill extends from north-central Finney County for 304 km northeastward to the Nebraska state line in northeastern Jewell County. The chalk is olive gray in color, impure, well laminated to nonlaminated, and flaky in its weathering habit. Over 100 zones of bentonite have been recognized by Hattin; they range in thickness up to 11.3 cm, but are usually less than 3 cm. They are most numerous in the lower portion of the member and weather to a rusty gray, but the color of the member varies geographically. The basal part, cropping out in the southeastern corner of the county, is blue-gray, and the middle portion of the member, exposed in the central part of the county, is predominately tan or pink. A pink to orange color characterizes the upper part of the member which outcrops in the northern and western parts of the county. Vertebrate and invertebrate fossil material is common in the chalk, the most obvious being a clam (*Inoceramus grandis*) and oyster (*Ostrea congesta*).

The Fort Hays Member, a marine limestone, lies conformably on the Carlile Shale. The Fort Hays is a buff-colored, chalky limestone exhibiting massive beds of chalk, up to 1.5 m thick, separated by thin shale partings. Upon weathering, the chalk beds become gray in color and limonite-stained on the surface.

The Niobrara underlies the entire dam site and forms most of the foundation. As exposed, it is a soft, gray, chalk (primarily of minute calcareous shells) that is medium to thick-bedded, compact, and somewhat brittle. Where weathered, it is light gray, compact and stiff calcareous clay. Thin (<10cm ) bentonite seams and associated pyrite were common. Approximately 61m of Niobrara chalk were present in cores from the dam site (U.S. Army Corps of Engineers, 1977).

Permian deposits have been divided and subdivided into a number of groups, formations and members. One particular unit, the Stone Corral of the Sumner Group, is of interest, however, in that it is has been recognized in a borehole near the study area (R. Burchett, pers com). The Stone Corral, situated in the Permian redbed section, is unique in that it can be traced laterally over a large area. The unit, typically a dolomite or anhydrite, serves as an important marker bed for structural and stratigraphic work because it is easily recognized in well samples and logs and is located relatively close to the surface. The eastern limit of the Stone Corral Formation is presumed to be immediately to the east of Harlan County Lake based on maps presented in Merriam (1963). Its presence was apparent in seismic reflection investigations associated with this study.

The remaining Paleozoic and older stratigraphy is undocumented at the site. Merriam (1963) noted, however, that Mississippian rocks are absent in Kansas adjacent to the study area.

**Structure.** The structural features relevant to this investigation are the Central Kansas Uplift and the Chadron Cambridge Arch (Fig. 2). The Central Kansas Uplift is a post-Mississippian, northwest-trending uplift and represents the largest positive feature in Kansas. Cretaceous and younger beds hide the underlying structure, which has a crest consisting of Precambrian and Pennsylvanian rocks. Several subsidiary anticlines and other structures are associated with the crest and flanks. The northwest-trending continuation of the Central Kansas Uplift is represented by the Cambridge and Chadron Arches. The Cambridge Arch of northwestern Kansas is separated from the Central Kansas Uplift by a structural saddle. Anomalous stream gradients, knickpoints where rivers cross the arch, and the nature of the distribution of alluvial deposits across the arch in south-central Nebraska suggest Pleistocene and possibly Holocene tectonic upwarping centered along the arch (Stanley and Wayne, 1972).

## Regional Seismic Activity

Over 30 felt earthquakes with epicenters in Kansas were recorded during the period 1867 to 1978 (DuBois and Wilson, 1978). Concentrations of historic and microearthquakes have been documented along the Chadron Cambridge Arch and the Central Kansas Uplift (Woollard, 1958; Steeples and Roth, 1982; Evans and Steeples, 1987). One of the largest, the Stockton event of April 27, 1879, was located about 80km south of Harlan County Lake on the northeast flank of the Central Kansas Uplift.

From August, 1977, to July, 1989, the Kansas Geological Survey operated a Nuclear Regulatory Commission-funded, microearthquakes seismic activity network in Kansas and Nebraska (Fig. 3). The northwest-southeast trend of events in north-central/western Kansas and Nebraska is related to faults flanking the Central Kansas Uplift--Chadron-Cambridge Arch system. The distribution of microearthquakes throughout Kansas and Nebraska, established over the 12-year period, correlates very well with the last 125-year pattern of historical tremors. An increase in earthquake activity along the uplift and arch over the last two years has been documented on earthquake seismographs and by earthquake felt-reports. The majority of felt reports prior to 1989 were from 8 events located on the eastern flank of the arch in Kansas counties near the Nebraska state line. Several earthquakes, with sufficient intensity to be felt, have also occurred since the seismograph network shut down. The foci of the earthquakes have been approximated at 5-km depth, with no evidence of late-Quaternary surface expression associated with activity on either structure.

**Significance of the study.** The possibility of the Harlan County Lake area fault being tectonically induced is important to the regional earthquake risk potential. The midcontinent region of the United States has historically been classified as the Central Stable Region (Snyder, 1968). The apparent regionally isolated, relatively weak seismicity of the region has been correlated to specific geologic structures (Nuttli, 1979; Algermissen et al., 1982; Gordon, 1988). Quaternary surface faulting was only recently confirmed in the Midcontinent (Howard et al., 1978). Historic earthquake epicenters have, for the most part, been the main guides in defining seismic source zones in the midcontinent (Coppersmith, 1988).

Recognition of potentially significant earthquake activity in this area of the Midcontinent is quite recent. The significance of the 1879 Stockton event, with a probable magnitude of 4.5 to 5.0, was not realized until recent years (Steeples et al., 1990): originally the event was listed as only a Modified Mercalli Intensity IV-V (DuBois and Wilson, 1978), which is clearly too low, but the listing was based on a single felt report from Kirwin, Kansas, a location 60 km from the highest reported intensity. The detection of 311 earthquakes and location of 179 of these within 27 months by Evans and Steeples (1987) in a small area about 80 km west of the study area is surprising. Over 50 earthquakes were located by Armbruster et al. (1989) during only a few weeks of recording in August, 1989 near Palco, Kansas, about 100 km south of Harlan County Lake. Prior to these in the first half of June, 1989, three earthquakes with local magnitudes between 3.4 and 4.0 were recorded. It is possible that both of these pockets of activity were induced by secondary oil recovery, but the occurrence of the 1879 event prior to the advent of oil production indicates that tectonic activity is naturally present to some extent. Clearly, the earthquake activity near the study area is greater than current activity in the vicinity of the Meers fault in southwestern Oklahoma (Crone and Luza, 1990).

Until recently, the New Madrid fault system of Missouri, Tennessee, Arkansas, and Illinois was the only documented Quaternary fault zone with surface expression in the Midcontinent (Russ, 1979). Even though the Meers fault in southwestern Oklahoma was first mapped in the late 1930s (Harlton, 1951), its Quaternary significance was not documented until recently (Crone and Luza, 1990). Consequently, the fault exposed at Harlan County Lake needed to be investigated to prove or disprove a tectonic cause.

The present tectonic stress regime suggests east-west relative compression (Zoback and Zoback, 1980) which would suggest thrusting mechanisms on faults with north-south orientations. The faults described above are mostly high-angle normal faults that trend mostly east-west. Evans and Steeples (1987) located 176 earthquakes in the Sleepy Hollow oil field, Nebraska, about 80 km west of Harlan County Lake, in a period between April, 1982 and June, 1984. Evans (1984, p. 44) displayed a composite first-motion plot that "gives a well-constrained fault plane solution which indicates movement on a normal fault striking east-northeast." Hence, despite the east-west compressional tectonic stress regime, there is evidence that normal faulting may be occurring at the present time along faults oriented primarily east-west.

During dam construction, numerous minor faults (small displacement) and several major faults were recognized in the foundation of the spillway, cutoff trench, and right abutment. Although the faults intersect at various angles and display irregular curved traces, they generally strike northeast and southwest with dips between 30 and 72° (U.S. Army Corps of Engineers, 1977). Most of the faults are normal, and several have a dip of 9m or more. Prominent jointing is also prevalent, with a regular spacing of 1.5-7.6m and with a southwest strike. Most of the faults and joints were described as being tight, i.e., only a few were either open or contained solutional channels along the fault plane.

Given the regional tectonic situation, existence of major fault sytem in the New Madrid region of Missouri, as well as others in Colorado, Kansas, and Oklahoma (Fig. 4), and recent earthquake activity in the region, investigation of the faults exposed at Harlan County Lake was warranted. It was appropriate to determine if the fault features are due to tectonic activity or slip features associated with mass movements.

## Study Site

The research area is situated on Harlan County Lake, a Army Corps of Engineers impoundment on the Republican River in south-central Nebraska (Fig. 5). Exposure of bedrock along the lake margins by wave action reveals evidence of a valley-axis fault. The Pierre Shale occurs at mean water level on the north side, whereas the underlying Niobrara Formation is exposed on the south side. This relationship indicates the south side is upthrown. Further, the faulting was recognized previously and considered to be Quaternary in age due to truncation of the Ogallala Formation and overlying early Pleistocene formations (Zakrewska, 1963).

Northeast-southwest trending fractures were observed in North Cove, on the north side of the lake, and in Bone Cove on the south side. This study focused on the Bone Cove fracture system because of the better expression and exposure. Wave action in Bone Cove has exposed the Cretaceous and Tertiary-age bedrock, and the overlying late-Quaternary sediments. Late-Quaternary stratigraphy of the site includes the alluvial sand of the Crete Formation, Sangamon Soil developed in the Crete, Gilman Canyon Formation consisting of loess and soil overprinting, and the Peoria Loess with modern surface soil development.

The fracture system is exposed on the west side of Bone Cove, with the upthrown side to the north. The direction of movement is evidenced by displacement of the Gilman Canyon Formation soil and by presence of Ogallala Formation only on the north side, i.e., the movement has juxtaposed the Peoria Loess against the Gilman Canyon Formation with its multiple buried A horizons (Fig. 6). The total displacement visible in the wave-cut exposure is over 6m.

## Methodology

The Bone Cove fracture system was evaluated both geomorphically, through an examination of the late-Quaternary sediments, and geophysically, through shallow seismic reflection methods in the bedrock. Geomorphic methods employed are described below, and the nature of the shallow seismic reflection survey, along with results, are reported by Miller and Steeples (1996).

**Field methods.** The face of the 7 to 8m-high wave-cut exposure was cleaned and excavated as much as possible to provide a clear, uncontaminated, and unobscured view of the fracture zone. Exposure preparation was done manually due to the inaccessibility of the face by a backhoe or other equipment; an attempt to approach the face with even a "bobcat"-type machine failed. A grid was established on the face using a system of spikes and twine. The exposure was then profiled using the grid and its datum. The gridding and profiling were done by A.J. Crone, M.N. Machetté, and K.M. Haller of the U.S. Geological Survey, Denver office.

Two vertical profiles were established, one on the north side of the fracture planes and one between the two visible fracture planes. Magnetic samples were collected along these profiles and stored in sterile plastic bags. Magnetic samples were collected in 2cm$^2$ cubes (8cm$^3$) in a contiguous fashion, which resulted in about 40 cubes per meter. The cubes were numbered, hammered into the exposure face, extracted with a trowel, and stored in a nonmagnetic tray. Sediment samples were collected contiguously every 10cm, using a trowel, along Profile 1.

At selected locations on the face, samples were collected for radiocarbon dating. Material was excavated with a trowel and placed in sterile plastic bags. The sampling design was intended to date the lowermost part of the exposed north side, correlate the complex of Gilman Canyon Formation soils across the north fracture, and obtain an age on the uppermost Peoria loess in order to ascertain how much had been eroded at the site.

Since no visible scarp appears at the surface, it was necessary to look to the subsurface on the upland beyond the face. Accordingly, a complex of backhoe trenches was excavated into the Peoria loess several meters back from the exposure face (west) in order to verify the traceability of the fracture system, and, in the process, its strike and dip (Fig. 7). Samples were collected from within on of the trenches for magnetic analysis.

**Laboratory Analyses.** Physical and chemical sediment analyses were conducted on samples collected in order to characterize the stratigraphy and to provide stratigraphic control from one side of the north fracture to the other. Sediment samples collected along Profile 1 were analyzed for particle size, pH, and organic carbon content. Magnetic susceptibility was measured on all samples collected in both profiles on the exposure face and a profile collected from one of the trenches in order to produce high-resolution loess stratigraphy for purposes of correlation. This parameter is an indication of the bulk magnetism, or concentration of magnetic material within the sample. In loess deposits of the central Great Plains, susceptibility is useful for defining weathering zones and soil development, as well as former surfaces or sediments that experienced burning.

Samples collected for radiocarbon dating were prepared using the technique outlined by Johnson and Valastro (1994) for bulk carbon samples. They were then submitted to the University of Texas Radiocarbon Laboratory in Austin for analysis. One exception was a small amount of charcoal collected and submitted to Beta Analytic for accelerator dating (AMS) by A.J. Crone. All ages were corrected for the effects of isotopic fractionation.

## Results

Mapping of the exposure face documented the fracture plane positions and distribution of buried soils (Fig. 8). The north fracture plane is more distinct and better defined than the south one. The chronostratigraphy of the site was derived from radiocarbon ages distributed from below the 4Ab horizon to the uppermost Peoria Loess exposed. The two burn layers dated appear discontinuously for nearly 7km along the south shore of the lake to the west of Bone Cove.

### Age Dating

A total of 15 radiocarbon ages were obtained from the exposure face (Table 1). Age determinations were concentrated on the north side of the feature. The lowermost age of 35,580±1580 yr B.P. was the oldest and represented the basal Gilman Canyon Formation loess. Below this level was Crete Formation sand capped by the alluvial phase of the Sangamon Soil. An attempt to radiocarbon date any material below the lower Gilman Canyon Formation would likely have resulted in an infinite age, even with the AMS technique. Ages obtained from the basal Gilman Canyon Formation elsewhere in the region have yielded ages ranging from about 35 to 45ka (Johnson and May, 1996).

An attempt was made to date the various intervals of soil formation during Gilman Canyon time since this was the marker zone for gaging displacement and because the north side exhibited three discrete buried A horizons and the south side only one. Ages on the soil complex ranged from 33,490±870 yr B.P. immediately below the 4Ab horizon to 27,580±440 yr B.P. in the 2Ab. As the ages indicate, the periods of pedogenesis were relatively brief and separated by short-lived intervals of accelerated loess influx. Only one age, 27,510±490 yr B.P., is out of sequence. This inconsistency is likely due to inadvertent sampling of a krotovina, a common and often obscure feature in the Gilman Canyon Formation; the ground squirrel *Spermophilous* was a ubiquitous biotic element at the time these grassland soils were forming. The 2Ab age of 27,580±440 yr B.P. corresponds well with the age of 27,810±590 yr B.P. on the Ab horizon exposed on the downthrown side of the north fracture plane, verifying that these are the same pedostratigraphic unit.

Five ages were secured from above the soil complex in order to verify the age of the transitional loess zone between the Gilman Canyon Formation and the Peoria Loess, age of two burn layers, and the age of the uppermost Peoria Loess. The radiocarbon age of 23,460±270 yr B.P. approximates the interval of transition between relatively stable Gilman Canyon time (i.e., low rate of loess deposition) and Peoria time when high rates of loess accumulation prevailed. This transition loess of the region often appears to have been reworked or otherwise disturbed, which may be the case at this site. The two burn layers were dated to 22,450±210 and 20,090±240 yr B.P. using charcoal present. An age of 16,080±180 yr B.P., obtained on total humates from a bulk carbon sample of loess adjacent to the upper charcoal layer, is about 4,000 radiocarbon years younger, indicating that contamination had occurred (e.g., rootlets, krotovinas). Better results may have been obtained if the humin, or residue, fraction had been dated rather than total humates (Martin and Johnson, 1994). An attempt was made to date the upper part of the Peoria loess in order to ascertain about how much of the overlying Peoria loess had been eroded. The age of 7,310±70 yr B.P. is clearly contaminated, likely by modern carbon from the surface soil and/or an associated krotovina. Given the rate of loess deposition and the thicknesses elsewhere along the valley wall, the Peoria Loess at this site had likely been eroded from its 10.5ka upper limit to about the 17ka level, or a loss of about 6,500-7,000 years of deposition. Given this same mode of estimation, the downward-displaced side should have only about 3,000-4,000 years of deposition missing.

Prior to this investigation, radiocarbon ages were obtained from Bone Cove and adjacent areas along the Lake by C.W. Martin and myself. Two ages of 25,555±500 (PITT-0826A) and 26,260±680 yr B.P. (Tx-5910) were obtained on the uppermost part of the 2Ab horizon several meters north of the fractures (Martin, 1993; Martin and Johnson, 1995). These ages are in general agreement with the 2Ab-derived age of 27,580±440 yr B.P. resulting from this study. Approximately 6.5km to the west along the south lake shore near Coyote Canyon, the upper burn layer yielded an age of 21,550±500 yr B.P. (Martin, 1993). To the north across the lake in North Cove, three ages were determined from a vertical profile of the Gilman Canyon Formation: 27,850±830 (Tx-7073), 29,950±900 (Tx-7074) and 30,700±990 yr B.P. (Tx-7072) (Martin, 1993). At North Cove the Gilman Canyon Formation exhibits on one thick Ab horizon rather than three thin ones, but the radiocarbon ages correspond well to those from Bone Cove. Additionally, an age of 21,440±200 yr B.P. (Tx-7711) was obtained from the remains of a burnt *Picea* stump within the upper burn layer exposed at Sindt Point, located about 4.5km west of Bone Cove (Johnson, 1996).

## Sediment Data

Particle-size data indicates appreciable fine to very fine sand throughout Profile 1, with an overall decrease upward from the sand of the Crete Formation (Fig. 9). Accordingly, silt increases upward, particularly above the 2Ab horizon of the Gilman Canyon Formation, i.e., into the Peoria Loess. Also, the two burn zones occur within a zone of relatively high silt content. Clay content is conservative and exhibits a small increase upward, with a few peaks such as in the B horizon of the 2Ab horizon. Statistical parameters of grain size calculated included median, mean, and sorting (Fig. 10). At the base of the profile, the median is about 3.5$\phi$, or very fine sand size, and increases upward to nearly 5$\phi$, or coarse to medium silt. Mean size values exhibit a similar range and vertical distribution. The most notable feature of the two curves is a discontinuity appearing at the 2Ab horizon within the Gilman Canyon Formation, indicating the abrupt upward coarsening visible in the particle-size distribution. Sorting ranges from very poorly sorted to poorly sorted ($\geq 2\phi$) below about 3m (Gilman Canyon Formation) to poorly sorted in the upper 3m (Peoria Loess).

Organic carbon determinations were made on only a selected number of samples (8) from the Ab horizons on the north side of the feature; three samples were also analyzed from the Ab exposed between the two fracture planes. Organic carbon content ranged from 1.7% to 2.4% among the samples; the 3Ab and 4Ab were less than 2%, whereas with the highest values came from the 2Ab on both sides of the north fracture plane.

## Magnetic Data

Magnetic susceptibility provides a indication of the degree of weathering/soil formation and an additional means of relatively precise stratigraphic correlation from one side of the feature to the other. The susceptibility curve for Profile 1 exhibits a number of peaks relating to major stratigraphic elements (Fig. 11). At about 1.5 to 2.0m above datum, the uppermost Gilman Canyon Formation soil, 2Ab, is well expressed; horizons 3Ab and 4Ab are weakly indicated by the two small bumps between 0 and 1m and are therefore not as well developed. The transitional or reworked loess zone in the upper Gilman Canyon Formation/lower Peoria occurs between 2 and 3m above datum. The narrow peak at about 4m represents the upper burn layer. A large peak occurs just below 5m, but the origin is uncertain; it may be a weathering zone not readily visible or a reflection of a change in loess source region. The surface soil is readily apparent, producing the highest susceptibility values of the profile. Data collected from Profiles 1 and 2 exhibit several common features that afford detailed correlation. On the basis of these correlations, the displacement between the two fractures is 2m.

Magnetic susceptibility data were collected from a single profile on the north side of the fractures in one of the trenches excavated on the upland above the exposure face. Although a short profile, the magnetic curve from the trench displays features that permit correlation with Profile 1 in the face (Fig. 12).

## Nature of the Fracture System

Most time and effort was spent sampling and documenting fracture geometry as portrayed in the freshened wave-cut exposure. This face exhibits two fracture planes about 3.5m apart, both of which dip 65° to 72°. The better-defined plane of the north fracture can be followed into the modern surface soil and is tracable to within 15cm of the modern surface, indicating that only the uppermost part of the trace has been obliterated by pedogenic processes; no evidence exists for pre-reservoir cultivation at the site, which would have disrupted expression of the trace in the surface A horizon.

Displacement along the primary feature is 2m based on correlation of the magnetic data and the 2Ab horizon of the Gilman Canyon Formation soils.

Strike of the north fracture was measured both on the plane of movement in the exposure face and from the bluff edge to the backhoe trenches, producing an average strike of N31E, or northeast-southwest. The trace of the fracture was followed through backhoe trenches and hand-dug pits for about 30m southwest from the bluff edge; it is unknown how far beyond that it extends.

A slight decrease in dip from the top to the bottom of the fracture planes, particularly the south one, suggests a change in geometry not evident in the wave-cut face. Three unsuccessful attempts were made with a backhoe and bobcat to excavate the covered interval during low-water stages. A.J. Crone and colleagues from the U.S. Geological Survey (Denver) were on site as recently as April, 1996, when low-water made the bluff face accessible for hand excavation. A 7-m-long, 1.5-m-deep trench was hand excavated at the base of the bluff below the south fracture. The excavation revealed dramatic decreases in fracture plane dip within the shallow subsurface at about 8m depth, from 65-72° to about 35° (Fig. 13). Further, an intricate pattern of thrusts and cross-cutting relationships of the planes reveal a sequential movement on the south-dipping master planes and the north-dipping antithetic planes (Crone et al., 1996). Both the decrease in dip and pattern of planes documented at the base of the south plane of movement indicate the event was a mass movement of the loess. It therefore appears that the features are slip planes, rather than fault planes. This landslide likely represents failure of the loess along the north side of a pre-existing tributary gully to Bone Cove.

## Shallow Seismic Reflection

Miller and Steeples (1996) used high-resolution seismic surveying techniques in an attempt to delineate the subsurface expression of the fault-like displacement exposed in the loess exposure. The seismic line was run along the water's edge. Preliminary walkaway tests at the site included the use of several different types of sources and source configurations due to the limited access problems and extremely wet near-surface conditions. Results indicate one or more faults may have offset consolidated rocks between 70 and 500m depth immediately north of the fracture in the wave-cut face. The fracture system observed at the surface does not, however, appear to connect in an obvious way to the faults in the subsurface.

## Age of the Event

Radiocarbon ages from the face are useful in stratigraphic correlation across the feature, but do not provide definitive absolute age information on the age of the event. The age of the Peoria Loess, as documented regionally (Johnson, 1993) and at this site, is a minimum age for the event, i.e., 20-10ka. It is, however, likely that deposition of the Peoria Loess had terminated, and early Holocene entrenchment had begun. The entrenchment would have created oversteepening in these small tributary valleys, a condition that would create a geomorphic environment for such failures. Given the chronology of Holocene stream entrenchment for the region (Johnson and Martin, 1987; Johnson and Logan, 1990; Mandel, 1995), conditions for a failure such as this could have been present periodically until about 5,000 to 4,000 years ago, perhaps even 2,000 years ago.

The lack of a surface scarp indicates that the event occurred long enough ago to provide time for the erosion of the 2-6m-high scarp and formation of a modern surface soil. The slope down to the site is, however, sufficiently steep that several meters of loess, including the scarp, could have been eroded within the last 2,000 years and still leave time for the modern surface soil to develop.

## Conclusions

The slip-plane complex, revealed in the wave-cut exposure on the west side of Bone Cove, consists of a south-dipping set of fractures in unconsolidated sediments, with over 6m of offset. The Quaternary-age stratigraphy exposed consists of Illinoian-age alluvium and Sangamon Soil, loess and soils of the Gilman Canyon Formation, and Peoria Loess capped by the modern surface soil. Movement along the south-dipping planes have displaced the Gilman Canyon Formation against the Peoria Loess.

The rapid decrease in angle of plane orientation from 65-72° in the upper few meters to about 35° at the base of the south fracture strongly suggests that the offset in the feature at this locality is not a product of deep-seated tectonic activity, but rather one of mass movement manifest as a landslide into an ancient tributary valley or gully of Bone Cove. Regionally-expressed stream entrenchment during the Holocene may have been responsible for the oversteepening often related to such failures. Due to the relatively high number of historical felt and microearthquakes recorded in the region, failures such as this may have had a tectonic trigger.

Given the findings of this study, a Holocene-age fault system has yet to be recognized in Nebraska and Kansas. A.J. Crone and colleagues from the U.S. Geological Survey are examining features in Colorado, Kansas, Nebraska, and Oklahoma in order to assess regional neotectonic activity. Features such as the Ord Escarpment and Fowler Scarp appeared to lack a neotectonic association (Fig. 14).

Bone Cove is the first reported late-Quaternary mass movement that I am aware of in Nebraska and Kansas. Documentation of this feature provides us with greater insight into the evolution of the loess-mantled landscape of the central Great Plains. Behavior of late-Pleistocene and Holocene fluvial systems is relatively well understood, but very little in the way of slope process has been documented.

## Acknowledgments

The fault complex exposed in Bone Cove was brought to the attention of this investigator by C. W. Martin, Kansas State University, who discovered it while conducting dissertation field research. A.J. Crone, M.N. Machetté, and K.M. Haller of the U.S. Geological Survey office in Denver provided invaluable assistance in mapping of the profile and were instrumental in the evaluation of the site. K. Park assisted with field work and laboratory analyses. This research project was funded by a grant from the U.S. Geological National Earthquake Hazards Reduction Program.

**Table 1. Radiocarbon Ages**

| Lab no. (Tx-) | Depth (cm wrt datum) | Stratigraphic unit | Source of assay | Age (uncorr.) | δ13C (‰) | Age (corr.) |
|---|---|---|---|---|---|---|
| 8353 | +290 to +295 | Peoria loess | charcoal | 20,850±270 | -23.2 | 20,890±270 |
| 8354 | +400 | Peoria loess | ash and charcoal | 20,070±240 | -23.5 | 20,090±240 |
| 8355 | +395 to +405 | Peoria loess | humates | 16,050±180 | -22.8 | 16,080±180 |
| 8356 | +285 to +295 | Peoria loess | humates | 23,390±270 | -20.8 | 23,460±270 |
| 8357 | +501 to +511 | Peoria loess | humates | 7,220±70 | -19.3 | 7,310±70 |
| 8358 | +185 to +195 | upper soil in Gilman Canyon Fm. | humates | 27,460±430 | -17.5 | 27,580±440 |
| 8359 | +158 to +148 | Gilman Canyon loess | humates | 29,100±530 | -15.9 | 29,260±540 |
| 8360 | +130 to +116 | middle soil in Gilman Canyon Fm. | humates | 30,440±630 | -15.2 | 30,590±640 |
| 8361 | +78 to +88 | Gilman Canyon loess | humates | 30,610±640 | -17.1 | 30,720±650 |
| 8362 | +46 to +56 | upper part of lower soil in Gilman Canyon Fm. | humates | 27,350±480 | -16.2 | 27,510±490 |

| **Lab no. (Tx-)** | **Depth (cm wrt datum)** | **Stratigraphic unit** | **Source of assay** | **Age (uncorr.)** | **δ13C (‰)** | **Age (corr.)** |
|---|---|---|---|---|---|---|
| 8363 | +20 to +30 | lower part of lower soil in Gilman Canyon Fm. | humates | 33,340±690 | -17.2 | 33,450±700 |
| 8364 | -5 to -15 | lower Gilman Canyon loess | humates | 33,380±860 | -19.5 | 33,490±870 |
| 8365 | -55 to -65 | lower Gilman Canyon loess | humates | 35,500±1580 | -19.4 | 35,580±1590 |
| 8366 | -44 to -53 | upper soil in Gilman Canyon Fm. | humates | 27,630±580 | -14.2 | 27,810±590 |
| Beta-81214<br>ETH-14126 | +310 | Peoria loess | charcoal | 22,390±210 | -21.1 | 22,450±210 |

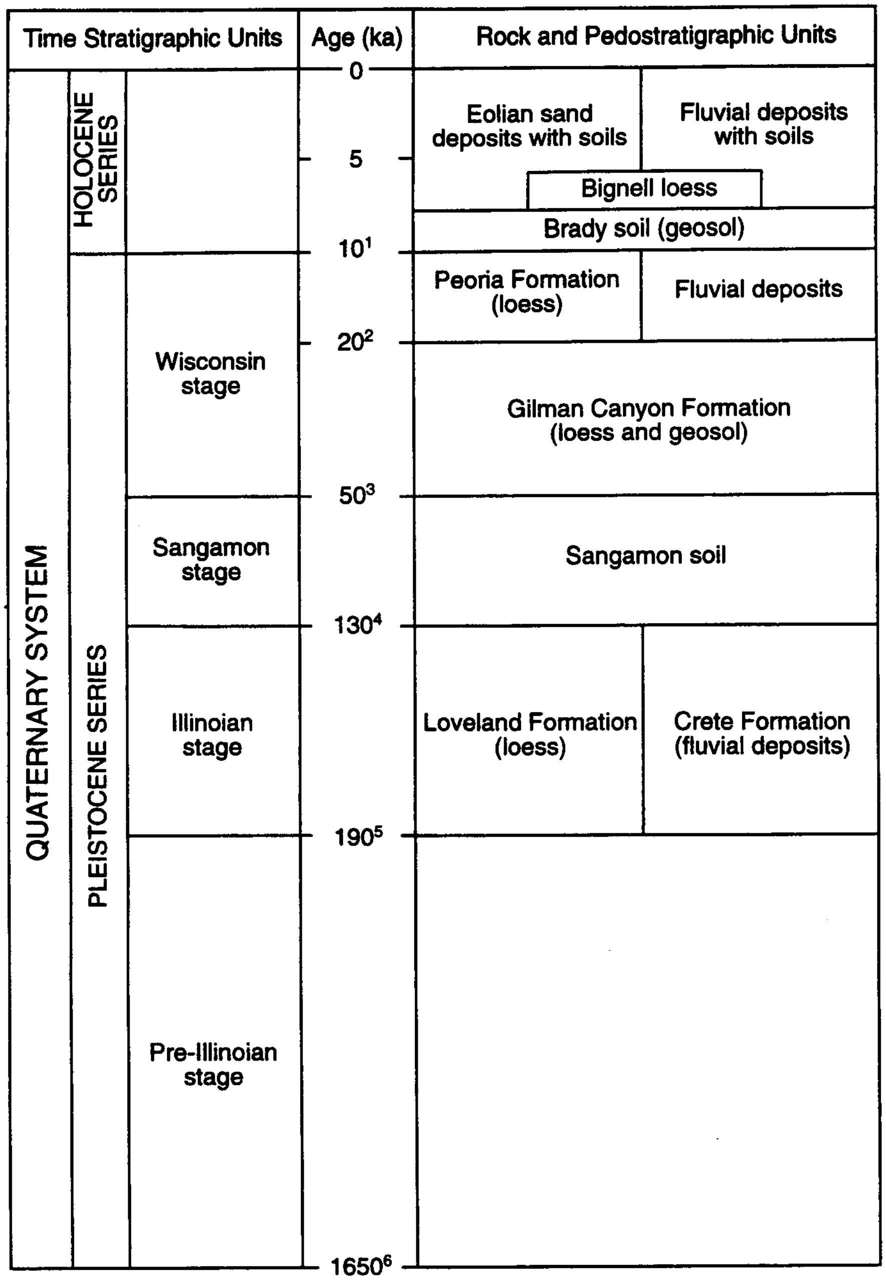

Figure 1. Quaternary stratigraphy of the central Great Plains. Notes: (1) Pleistocene-Holocene boundary after Hopkins (1975). (b) The upper Gilman Canyon Formation dates to about 20ka (Johnson, 1993). (3) The age of 50ka is only a minimum age for the Sangamon, i.e., it is the apparent maximum age on the Gilman Canyon Formation. This age also reflects the little temporal data available for the Sangamon Soil and its apparent time-transgressive nature of the Sangamon Soil (Folmer, 1983; Bowen et al., 1986, chart 1). (4)The date of 130ka (isotope stage boundary 5e-6), taken from Martinson et al. (1987), represents the isotopically-defined end of Illinoian glaciation. (5) Age of marine isotope boundary 6-7 as determined by Martinson et al. (1987). An alternative age of 302ka has been proposed for the lower Illinoian (Richmond and Fullerton, 1986). (6) Age of the Pliocene-Pleistocene boundary at the Virca, Italy, section (Aguirre and Pasini, 1985).

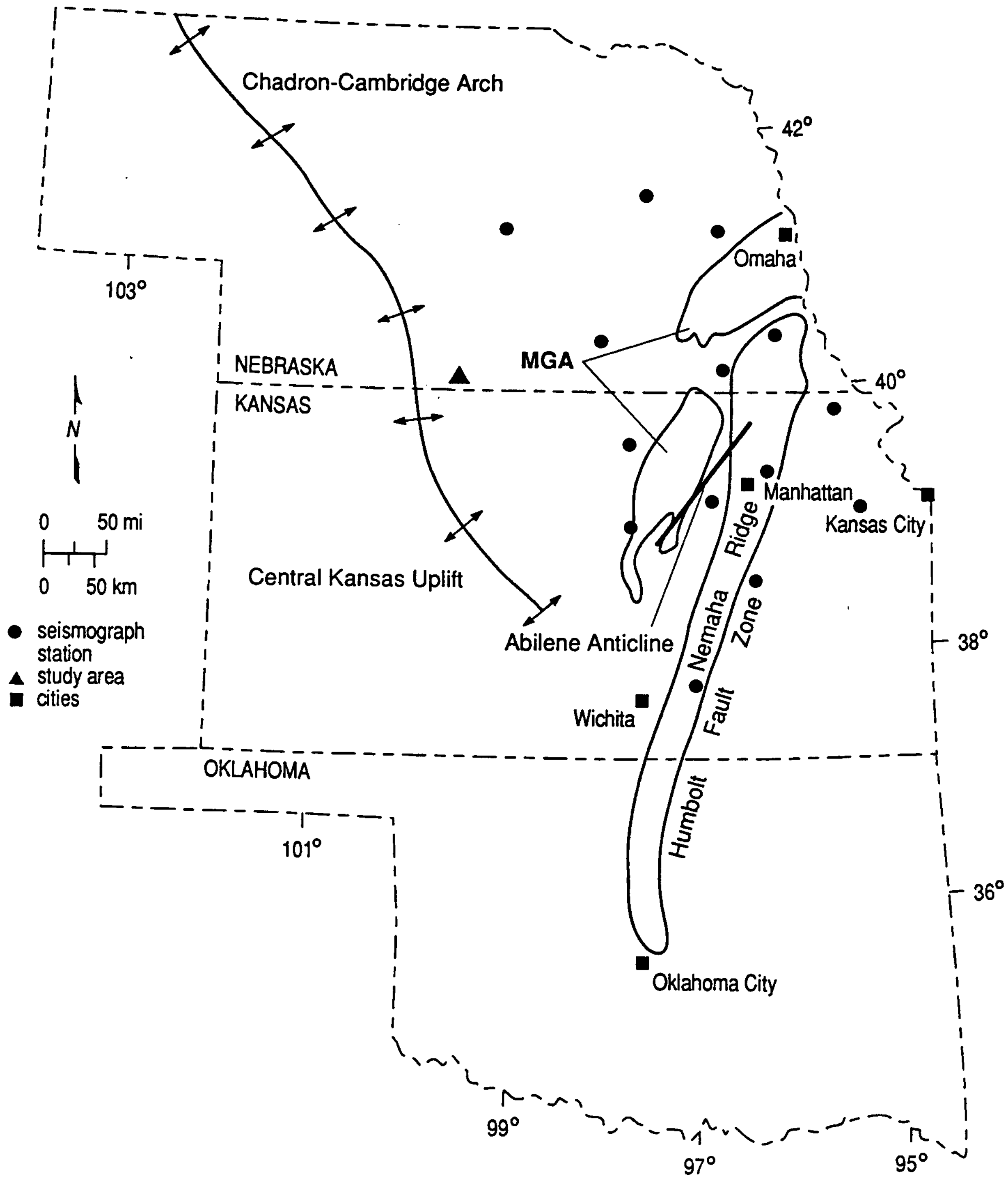

Figure 2. Major regional tectonic features that are apparently related to earthquake activity. Note the location of the Chadron-Cambridge Arch and the research site in southern Nebraska (triangle). MGA refers to structures of the Midcontinent Geophysical Anomaly. (modified from Steeples et al., 1990)

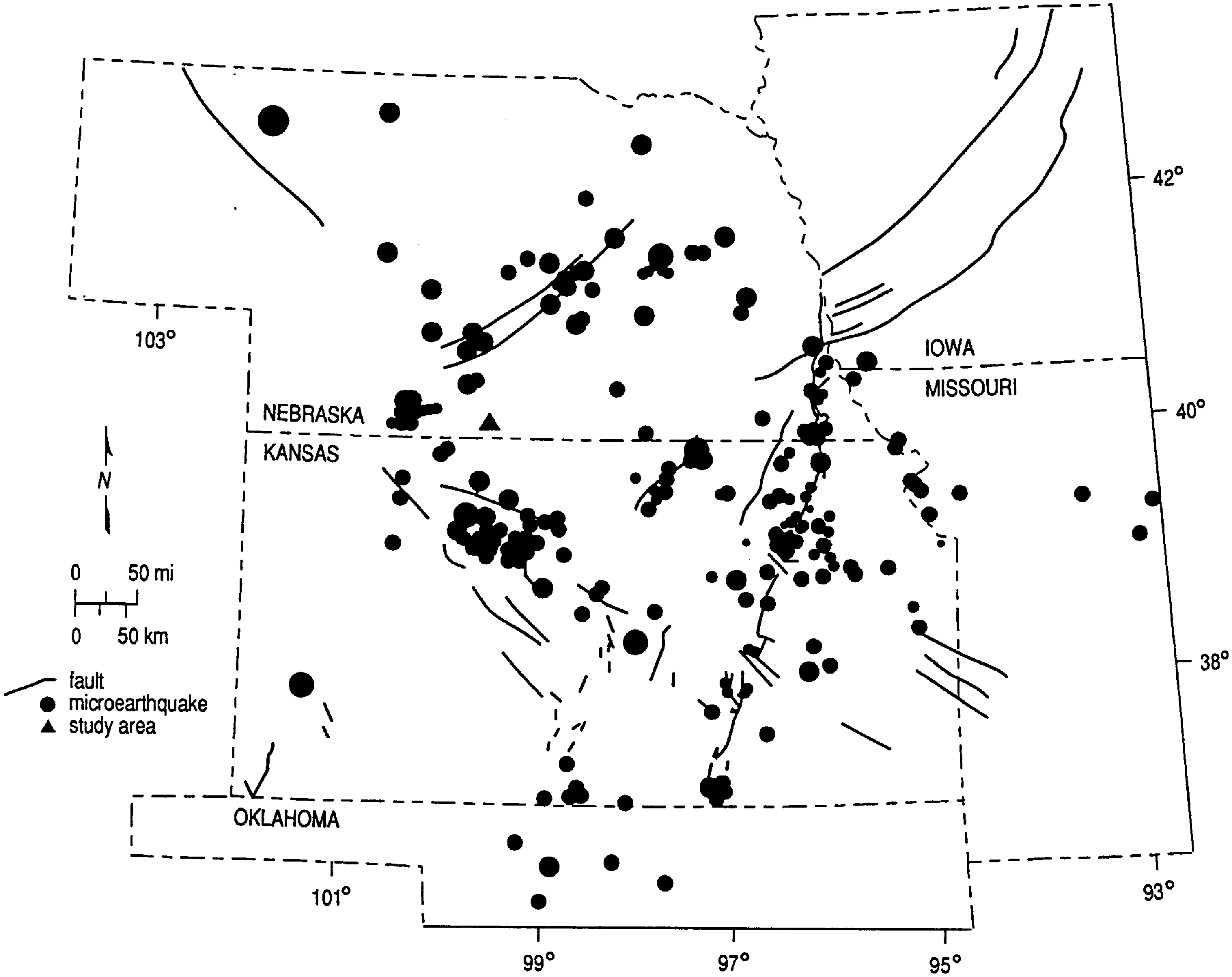

Figure 3. Microearthquakes recorded by the Kansas Geological Survey between August 1977 and August 1989 are size-coded by local magnitude. The largest event has magnitude 4.0 and the smallest is local magnitude 0.8.

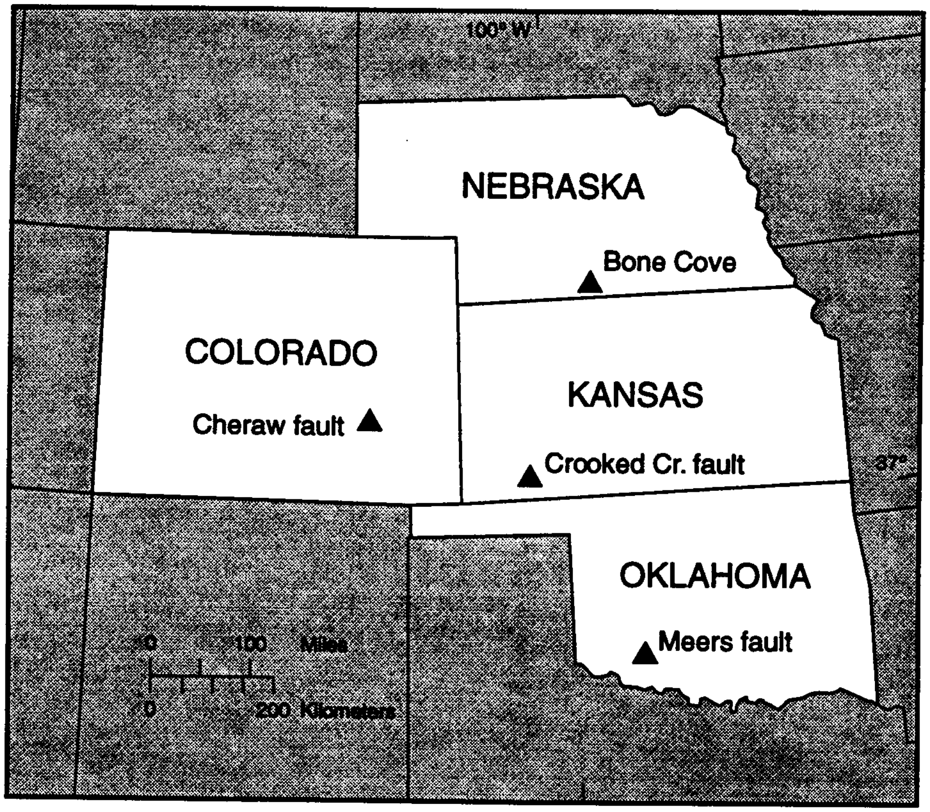

Figure 4. Four-state area of the central Great Plains with the study area and two well-documented fault sites indicated. Over the past few years A.J. Crone and colleagues have documented the paleoseismic history of the Meers and Cheraw faults of Oklahoma and Colorado, respectively. Their future studies will examine the Crooked Creek fault of southwestern Kansas.

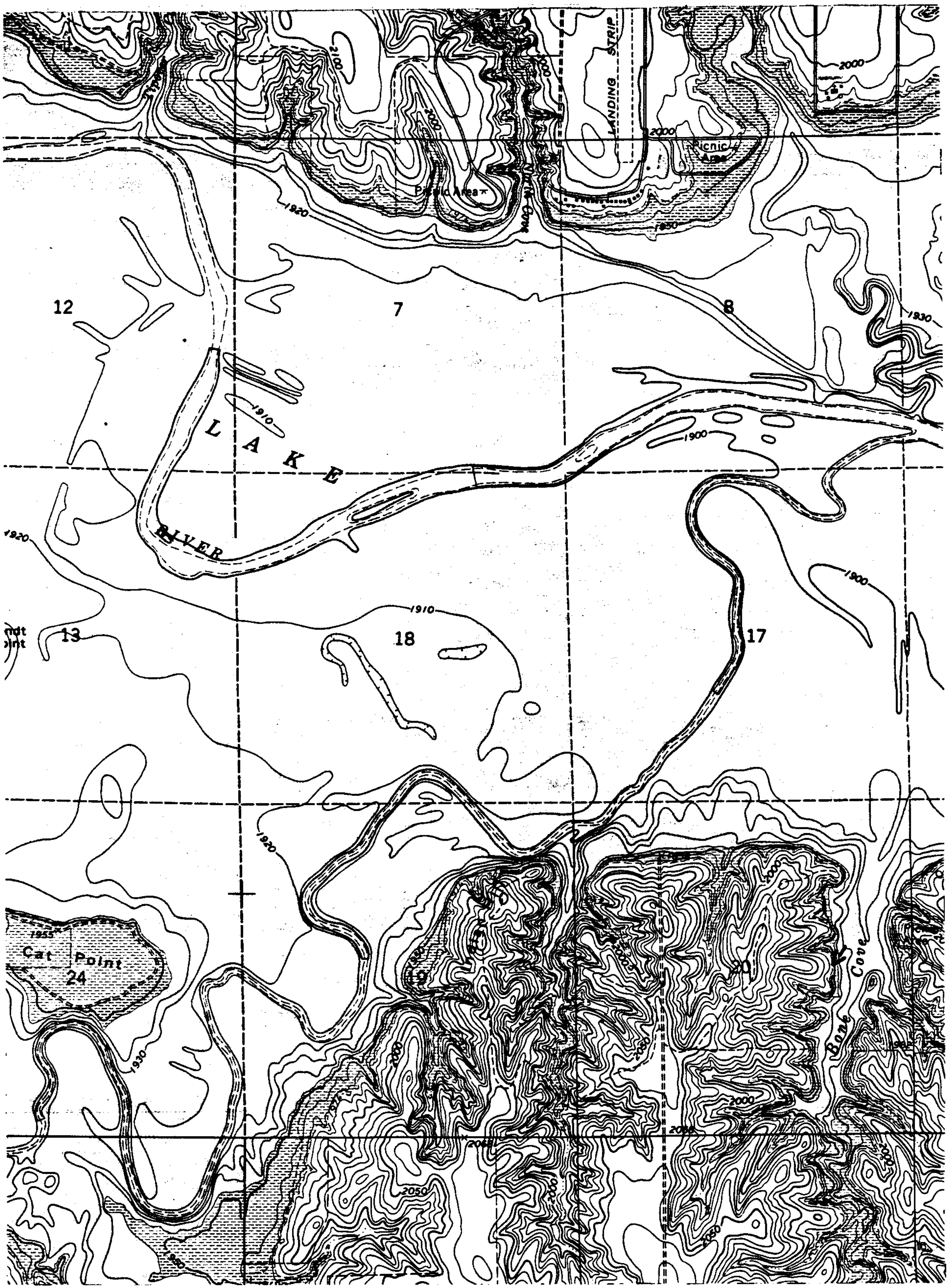

Figure 5. Topographic map of the Bone Cove area and the fracture location (arrow).

Figure 6. Wave-cut exposure and the fractures (arrows). North is to the right.

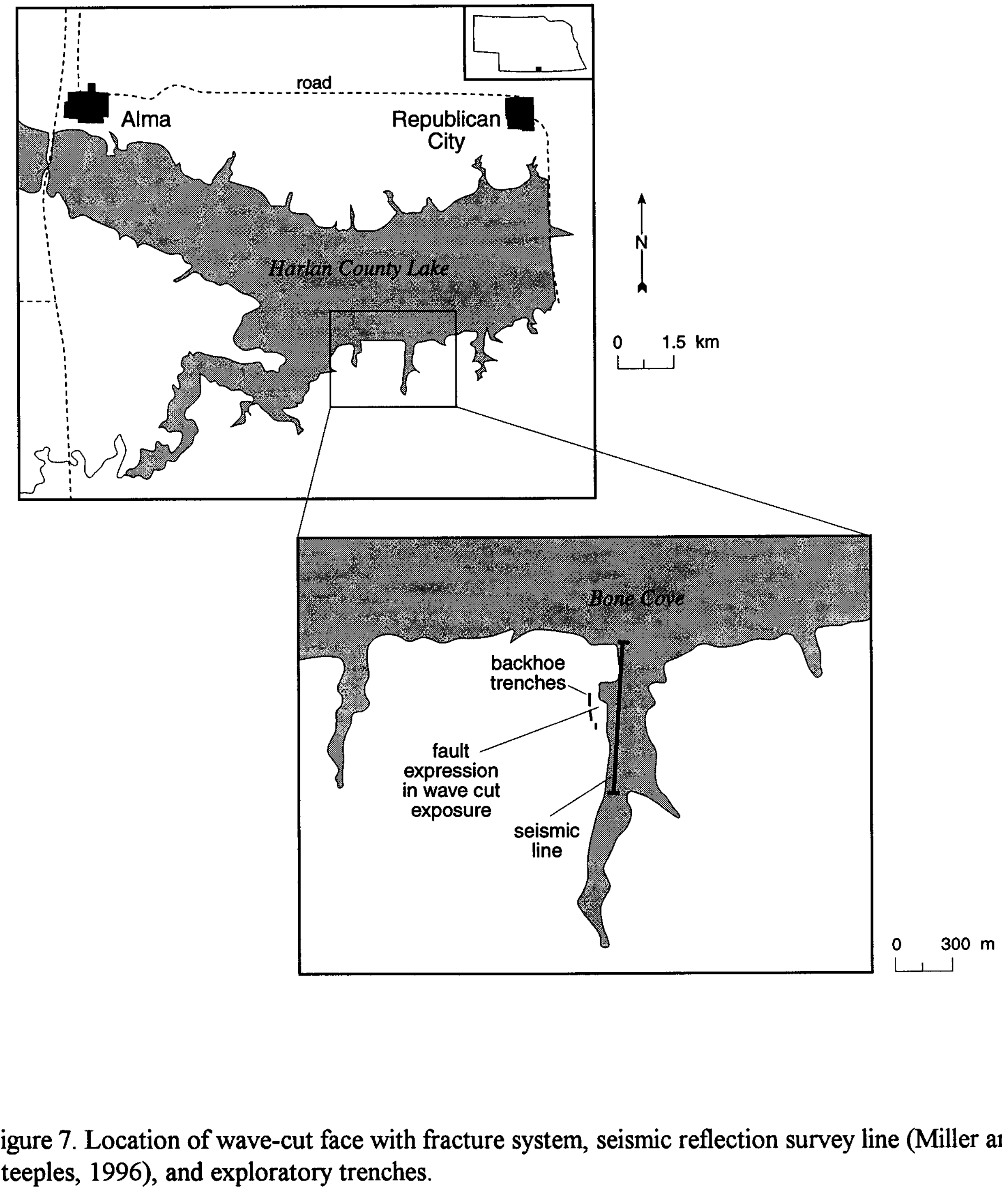

Figure 7. Location of wave-cut face with fracture system, seismic reflection survey line (Miller and Steeples, 1996), and exploratory trenches.

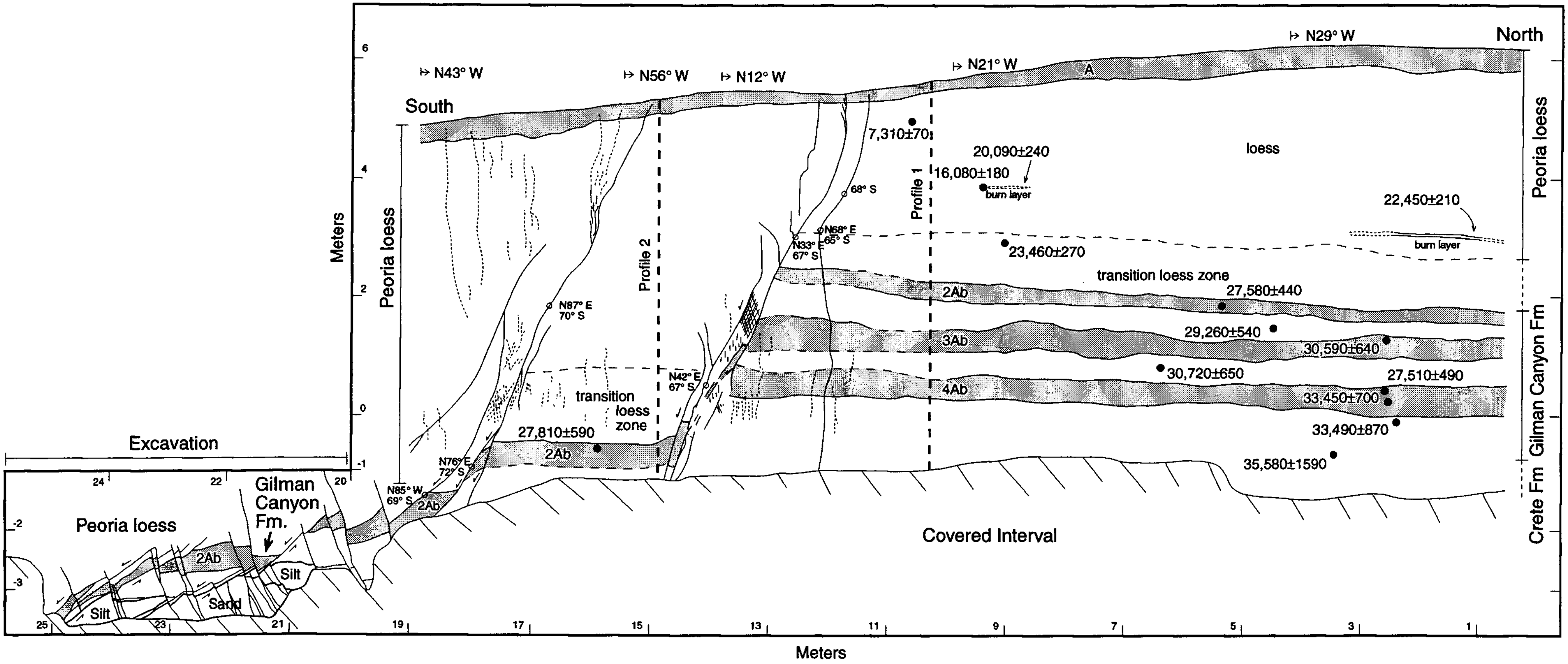

Figure 8. Site profile with stratigraphy, radiocarbon ages and location of magnetic sampling profiles.

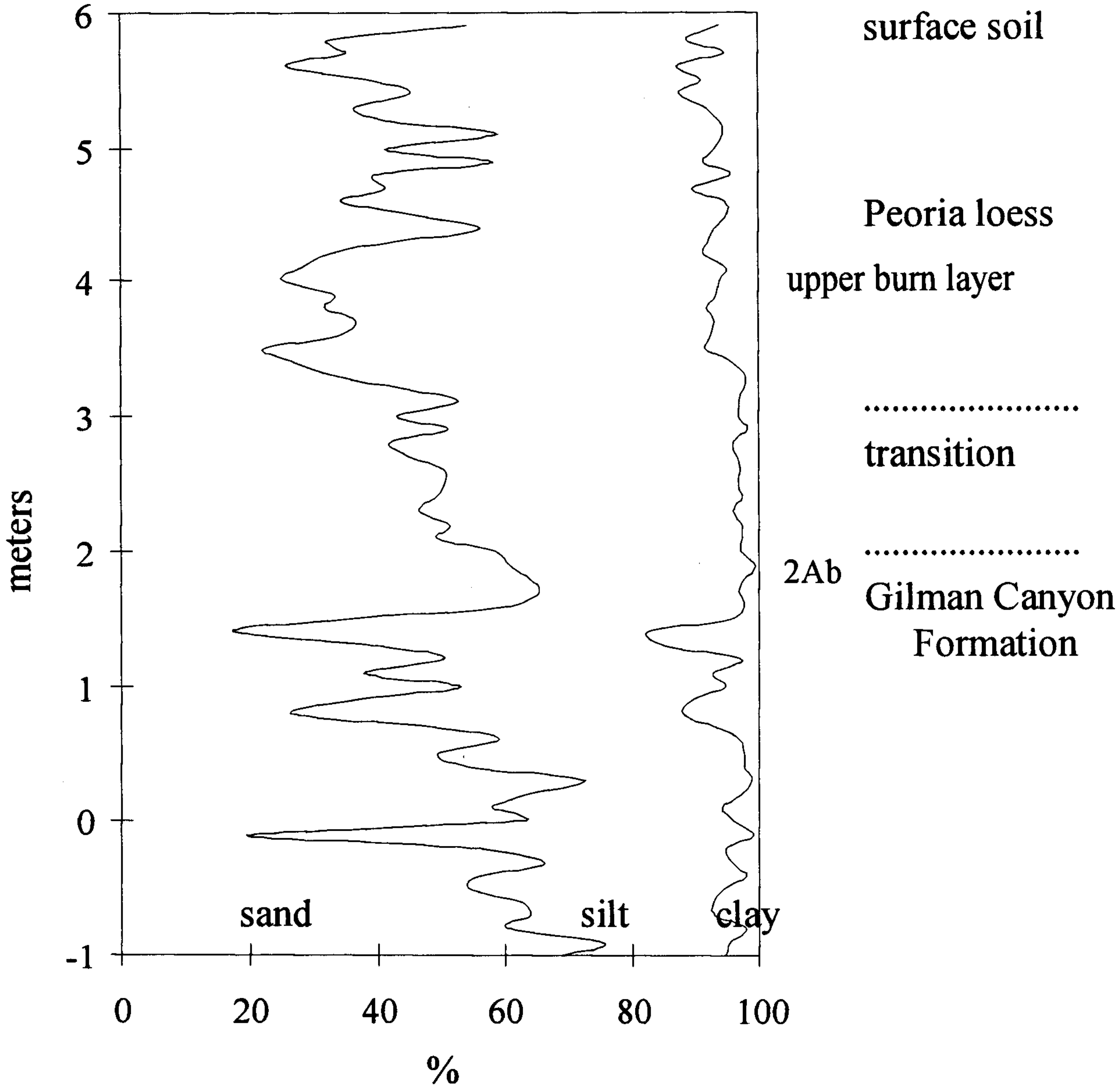

Figure 9. Particle-size distribution for Profile 1.

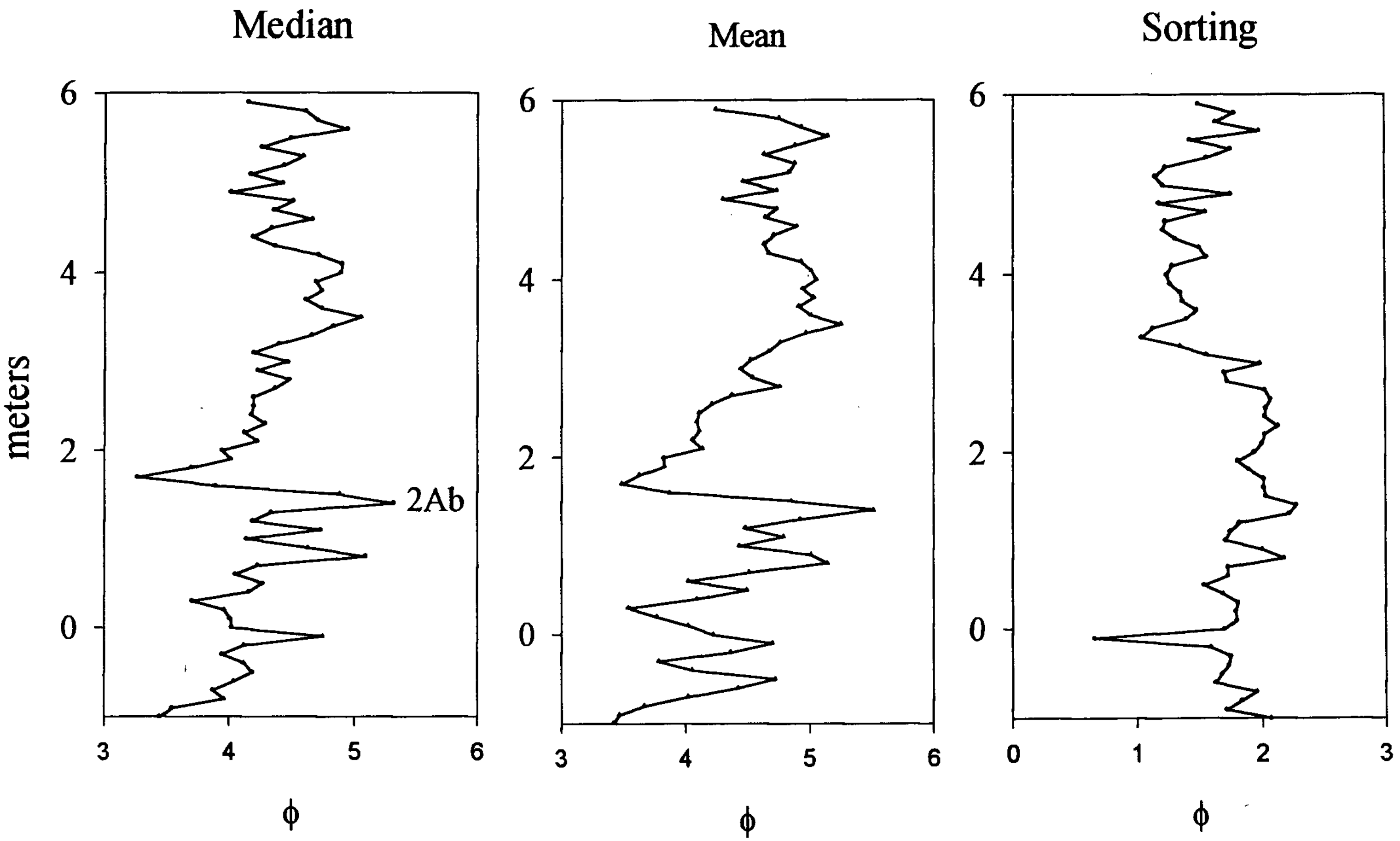

Figure 10. Statistical parameters of particle size for Profile 1.

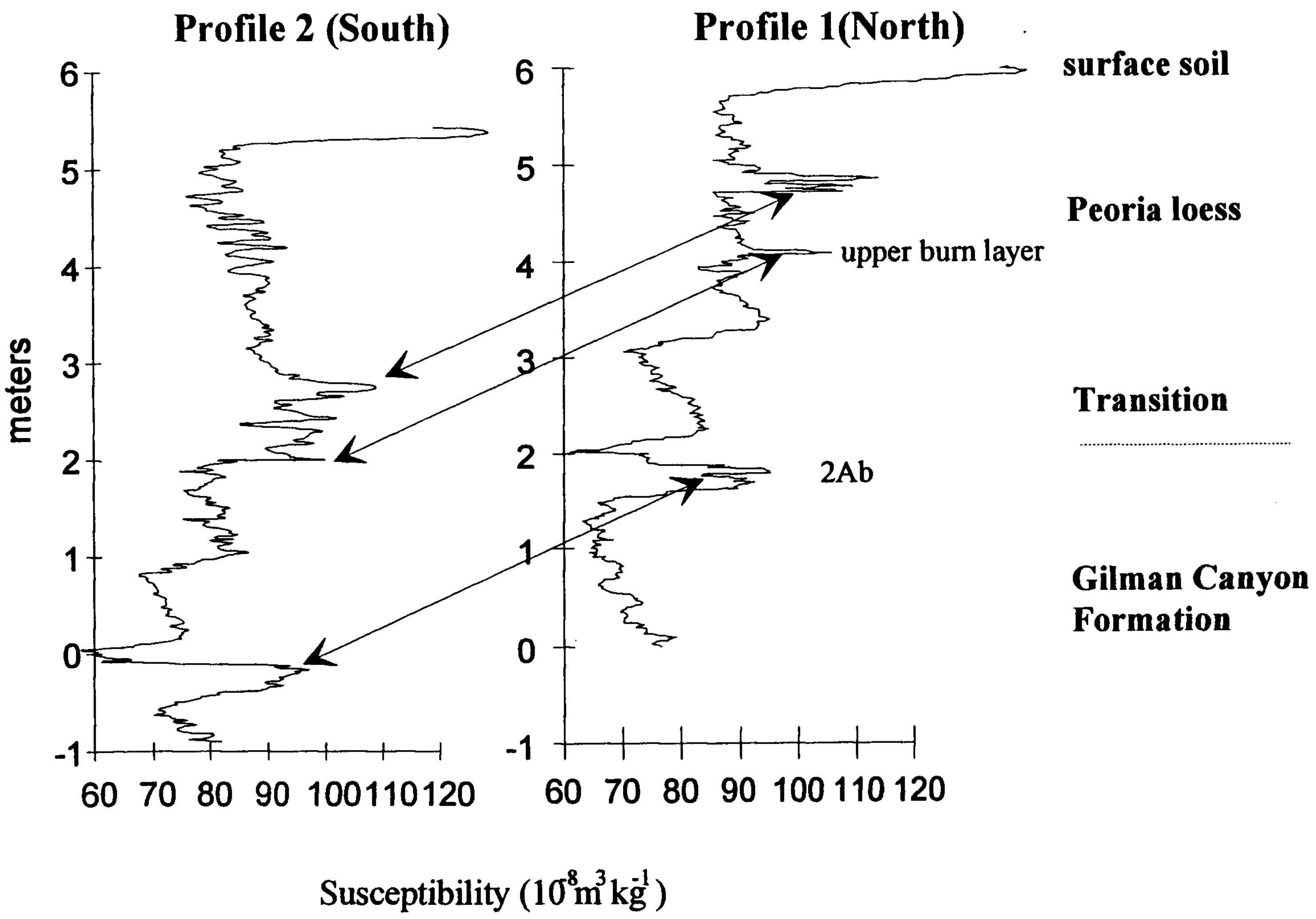

Figure 11. Magnetostratigraphy of Profiles 1 and 2.

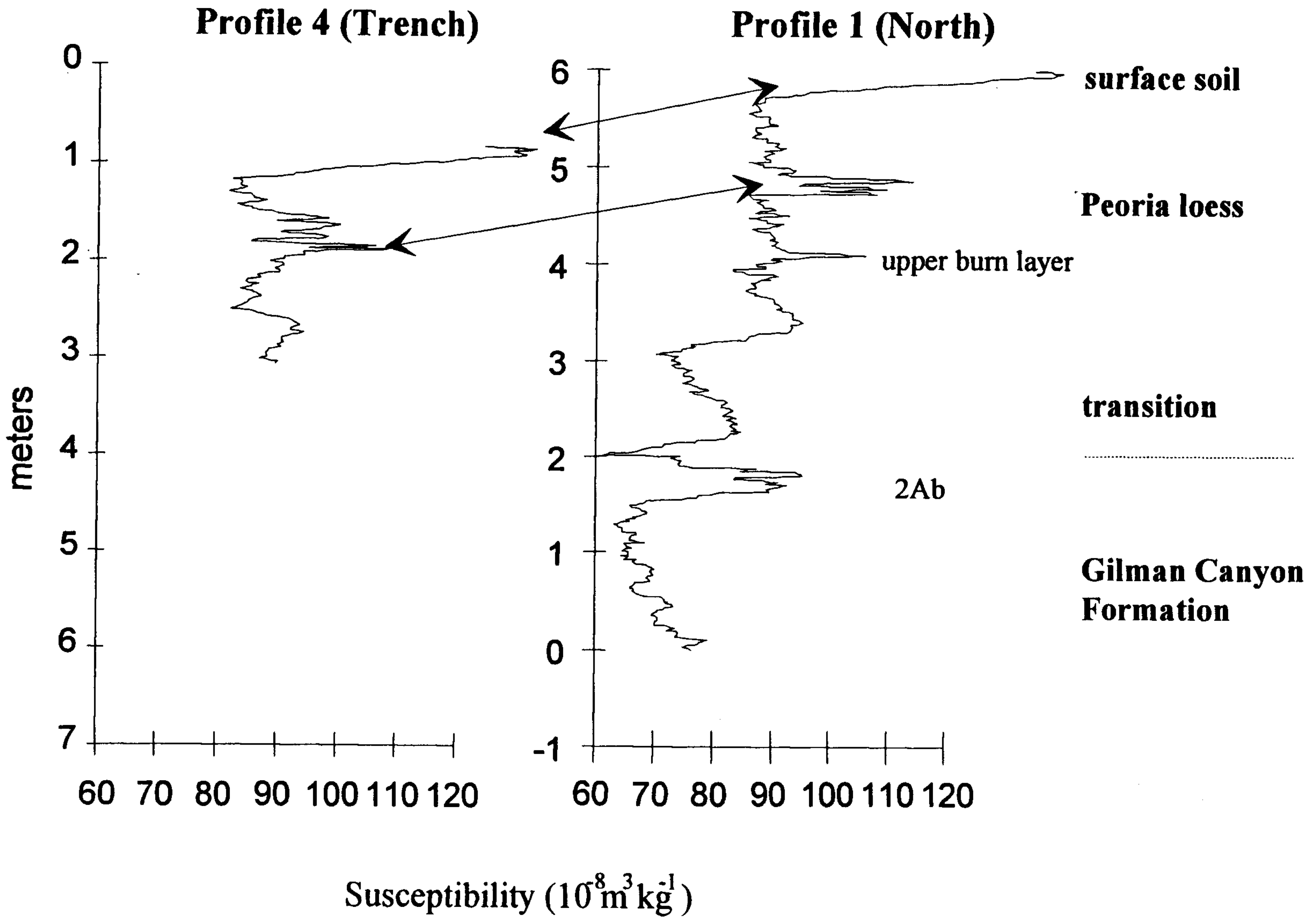

Figure 12. Magnetostratigraphy of the upthrown side from the exposure face (profile 1) and from west of the face (profile 4-backhoe trench).

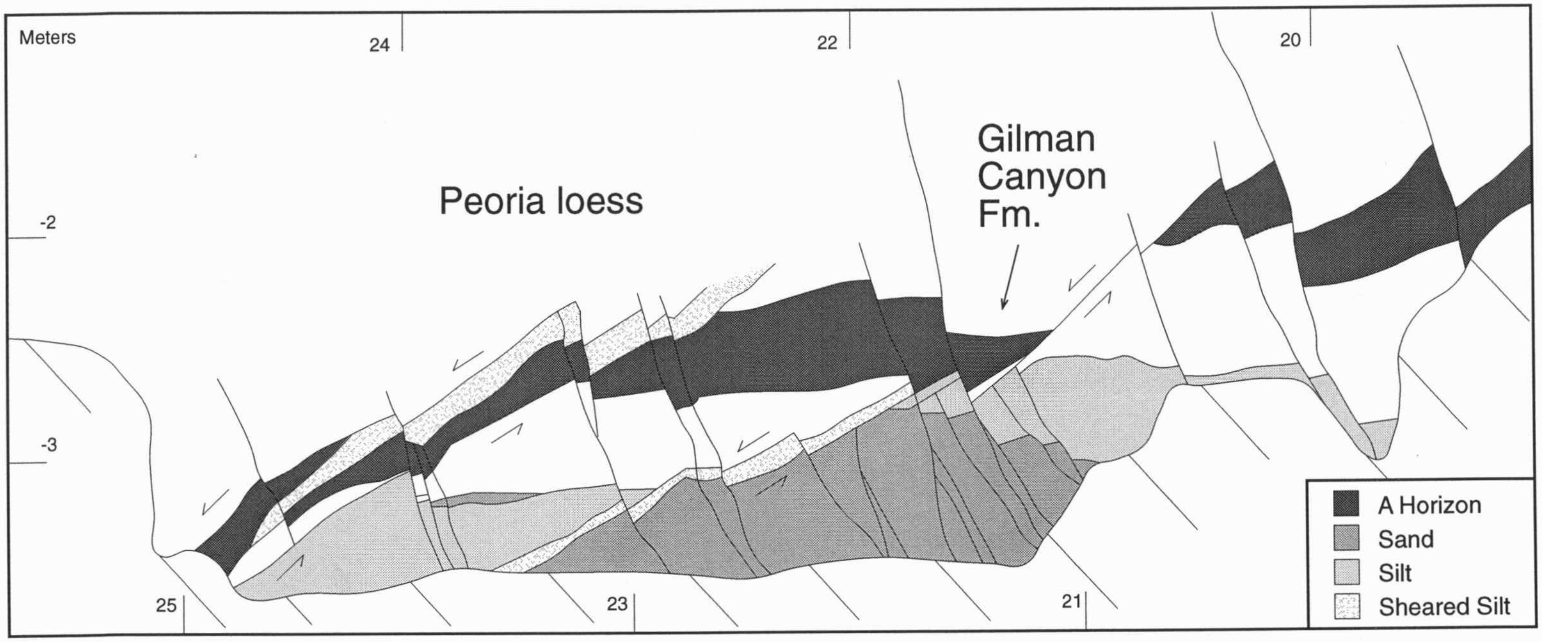

Figure 13. Profile of hand-dug excavation at base of south fault plane.

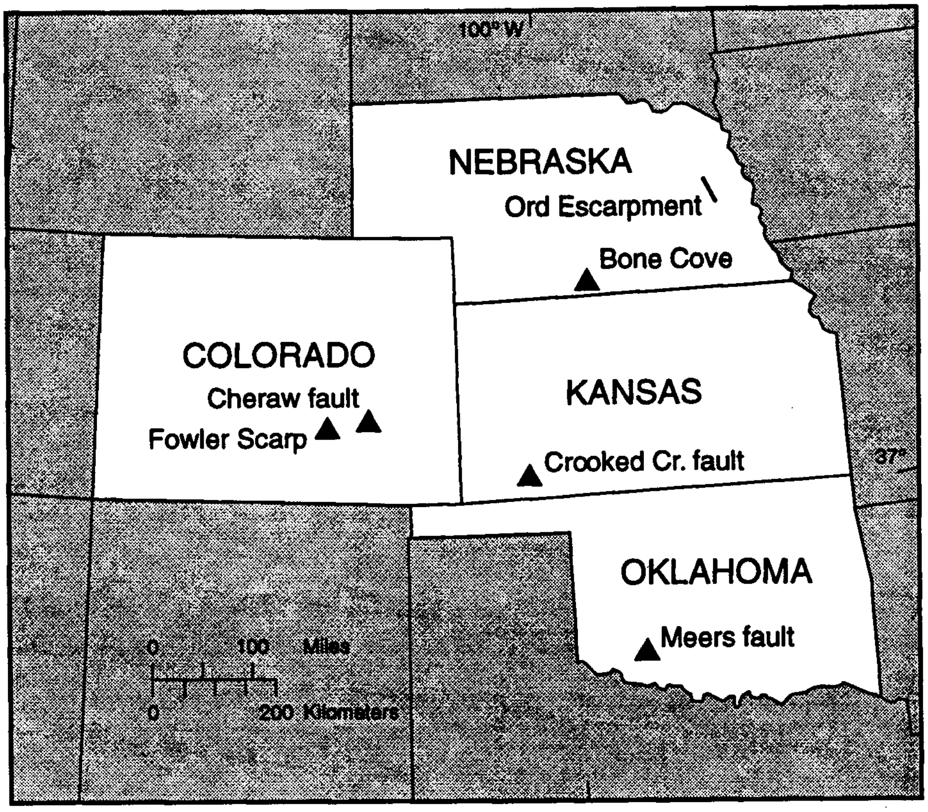

Figure 14. Known and suspected Quaternary age faults in the central Great Plains (Crone et al., 1996).

# References

Aguirre, E. and Pasini, G., 1985, The Pliocene-Pleistocene boundary: Episodes, v. 8, p. 116-120.

Algermissin, S.T., Perkins, D.M., Thenhaus, P.C., Hanson, S.L., and Bender, B.L., 1982, Probabilistic estimates of maximum acceleration and velocity in rock in the contiguous United States: U.S. Geological Survey Open-file Report 82-1033, 99 p.

Alden, W.C., and Leighton, M.M., 1917, The Iowan drift, a review of the evidence of the Iowan stage of glaciation: Iowa Geological Survey, v. 26, p. 49-212.

Armbruster, J.G., Steeples, D.W., and Seeber, L., 1989, The 1989 earthquake sequence near Palco, Kansas: a possible example of induced seismicity (abs.): Seismological Research Letters, v. 60, p. 141.

Bayne, C.K., and O'Connor, H.G., 1968, Quaternary System, *in* The Stratigraphic Succession in Kansas, Zeller, D.E., ed.: Kansas Geological Survey Bulletin 189, p. 59-67.

Bettis, E.A., III (ed.), 1990, Holocene Alluvial Stratigraphy and Selected Aspects of the Quaternary History of Western Iowa, Midwestern Friends of the Pleistocene: Iowa City, University of Iowa Quaternary Studies Group Contribution No. 36, 197 p.

Bowen, D.Q., Richmond, G.M., Fullerton, D.S., Sibrava, V., Fulton, R.J., and Velichko, A.A., 1986, Correlation of Quaternary glaciations in the Northern Hemisphere, *in* Sibrava, V., Bowen, D.Q., and Richmond, G.M., eds., Quaternary Glaciations in the Northern Hemisphere: Quaternary Science Reviews, v. 5, p. 509-510.

Burchett, R., Personal communication: Conservation and Survey Division, University of Nebraska, Lincoln.

Bushue, L.J., Fehrenbacher, J.B., and Ray, B.W., 1974, Exhumed paleosols and associated modern till soils in western Illinois: Soil Science Society of America Proceedings, v. 34, p. 665-669.

Caspall, F.C., 1970, The spatial and temporal variations in loess deposition in northeastern Kansas: Ph.D. dissertation, University of Kansas, Lawrence, 294 p.

Clark, P.U., Clague, J.J., Curry, B.B., Dreimanis, A., Hicock, S.R., Miller, G.H., Berger, G.W., Eyles, N., Lamothe, M., Miller, B.B., Mott, R.J., Oldale, R.N., Stea, R.R., Szabo, J.P., Thorleifson, L.H., and J.-S., 1993, Initiation and development of the Laurentide and Cordilleran ice sheets following the last interglaciation: Quaternary Science Reviews, v. 12, p. 79-114

COHMAP members, 1988, Climatic changes of the last 18,000 years: observations and model simulations: Science, v. 241, p. 1043-1052.

Condra, G.E., Reed, E.C., and Gordon, E.D., 1947, Correlation of the Pleistocene deposits of Nebraska: Nebraska Geological Survey Bulletin 15, 71 p.

Coppersmith, K.J., 1988, Temporal and spatial clustering of earthquake activity in the central and eastern United States: Seismological Research Letters, v. 59, p. 299-304.

Crone, A.J., and Luza, K.V., 1990, Style and timing of Holocene surface faulting on the Meers fault, southwestern Oklahoma: Geological Society of America Bulletin, v. 102, p. 1-17.

Cone, A.J., Machette, M.N., Haller, K.M., Stephenson, Williams, R.A., and Odum, J.K., 1996, Late Quaternary paleoearthquakes in central Nebraska?-- new evidence favoring general tectonic stability (abs.): Geological Society of America Abstracts with Programs, v. 28, no. 7, A-55.

Curry, B.B. and Follmer, L.R., 1992, The last interglacial-glacial transition in Illinois: 123-125 ka, *in* Clark, P.U., and Lea, P.D., eds., The last interglacial-glacial transition in North America: Geological Society of America Special Paper 270, p. 71-88

Daniels, R.B., Handy, R.L., and Simonson, G.H., 1960, Dark-colored bands in the thick loess of western Iowa: Journal of Geology, v. 67, p. 114-119

Dubois, S.M., and Wilson, F.W., 1978, List of earthquake intensities for Kansas, 1867-1977: Kansas Geological Survey Environmental Geology Series 2.

Evans, D.G., and Steeples, D.W., 1987, Microearthquakes near the Sleepy Hollow oil field, southwestern Nebraska: Seismological Society of America Bulletin, v. 77, p. 132-140.

Feng, Zhaodong, 1991, Temporal and spatial variations in the loess depositional environment of central Kansas during the past 400,000 years: Ph.D. dissertation, University of Kansas, 250 p.

Feng, Zhao-dong, Johnson, W.C., Sprowl, D.R., and Lu, Yan-chou, 1994a, Loess accumulation and soil formation in central Kansas, United States, during the past 400,000 years: Earth Surface Processes and Landforms, v. 19, p. 55-67

Feng, Zhao-dong, Johnson, W.C., Lu, Yan-chou, and Ward, P. A. III, 1994b, Climatic signals from loess-soil sequences in the central Great Plains, U.S.A.: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 110, p. 345-358.

Follmer, L.R., 1979, A historical review of the Sangamon soil, *in* Wisconsinan, Sangamonian, and Illinoian stratigraphy in central Illinois: Illinois State Geological Survey Guidebook 13, p. 79-91.

Follmer, L.R., 1983, Sangamon and Wisconsinan Pedogenesis in the Midwestern United States, *in* Porter, S.C., ed., Late-Quaternary Environments of the United States, Volume 1. The Late Pleistocene: University of Minnesota Press, Minneapolis, p. 138-144.

Forman, S.L., 1990, Thermolumenescence and radiocarbon chronology of loess deposition at the Loveland paratype, Iowa, *in* Bettis, E.A., III ed., Holocene Alluvial Stratigraphy and Selected aspects of Quaternary History of Western Iowa: Iowa City, Midwestern Friends of the Pleistocene, University of Iowa Quaternary Studies Group Contribution, No. 36, p. 165-172.

Forman, S.L., Goetz, A.F.H., and Yuhas, R.H., 1992, Large-scale stabilized dunes on the High Plains of Colorado: understanding the landscape response to Holocene climates with the aid of images from space: Geology, v. 20, p. 145-148.

Fredlund, G.G., Johnson, W.C., and Dort, W., Jr., 1985, A preliminary analysis of opal phytoliths from the Eustis ash pit, Frontier County, Nebraska: Nebraska Academy of Sciences, Institute for Tertiary-Quaternary Studies, TER-QUA Symposium Series, v. 1, p. 147-162.

Frye, J.C., and Fent, O.S., 1947, The late Pleistocene loesses of central Kansas: Kansas Geological Survey Bulletin 70, part 3, p. 29-52.

Frye, J.C., and Leonard, A.B., 1949, Pleistocene stratigraphic sequence in northeastern Kansas: American Journal of Science, v. 247, p. 883-899.

Frye, J.C., and Leonard, A.B., 1952, Pleistocene geology of Kansas: Kansas Geological Survey Bulletin 99, 230 p.

Frye, J.C., and Leonard, A.B., 1954, Significant new exposures of Pleistocene deposits at Kirwin Phillips County, Kansas: Kansas Geological Survey Bulletin 109, part 3, p 29-48.

Frye, J.C., Leonard, A.B., Willman, R.B., Glass, H.D., and Follmer, L.R., 1974, The late Woodfordian Jules soil and associated molluscan faunas: Illinois State Geological Survey, Circular 486, 11 p.

Frye, J.C. and Willman, R.B., 1973, Wisconsinan climatic history . interpreted from Lake Michigan lobe deposits and soils, *in* R.F. Black, R.P. Goldthwait, and H.B. Willman, eds., The Wisconsinan Stage: Geological Society of America Memoir 136, p. 135-152.

Gordon, D.W., 1988, Revised instrumental hypocenters and correlation of earthquake locations and tectonics in the central United States: U.S. Geological Survey Professional Paper 1364, 69 p.

Hall, R.D., 1973, Sedimentation and alteration of loess in south-western Indiana: Ph.D. dissertation, Indiana University, Bloomington, 103 p.

Harlton, B.H., 1951, Faults in sedimentary part of Wichita Mountains of Oklahoma: American Association of Petroleum Geologists Bulletin, v. 35, p. 988-999.

Hattin, D.E., 1982, Stratigraphy and depositional environment of Smoky Hill Chalk Member, Niobrara Chalk (Upper Cretaceous) of the type area, western Kansas: Kansas Geological Survey Bulletin 225, 108 p.

Hibbard, C.W., Frye, J.C., and Leonard, A.B., 1944, Reconnaissance of Pleistocene deposits in north-central Kansas: Kansas Geological Survey Bulletin 52, part 1, p. 1-28.

Hopkins, D.M., 1975, Time-stratigraphic nomenclature for the Holocene Epoch: Geology, v. 3, p. 10.

Johnson, W.C., 1989, Stratigraphy and late-Quaternary landscape evolution, *in* Adair, M.J., ed.,. Archaeological investigations at the North Cove site, Harlan County Lake, Harlan County, Nebraska:: University of Kansas Office of Archaeological Research, p. 22-52.

Johnson, W.C., 1993, Surficial geology and stratigraphy of Phillips County, Kansas, with emphasis on the Quaternary Period: Kansas Geological Survey, Technical Series 1, 66 p.

Johnson, W.C., 1996, Unpublished radiocarbon ages.

Johnson, W.C., May, D.W., and Valastro, S., 1993, A 36,000-year chrono-, bio-, and magneto-stratigraphic record from loess of south-central Nebraska (abs.): Association of American Geographers, 89th Annual Meeting, Abstracts with Programs, p. 115

Johnson, W.C. and Logan, B., 1990, Geoarchaeology of the Kansas River Basin, central Great Plains, *in* Lasca, N.P., and Donahue, J., eds., Archaeological Geology of North America: Geological Society of America, Decade of North American Geology Centennial Special Volume 4, p. 267-299.

Johnson, W.C., and Martin, C.W., 1987, Holocene alluvial-stratigraphic studies from Kansas and adjoining states of the east-central Plains, *in* Johnson, W.C., ed., Quaternary environments of Kansas: Kansas Geological Survey Guidebook Series 5, p. 109-122.

Johnson, W.C., May, D.W., and Souders, V.L., 1990, Age and distribution of the Gilman Canyon Formation of Nebraska and Kansas (abs.): Geological Society of America, Abstracts with Programs, v. 22, p. A87.

Johnson, W.C., and May, D.W., 1996, Unpublished database of radiocarbon ages from the Gilman Canyon Formation of Nebraska and Kansas.

Johnson, W.C., and Valastro, S., 1994, Laboratory preparation of soil and sediment samples for radiocarbon dating of humates (total, humic acid, and humin fractions) : Kansas Geological Survey Open-file Report 94-50.

Johnson, W.H., Hansel, A.K., Follmer, L.R., and Curry, B.B., 1991, Later Quaternary temporal classification in Illinois--geochronologic or diacronic? (abs.): Geological Society of America

Abstracts with Programs, v.23, no. 3, p. 19-20.

Leigh, D.S., 1991, Origin and paleoenvironment of the Upper Mississippi valley Roxana silt: Ph.D. dissertation, University of Wisconsin, Madison, 186 p.

Leigh, D.S., 1994, Roxana silt of the upper Mississippi valley: lithology, source, and paleoenvironment: Geological Society of America Bulletin, v. 106, p. 430-442.

Leigh, D.S., and Knox, J.C., 1993, AMS radiocarbon age of the upper Mississippi valley Roxana silt: Quaternary Research, v. 39, p. 282-289

Leverett, F., 1899, The Illinois Glacial Lobe: U.S. Geological Survey Monograph 38.

Logan, W.N., 1897, The Upper Cretaceous of Kansas: University Geological Survey of Kansas, v.2, p. 202-234.

Lugn, A.L., 1935, The Pleistocene geology of Nebraska: Bulletin of the Nebraska Geological Survey (2d Series), v. 10, p. 1-223.

Maat, P. and Johnson, W.C., 1995, Thermoluminescence and new $^{14}C$ age estimates for late Quaternary loesses southwestern Nebraska: Geomorphology, v. 17, p. 115-128.

Mandel, R.D.,1995, Geomorphic controls of the Archaic record in the central Great Plains of the United States, *in* Bettis, E.A., III, ed., Archaeological Geology of the Archaic Period in North America: Geological Society of America Special Paper 297, p. 37-66.

Martin, C.W., 1993, Radiocarbon ages on Late Pleistocene loess stratigraphy of Nebraska and Kansas, central Great Plains, U.S.A.: Quaternary Science Reviews, v. 12, p. 179-188.

Martin, C.W., and Johnson, W.C., 1995, Variation in radiocarbon ages of soil organic matter fractions from Late Quaternary buried soils: Quaternary Research, v. 43, p. 232-237.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Jr., and Shackleton, N.J., 1987, Age dating and the orbital theory of the Ice Ages-development of a high-resolution 0 to 300,000-year chronology: Quaternary Research, v. 27, p. 1-29

May, D.W., and Souders, V.L., 1988, Radiocarbon ages for the Gilman Canyon Formation in Dawson County, Nebraska, (abs.): Nebraska Academy of Sciences, Proceedings, p. 47-48.

McCraw, D.J. and Autin, W.J., 1989, Lower Mississippi Valley loesses: Field guide for 1989 Mississippi Valley loess tour: International Quaternary Association Commission on Loess and the North American Loess Working Group.

McKay, E.D., 1979a, Wisconsinan loess stratigraphy of Illinois, *in* Wisconsinan, Sangamonian, and Illinoian Stratigraphy in central Illinois: Illinois State Geological Survey, Guidebook 13, p. 95-108.

McKay, E.D., 1979b, Stratigraphy of Wisconsinan and older loesses in southwestern Illinois, *in* Geology of Western Illinois: Illinois State Geological Survey, Guidebook 14, p. 37-67.

Merriam, D.F., 1963, The geologic history of Kansas: Kansas Geological Survey Bulletin 162.

Miller, R.D., and Steeples, D.W., 1996, Evaluation of fault scarp at Harlan County Lake, Harlan County, Nebraska using high resolution seismic reflection surveying: Kansas Geological Survey Open-file Report 96-32.

Morrison, R.B., 1965, Principles of Quaternary soil stratigraphy, *in* Morrison, R.B., and Wright, H.E., Jr., eds., Quaternary soils: International Quaternary Association VII Congress Proceedings, v. 9, p. 1-69.

Morrison, R.B., 1987, Long-term perspective: changing rates and types of Quaternary surficial processes: erosion-deposition-stability cycles, *in* Graf, W.L., ed., Geomorphic systems of North America: Geological Society of America Decade of North American Geology Centennial Special Volume 2, p. 167-176.

North American Commission on Stratigraphic Nomenclature, 1983, North American Stratigraphic Code: American Association of Petroleum Geologists Bulletin, v. 67, p. 841-875.

Nuttli, O.W., 1979, Seismicity of the central United States, in Hathaway, A.W., and McClure, C. R., eds., Geology in the siting of nuclear power plants: Geological Society of America Reviews in Engineering Geology, v. 4, p. 67-93.

Paterson, W.S.B., and Hammer, C.U., 1987, Ice core and other glaciological data, *in* Ruddiman, W.F., and Wright, H.E., Jr., eds., North America and adjacent oceans during the last deglaciation: Geological Society of America Decade of North American Geology, The Geology of North American, v. K-3, p. 91-109.

Reed, E.C., and Dreeszen, V.H., 1965, Revision of the classification of the Pleistocene deposits of Nebraska: Nebraska Geological Survey Bulletin 23, 65 p.

Richmond, G.M., and Fullerton, D.S., 1986, Introduction to Quaternary glaciations in the United States of America: *in* Sibrava, V., Bowen, D.Q., and Richmond, G.M., eds., Quaternary Glaciations in the Northern Hemisphere: Quaternary Science Reviews, v. 5, 3-10 p.

Ruddiman, W.F., 1987, Synthesis; the ocean/ice sheet record, *in* Ruddiman, W.L., and Wright, H.E. Jr., eds., North America and adjacent oceans during the last deglaciation: Geological Society of America, The Geology of North America, v. K-3, p. 463-478.

Ruhe, R.V., 1956, Geomorphic surfaces and the nature of soils: Soil Science, v. 82, p. 441-455.

Ruhe, R.V., 1969, Quaternary landscapes in Iowa: Iowa State University Press, Ames, Iowa, 255 p.

Ruhe, R.V., 1976, Stratigraphy of midcontinent loess, U.S.A., *in* Mahaney, W.C., ed., Quaternary stratigraphy of North America: Dowden, Hutchinson, and Ross, Stroudsburg, Pennsylvania, p. 197-211

Ruhe, R.V., 1983, Depositional environment of late Wisconsin loess in the Midcontinental United States, *in* Porter, S.C., ed., Late-Quaternary environments of the United States, Volume 1. The Late Pleistocene: Minneapolis, University of Minnesota Press, p. 130-137.

Ruhe, R.V., Hall, R.D., and Canepa, A.P., 1974, Sangamon paleosols of southwestern Indiana, USA, Geoderma, v. 12, p. 191-200.

Ruhe, R.V., Miller, G.A., and Vreeken, W.J., 1971, Paleosols, loess sedimentation and soil stratigraphy; *in* Yaalon, D.H., ed. Paleopedology-origin, nature, and dating of paleosols: Hebrew University Press, Jerusalem, Israel, p. 41-60

Ruhe, R.V. and Olson. C.G., 1980, Clay-mineral indicators of glacial and nonglacial sources of Wisconsinan loesses in southern Indiana, U.S.A.: Geoderma 24 , p. 283-97.

Russ, D.F., 1979, Late Holocene faulting and earthquake recurrence in the Reelfoot Lake area, northwestern Tennessee: Geological Society of America Bulletin, v. 90, p. 1013-1018.

Schaetzl, R.J., 1986, The Sangamon paleosol in Brown County: Kansas Academy of Science, Transactions, v. 89, p. 152-161

Schultz, C.B., and Stout, T.M., 1945, Pleistocene loess deposits of Nebraska: American Journal of Science, v. 243, p. 231-244.

Schultz, C.B., and Tanner, L.G., 1957, Medial Pleistocene fossil vertebrate localities in Nebraska: University of Nebraska State Museum Bulletin 4, p. 59-81.

Shimek, B., 1909, Aftonian sands and gravels in western Iowa: Bulletin of the Geological Society of America, v. 20, p. 399-408.

Simonson, R.W., 1941, Studies of buried soils formed from till in Iowa: Soil Science Society of America, Proceedings, v. 6, p. 373-381

Snyder, F.G., 1968, Tectonic history of midcontinental United States: UMR Journal, no. 1, p. 65-77.

Stanley, K.O., and Wayne, W.J., 1972, Epeirogenic and climatic controls of early Pleistocene fluvial sediments in Nebraska: Geological Society of America Bulletin, v. 83, p. 3675-3690.

Steeples, D.W., and Roth, G.H., 1982, Kansas earthquakes, 1980, *in* Stover, C.W., and van Hake, C.A., United States Earthquakes: U.S. Geological Survey, p. 139-141.

Swinehart, J.B., and Diffendal, R.F., 1989, Geology of the pre-dune strata, in Bleed, A., and Flowerday, C., eds., An Atlas of the Sand Hills: Conservation and Survey Division Resource Atlas no 5a, Lincoln, p. 29-42.

Thorpe, J., Johnson, W.M., and Reed, E.C., 1951, Some post-Pliocene buried soils of central United States: Journal of Soil Science, v. 2, p. 1-22.

United States Army Corps of Engineers, 1977, Harlan County Lake Construction foundation report: U.S. Army Corps of Engineers, Kansas City District.

Wayne, W.J., and Aber, J.S., 1991, High Plains and plains border sections in Nebraska, Kansas, and Oklahoma, in Quaternary nonglacial geology; conterminous U.S., Morrison, R.B., ed.: Geological Society of America, Geology of North America, v. K-2, p. 462-469.

Welch, J.E., and Hale, J.M., 1987, Pleistocene loess in Kansas; Status, present problems, and future considerations, *in* W.C. Johnson, ed., Quaternary environments of Kansas: Kansas Geological Survey Guidebook Series 5, p. 67-84.

Willman, R.B. and Frye, J.C., 1970, Pleistocene stratigraphy of Illinois: Illinois State Geological Survey, Bulletin 94, 204 p.

Woollard, G.P., 1958, Areas of tectonic activity in the United States as indicated by earthquake epicenters: American Geophysical Union Transactions EOS, v. 39, p. 1135-1150.

Zakrewska, B., 1963, An analysis of landforms in a part of the central Great Plains: Association of American Geographers Annals, v. 53, p. 536-568.

Zeller, D.E., 1968, The stratigraphic succession in Kansas: Kansas Geological Survey Bulletin, 189, 81 p

Zoback, M.L., and Zoback, M.D., 1980, State of stress in the conterminous United States: Journal of Geophysical Research, v. 85, p. 6113-6156.