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Geology of the Loess Hills Region[1]

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The narrow ridges and steep bluffs which extend in a narrow band along the Missouri Valley form the Loess Hills region. These bluffs stand in sharp contrast to the flat-lying Missouri River floodplain. The unique ridge forms are composed of thick accumulations of late Wisconsinan wind-blown silt (loess). Older Quaternary deposits as well as Cretaceous and Pennsylvanian bedrock outcrop beneath the loess in the region. The intricate texture of the topography results from the combined effects of eolian deposition, fluvial erosion, and mass-wasting. Physical properties of loess allow it to maintain nearly vertical faces when exposed. These properties also produce special problems: slope instability, severe gullying, and high erosion rates. The high relief and rough terrain provide slope aspects which vary widely in exposure to sun, wind, and moisture. These factors have produced a mosaic of microenvironments noted for their unusually xeric ecology.

INDEX DESCRIPTORS: Quaternary geology, loess, Loess Hills, landscape development, landuse hazards, soil engineering.

The Loess Hills are one of Iowa's most distinctive physiographic regions. These hills border the full length of the Missouri Valley in western Iowa, and are characterized by an angular, corrugated appearance of steeply pitched ridges and troughs (Figs. 1 and 2). The western boundary of this picturesque region is abrupt, with precipitous bluffs rising sharply from the level lowlands of the Missouri River floodplain to ridge-top summits 60 to 90 m (200 to 300 ft) higher. The eastern boundary is not as well defined, and the hills merge gradually into the more rolling, rounded landscapes characteristic of western Iowa. In the heart of these hills, usually within 4 to 16 kilometers (2.5 to 10 mi) of the Missouri Valley, the terrain is sharp-featured, with irregular peaks and saddles along the narrow ridge crests, numerous steep sidespurs often marked by series of terracettes or "catsteps," and a dense drainage network with intricate patterns of dissection (Fig. 3). The region's distinct topography is also reflected in strong contrasts of landuse. Surrounded by geometric, cultivated field patterns, the rough-textured hills retain their natural vegetative cover of short-grass prairie on exposed and excessively drained ridges, with wooded galleries on the lower hillslopes and in protected hollows where a cooler and more moist soil-moisture regime prevails.

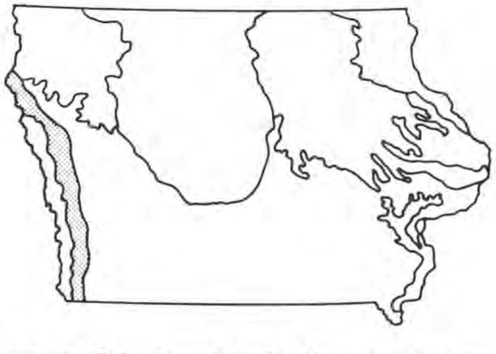

Fig. 1. Location of the Loess Hills landform region in Iowa.

Fig. 2. Aerial view of a typical Loess Hills landscape near Preparation Canyon State Park in Harrison County.

Loess is a light yellowish brown, brownish yellow, brown, grayish brown or pale brown (10YR 5/2, 5/3, 5/4, 6/3, or 6/6) gritty, wind-deposited silt whose predominate mineral is quartz. {These color terms and letter/numeral descriptors are part of the Munsell color system for identifying and recording the color of soils and deposits. This is a standard system used extensively by soil scientists and geologists in the United States and Canada (e.g., Hallberg et al., 1978A).} Tens of thousands of square kilometers of the midwestern United States are covered with loess; in itself, it is not an unusual material. Indeed, loess forms the parent material for broad areas of the nation's richest agricultural soils. Notable deposits also occur along the Lower Mississippi Valley, the Platte Valley, and in eastern Washington, as well as in Europe and China. Many of these loess deposits are associated with major alluvial-valley sources, as they are in western Iowa.

The region of deep loess coincides closely with the wide, north-south segment of the Missouri River valley, roughly from Sioux City to Kansas City. The source of the silt was the adjacent valley, which during late Pleistocene time was flooded with sediment-laden melt-water released from glaciers to the north. Though loess occurs on both sides of the Missouri River, the deposits are thicker and more extensive in Iowa and Missouri than in Nebraska and Kansas. In western Iowa there existed just the right combination of climate, abundant outwash material, and valley width for unusually thick deposits to accumulate. These deposits are thick enough to obscure the older relief developed on the preexisting landscape. Loess thickness is generally in excess of 19 m (60 ft) and depths of 47 to 62 m (150 to 200 ft) have been recorded. The result is that thick loess deposits and their subsequent modification by erosion are the dominant elements in the develop-

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Fig. 3. Intricately dissected Loess Hills near the junction of the Maple (background) and Missouri Rivers at Turin, Monona County.

ment of the present day Loess Hills topography.

The exceptional loess thickness, plus its uniform grain-size, permeable character, easy erodibility, and propensity to stand in near-vertical faces explains much about this striking topography and the interest it holds for geologists, ecologists, engineers, and past as well as present inhabitants. The unique topographic expression of the Loess Hills has prompted comment and study by geologists and naturalists for many years. David Dale Owen writing in the mid-1800s referred to the deposits as "silicious marl," the left-overs of sediment accumulated in an ancient lake (Owen, 1852). By 1870, State Geologist Charles A. White still agreed with Owen on the origins, but referred to the hills as the "Bluff Deposit" and noted its similarity to ". . . that deposit in the valley of the Rhine (Germany), known there by the provincial name of 'loess'." (White, 1870, p. 104). White correctly looked to northwestern Iowa, the Dakotas and Nebraska for the source of this material, and commented that fine sediment was especially abundant within the drainage basin of the Missouri ". . . because the whole region was strewn with grindings fresh from those 'mills of the gods' — the glaciers." (ibid, p. 117). It remained for Bohumil Shimek, writing on the *Geology of Harrison and Monona Counties*, in the Iowa Geological Survey Annual Report for 1909, to accurately describe the remaining important factors — wind and erosion.

ORIGIN AND PROPERTIES OF THE LOESS

The Missouri River valley occupies a key position in the geologic history of the Loess Hills. Extensive late Wisconsinan ice sheets in northcentral Iowa, western Minnesota, and the Dakotas were drained by the Missouri. During this time, the Missouri Valley served as a major channelway for large volumes of meltwater and sediment. The broad valley contained a braided river with numerous, interconnected shifting channels and, during low stage, an extensive barren floodplain. As melting slowed and water volumes were reduced during thousands of Pleistocene winters, strong winds winnowed and sorted the dried deposits exposed on the wide floodplain and swept the finer material aloft into long columns and clouds of dust. These sediment-laden winds dropped most of their load quickly as they moved out of the broad valley and away from the turbulent air along the valley margins. Modern analogs to this process of loess deposition have been described in some Alaskan valleys draining large valley glaciers (Péwé, 1951; Trainer, 1961). The greatest and coarsest accumulations of loess occurred nearest the Missouri Valley source. Finer-size particles were carried as far as 256 km (160 mi) downwind.

Several loess dispersion models have been developed to explain the distribution, thickness, particle-size distribution, and age of the loess relative to its source. These models mathematically describe systematic variation in selected properties of the loess. Hutton (1947) described thinning of the loess away from the Missouri River in southwestern Iowa using a semilogarithmic relationship. To account for thicker Wisconsinan loess close to the source, his equation required a change in constants at a distance of about 22 km (14 mi) from the source. Ruhe (1969) and Worcester (1973) emperically fitted hyperbolic relations of the form $y = 1/(a+bx)$ where y is the loess thickness and x is the distance from the source. These equations describe the fact that the loess progressively thins away from the source and that the rate of thinning progressively decreases per equal unit of distance along the way (Ruhe, 1969).

These studies assumed that the loess thickness pattern observed in western Iowa resulted from the transport and deposition of the loess by prevailing northwesterly winds. These models did not adequately explain the great thickness of the Wisconsinan loess in the Loess Hills region or the occurrence of loess on the upwind (west) side of the Missouri River valley.

Handy (1976) developed a model which suggests that the linear relationship between loess thickness and logarithm of distance from the source is not a result of prevailing winds but of the natural, variable wind directions (Fig. 4). This model explains the observed loess thickness nearer the source as resulting from winds nearly paralleling the source, thereby restricting the corridor of deposition and increasing the rate of loess deposition close to the source. This model does not explain the extraordinary loess thickness observed within the Loess Hills immediately adjacent to the source. He suggests several causes for this phenomenon including: a still-rising dust cloud near the source which would produce a higher concentration of particles in the air and increased deposition in that area; the bluffs along the valley locally deflecting the winds to a higher crossing angle, thereby locally modifying the deposition pattern; and local interbedding of dune sands.

Particle-size distribution of the loess also relates systematically to distance from the source (Ruhe, 1969; Worcester, 1973; Olson and Ruhe, 1979). Coarse silt content decreases away from the source while the amount of fine silt and clay-sized particles increases. The median diameter, which is the midpoint size of all particles, decreases. These changes occur as a result of sorting by wind. Lutenegger (1979) elaborated on the Handy-model, and developed a random-walk, variable wind model that simultaneously predicted loess thickness and particle-size distribution in relation to source and wind variables. This expanded model helps to explain many of the variations in loess thickness and distribution patterns exhibited in the Upper Mississippi Valley.

Three stratigraphically superposed loesses are present within the Loess Hills (Ruhe, 1969). All of these thin with distance away from the Missouri Valley source. The depositional systems of the three loesses — Loveland of supposed Illinoian age, lower Wisconsinan (Roxana), and upper Wisconsinan (Peoria) — are alike in kind but differ in detail.

A third interesting feature of Missouri River valley-source loesses is that the basal radiocarbon age of the upper two loess units becomes progressively younger with distance from the source area (Ruhe, 1969; Olson and Ruhe, 1979). The age of the base of the lower Wisconsinan loess is 31,080 RCYBP (radiocarbon-years before present) near the source and 22,200 to 23,200 RCYPB at a distance of about 40 km (25 mi) (Ruhe, 1976). The age of the base of the upper Wisconsinan loess decreases from 24,750 years near the source to 19,200 RCYBP at a distance of about 260 km (162 mi) (Ruhe, 1969; Olson and Ruhe, 1979). The loess units then, can be envisioned as progressively younger, thicker wedges which have greater distribution

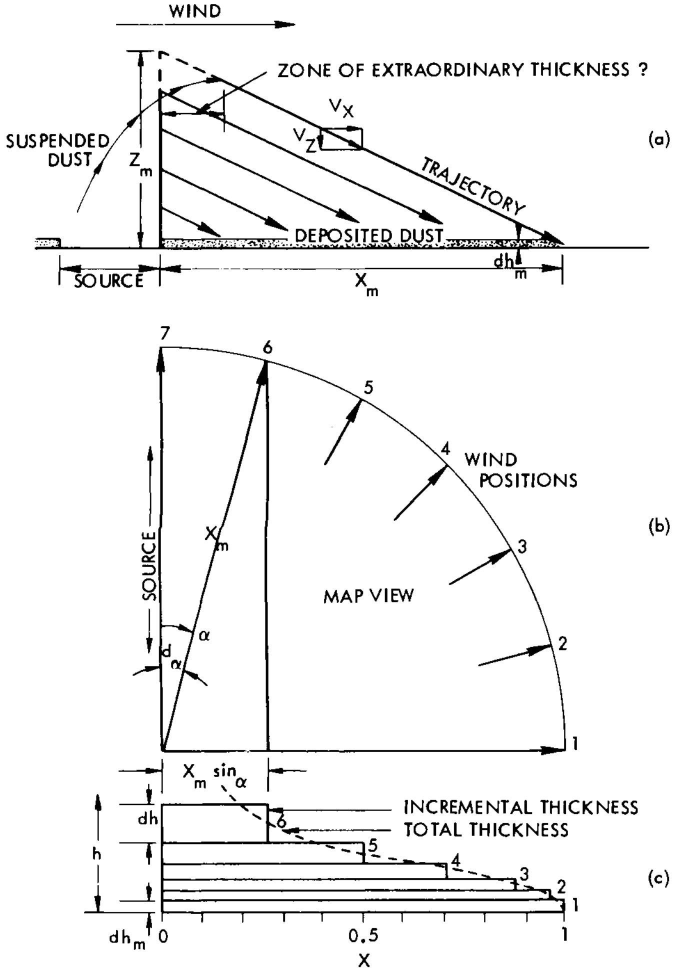

Fig. 4. Theoretical loess thickness distribution developed by a variable wind direction, other factors being constant. a. Uniform layer thickness dh_m is deposited by a wind perpendicular to the source, the layer extending to a maximum distance X_m from the source. b. Width of the dust depositional corridor is compressed to X_m sin α where α is the wind angle, causing (c) corresponding increases in thickness close to the source (Handy, 1976, Figure 3).

away from the source area. Additionally, the rate of loess deposition was not uniform throughout the late Wisconsinan. In the Loess Hills region, thin "dark bands" enriched in organic carbon, representing local incipient soils developed during periods of very slow or no deposition, are encountered within the loess section (Daniels et al., 1960). Radiocarbon dating of organics contained within the dark bands indicates that loess deposition rates also varied between these intervals (Ruhe et al., 1971).

The lowest and oldest tracable loess unit in the Loess Hills is the Loveland Loess (Ruhe, 1969; Daniels and Handy, 1959). This unit is inferred to be of Illinoian age for three reasons: 1) the loess buries a paleosol (Yarmouth?) developed on underlying deposits and is in turn buried by Wisconsinan loesses; 2) it has long been assumed that loess deposits are associated with glacial conditions, and the glacial episode preceding the Wisconsinan is the Illinoian; and 3) a soil correlated with the Sangamon Soil in Illinois is developed into the Loveland Loess; in Illinois and southeastern Iowa, the Sangamon Soil is developed into Illinoian till (Follmer, 1978; Hallberg et al., 1980).

The characteristics of loess often are not uniform at a given location. Near the Missouri River valley, eolian sand as well as sandy and gravelly sidevalley alluvium may interfinger with the loess. This is typically the case where extreme thicknesses occur. In these settings the loess often buried pre-existing valleys and the loess and local fluvial deposits are interbedded, filling the old valley form.

Several post-depositional alterations of the Wisconsinan loess also cause it to vary in appearance from exposure to exposure and even within a single locality. In most exposures the loess is brown or yellowish brown colored and is referred to as the oxidized zone. Deeper exposures often reveal a gray-colored zone which contains dark-brown iron stains (mottles) as well as vertical tubular iron segregations commonly called "pipestems." This is the deoxidized zone, often referred to as "deoxidized loess" (Ruhe, 1969; Hallberg et al., 1978A). Sometimes a gray or greenish-gray zone having no iron segregations lies beneath the deoxidized zone. This is the unoxidized zone. The deoxidized and unoxidized weathering zones owe their origin to chemical reactions (reduction of iron) associated with water-saturated conditions. In the past, water tables were higher and these zones were saturated. The deoxidized zone was characterized by fluctuations of the water table producing occasional oxidizing conditions and promoting segregation of free iron into mottles and pipestems along old root channels and other large voids in the loess matrix. The oxidized zone, on the other hand, was generally above the water table, and its iron compounds are in a more oxidized state resulting in the characteristic brown or yellowish brown color.

Weathering has produced other secondary changes in the loess. Most of the Wisconsinan loess contained abundant silt-size grains of carbonate when it was deposited. As water percolates through the soil at the land surface, it reacts with organic matter to produce weak acids which move downward with the infiltrating water and dissolve carbonate grains in the loess matrix. The uppermost zone in some loess sections has had all of its original carbonate removed. This is referred to as the leached zone (Hallberg et al., 1978A). Most of the loess in the Loess Hills still retains a large amount of its original carbonate and is referred to as unleached. Some of the carbonate removed from the leached zone by percolating water is segregated into nodules or concretions called "secondary carbonate." These concretions of secondary carbonate can reach baseball or grapefruit size and may be spheroid or elongate and branching. These hard carbonate concretions are often called "loess kindchen" (loess dolls), a German name applied to similar concretions found in the thick loess deposits along the Rhine Valley.

OTHER GEOLOGIC MATERIALS IN THE LOESS HILLS

The appearance of the Loess Hills landscape at the close of loess deposition, and the character of the topographic relief on the underlying glacial drift and bedrock surfaces are not well known. It is known, however, that the loess varies considerably in thickness and, close to the Missouri Valley, numerous outcroppings of other geologic materials are observed. Extensive post-glacial erosion has stripped large quantities of loess from the upper slopes. Beneath the loesses are older deposits consisting of bedrock, Pre-Illinoian tills, and fluvial sands and gravels.

In the southern two-thirds of the Loess Hills region, the Quaternary deposits are underlain primarily by Pennsylvanian bedrock. Quarries are developed into Upper Pennsylvanian Kansas City Group limestones along the bluff line near Thurman, Council Bluffs, and Crescent (Hershey et al., 1960; Landis and Van Eck, 1965). The northern third of the region is underlain by Cretaceous bedrock deposits. Fossiliferous Greenhorn Limestone and the underlying Graneros Shale both outcrop in Stone State Park north of Sioux City and along the Big Sioux River in Plymouth County. In the Sioux City area the upper Dakota Formation Woodbury Member, consisting of interbedded shales, limestones and sandstones, outcrops beneath the

Graneros Shale (Brenner et al., 1981). Numerous brick and tile quarries are developed into these shale units. The differing bedrock lithologies affect the overall morphology of the Missouri Valley adjacent to Iowa. The very broad valley, in the north, is underlain by the Cretaceous deposits; the valley narrows abruptly in the Harrison County area where it enters the more resistant Pennsylvanian strata.

Eroded remnants of Pre-Illinoian till sheets often bury the bedrock surface. Formerly only two major till sheets were recognized, Kansan and Nebraskan, but recent work has demonstrated that at least seven distinct tills are present (Shimek, 1910; Ruhe, 1969; Hallberg and Boellstorff, 1978). Since these tills are overlain by Illinoian-age Loveland Loess and are, in part, correlative with tills buried by the Illinoian-age Kellerville Member till in southeastern Iowa, they are collectively referred to as Pre-Illinoian (Hallberg et al., 1980).

Numerous sand and gravel sequences are interbedded with the Pre-Illinoian tills in this region. Because these deposits are buried by "Kansan" till they were called "Aftonian" by early geologists (Calvin, 1905; Shimek, 1909; Hay, 1914). Since there are not just two but several Pre-Illinoian tills in western Iowa, the correlation of all gravels and paleosols, buried by a till, to the Aftonian period is not valid, and therefore we now include all these deposits in the broad time period — Pre-Illinoian. Sand and gravel deposits in the Loess Hills are of particular interest and importance because some contain vertebrate and invertebrate fossils. Localities such as the Turin gravel pit in Monona County have yielded outstanding fossil remains which give us glimpses of the environments and fauna of the past (see Rhodes and Semken this volume). These deposits also record histories of valley development interrupted by advancing glaciers and loess deposition. As yet, these histories are poorly understood.

A notable wind-blown deposit occurring within the Pre-Illinoian sequence in the Loess Hills is volcanic ash. A well known exposure of this deposit is found at the County-Line Ash Site, along the bluff line near the Harrison-Monona County line (Shimek, 1910). This ash deposit, fission-track dated at approximately 600,000 years before present, originated from eruptions of now-extinct volcanoes in Yellowstone National Park, Wyoming. This is one of the Pearlette Family of ashes widespread in the Quaternary sequence of the mid-continent (Nasser et al., 1973; Boellstorff, 1978; Izett and Wilcox, 1982). This and other ash deposits in western Iowa, although patchy in distribution, play an important role in dating and correlation of the Pre-Illinoian sequence.

Thus, while the Loess Hills are foremost a topographic form developed in thick loess deposits, older diverse geologic materials occur beneath them and here and there are exposed to view. The scalloped character of the Missouri Valley bluff line results in part from the presence or absence of these older materials near the land surface and their differential resistance to lateral erosion of the valley sides. Similarly, abrupt changes in hillslope form are likely coincident with changes in these materials. The steep, upper slopes, often marked by "catsteps," are formed in loess; these slopes often change abruptly to more gentle slopes below, developed on glacial till or on sand and gravel with a mantle of colluvial deposits.

Although the loess originated as a wind-blown deposit, the Loess Hills landscape is equally a product of fluvial erosion. The thick, late Wisconsinan loess which is so prevalent in the area today accumulated on an eroded landscape with ridges and deep narrow valleys. In some areas this pre-late Wisconsinan topography is mimicked in the modern landscape, but in other areas, the old landscape is not evident and its former valleys are filled with thick increments of interfingering late Wisconsinan loess, colluvium, and alluvium. Some of the deeper "loess" thicknesses measured in wells clearly reflect this situation.

Loess also covers older Missouri River terraces. Today most of the remaining loess-mantled terraces in the Missouri River valley are in the Sioux City and Omaha-Council Bluffs areas and in the lower reaches of the major valleys draining western Iowa. Several radiocarbon dates on wood contained in alluvium within the loess-mantled terrace in the Omaha-Council Bluffs area indicate that this former Missouri River floodplain was active about 22,000 RCYBP (Dahl, 1961; Miller, 1964; IGS unpublished data). Lateral migration of the Missouri River into the bluff line during and following loess deposition produced the crescent-shaped valley margin and other topographic features such as hanging valleys and truncated spurs (Fig. 5). The latter represent former stream divides which were partially removed by migration of the river into the bluff line producing a roughly triangular-shaped steep slope rising abruptly to the upland.

Fig. 5. Truncated spurs and catstep development along the bluff line near the Harrison-Monona County border. The flat-lying Missouri River floodplain is in the foreground.

Many streams in the Loess Hills remained active during loess deposition. Hallberg (1979) suggests that upper parts of the drainage network in the Loess Hills developed preferential northwest to southeast alignment in response to strong northwesterly winds during the late Wisconsinan. Streams occupied deep gullies which were episodically filled with silty deposits derived from erosion of the gully walls and adjacent valley slopes, then trenched again as a new gully extended headward up the valley. Episodic cutting and filling of gullies in the Loess Hills continued throughout the postglacial or Holocene period. Investigations in western Iowa and eastern Nebraska have shown that at least five episodes of gully cutting and filling occurred in small valleys in the Middle Missouri River drainage during the last 10,500 years (Daniels and Jordan, 1966; Bettis and Thompson, 1981; 1982). The timing of each episode was synchronous in similar parts of the drainage system throughout the area.

Silty Holocene alluvial deposits resulting from the gully filling episodes are collectively referred to as the DeForest Formation (Daniels et al., 1963). Six lithologically distinct alluvial fills produced during these episodes of gully filling have been recognized in the DeForest Formation (Bettis and Thompson, 1982). Figure 6 outlines changes in an idealized small western Iowa valley during the last four of the gullying episodes. The Watkins Member of the DeForest Fm. began accumulating around 10,500 RCYBP and continued to fill the small valleys until about 8,000 RCYBP. During that time, early Holocene deciduous forests gave way to savannah, and eventually to prairie as the climate became drier (Van Zant, 1979; Grüger, 1973). In the mid-to-late-middle Holocene (approximately 7,000 to 3,500 RCYBP) numerous gullying episodes removed large quantities of early Holocene and late Wisconsinan deposits from small valleys. This major hiatus, spanning the driest portion of the post-glacial period ("Altithermal"), is called the DeForest Gap. Deposits eroded from upper portions of the drainage network during development of the

DeForest Gap accumulated in alluvial fans at the junction of the small valleys with larger valleys, such as the Boyer River valley. Deposits making up the alluvial fans are the Corrington Member of the DeForest Fm. Following this major period of gully erosion and alluvial fan construction, the climate became more moist and valleys filled with large volumes of sediment derived from fluvial erosion and mass-wasting of gully walls and steep slopes developed in thick loess. These deposits are known as the Hatcher Member. Between 2,000 and 1,800 RCYBP another gullying episode occurred, but the gullies did not extend as far up the drainage network as they had during previous episodes. After 1,800 RCYBP these gullies stabilized and were subsequently filled with the Mullenix Member. Around 750 RCYBP another episode of gully growth took place and the Mullenix fill was trenched. This gullying episode was short-lived and much less extensive in effect than were previous episodes. By 250 years ago the former gullies were rapidly filling with the Turton Member. The present gully growth cycle began between about 1860 and 1900 A.D. Effects of the historic episode have been enhanced by land clearing, channelization, grazing, and cultivation. Deposits accumulating at the base of slopes, along streams, and in gullies during the historic period are collectively referred to as the Camp Creek Member.

The modern Loess Hills landscape is a product of several gully cutting and filling episodes which have altered the thick loess accumulations. These episodes have occurred repeatedly during at least the last 25,000 years (Daniels et al., 1963; Rhodes, 1984). Throughout most of this period, man was not significantly affecting vegetation cover and runoff patterns. Viewed in this light, the modern gullying episode was probably not caused by human activity but only exacerbated by it.

In addition to providing information on the Holocene evolution of the Loess Hills landscape, these fills also contain detailed records of the paleo-environmental and cultural history of the region (see Rhodes and Semken, this issue). Recent studies in the Loess Hills and adjacent parts of western Iowa and Nebraska have shown that the Holocene gully fills preserve an extensive — and previously unsuspected — archaeological record of prehistoric cultural adaptations in the Prairie-Plains environment. The extant archaeological record has been conditioned by the magnitude of gullying and slope erosion episodes (Bettis and Thompson, 1981; 1982; Thompson and Bettis, 1981).

The rugged character of the Loess Hills landscape promotes, and is in part produced by, strong contrasts in soil moisture, temperature, and vegetation. South and west-facing slopes are exposed to greater amounts of solar radiation than north and east-facing slopes. In response, the former slopes are warmer and drier than the latter (Shimek, 1911). Vegetation cover is often patchier on the more xeric south and west-facing slopes and surficial erosion rates tend to be higher. Evaporation and transpiration on ridges and exposed upper slopes is greater than in the protected hollows. The drainageways also tend to be more moist because the water table is closer to the surface in those areas and because of the movement of surface and shallow groundwater toward the drainages. Trees and other more mesic vegetation types find favorable habitats on the lower slopes and in the drainageways of the Loess Hills.

LANDUSE HAZARDS IN THE LOESS HILLS

The steep, ridged topography combined with the special physical properties of loess also impart some pecularities and problems to this region. Loess has sometimes been referred to as the "clay" which stands in vertical cliffs. Loess is not a clay, and the cliffs are seldom vertical. Here, in western Iowa, the loess is composed dominately of coarse silt particles. The steep slopes often range from 50 to 75 degrees in angle, and the steepness is related to geotechnical or engineering properties of the loess including its extreme erodibility and inherent vertical cleavage. The loess has a very low shear-strength when water-saturated, so low, in fact, that it can not bear its own weight in such high, steep cliffs. When relatively dry, however, the loess develops a greater apparent cohesion. This allows the loess to maintain the spectacularly bold bluffs and ridge-forms along the Missouri Valley, albeit in a rather tenuous fashion. Highway and railroad engineers in the region also utilize this property in constructing roadcuts, which commonly have steep, single walls or are benched with nearly vertical risers and horizontal treads. The relatively dry condition of the loess is maintained by the steep slopes which do not allow much infiltration, as well as by the relatively low precipitation and enhanced exposure to sun and wind. With construction and development in the area, however, these conditions can be altered — sometimes dramatically.

The strength of loess to resist block slides is mainly a function of its high porosity and resulting inability to sustain a high water table; if and when the loess ever does become wet to near-saturation, it loses strength and takes on the consistency of toothpaste. Usually saturation occurs only in the lower portion of the loess where the consequences remain invisible until they form a "skating surface" for landslides (Ruhe, 1954). Construction workers therefore must be cautious about cutting too deep into the loess, and should first have test borings made to determine the position of the saturated zone and the possible need to intercept the groundwater flow with drains.

When a saturated zone does not affect slope stability, the maximum height of a truly vertical cut in the loess is only about 4.9 m (16 ft) (Lohnes and Handy, 1968). Highway cuts therefore are either benched with bench heights less than 5 meters, or more commonly, they are cut back at less steep angles (Gwynne, 1950). The common county road cut that *looks* vertical is usually about 76°, or a rise of 4 vertical to 1 horizontal. Such a cut can stand to a height of about 7.3 m (24 ft). These figures are based on an average loess cohesion of $c = 200$ psf, a friction angle $\phi = 25°$, and an average wet unit weight $\gamma = 80$ pcf, substituted into the equation

$$H_{max} = \frac{4c \sin i \cos \phi}{\gamma[1 - \cos (i - \phi)]} = 9.06 \frac{\sin i}{1 - \cos (i - 25)}$$

where i is the slope angle (Lohnes and Handy, 1968).

A second well-known behavior of friable loess in the Loess Hills also relates to its porosity and water content: if saturated, it is not strong enough to support even its own weight. A natural result of this is that any inflow of water from the surface can create an area of severe settlement, or collapse. If there is a lower lateral exit for the slumping, eroding silt, the result is a "chimney" with a geometry as the name implies. Collapse also is common underneath pavements, initiating at leaky joints in the gutters. This is often counteracted by drilling holes through the pavement and pumping in grout. Collapse also can occur underneath building foundations, with devastating consequences, if care is not taken to divert surface-runoff water and water from downspouts, and to avoid excessive lawn watering or leaky water pipes. In one instance, collapse of a school foundation was initiated by levelling an adjacent area for a playground, which increased the infiltration of rain water. When the problem was recognized, further collapse was halted merely by paving the playground with asphalt and providing runoff gutters. Problems such as this are not confined to the Loess Hills but also occur in areas of intermediate loess thickness in southwestern and east-central Iowa (Handy, 1973).

A third, less well-known engineering problem with loess is that collapse can be initiated not only by excess water, but also by the weight of fill. Residential land developers frequently engage in cut-and-fill operations to soften the land contours, to flatten out slopes for yards and roads. Even though the fill may be placed and compacted with moisture-density control and tested in accordance with accepted engineering procedures, this still ignores what inevitably must occur

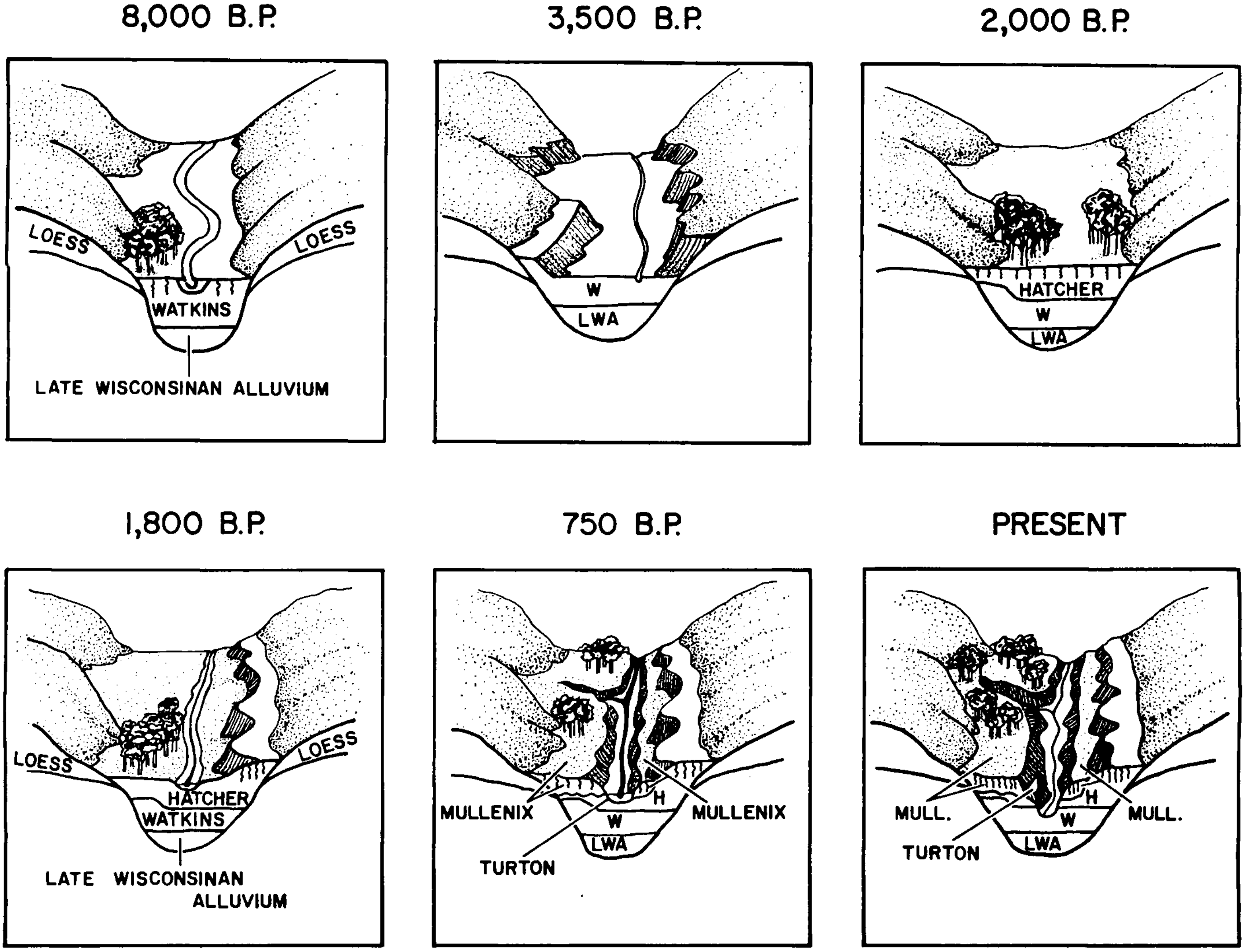

Fig. 6. Landscape evolution in an idealized, small Loess Hills valley during the last 8,000 years.

in the underlying loess; now overloaded beyond any previously existing load, the loess sooner or later will collapse and allow severe settlement to occur. Unfortunately such settlement is not uniform but depends on the thickness of the fill, which of course is quite variable as it feathers out toward the boundaries of cut areas. The worst situation is where structures bridge the boundary from a cut, where there should be little settlement, to a fill, where under some circumstances settlements may exceed 0.3 m (1 ft) or more. This can destroy a structure and is very difficult to repair, because even if the structure is supported on pile, the surrounding yard and interior garage and basement floors-on-grade will continue to settle. A required precaution can be to inject water into loess underneath the fill and use settlement monitoring devices to insure that all settlement has occurred prior to the initiation of construction.

Although most of the loess in the Loess Hills appears to be underconsolidated, which means that its density is less than the equilibrium density under the existing load, some is normally consolidated or has been compressed to equilibrium. Nevertheless, even though a collapse already may have occurred, as in the saturated lower loess and loess-derived alluvium, adding fill will, by adding weight, make the loess effectively underconsolidated and collapsible again. This gives rise to an interesting phenomenon; the added weight first squeezes water out of the lower, saturated loess upward into the unsaturated loess so that it collapses, and in turn, squeezes the water further upward to repeat and continue the cycle. This "retarded collapse" can continue for years or even decades and is indicated by an otherwise inexplicable upward mounding of the groundwater table. The point is that simply preventing the entry of surface water may not prevent loess collapse but will only retard it, because water for collapse may already be available within the lower reaches of the loess itself.

A particular kind of problem reported by several geotechnical consulting engineers and described by Hallberg et al. (1978) as "loess mush" has recently been investigated in some detail by Lamb and coworkers (Lamb, 1985). Lamb reports that loess mush, or liquid silt, is saturated and normally consolidated, but with an overburden load so low that the natural moisture content exceeds the soil liquid limit. This means that the mushy condition probably occurs only rarely if at all in the Loess Hills, where the water table is too low and overburden pressures too high. However, it does occur in loess elsewhere in Iowa and other areas, and only now is becoming recognized as a serious foundation problem.

The small-scale terracettes or "catsteps" (Fig. 5) present on many of the steep slopes in the Loess Hills represent another example of slope instability. Some investigators have suggested that these arise from

Fig. 7. Active gully in Mills County. Note nearly vertical sidewalls and slump in the gully bottom. Gully is approximately 30 m (98 ft) deep.

animal trampling (White, 1984), while others suggest that they are microslumps produced by shallow, successive failure of the loess and soils developed into it (Carson and Kirkby, 1972; Ruhe, et al., 1983).

Because loess is "loose" or friable, it is easily eroded by running water. This factor, combined with its collapsibility, contributes to other major natural problems — soil erosion and gullying. Soil erosion rates are very high in the Loess Hills. This results from a combination of long, steep slopes, easily eroded surficial deposits (loess), a climate characterized by recurrent drought and periods of intense rainfall, often patchy vegetative cover, and human or domestic-animal disturbance. Some of the soil eroded from the steep slopes enters gullies and drainage ditches, but a larger percentage is deposited at the base of the slopes or along gully margins. Within the Loess Hills proper, slopes are generally too steep to cultivate and domestic animal trails, over-grazing, feedlots, access roads, urbanized areas, and construction sites are the major types of disturbances. In these disturbed areas, soil erosion rates can be very high and the surface soil can be totally lost in a very short time. Even under native vegetation cover, the Loess Hills is an area of high soil-erosion rates. This is reflected in the dominant upland soils found in the area — Entisols and minimally developed Mollisols. These soils are thin and minimally developed as a result of continual surficial erosion and rapid runoff.

Western Iowa and the Loess Hills have a national reputation for high sediment loads in streams (Bondurant, 1970). This phenomena results, in large part, from gully erosion, rather than hillslope erosion. Thousands of acres of potential cropland are affected, or even lost from production annually as a result of gully growth (Fig. 7). In addition, large amounts of time and money are spent maintaining drainage ditches and stream channels which become choked with sediment eroded from gullies. Heavy sediment loads in many of the area's surface waters result in detrimental conditions for many aquatic species. Bridge and pipeline relocations necessitated by gully widening are a recurrent and costly problem in the region.

Large slump blocks often develop where contrasting materials, such as glacial till or sand and gravel outcrop beneath the loess. These may present problems for highway engineers and residents alike. The bluff line and valley slopes in the Loess Hills owe much of their character to slumpage of these diverse materials.

CONCLUSIONS

Iowa's Loess Hills are one of the state's and nation's unique scenic, geological, and biological resources. In addition, they are an outstanding example of two fundamental geological processes — the strong influence of past eolian or wind deposition, and erosional sculpture of the land. These origins also contribute to environmental hazards of gullying, slope failure, and collapse. In addition, the association of the loess, the topography, and the vegetation combine for a classic display of the close relationship between geology and ecology. In this high-relief area, the terrain provides a mosaic of unique ecological niches. The precipitous bluffs nearest the Missouri Valley are exposed to the enhanced effects of wind and weathering, and sustain distinctive, desert-like habitats which are important undisturbed footholds for unusual, native plant and animal communities. Much attention is currently focused on research and interpretation, as well as on inventory and preservation of these special natural areas within the Loess Hills.

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