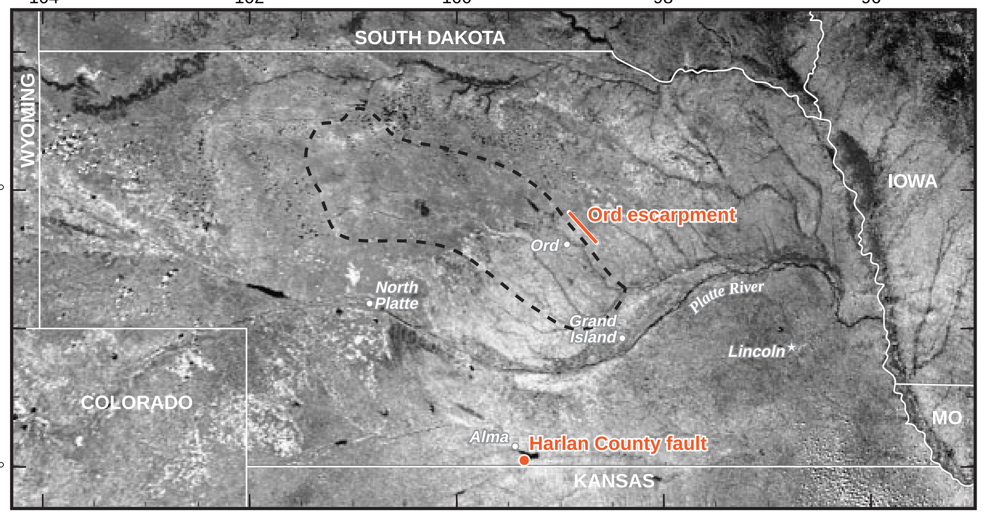


Figure 1. Index map showing the locations of the Harlan County landslide and Ord escarpment in Nebraska. Dashed line indicates approximate boundary of South, Middle, and North Loup River drainage. Satellite image downloaded and published with permission from R. Sterner (web site: fermi.jhuapl.edu/states/avhrr/NE_213.n14.96apr09_1934.gif).

0 50 100 150 km
0 50 100 mi

INTRODUCTION

The Great Plains of central Nebraska are commonly viewed as a region of long-term tectonic stability and low earthquake hazard. However, recent studies (Dort and others, 1993, 1995; W.C. Johnson, written commun., 1991) have reported possible evidence of latest Quaternary surface faulting in two widely separated parts of the state. If valid, this evidence implies late Pleistocene and Holocene, large-magnitude earthquakes have occurred in this part of the stable mid-continent in the geologically recent past, which contrasts with the historical record of only 51 felt earthquakes between 1866 and 1989 (Burchett, 1990). If confirmed, this geologic evidence of multiple large paleoearthquakes in the region would have significant ramifications in terms of the region's seismic hazard assessment. As a result, we conducted field investigations of two significant features: a prominent, linear escarpment, herein referred to as the Ord escarpment, in east-central Nebraska, and the Harlan County fault in the south-central part of the state (fig. 1). The Ord escarpment is an abrupt, 36-km-long escarpment located about 14 km northeast of the town of Ord, in Garfield, Valley, and Greeley Counties. The Harlan County fault is a feature exposed in a wave-cut bluff in Bone Cove along the southern shore of Harlan County Lake, located about 12 km southeast of the town of Alma, Nebraska.

Because of the potential impact these features could have on our understanding of Quaternary tectonics and seismic hazards in much of the central-interior of the United States, it was crucial to critically evaluate the reported evidence. Therefore, during the period 1994-96, we conducted detailed geological field investigations at the Harlan County site to clarify the origin of the "Harlan County fault," and we conducted reconnaissance geological field studies of the Ord escarpment and surrounding region, including the collection of high-resolution seismic-reflection data at three sites along the escarpment. Below we describe the respective studies in each of these areas and summarize our conclusions about the origin of these features. Our investigations were funded under the auspices of the U.S. Nuclear Regulatory Commission and the National Earthquake Hazards Reduction Program of the U.S. Geological Survey.

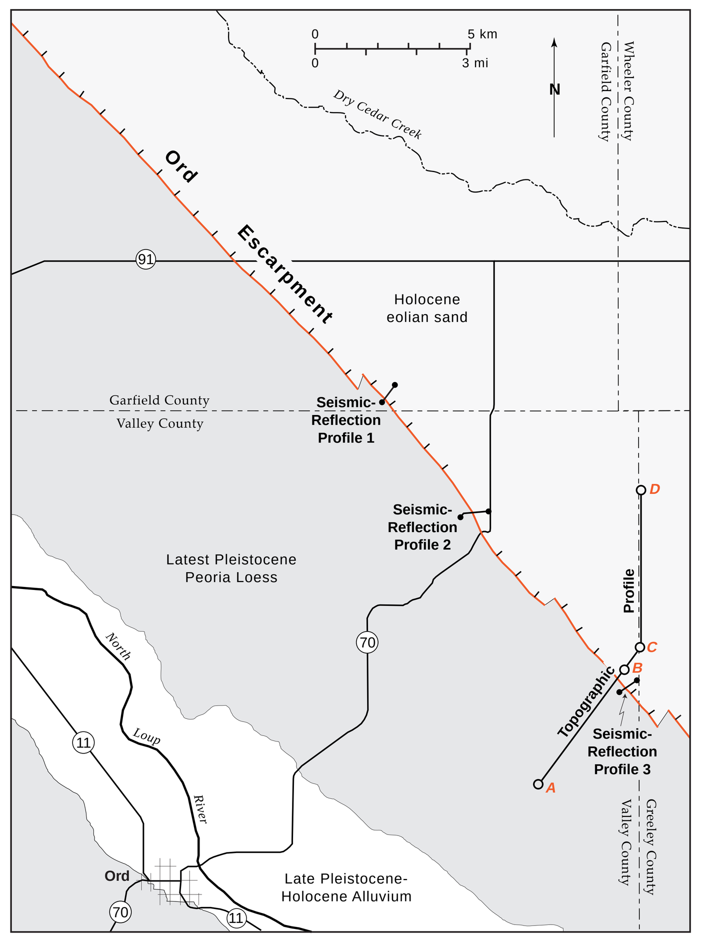


Figure 2. Location map of the Ord escarpment showing distribution of Peoria Loess, Holocene eolian sand, and locations of seismic-reflection profiles. Black hachures on red escarpment point toward lowlands. Open circles show locations of drill holes. Topographic profile and shallow subsurface stratigraphy are shown in figure 3.

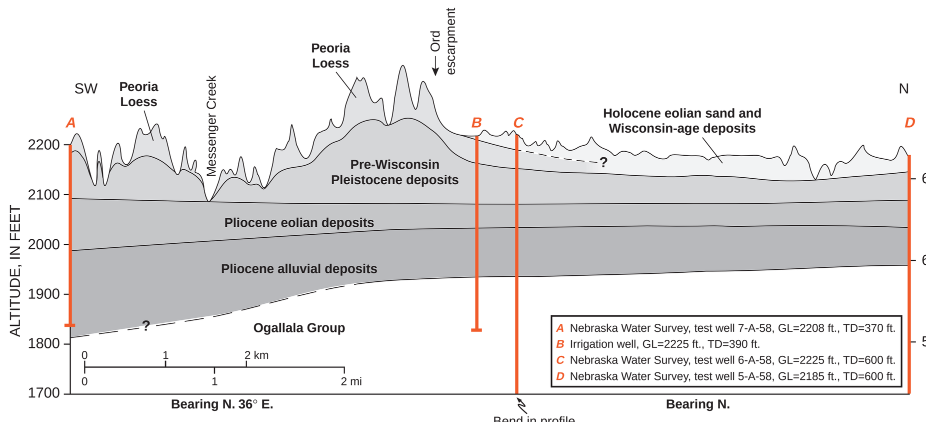
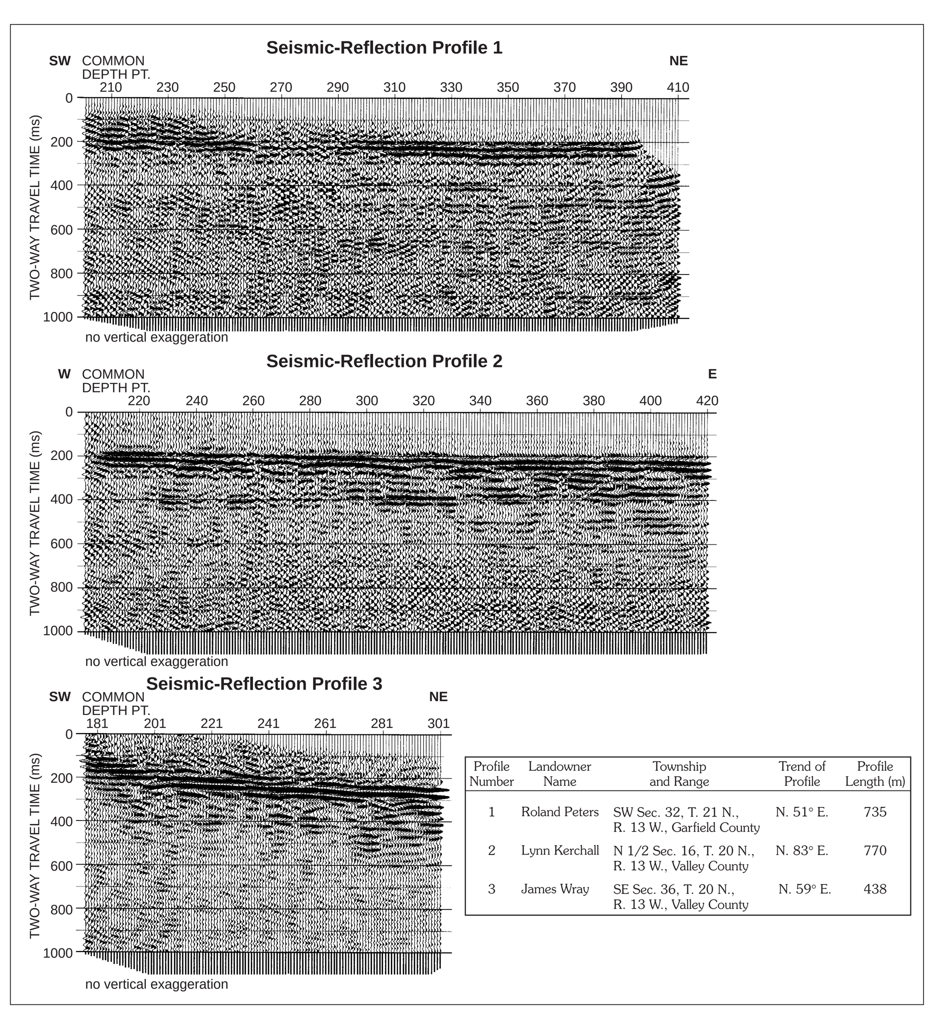


Figure 3. Topographic profile and cross section across the Ord escarpment. Location of profile is shown in figure 2. Note the highly dissected character of the Peoria Loess in the uplands southwest of the escarpment. Vertical exaggeration is about 20x. GL, ground level; TD, total depth. See text for description of stratigraphic units.



Profile Number	Landowner Name	Township and Range	Trend of Profile	Profile Length (m)
1	Roland Peters	SW Sec. 32, T. 21 N., R. 13 W., Garfield County	N. 51° E.	735
2	Lynn Kerchall	N 1/2 Sec. 16, T. 20 N., R. 13 W., Valley County	N. 83° E.	770
3	James Wray	SE Sec. 36, T. 20 N., R. 13 W., Valley County	N. 59° E.	438

Figure 4. High-resolution seismic-reflection profiles across the Ord escarpment and adjacent valley to the northeast. Locations of profiles are shown in figure 2. The continuity of the strong, multicycle reflection on the profiles shows that the escarpment is not the product of late Quaternary faulting. This strong reflection correlates with the top of the Miocene Ogallala Group.

THE ORD ESCARPMENT

Possible late Quaternary faulting in the Ord area (fig. 1) was reported by Dort and others (1993, 1995), who described a series of prominent, linear, northwest-trending topographic escarpments bounding narrow, linear valleys that contain underfit streams in the Loup River drainage system. The most prominent escarpments trend about N. 40° W., whereas a set of conjugate features trend east-west. They described broad, flat-floored valleys that have anomalously blunt heads and noted that surface escarpments coincide with gradients in geophysical data, which suggests significant offsets in subjacent bedrock. They also reported that upper Tertiary bedrock units have been uplifted enough to be exposed at the surface, but generally, the landscape is formed by the latest Pleistocene Peoria Loess (see description of Peoria Loess under "Harlan County fault"). The highest escarpments have about 60 m (200 ft) of topographic relief. They interpreted these escarpments as possible late Quaternary fault scarps, and speculated that this topographic relief is structural—the result of uplift that has occurred since deposition of the loess, which ceased at about 10-12 ka. They further speculated that some of the faulting could be early to mid-Holocene in age because paleosols younger than the Peoria Loess (and possibly the early Holocene Bignell Loess) are truncated by faulting. These purported relations would imply extremely high slip rates (about 5 mm/yr) on previously unknown yet seismically quiescent tectonic features. The possible presence of very active, large-scale tectonic features in the stable mid-continent of Nebraska prompted our efforts to collect new information that would clarify the origin of these escarpments (Crone and others, 1996).

GEOMORPHIC EXPRESSION AND SUSPECTED SURFACE FAULTING

The Ord escarpment is the most prominent of the series of escarpments in the Loup River drainage (fig. 1) and therefore became the focus of our efforts. The northeast-facing Ord escarpment trends N. 42° W. and separates highly dissected loess-covered highlands on the west from the relatively low-relief, sand dune-filled lowlands of Dry Cedar Creek to the east (fig. 2). The eolian sand that fills the Dry Cedar Creek Valley is an eastward extension of the dunes that form the Nebraska Sand Hills (Lawton and Hiergesell, 1988). On satellite imagery and at regional scales (1:250,000), the escarpment is continuous for as much as 32 km (20 mi) and has as much as 47 m (155 ft) of relief in the area of our detailed studies (fig. 3). At more detailed scales (for example, 1:24,000), the escarpment front appears dissected, embayed, and less well-defined. If the net relief across the escarpment shown in figure 3 is truly the product of post-Peoria Loess faulting, then the inferred fault beneath the escarpment has a latest Pleistocene vertical slip rate on the order of 4-6 mm/yr.

The geomorphic expression of the Ord escarpment is the first line of evidence that argues against the feature being the result of high slip-rate, latest Pleistocene tectonics. Active faults that have vertical slip rates comparable to the inferred 4-6 mm/yr rate for the Ord escarpment are marked by abrupt, linear escarpments, even at local scales. For example, the Wasatch fault zone, which has a slip rate of about one-third (0.5-1.5 mm/yr; Machette and others, 1992) that inferred for the Ord escarpment, forms a precipitous, linear mountain front along much of its length. Furthermore, the Wasatch fault zone is marked by distinct, large fault scarps that are obvious evidence of repeated displacement. In many places, the scarps are more than 10-m high on latest Pleistocene and early Holocene deposits (Machette and others, 1992). If the vertical slip rate on the Ord escarpment is really three times greater than the rate on the Wasatch fault zone, then scarps at least 10-m high should be widespread along the entire feature. We did not find fresh, prominent scarps along the Ord escarpment during our field reconnaissance.

In May 1996, we spent several days in the field with Dr. Wakefield Dort to examine the field evidence of Quaternary faulting. Other than the regional geomorphic evidence of unusual northwest-trending drainage patterns, the primary source of field evidence of faulting was based on stratigraphic relations in numerous road cuts throughout the region. In many of these exposures, Dort and others (1993, 1995) interpreted a lack of correlation of stratigraphic units across the exposure as evidence of young faulting. We found that many of the road cuts were only partially exposed, and slumped debris buried much of the lower part of the steeper exposures. The slumped debris concealed important details and critical stratigraphic relations, but at all of the sites we visited, we excavated the debris by hand, exposed the deposits, and clearly determined that none of the strata were faulted. Thus, upon careful scrutiny, we did not find any compelling field evidence of late Quaternary faulting in the area.

HIGH-RESOLUTION SEISMIC-REFLECTION AND SUBSURFACE DATA

High-Resolution Seismic-Reflection Data

Despite our field observations that favored a non-tectonic origin, we needed compelling subsurface evidence to prove that these northwest-trending, topographic escarpments were not related to late Quaternary faulting. One way to obtain this evidence was to use high-resolution, shallow seismic-reflection imaging to determine the relation between the topographic escarpment and possible offsets in the underlying Tertiary bedrock. If the underlying bedrock is vertically offset at least as much as the topographic scarp (that is, ≥50 m), then this would support a tectonic origin, whereas the absence of such offsets would be strong support for a non-tectonic origin.

Accordingly, in July 1996, we collected a total of about 2 km of high-resolution seismic-reflection (Mini-Sosie) data (Stephenson and others, 1992) at three sites across the Ord escarpment (fig. 2). The three sites are along the central portion of the escarpment where it is near its maximum height and where it is best-defined (fig. 2). We recorded 2.0 seconds of data (2 ms sample rate) along the profiles using three earth compactors as energy sources. The earth compactors were operated simultaneously at each shot point in a 7-m-long, linear array (1 compactor every 3.5 m). We recorded 1,000 impacts per shot point on 24 channels in an end-on shooting pattern using a receiver spacing of 7 m. This spacing pattern resulted in a maximum of 12-fold data coverage for most of the profile lengths. The following parameters and techniques were applied in conventional processing of the reflection data: (1) bandpass filter (20-40-160-250 Hz), (2) automatic gain correction (1,500 ms operator length), (3) first arrival mute, (4) F-K filter, (5) elevation statics, (6) normal moveout correction, (7) residual statics, (8) CMP stack, (9) Eigenvector filter (to eliminate residual ground roll), (10) post-stack time migration, and (11) time-depth conversion.

The key feature visible on all three reflection profiles is a sequence of strong, multicycle reflections (fig. 4) that are continuous beneath the escarpment. Clearly, these reflections are not vertically offset by faults having tens of meters of throw, which is strong evidence that the Ord escarpment is not the product of Quaternary tectonism.

Shallow Subsurface Stratigraphy

We used stratigraphic data from several nearby irrigation wells and bore holes to correlate the strong reflection on the seismic data with stratigraphic units and to construct a generalized section across the escarpment (fig. 3). The section shows that the latest Pleistocene Peoria Loess is present at the surface in the highly dissected uplands southwest of the escarpment, whereas, Holocene eolian sand and Wisconsin-age deposits are present in Cedar Creek Valley northeast of the escarpment. We divide the shallow subsurface deposits into four general units: pre-Wisconsin Pleistocene deposits, Pliocene eolian deposits, Pliocene alluvial deposits, and the upper to middle Miocene Ogallala Group. The pre-Wisconsin Pleistocene deposits consist of undifferentiated eolian deposits composed mainly of clayey to sandy silt and silty clay with some fine sand. The Pliocene eolian deposits consist of clayey to sandy silt and may correlate, at least in part, with the Fullerton Formation (May and others, 1995). The Pliocene alluvial deposits consist mainly of sand and gravel that are probably derived from source areas to the west in Wyoming and Colorado and are probably equivalent to the Broadwater Formation in western Nebraska (Swinehart and Diffendal, 1995). The Ogallala Group is predominantly fluvial deposits composed of clay, silt, sand, and pebbly to gravelly sand; in the Ord area, the Ogallala Group deposits are probably equivalent to the Ash Hollow and Valentine Formations (Swinehart and others, 1985).

Faulting associated with the Ord escarpment would result in stratigraphic units on the northeastern side of the escarpment being downdropped relative to those in the southwest. However, the drill-hole data show just the opposite relations; the tops of the Pliocene alluvial deposits and Ogallala Group are at slightly lower elevations on the southwest side of the escarpment compared to the northeast side (fig. 3). Thus, the drill-hole data do not provide any support for the idea of the escarpment being the result of down-to-the-northeast Quaternary faulting.

The subsurface data indicate that the strong, multicycle reflection on the high-resolution reflection data correlate with the top of the Miocene Ogallala Group, which is present at depths generally between 50 and 85 m in the area of the profiles (fig. 3). As noted, the continuity of this strong reflection is compelling evidence that a Miocene-age datum is not vertically offset by faulting, and thus the escarpment must have a non-tectonic origin.

CONCLUSIONS

Our field observations, seismic-reflection data, and drill-hole data all indicate that the Ord escarpment is not a late Quaternary tectonic feature and thus must have a non-tectonic origin. The gross geomorphic expression of the escarpment and the absence of younger superposed fault scarps along its northeastern flank are first-order field evidence of a non-tectonic origin. The lack of any convincing evidence supporting faulting in exposures of latest Pleistocene loess further argues against a tectonic origin for a feature that would have a purported slip rate of about 5 mm/yr. The drill-hole data show that the tops of the older stratigraphic units are at slightly lower elevations southwest of the escarpment compared to the area northeast of the escarpment, which is opposite to the relation that would result from faulting. Furthermore, the continuity of the strong reflectors on all of the high-resolution reflection profiles precludes the possibility of faults having any substantial post-Miocene throw beneath the escarpment. Lastly, only minor earthquakes have occurred historically in central Nebraska, which argues against the presence of highly active tectonic features. Collectively, these observations and data indicate that the Ord escarpment is not a tectonic feature.

We speculate that the Ord escarpment, and by inference, similarly oriented linear escarpments in the Loup River drainage, is a fluvial escarpment. The Ord escarpment probably marks the southwestern margin of a late Pleistocene valley that originally may have formed during a prolonged period of erosion in early to mid-Wisconsin time. In Holocene time, the valley was inundated by eolian sand, which choked the drainage and resulted in an underfit stream (Dry Cedar Creek) draining the valley northeast of the escarpment. However, northwest-trending drainage patterns and linear escarpments are so prevalent in the Loup River drainage basin that it seems likely they reflect some unknown underlying structural control.

HARLAN COUNTY FAULT

The Harlan County fault in south-central Nebraska (fig. 1) has no surface expression and is only exposed in a 7-m-high, wave-cut bluff on the western shore of Bone Cove, which is along the southern shore of Harlan County Lake (fig. 5 and 6). This exposure was discovered by William C. Johnson (University of Kansas) in the late 1980's during his studies of the Quaternary stratigraphy of loesses in southern Nebraska and northern Kansas (see Johnson and Logan, 1990). The primary reason that the slip planes were initially related to late Quaternary faulting by Johnson as opposed to a landslide (or another non-seismic origin) was that their sense of movement was southward, away from the topographically lower Republican River Valley. If the planes had dipped north toward the valley, a gravitational origin would have been more culpable. However, interpretation of these slip planes as reflecting surface faulting is significant because (1) they appear to offset upper Pleistocene deposits and thus may be as young as Holocene; (2) as mapped, they strike northeast toward the dam, which is an earth-filled structure dating from the 1930's, and (3) the presence of young surface faulting would be evidence of prehistoric seismicity in a region having little seismicity during its short recorded history (about 130-140 years). Thus, determining the origin of the slip planes would have great impact on the seismic safety of the dam and reservoir as well as resolve conflicting reports of inferred paleoseismicity in an area long considered to be mostly aseismic (see discussion of the Ord escarpment).

To distinguish between these two interpretations, we had to expose the slip planes lower in the section and determine if they decreased in dip with depth and if they could surface or sole out to the south. If the geometry of slip planes flattened with depth in alluvial deposits, then this would be strong evidence that the Harlan County fault is probably related to a shallow slope failure (landslide). For the first two years of the study (1994-1995), the water level in the reservoir remained extremely high, which prevented us from excavating the lowermost part of the exposure without massive slumping. When the water level dropped in May 1996, we excavated and mapped a hand-dug trench at the base of the natural exposure at Bone Cove (fig. 7).

STRATIGRAPHY

We first visited the Bone Cove site in May 1994 with William Johnson (University of Kansas) to make a preliminary appraisal of the Harlan County fault. Our work complemented ongoing studies of late Quaternary loess deposits in the central Great Plains by Johnson (University of Kansas) and seismic-reflection and geophysical characterizations of faults in the shallow subsurface by Donald Steeples (University of Kansas) and Richard Miller (Kansas Geological Survey) (Miller and Steeples, 1996). Our work continued, somewhat sporadically, for the next 3 years. Our initial studies in the summer of 1994 documented several south-dipping, down-to-the-south slip planes that offset the top of the late Pleistocene Gilman Canyon Formation at least 6 m. The slip planes extend upward through the overlying Peoria Loess (latest Pleistocene age) to within 30 cm or less of the surface suggesting young movement (fig. 7A); however, no scarp or other topographic expression of the slip planes is present at the surface. These relations suggested that the offset occurred in the late stages of loess deposition or shortly thereafter, during early Holocene time.

In Nebraska, the top of the Gilman Canyon Formation is characterized by a paleosol (single to multiple A and B horizons; fig.6), which is rarely seen in exposures of other loesses. The age of this paleosol establishes a maximum time since the last movement on the Harlan County fault. The paleosol has been dated at many locations throughout south-central Nebraska and Kansas, and the ages range between 38 ka at the base of the formation, to 35 ka at the base of the soil and about 20 ka near the top of the soil (Johnson, 1996; Martin, 1993). At the Bone Cove site, Martin (1993) had obtained ages of 26,260±680 ^{14}C yr B.P. and 25,555±500 ^{14}C yr B.P. for soil humate from the upper part of the Gilman Canyon paleosol (undifferentiated A horizon, probably 2Ab horizon in fig. 7A), whereas Johnson (1996) reported a suite of ages ranging from 35,580 ^{14}C yr B.P. at the base of the exposure to 27,580 ^{14}C yr B.P. from the uppermost A horizon of the Gilman Canyon Formation (2Ab horizon, fig. 7A). Thus, movement on the Harlan County fault must be younger than about 25-27 ka on the basis of the age of the uppermost faulted A horizon.

The age of the Peoria Loess in the central Great Plains provides additional information on the timing of the fault's movement. To our knowledge, the Peoria Loess was dated in the region, but not at the Bone Cove site. Studies of other exposures around Harlan County Lake show that the deposition of the Peoria Loess began about 21 ka and regional studies indicate that loess deposition ended between 11.8 ka and 10.2 ka (that is, latest Pleistocene time). Thus, depending on the age of the uppermost Peoria Loess at the Bone Cove exposure, the time of the most recent faulting could be as young as 10-11 ka. During our mapping of the bluff at Bone Cove, we discovered and sampled charcoal from the basal part of the Peoria Loess, which yielded a radiocarbon age of 22.4 ka (fig. 7A). Johnson (1996) reported a suite of ages ranging from 7,310±70 and 16,080±180 ^{14}C yr B.P. in the upper part to 23,460±270 ^{14}C yr B.P. from the lower (transitional) part of the Peoria Loess. Thus, movement on the Harlan County fault must be younger than 16 ka on the basis of the dated Peoria Loess (the 7 ka date is probably not a reliable age for the Peoria Loess).

STRUCTURE

At the Bone Cove site, the slip planes are very conspicuous because they abruptly truncate a sequence of three pronounced, dark paleosols (A horizons) at the top of Gilman Canyon Formation (loess) and place them against light-brown Peoria Loess (fig. 7A) to the south. Two prominent strands of the fault are visible in the natural exposure (see fig. 6): the cumulative throw of the top of the Gilman Canyon Formation is 3.85 m across the strands. The major (northern) strand of the fault has about 3.0 m of throw, strike N. 33°-42°E., and dips 67° S. (fig. 8). The subsidiary (southern) strands have about 0.85 m of throw, strike N. 87°-105°E., and dip 69°-70° S. Both the northern and southern strands have a down-to-the-south, normal sense of slip. The faults form sharp boundaries that are typically less than 1 cm wide. Along the northern strand, individual shears in the fault planes form a right-stepping (northward) echelon pattern from the base upward. The faults can be clearly traced upward into the Peoria Loess to within 30 cm or less of the modern ground surface. We suspect that these faults once extended higher in the section and that the upper part of the Peoria Loess has been eroded at this site; the apparent lack of shearing in the uppermost 30 cm is probably the result of modern surficial processes (pedogenesis, bioturbation, and freeze-thaw) that have obscured the fractures.

Our attempts to see deeper in the exposure were thwarted by years of record high-water levels of the lake. However, in May 1996 water levels had dropped several meters so we hand-excavated a 7-m-long, 1.5-m-deep trench at the base of the bluff to expose the slip planes and the A horizon of the Gilman Canyon Formation (fig. 7A). The slip planes, which average about 68° dip in the upper part of the bluff, curve downward and decrease to about 35° dip in the base of our hand-dug trench (fig. 7B). In addition, the intricate pattern and cross-cutting relations of the slip planes indicate sequential movement on the south-dipping (master) and north-dipping (antithetic) planes. These cross-cutting structural relations probably resulted from volumetric adjustments of the sediment as it slid down curving fault planes. These observations are consistent with a landslide origin rather than deeper-seated faulting.

There is additional evidence that supports a landslide origin. The buried A horizon on the top of the Gilman Canyon Formation, which is exposed in the bluff (2Ab, fig. 7A) and hand-dug trench (2Ab/5Ab, fig. 7B), is found in an exposure about 50 meters to the south of the trench across a shallow sediment-filled valley that trends east, parallel to the fault (fig. 9). Apparently the A horizon of the Gilman Canyon Formation has been eroded in this valley, thereby removing our marker bed. Where exposed in the next bluff south (80 m south of the trench), the A horizon is at an elevation that is only 0.5 m lower than on the upthrown (north) block in the northern bluff. This relation fits with our interpretation of landslide movement from the bluff southward into the east-trending valley. If the slip planes were tectonic, this would mean that the documented 6 m of slip at the fault is resolved to only 0.5 m in a lateral distance of 100 m.

Miller and Steeples' (1996) seismic-reflection profile along the base of the bluff (fig. 5B) shows that deep reflectors are not offset in the area beneath the bluff. A very strong reflection on their profile, which probably correlates with the Permian Stone Corral anhydrite, is clearly unfaulted in the area of the slip planes in the bluff. This reflection is offset by reverse faults about 100 m to the north of the slip planes, but their northerly dip precludes the possibility that the south-dipping slip planes in the bluff are connected to these deeper reverse faults.

Scattered outcrops of Ogallala Group rocks in Bone Cove provide additional evidence that the stratigraphic offset in the bluff is not related to deep tectonic faulting. Blocks of calcium-carbonate cemented sandstone that mark the top of the Ogallala Group are present near the water line in Bone Cove (fig. 9). These outcrops are present at similar elevations both north and south of the bluff, which indicates that the Ogallala Group has not been offset a comparable amount to the stratigraphic throw measured in the bluff (>6 m). Thus the stratigraphic offset in the bluff must be a shallow feature.

Finally, at the North Cove site on the north side of Harlan County Lake (fig. 6), Johnson reported that another fault (slip plane) with perhaps 0.5 m of offset was exposed in the lake-front bluffs (W.C. Johnson, written commun., 1992). During our field visit in May 1994, the lake level was too high to permit access to the bluff where the slip plane was exposed. However, Johnson reported that, unlike the Bone Cove site, the fault at North Cove could not be traced very far above the Gilman Canyon paleosol into the Peoria Loess. Also, it has a down-to-the-south slip, which is consistent with gravitational movement toward the topographically lower Republican River Valley. This site is likely a landslide feature that is slightly older than the Harlan County fault (landslide).

CONCLUSIONS

Although the Harlan County fault, as exposed in the bluff, represented a viable candidate for a tectonic feature, our further exposure of the slip planes coupled with seismic-reflection profiling and the geometry of underlying bedrock now suggest that the Harlan County fault (slip planes) is part of a post-Peorian (*i.e.*, latest Pleistocene to Holocene) landslide that slid southward into an east-trending tributary valley of Bone Cove. This interpretation is based on several lines of evidence: (1) the fault's curving geometry in section, (2) the absence of substantial net offset and absence of lateral extent of the 5Ab horizon on the Gilman Canyon Formation, (3) the absence of a geomorphic expression of faulting at the surface (and on aerial photos), (4) no substantiated offset on underlying sediment of the Ogallala Group, and (5) a plausable landslide geometry. The landslide is gravitationally driven with a headwall on the bluff and a toe in an east-trending tributary valley of Bone Cove. Eolian deposition probably buried the head scarp and may have contributed to further landsliding that was initiated by fluvial entrenchment of the eastward-trending tributary valley of Bone Cove, just south of the bluff.

As a result of these investigations, we propose that the Harlan County fault (slip planes) is a shallow feature not associated with tectonic offset on a seismogenic source (fault). The "Harlan County fault" is likely an ancient landslide that slid southward into a tributary valley of Bone Cove probably in latest Pleistocene or early Holocene time.

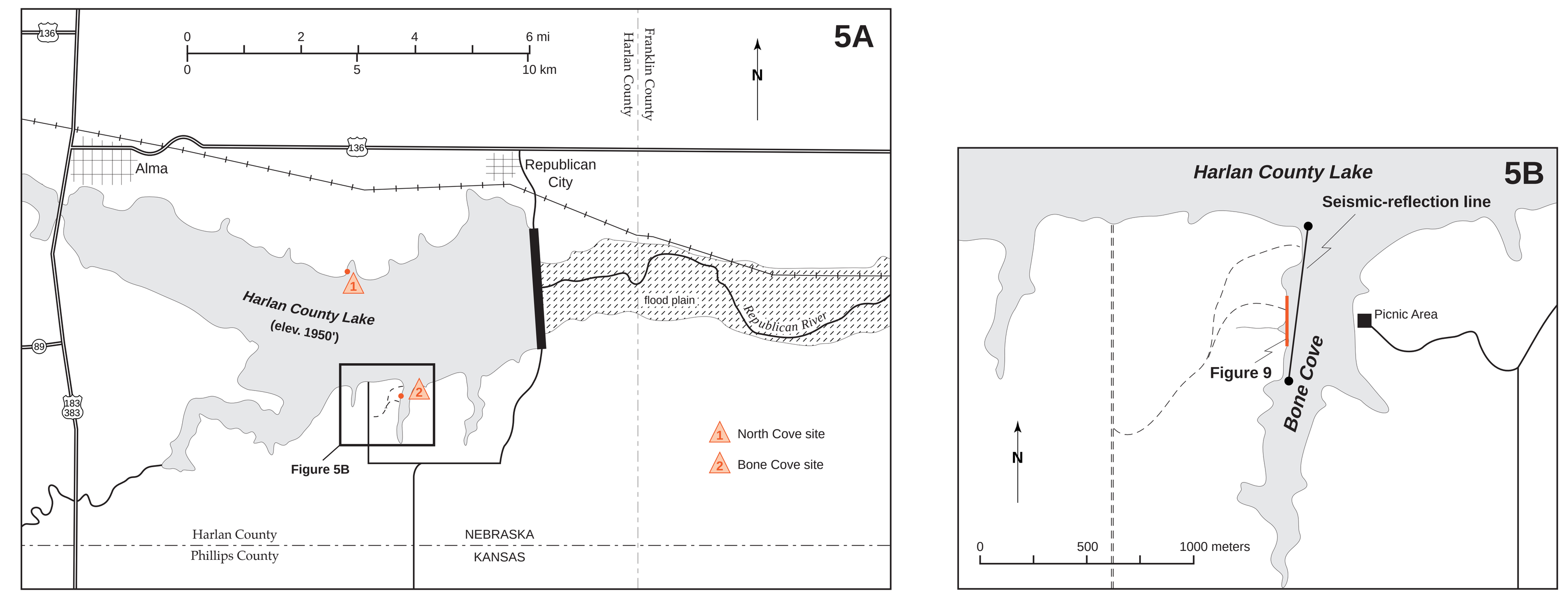


Figure 5. Regional location map of Harlan County Lake, south-central Nebraska (fig. 5A) and Bone Cove (fig. 5B). Figure 5B shows the location of Miller and Steeples' (1996) seismic-reflection profile and the schematic cross section (red line) shown in figure 9.

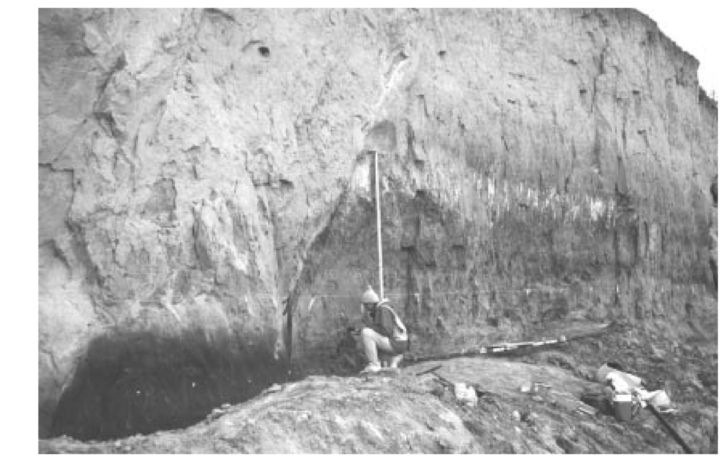
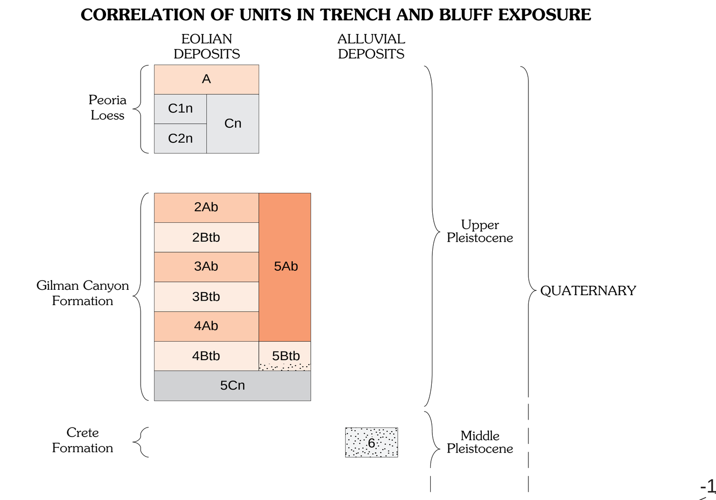


Figure 6. Oblique photograph of bluff exposure, west side of Bone Cove, Harlan County Lake. View is to the northwest. Down-to-the-southeast (toward viewer) movement on the slip planes has offset the dark A-horizons that mark the top of the late Pleistocene Gilman Canyon Formation more than 6 m vertically. Note the steep attitude (65°-70° S) of the slip planes.

CORRELATION OF UNITS IN TRENCH AND BLUFF EXPOSURE



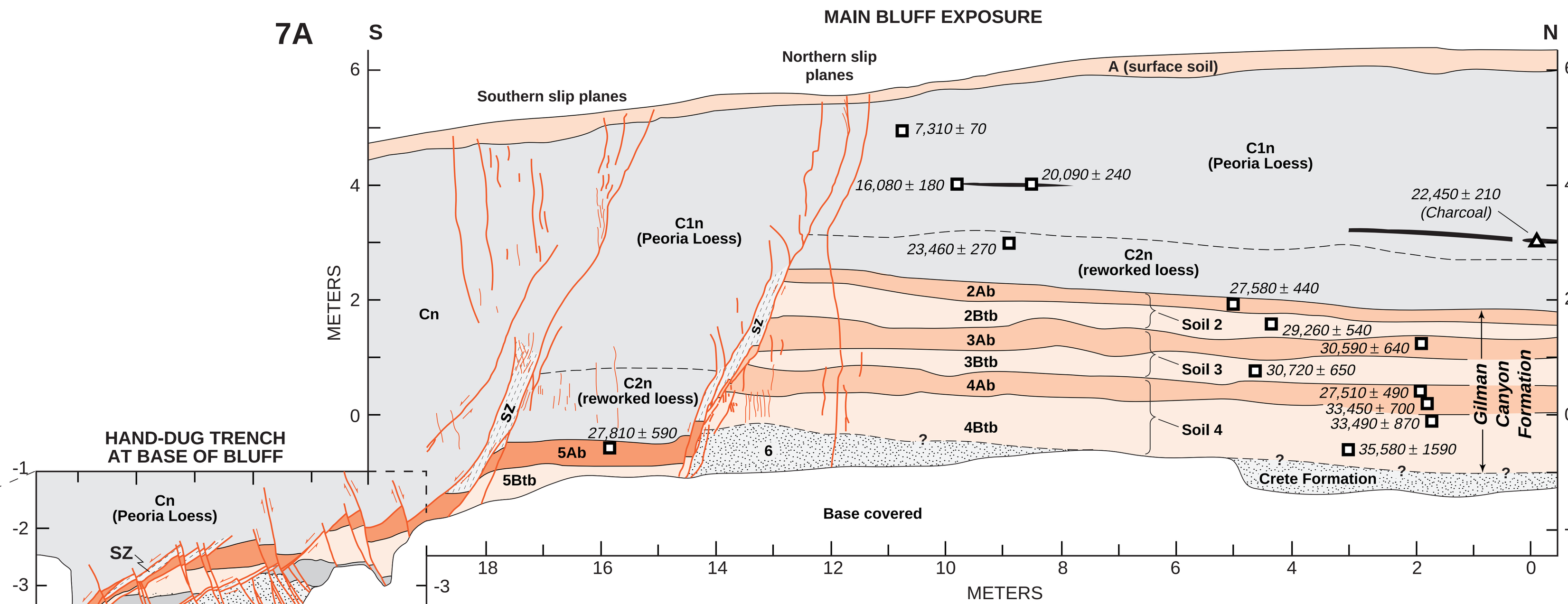
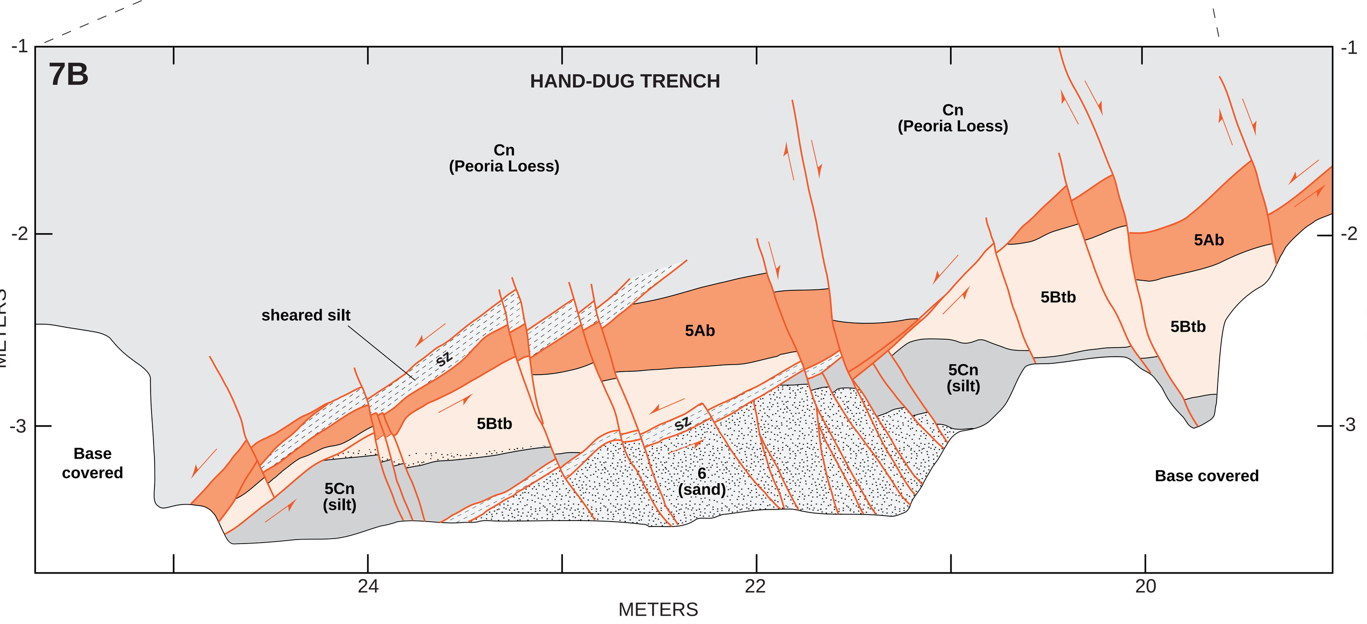


Figure 7. Detailed maps of units exposed in the bluff at Bone Cove site. Correlation and description of trench units apply to figures 7A and 7B. 7A) Map of main bluff exposure showing Peoria Loess (upper unit), Gilman Canyon and Crete Formations lower units, and Harlan County fault (slip planes). The exposure was mapped in August 1994 by A.J. Crone and K.M. Haller. All radiocarbon ages are from Johnson (1996) except the 22,450±210 yr B.P. date which is from this study (Beta-81214). 7B) Map of hand-dug trench (lower southeast end of bluff) showing offset on downward extension of slip planes. Upper unit is Peoria Loess; A horizon and lower units are upper part of Gilman Canyon Formation. The exposure was mapped in May, 1996, by M.N. Machette and A.J. Crone.



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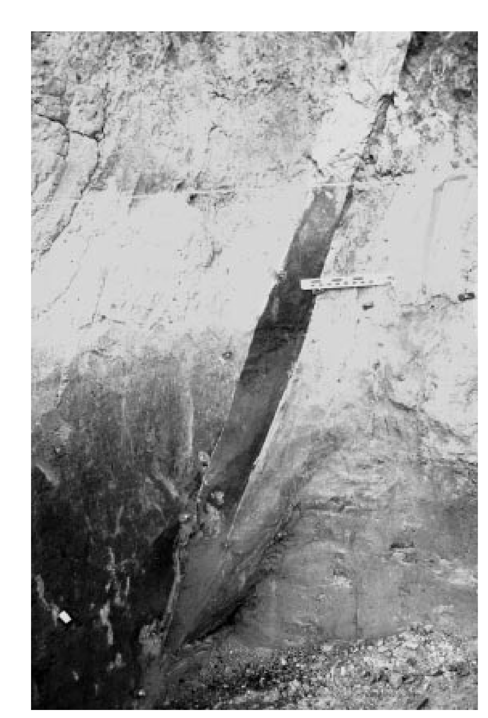

Figure 8. Photograph of A horizon of Gilman Canyon Formation caught between two slip planes of the main fault. Ruler (for scale) is 20 cm long. The fault crosses the string line at 0.0 m vertical and 14.5 m horizontal in fig. 7A.

DESCRIPTION OF UNITS IN TRENCH AND BLUFF EXPOSURE

Unit 1—Peoria Loess (latest Pleistocene; 10-23 ka)—Light-yellowish-brown silty sand to loam, slightly calcareous, compact, unbedded (bioturbated). Eolian deposit that mantles landscape, probably derived by deflation from glacial and fluvial deposits (active in late Pleistocene time) and from sediment of the Miocene Ogallala Group. Analytical data summarized from figure 9 in Johnson (1996)

A — **A horizon**—Light-gray organic-rich silty sand. Forms soil on eroded surface of loess. Grain-size distribution is typically 25-50% sand, 45-65% silt, and 5-10% clay

C1n — **C1n horizon**—Light-brown alternating layers (not visible) of sandy silt and silty sand. Contains two burn layers that indicate periodic stabilization and vegetation of land surface between 16 ka and 22 ka. Grain-size distribution is typically 25-50% sand, 35-60% silt, and 2-4% clay. Weathered material forms vertical columns

C2n — **C2n horizon**—Light-brown homogenous silty sand in transition zone between C1n of Peoria Loess and upper A horizon (2Ab) of the Gilman Canyon Formation. Grain-size distribution is more homogenous than above, and typically is composed of 45-55% sand, 30-50% silt, and about 5% clay

Cn — **Cn horizon**—Undifferentiated Peoria Loess (see units C1n and C2n above). Mapped south of the southern of two prominent faults (slip planes)

Units 2-5—Gilman Canyon Formation (latest Pleistocene; 25-36 ka)—Gray (organic) to light-brown silty sand to sandy silt (loess), noncalcareous (leached), compact, unbedded (bioturbated). Buried soils form discrete layers that reflect periodic sedimentation and surface stability (with soil formation). Grain size generally fines upward from about 60% sand, 35% silt, and 5% clay at the base to about 40% sand, 50% silt, and 10% clay at the top (grain-size data and radiocarbon dates summarized from figures 8 and 9 in Johnson, 1996)

2Ab — **2Ab horizon**—Light-gray organic sandy silt to silty sand. Forms uppermost horizon of buried surface of Gilman Canyon Formation. Radiocarbon date from bulk organic carbon sample are about 27.6 ka (see discussion and fig. 7A)

2Btb — **2Btb horizon**—Light-reddish-brown sandy silt. Bt horizon based on presence of blocky structure and superposition between A horizons. Radiocarbon date from bulk organic carbon sample is about 29.3 ka (see fig. 7A)

3Ab — **3Ab horizon**—Light-gray organic silty sand. Forms upper horizon of middle soil of Gilman Canyon Formation. Radiocarbon date from bulk organic carbon sample is about 30.6 ka (see fig. 7A)

3Btb — **3Btb horizon**—Light-reddish-brown sandy silt. Bt horizon based on presence of blocky structure and superposition between A horizons. Radiocarbon date from bulk organic carbon sample is about 30.7 ka (see fig. 7A)

4Ab — **4Ab horizon**—Light-gray organic silty sand. Forms upper horizon of lower soil of Gilman Canyon Formation. Radiocarbon dates from bulk organic carbon samples are 27.5 ka (not reliable, Johnson, 1996) and 33.5 ka (see fig. 7A)

4Btb — **4Btb horizon**—Light-reddish-brown sandy silt. Bt horizon based on presence of blocky structure and superposition between A horizons. Radiocarbon dates from bulk organic carbon samples are 33.5 ka and 35.6 ka (see fig. 7A)

5Ab — **5Ab horizon**—Dark-gray organic-rich silty sand. Forms single soil on buried surface of Gilman Canyon Formation on the downdropped (landslide) block. A single radiocarbon date from bulk organic carbon is 27.8 ka, which means that the 5Ab and 2Ab horizons were probably forming at the land surface concurrently (see fig. 7A)

5Btb — **5Btb horizon**—Light-reddish brown sandy silt. Bt horizon based on slight reddening of material, angular blocky structure, and position beneath 5Ab horizon. No radiocarbon dates from this horizon. Only exposed at base of bluff and in hand-dug trench. Locally grades to coarse sand at base (indicated by stipple pattern)

5Cn — **5Cn horizon**—Undifferentiated loess. Mapped south of the northern of two prominent faults (slip planes) at 15-18 m (horizontal distance) on the trench (fig. 7A)

6 — **Unit 6**—Crete Formation (middle? Pleistocene; >130? ka)—Light-reddish-brown (upper part) silty sand (Sangamon Soil?) and light-brown sand to sandy gravel (fluvial) containing rounded stream pebbles derived from upstream rocks having a Rocky Mountains provenance. Only about 1 m of section is exposed. Presence of Sangamon Soil, correlation with Crete Formation, and suggested age from Johnson (1996)

EXPLANATION OF SYMBOLS IN TRENCH AND BLUFF EXPOSURE

Contact, stratigraphic and/or soil horizon—Dashed where subtle or gradational, queried where uncertain

Fault (slip plane)—Arrows indicate relative sense of motion

Shear zone—Narrow zones of sheared material (primarily Peoria Loess, Cn) between slip planes. In the hand-dug trench, some shear zones contain mixtures of Peoria Loess and the 5Ab horizon of the Gilman Canyon Formation

Burn layer—Burn layer as evidenced by lateral concentrations of charcoal (chunks and fine disseminated particles). Reflects former vegetated land surface

Sample locality for radiocarbon analysis and corrected age determination in ^{14}C yr B.P.—Samples are bulk-organic carbon dated by accelerator mass spectrometry (AMS), except where noted (charcoal associated with burn layers). See Johnson (1996) for details of his analyses; sample localities are indicated by box symbols. Sample locality for this study is shown by a triangle symbol.

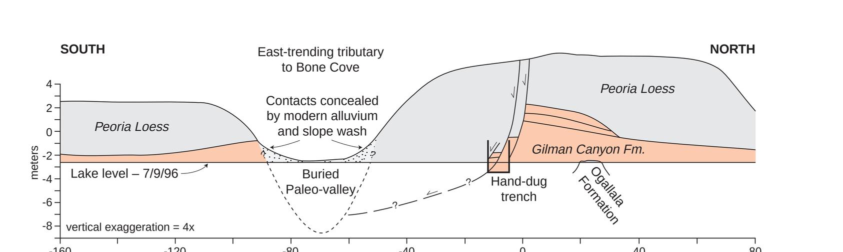

Figure 9. Schematic cross section along the west side of Bone Cove showing inferred geometry of the Harlan County fault (landslide).

FIELD INVESTIGATIONS OF SUSPECTED LATE QUATERNARY FAULTS IN CENTRAL NEBRASKA — EVIDENCE OF NON-TECTONIC ORIGINS

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