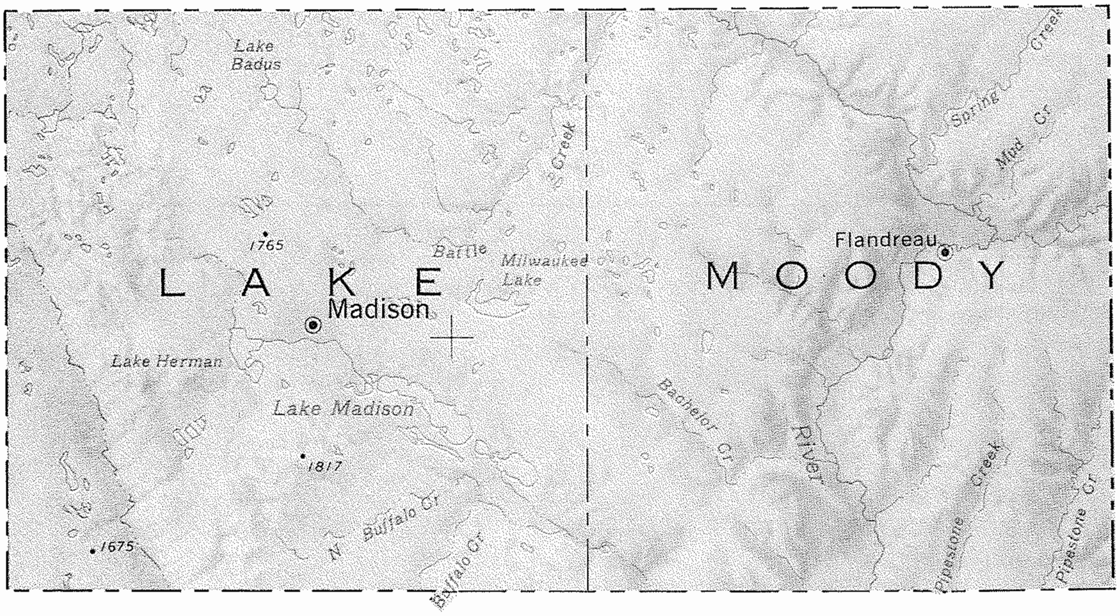
Bulletin 35

GEOLOGY OF LAKE AND MOODY COUNTIES, SOUTH DAKOTA

by R. H. Hammond
South Dakota Geological Survey



Prepared in cooperation with the
United States Geological Survey,
East Dakota Water Development District,
and Lake and Moody Counties.

DEPARTMENT OF ENVIRONMENT AND NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
Akeley Science Center
University of South Dakota
Vermillion, South Dakota
1991

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ABSTRACT

Lake and Moody Counties lie on the Coteau des Prairies in east-central South Dakota. Most of the surface of the two-county area is drained by the Big Sioux River except for a small area of southwestern Lake County which lies within the Vermillion River basin.

Rocks of Precambrian, Cretaceous, and Pleistocene ages are found in the area. The Precambrian rocks are composed of early Proterozoic igneous and metamorphic rocks overlain by early to middle Proterozoic Sioux Quartzite. The Sioux Quartzite forms a prominent ridge on the basement-rock surface, which rises sharply along the southern and eastern border of the study area.

Cretaceous rocks unconformably overlie the Precambrian complex and record a period of fluvial deposition in the Dakota Formation followed by cyclic-marine sedimentation of the Graneros, Greenhorn, Carlile, Niobrara, and Pierre Formations. An enigmatic, nearshore facies of these formations, the Split Rock Creek Formation, was apparently deposited along the shores of the Sioux Ridge during most of Late Cretaceous time.

Deposits of at least four Pleistocene continental glaciations are present in Lake and Moody Counties. Only the uppermost late Wisconsin drift may be confidently classified at this time. The next lower drift may be early Wisconsin in age, but could be much older. The two lowermost drift sheets are certainly pre-Illinoian.

The Pleistocene sediments are predominantly till but also contain outwash, loess, and lake deposits. The surface topography is dominated by youthful, stagnant-ice, constructional features where late Wisconsin drift forms the surface, while the older drift surfaces to the east are highly dissected by erosion and mantled with loess.

Sand and gravel deposits are the only economic minerals yet developed.

INTRODUCTION

This report describes a geologic investigation of Lake and Moody Counties, South Dakota. It is one of a series of cooperative studies conducted by the South Dakota Geological Survey (SDGS) and the United States Geological Survey (USGS). This study was designed to (1) gather, analyze and describe geologic data; (2) locate and evaluate the area's mineral and water resources; and (3) combine findings of this study with those from other similar studies to further the understanding of the geology of the state and region.

A companion volume, *Water Resources of Lake and Moody Counties*, (Hansen, 1986a) provides detailed information about the ground-water resources of the counties. Other reports completed during this study describe the sand and gravel resources (Tomhave, 1987a; 1987b) and the major aquifers (Hansen, 1986b) of the two-county area in short, easy-to-read pamphlets. All basic data resulting from the study will be available as an open-file report at SDGS in Vermillion.

Location

Lake and Moody Counties are located midway along the eastern border of South Dakota (fig. 1). They are bordered on the west by Miner County, on the north by Brookings and Kingsbury Counties, on the south by Minnehaha and McCook Counties, and on the east by Pipestone County, Minnesota. The combined area of Lake (582 square miles) and Moody Counties (520 square miles) is 1,102 square miles.

Physiography

Lake and Moody Counties lie upon the Coteau des Prairies, except for a small portion of southwestern Lake County which is within the James Basin (fig. 1). The Coteau is a broad, flatiron-shaped highland extending from Marshall County, South Dakota, at the North Dakota border, to Union County in the southeastern corner of South Dakota. In the northeastern part of the state, it forms a steep-sided plateau bounded on the east by the Minnesota River valley and on the west by the James River basin. In Lake and Moody Counties, the Coteau des Prairies is better termed a massive highland, the western edge gently sloping into the broad James River lowland to the west.

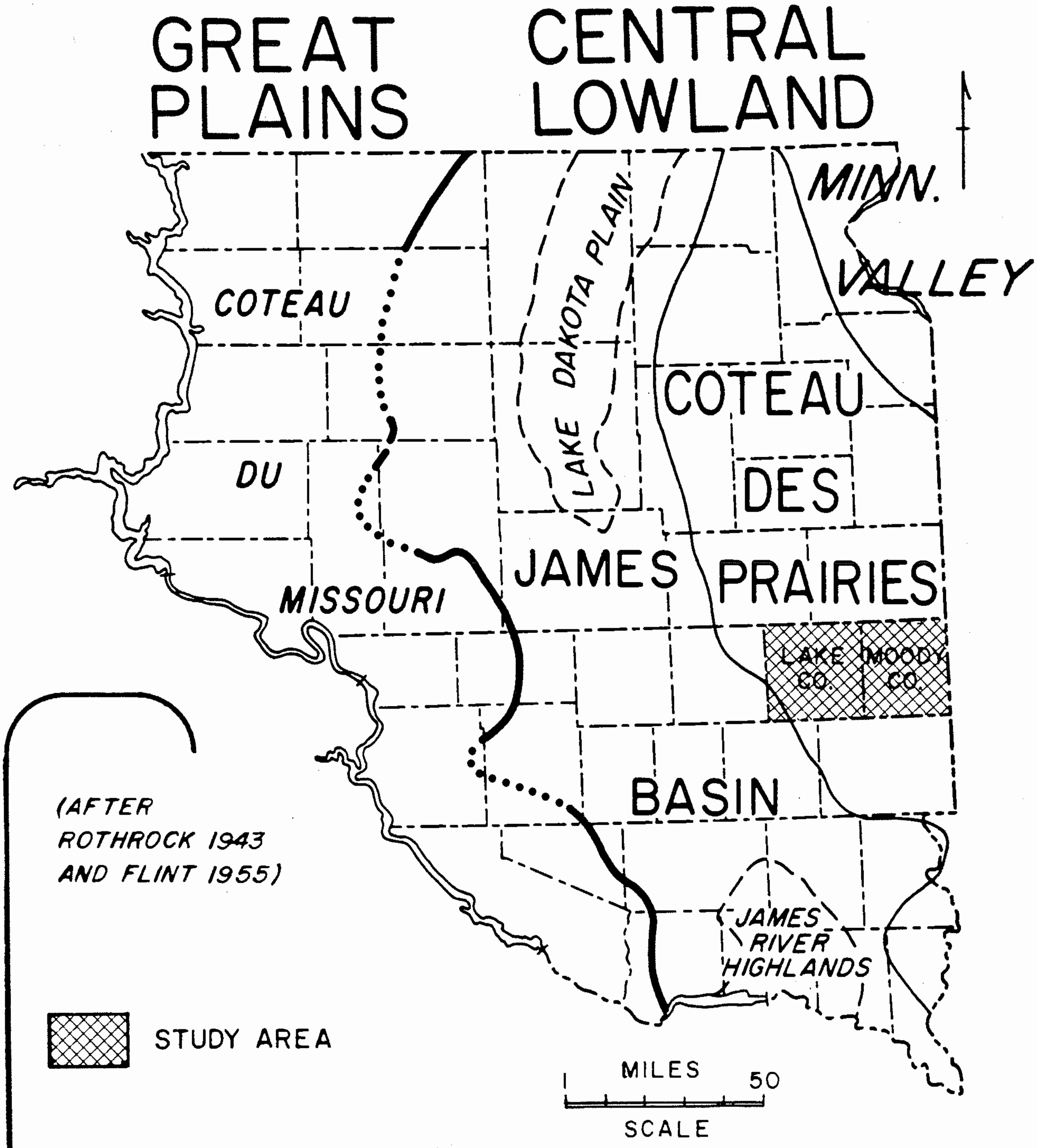
The Big Sioux River flows nearly the entire length of the Coteau, draining much of its central area. In the study area, as on much of the Coteau, the river separates two topographies. An older, well-drained, loess-mantled landscape is developed east of the Big Sioux valley, and rocky, lake-dotted, knob and kettle terrain is to the west.

That portion of the mapped area south of Winfred and west of the East Fork Vermillion River has been assigned to the James Basin Physiographic Division. In this area, the ground surface gradually declines to the southwest over low moraines separated by smoothly concave swales. These depressions commonly contain small, shallow lakes and poorly-incised, intermittent streams which flow southeastward between moraines.

Previous Investigations

Lake and Moody Counties have been included in a number of reconnaissance studies dealing with the general geology of South Dakota (Todd, 1894; Darton, 1909; and Rothrock, 1943). Flint (1955) mapped the Pleistocene sediments of eastern South Dakota. Tipton (1959a; 1959b) described the surface geology of the Dell Rapids and Chester quadrangles. Schroeder (1979) included the area in a study of till lithologies and stratigraphy.

In addition, ground-water surveys have been completed for the cities of Madison (Tipton, 1959c and Hammond and Green, 1991), and Dell Rapids (Barari, 1967). Lee and Powell (1961) investigated the geology and water resources of the Flandreau area. Ellis and Adolphson (1965) studied the hydrogeology of Skunk Creek-Lake Madison area; Ellis, Adolphson, and West (1969) studied portions of the Big Sioux basin.



(AFTER ROTHROCK 1943 AND FLINT 1955)

FIGURE I. PHYSIOGRAPHIC DIVISIONS OF EASTERN SOUTH DAKOTA AND THIS STUDY AREA.

Method of Investigation

Geologic work was completed during the field seasons of 1981 through 1984. Surface deposits and landforms were mapped on vertical aerial photographs having a scale of approximately 1:70,000 (1 inch = 0.9 miles) and on 1:24,000 topographic maps. This information was compiled on base maps at approximately 1 inch per mile. The resulting maps were drafted and reduced to publication dimensions (figs. 2 and 3).

Information obtained from widely spaced outcrops was supplemented by numerous power-auger holes, core-test holes, rotary-drill holes, and hand-auger holes. Subsurface information was obtained through field examination of drill cuttings, core, and electric logs from holes drilled by SDGS. Representative samples of drill cuttings and core were transported to Vermillion for laboratory testing and storage. Some information was obtained from the files of local well drillers and from an inventory of private wells (Hansen, 1986a).

Acknowledgements

The investigation and preparation of this report were performed under the supervision of C. M. Christensen. The writer wishes to thank State Geologist Merlin Tipton and the entire staff of SDGS for their advice and assistance throughout the project. Special thanks go to C. M. Christensen, Don Hansen, Wayne Schroeder, Rich Bretz, Bob Stach, and Derric Iles for sharing expertise and insights.

The study was initiated at the request of the County Commissioners of each county. The cooperation of the Commissioners and their constituents is gratefully acknowledged.

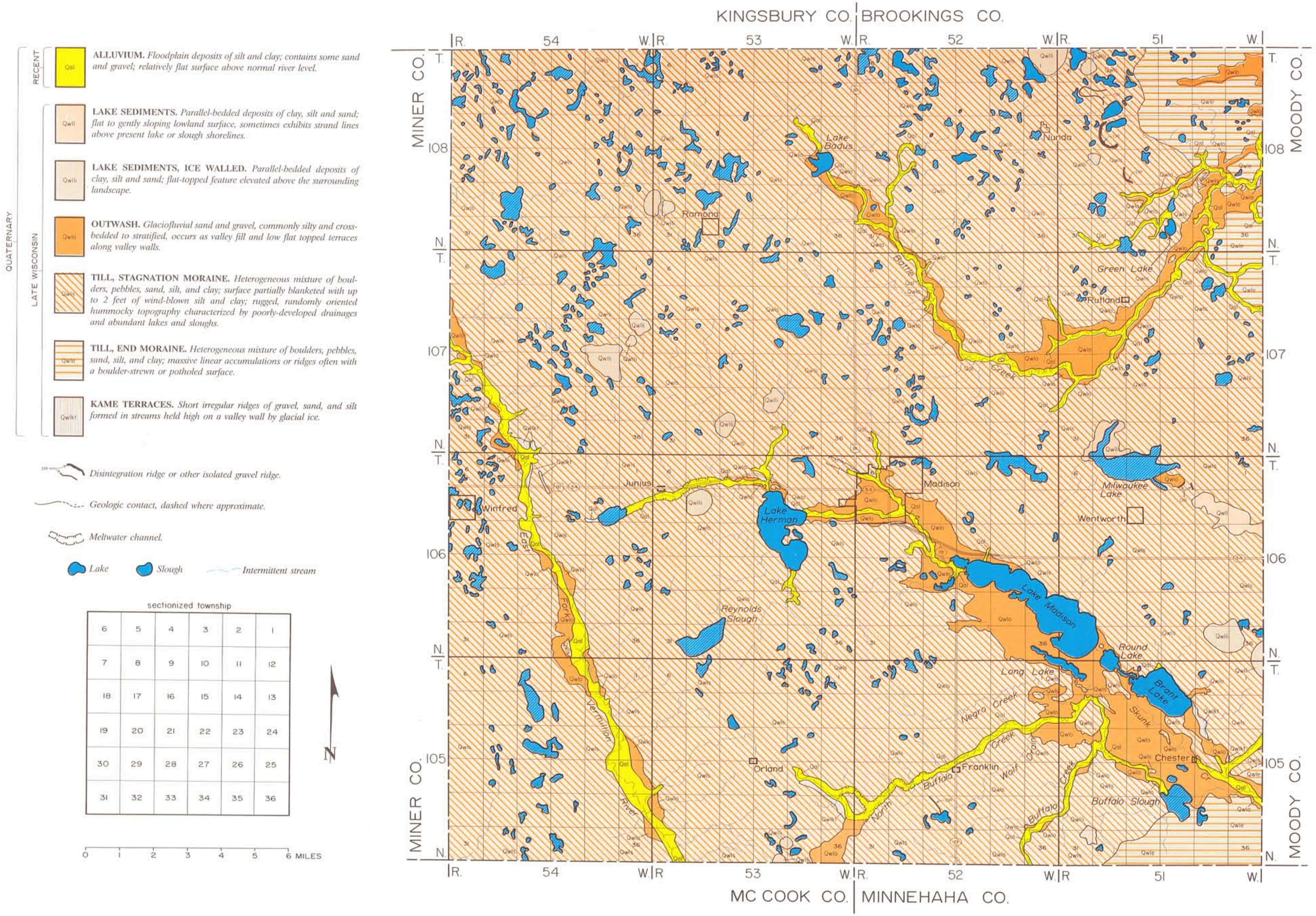
Financial assistance for the project was contributed by SDGS, USGS, East Dakota Water Development District as well as Lake and Moody Counties.

GEOLOGY

Bedrock Stratigraphy

Stratigraphic nomenclature used herein conforms to that accepted by SDGS (Agnew and Tychsen, 1965) and to the Code of Stratigraphic Nomenclature (North American Commission on Stratigraphic Nomenclature, 1983). Figure 4 shows the stratigraphy found within the study area. Only short descriptions of the bedrock formations encountered during the study are included in this report. For a more complete discussion of regional pre-Pleistocene stratigraphy, the reader is referred to Witzke and others (1983).

Figure 2. Geology and landforms of Lake County.



ALLUVIUM. *Floodplain deposits of silt and clay; contains some sand and gravel; relatively flat surface above normal river level.*

LAKE SEDIMENTS. *Parallel-bedded deposits of clay, silt and sand; flat to gently sloping lowland surface, sometimes exhibits strand lines above present lake or slough shorelines.*

LAKE SEDIMENTS, ICE WALLED. *Parallel-bedded deposits of clay, silt and sand; flat-topped feature elevated above the surrounding landscape.*

OUTWASH. *Glaciofluvial sand and gravel, commonly silty and cross-bedded to stratified, occurs as valley fill and low flat topped terraces along valley walls.*

TILL, STAGNATION MORAINE. *Heterogeneous mixture of boulders, pebbles, sand, silt, and clay; surface partially blanketed with up to 2 feet of wind-blown silt and clay; rugged, randomly oriented hummocky topography characterized by poorly-developed drainages and abundant lakes and sloughs.*

TILL, END MORAINE. *Heterogeneous mixture of boulders, pebbles, sand, silt, and clay; massive linear accumulations or ridges often with a boulder-strewn or potholed surface.*

KAME TERRACES. *Short irregular ridges of gravel, sand, and silt formed in streams held high on a valley wall by glacial ice.*

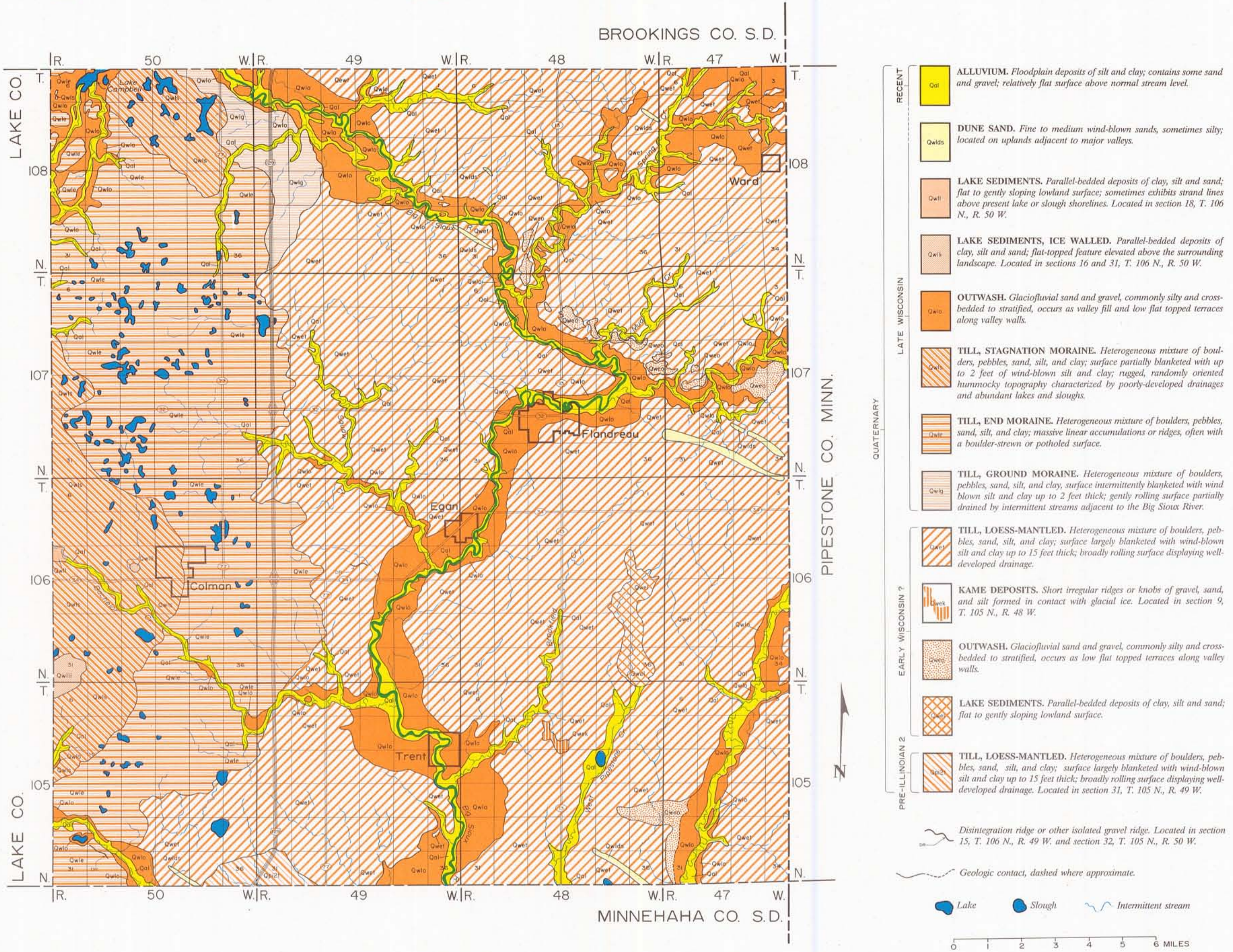
Disintegration ridge or other isolated gravel ridge.

Geologic contact, dashed where approximate.

Meltwater channel.

Lake *Slough* *Intermittent stream*

Figure 3. Geology and landforms of Moody County.



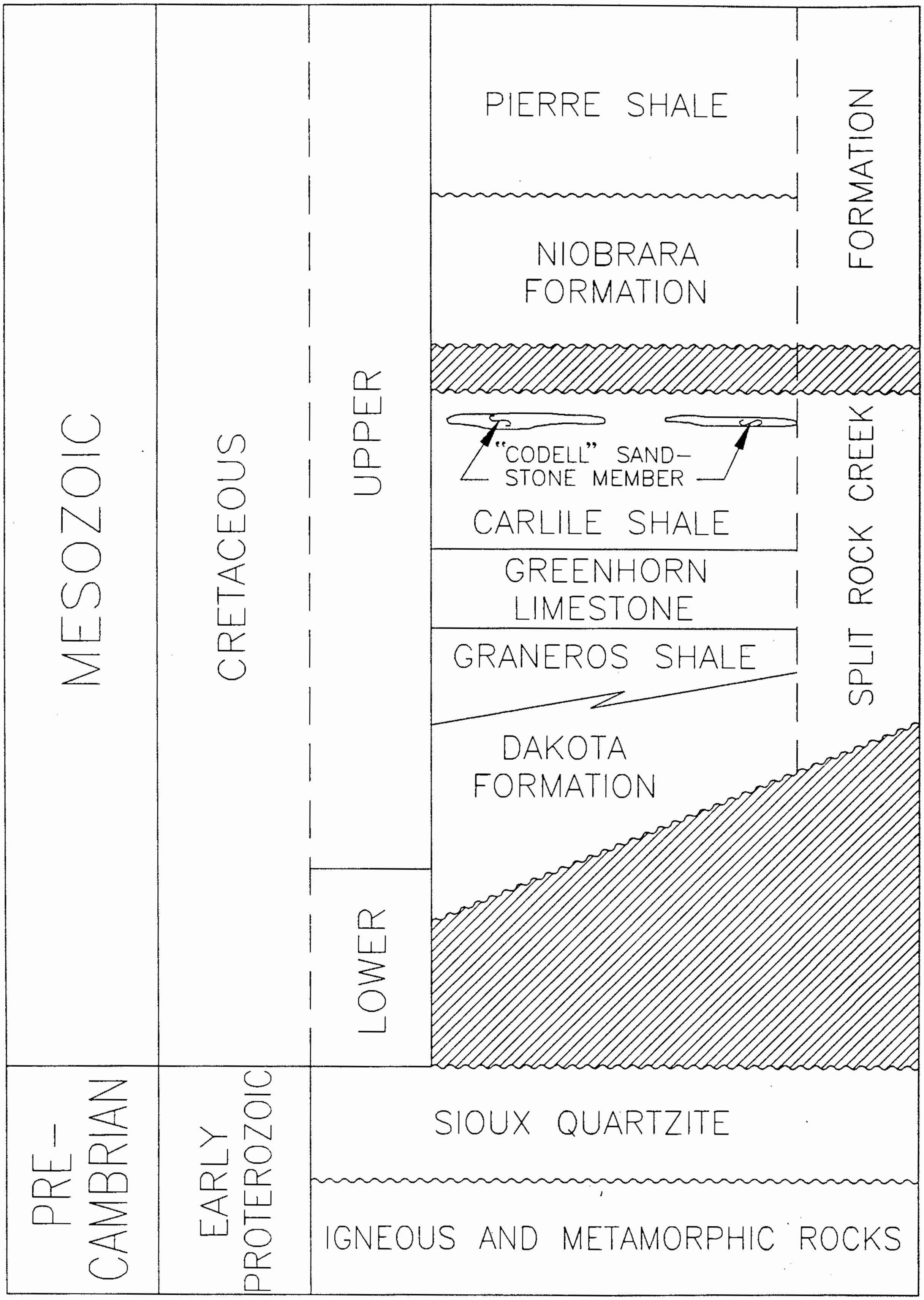


Figure 4. Stratigraphic correlation chart of bedrock formations in Lake and Moody Counties.

Precambrian System

CRYSTALLINE BASEMENT ROCKS

In east-central South Dakota, crystalline rocks have been found beneath the sedimentary sequence in several widely spaced drill holes. Rock types include granite, hornblende schist, andesite porphyry, quartz latite, felsitic tuff, and basalts.

Pink granite was encountered in an SDGS test hole located at sec. 22, T. 105 N., R. 54 W. in southwestern Lake County. This granite is presumably an eastern extension of granite occurrences noted by Steece (1961) in Davison, Hanson, and Miner Counties. Gravity and magnetic surveys of the study area (unpublished data from SDGS files) suggest that these granites underlie other parts of southern and southwestern Lake County as well.

The northeastern two-thirds of the area has a strong northwest-southeast banded pattern of highs and lows on both gravity and magnetic surveys. Subsequent drilling found narrow bands of widely divergent rock types to subcrop this area. Hornblende schist underlies the city of Madison in central Lake County while bands of felsic volcanics and mafic intrusives occur in central and western Moody County (Holtzheimer, 1987). Andesite porphyry and quartz latite previously discovered in adjacent Kingsbury County (Steece, 1961) may underlie part of the study area. The Kingsbury County rocks have been dated (Goldich, 1966) at 1,640 million years (Ma). The Moody County volcanics are slightly older, about 1,800 million years in age (W. R. Van Schmus, University of Kansas, personal communication, 1988).

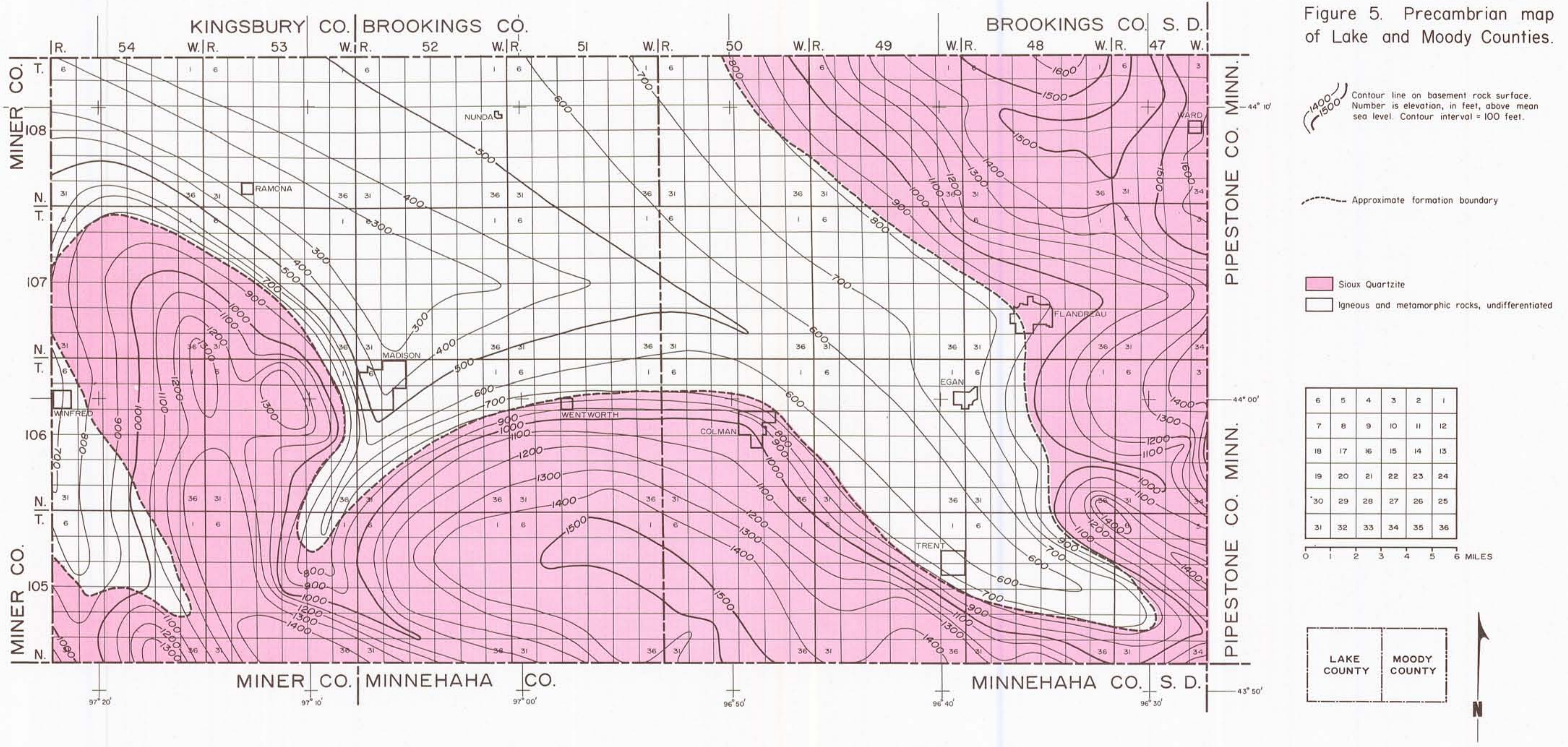
A white, sandy, kaolinitic regolith is developed on the crystalline basement surface in Moody County and probably exists in parts of Lake County (Holtzheimer, 1987). It appears to be similar to those in southwestern Minnesota earlier described by Sloan (1964) and Parham (1970).

SIOUX QUARTZITE

Most of the Precambrian surface in southern Lake County and southern and eastern Moody County is composed of Sioux Quartzite (fig. 5). It is a pink to white, fine-grained to conglomeritic orthoquartzite with occasional beds of red to purple catlinite. Bergstrom and Morey (1985) have suggested that the Sioux Quartzite is between 1,760 and 1,630 Ma. The maximum thickness of the quartzite has been a subject of some debate, with estimates ranging from under 1,000 feet (Gries, 1983) to over 3,000 feet (Baldwin, 1949). Although the structural relationships of the Sioux Quartzite with adjacent Precambrian rocks have not been fully explored, the quartzite appears to overlie the crystalline basement rocks except for some minor mafic intrusions (Southwick, Morey, and Mossler, 1986; Sklar, 1982).

The quartzite forms a high ridge on the Precambrian surface, extending from near New Ulm, Minnesota, to west of Mitchell, South Dakota. This feature, the Sioux Ridge, forms the highest part of the Transcontinental Arch (Shurr, 1981). Lake and Moody Counties lie on the north flank of the Sioux Ridge and, although no bedrock exposures exist within the mapped area, quartzite

Figure 5. Precambrian map of Lake and Moody Counties.



exposures exist less than 1 mile east of Moody County in Pipestone County, Minnesota. It is quarried less than 2 miles south of the study area near Dell Rapids, South Dakota. Beneath the southern and eastern portions of the mapped area, as little as 57 feet of overburden covers the quartzite surface. From these areas, where the quartzite surface is more than 1,600 feet above sea level, the Precambrian plunges steeply to the north and west, approximately along the erosional edge of the quartzite (fig. 5). This precipice, which forms the north flank of the Sioux Ridge, is deeply incised by a series of steep-sided, northwest-trending valleys. These valleys coalesce below 700 feet above sea level (ASL) on the crystalline basement rock surface.

The influence of the Sioux Ridge upon subsequent geologic events will be discussed later in this volume. For a discussion of the history, structure and petrology of the Sioux Quartzite, the reader is referred to Baldwin (1949) and Southwick (1984).

Cretaceous System

Late Cretaceous age rocks lap onto the Sioux Ridge, recording the transgression of an epicontinental sea into this portion of the North American interior from about 97.5 to about 76 Ma (Kauffman, 1985). Figures 6 through 14 illustrate the general stratigraphic relationships found in the mapped area.

QUARTZITE WASH

Quartzite wash is a term locally used to describe the fine- to medium-grained, pink sands derived from, and deposited adjacent to, the Sioux Ridge. It commonly contains well-sorted but often angular to sub-angular grains due to the nature and proximity of the detrital source. The wash defies easy stratigraphic classification, occurring at sub-Cretaceous positions, as a nearshore facies of Cretaceous formations, and in the lower portions of the Quaternary drift close to the ridge. For this reason, it will be mapped in this report as a facies of various formations or groups of formations and will be discussed at appropriate points in the text.

DAKOTA FORMATION

The Dakota Formation underlies approximately the northwestern two-thirds of Lake and Moody Counties. Near the Sioux Ridge, quartzite wash, sometimes over 100 feet thick, mantles the lower flanks of the quartzite (fig. 7). The wash grades to the northwest into fine, white to light-gray, well-rounded, cross-bedded sands with numerous beds and lenses of claystone and siltstone. This sandstone, known as the Nishnabotna Member (Munter and others, 1982) expands to a thickness of over 200 feet in central and northern Lake County. The Woodbury Member forms the upper 100 feet or more of the Dakota Formation. It consists of gray-brown siltstone containing minor sand lenses, coal, and claystone.

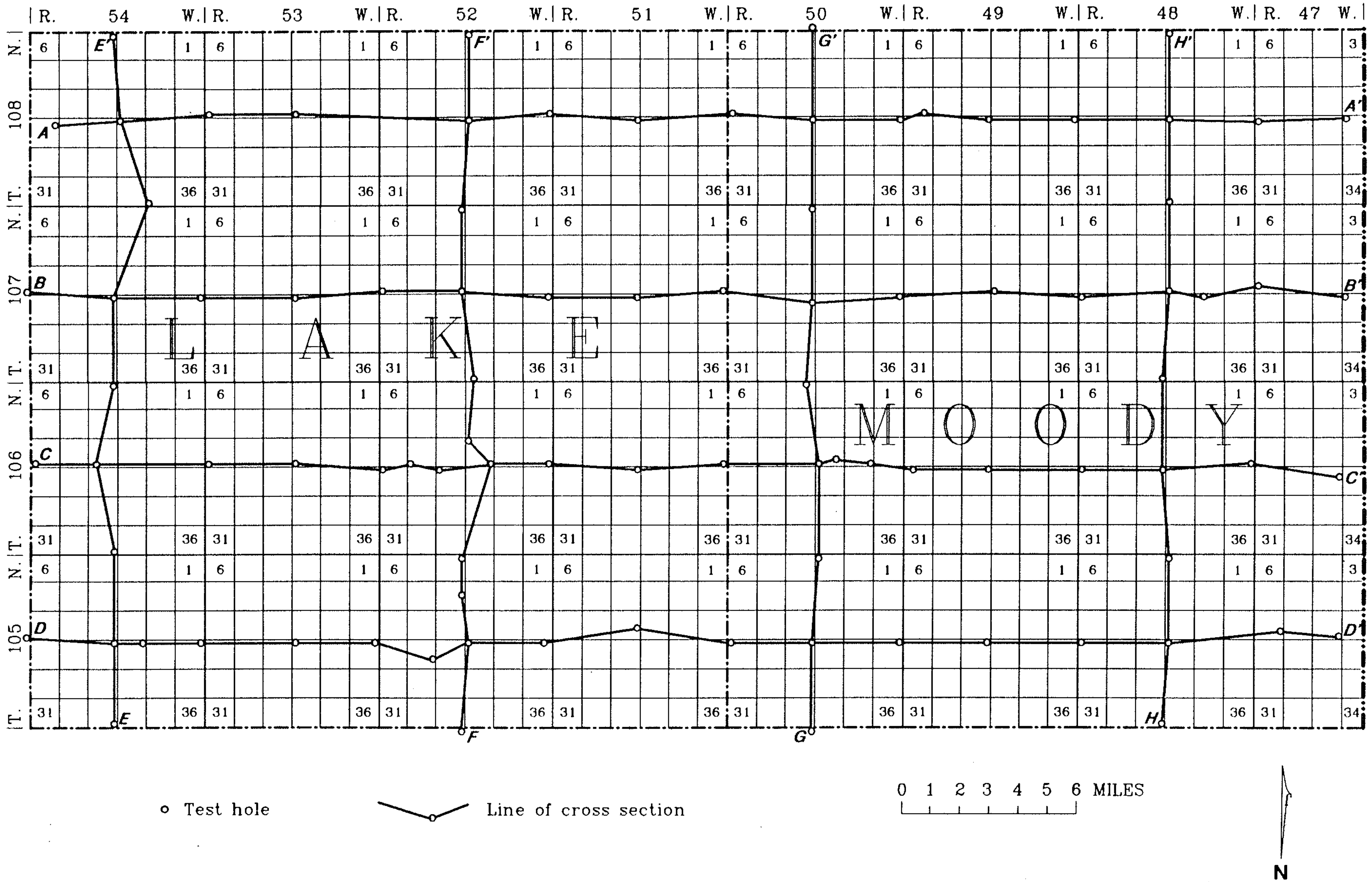
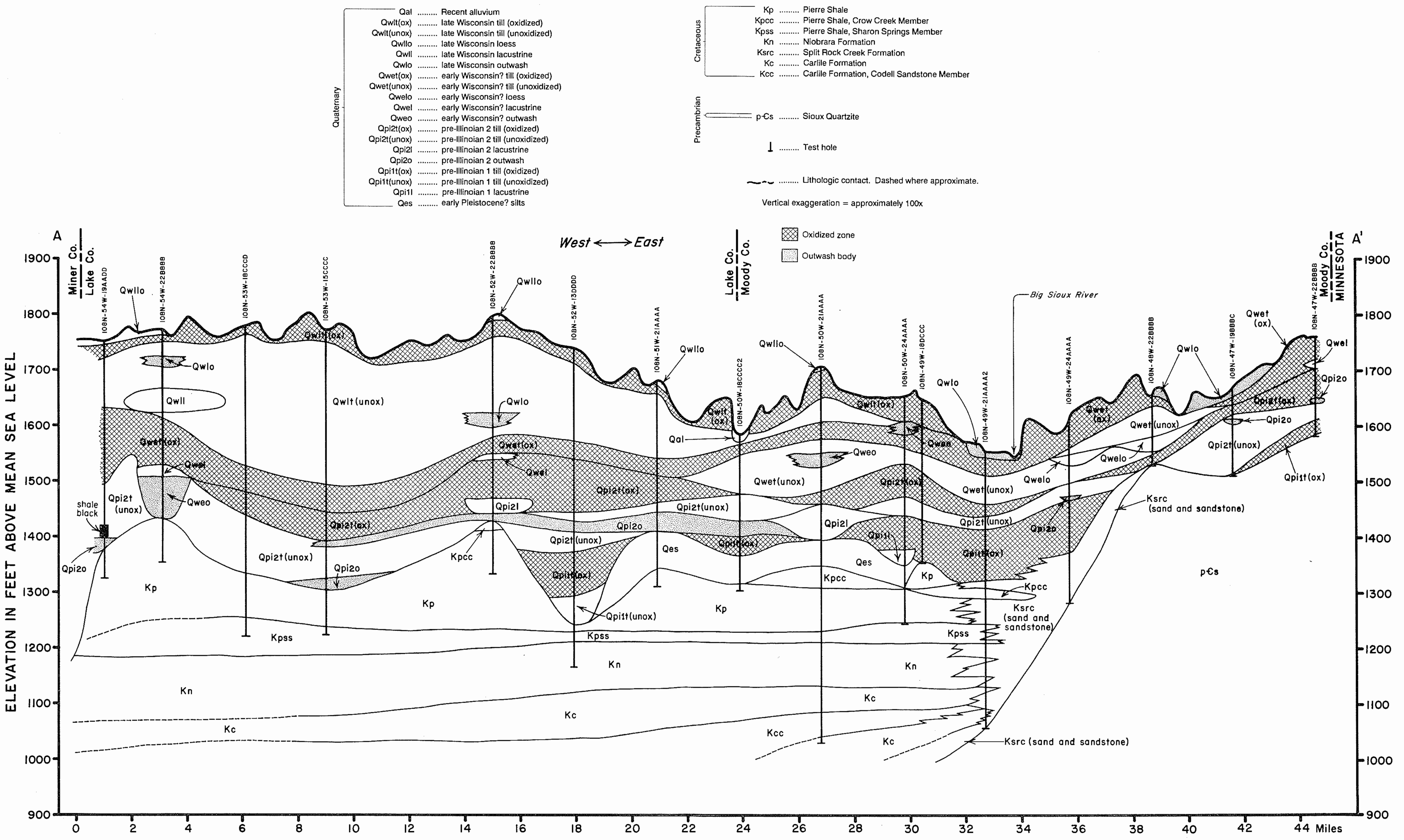


Figure 6. Location of cross sections (figs. 7–14) in Lake and Moody Counties.

Figure 7. Geologic cross section A - A'. See Figure 6 for location.



Quaternary

Symbol	Unit
Qal	Recent alluvium
Qwlt(ox)	late Wisconsin till (oxidized)
Qwlt(unox)	late Wisconsin till (unoxidized)
Qwllo	late Wisconsin loess
Qwll	late Wisconsin lacustrine
Qwlo	late Wisconsin outwash
Qwet(ox)	early Wisconsin? till (oxidized)
Qwet(unox)	early Wisconsin? till (unoxidized)
Qwelo	early Wisconsin? loess
Qwel	early Wisconsin? lacustrine
Qweo	early Wisconsin? outwash
Qpi2t(ox)	pre-Illinoian 2 till (oxidized)
Qpi2t(unox)	pre-Illinoian 2 till (unoxidized)
Qpi2l	pre-Illinoian 2 lacustrine
Qpi2o	pre-Illinoian 2 outwash
Qpi1t(ox)	pre-Illinoian 1 till (oxidized)
Qpi1t(unox)	pre-Illinoian 1 till (unoxidized)
Qpi1l	pre-Illinoian 1 lacustrine
Qes	early Pleistocene? silts

Cretaceous

Symbol	Unit
Kp	Pierre Shale
Kpcc	Pierre Shale, Crow Creek Member
Kpss	Pierre Shale, Sharon Springs Member
Kn	Niobrara Formation
Ksrc	Split Rock Creek Formation
Kc	Carlile Formation
Kcc	Carlile Formation, Codell Sandstone Member

Precambrian

Symbol	Unit
p-Cs	Sioux Quartzite
⊥	Test hole
~-~	Lithologic contact. Dashed where approximate.

Vertical exaggeration = approximately 100x

Symbol	Unit
▩	Oxidized zone
▨	Outwash body

Figure 8. Geologic cross section B - B'. See Figure 6 for location.

Quaternary	Qal	Recent alluvium
	Qwlt(ox)	late Wisconsin till (oxidized)
	Qwlt(unox)	late Wisconsin till (unoxidized)
	Qwllo	late Wisconsin loess
	Qwll	late Wisconsin lacustrine
	Qwlo	late Wisconsin outwash
	Qwet(ox)	early Wisconsin? till (oxidized)
	Qwet(unox)	early Wisconsin? till (unoxidized)
	Qwelo	early Wisconsin? loess
	Qwel	early Wisconsin? lacustrine
	Qweo	early Wisconsin? outwash
	Qpi2t(ox)	pre-Illinoian 2 till (oxidized)
	Qpi2t(unox)	pre-Illinoian 2 till (unoxidized)
	Qpi2l	pre-Illinoian 2 lacustrine
	Qpi2o	pre-Illinoian 2 outwash
	Qpi1t(ox)	pre-Illinoian 1 till (oxidized)
	Qpi1t(unox)	pre-Illinoian 1 till (unoxidized)
	Qpi1l	pre-Illinoian 1 lacustrine
	Qpi1o	pre-Illinoian 1 outwash
	Qes	early Pleistocene? silts

Cretaceous	Kp	Pierre Shale
	Kpss	Pierre Shale, Sharon Springs Member
	Kn	Niobrara Formation
	Ksrc	Split Rock Creek Formation
	Kc	Carlile Formation
	Kcc	Carlile Formation, Codell Sandstone Member
Precambrian	p€s	Sioux Quartzite

⊥	Test hole
—-—	Lithologic contact. Dashed where approximate.

Vertical exaggeration = approximately 100x

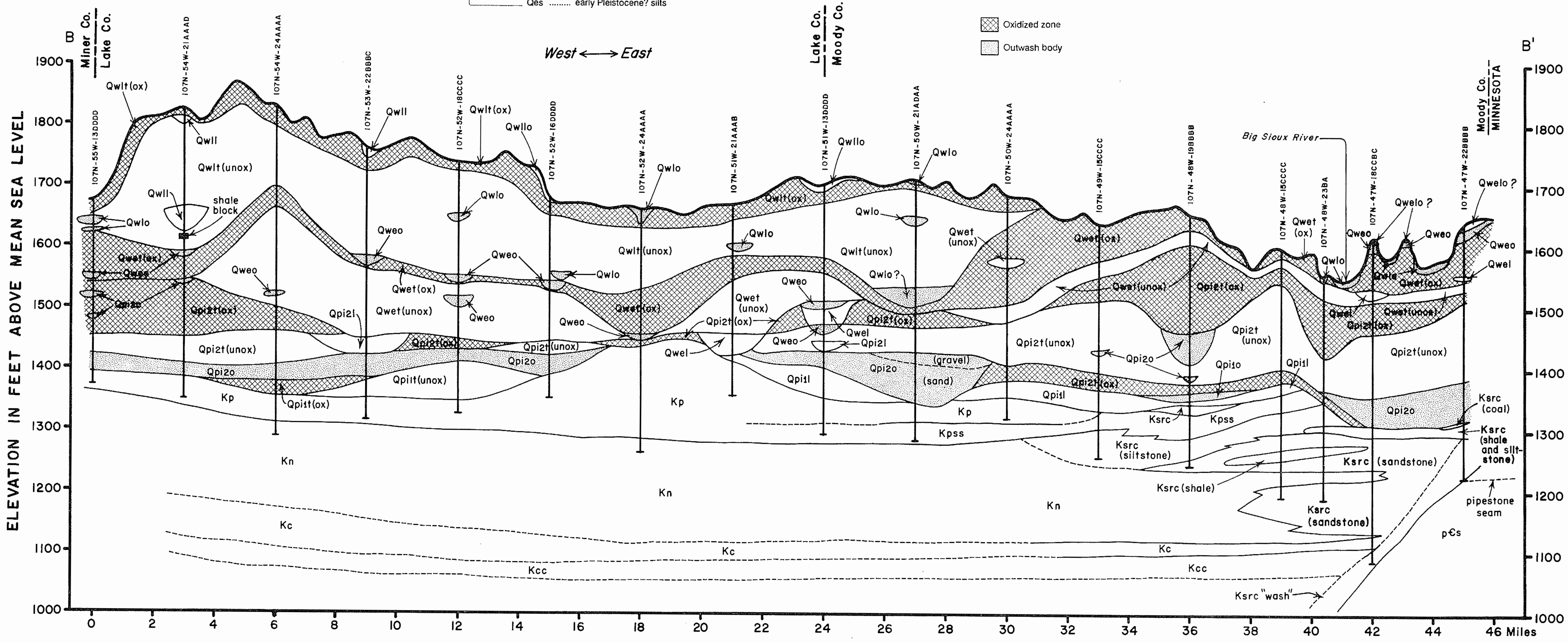


Figure 9. Geologic cross section C - C'. See Figure 6 for location.

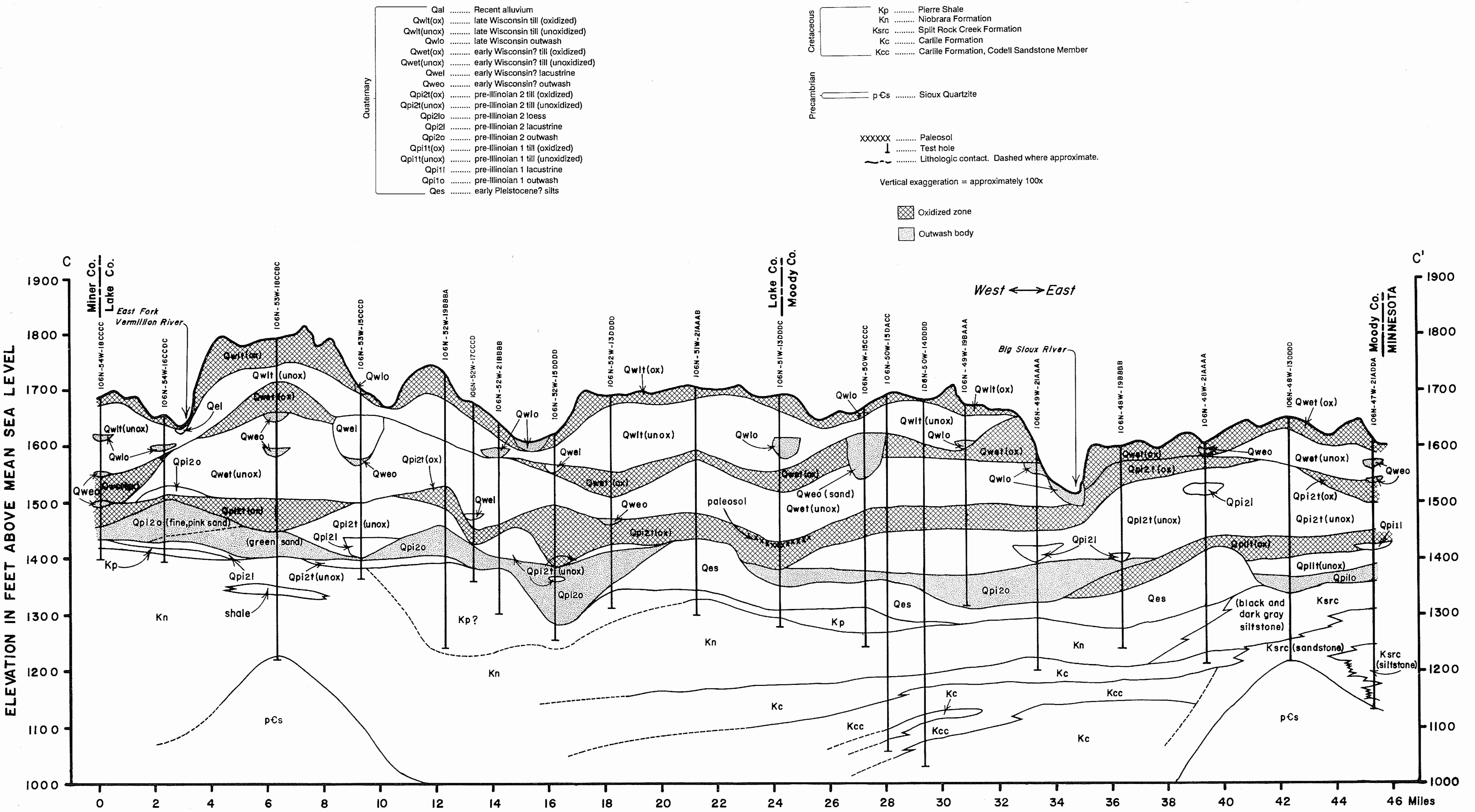


Figure 10. Geologic cross section D - D'. See Figure 6 for location.

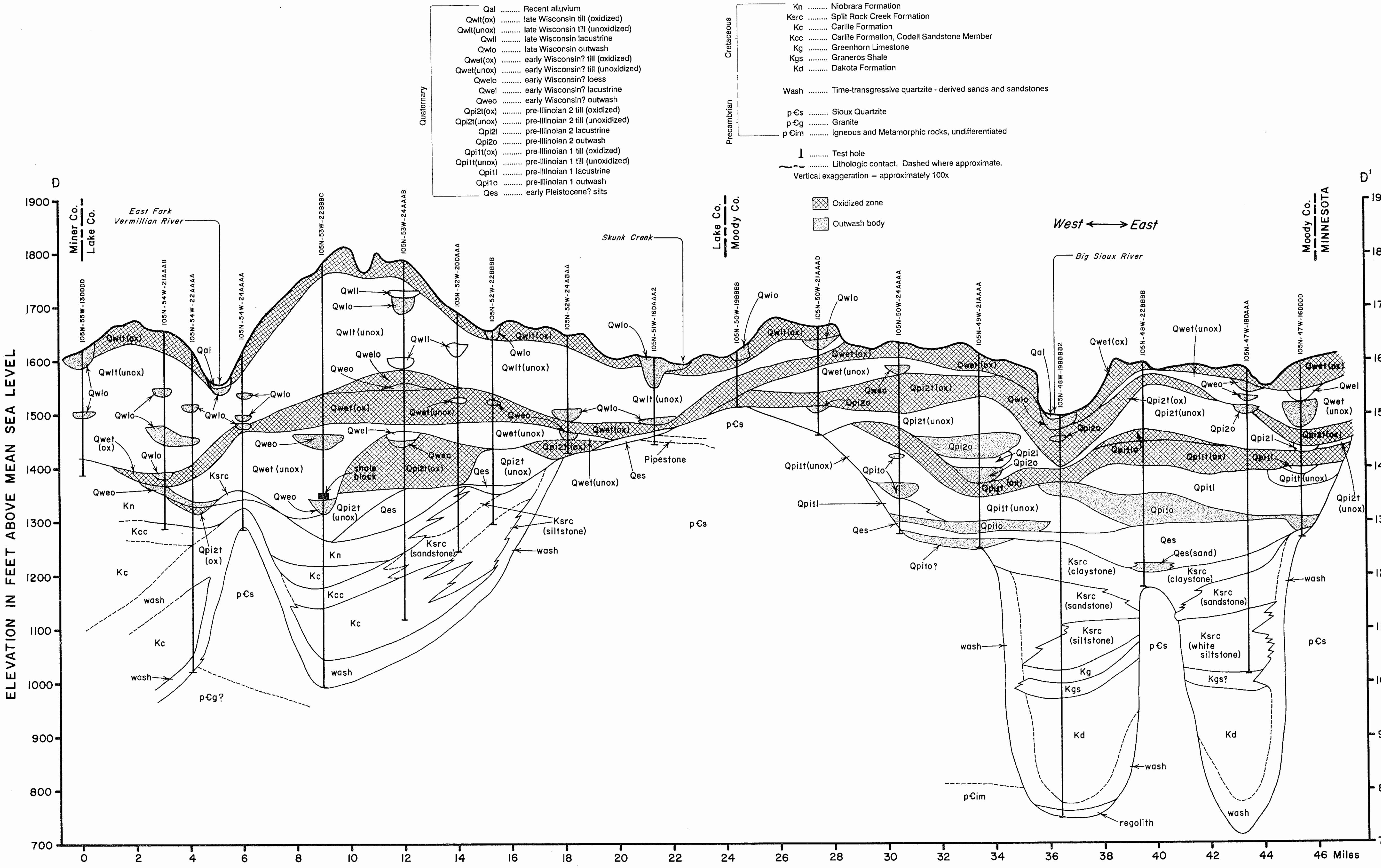


Figure 11. Geologic cross section E - E'. See Figure 6 for location.

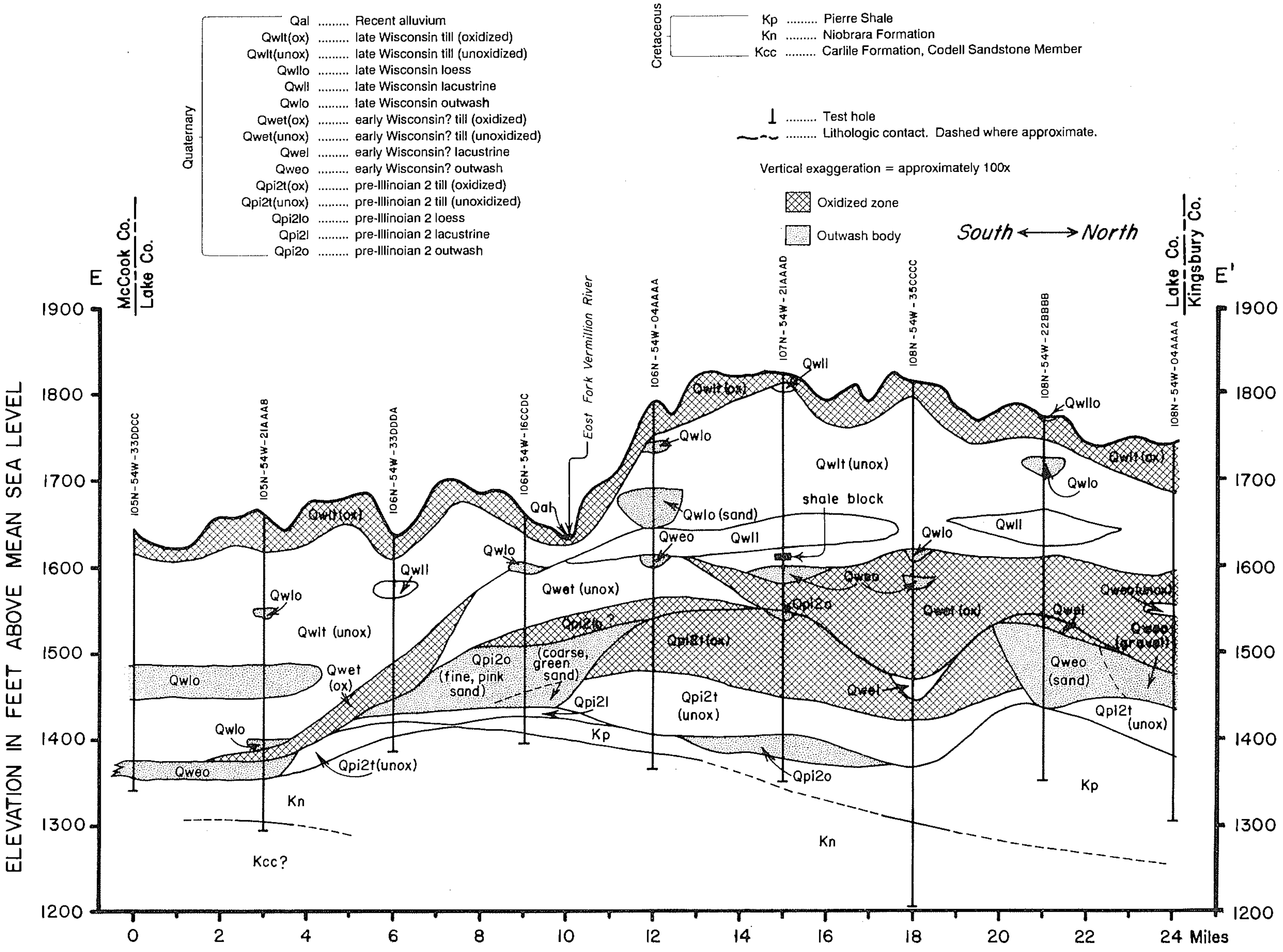


Figure 12. Geologic cross section F - F'. See Figure 6 for location.

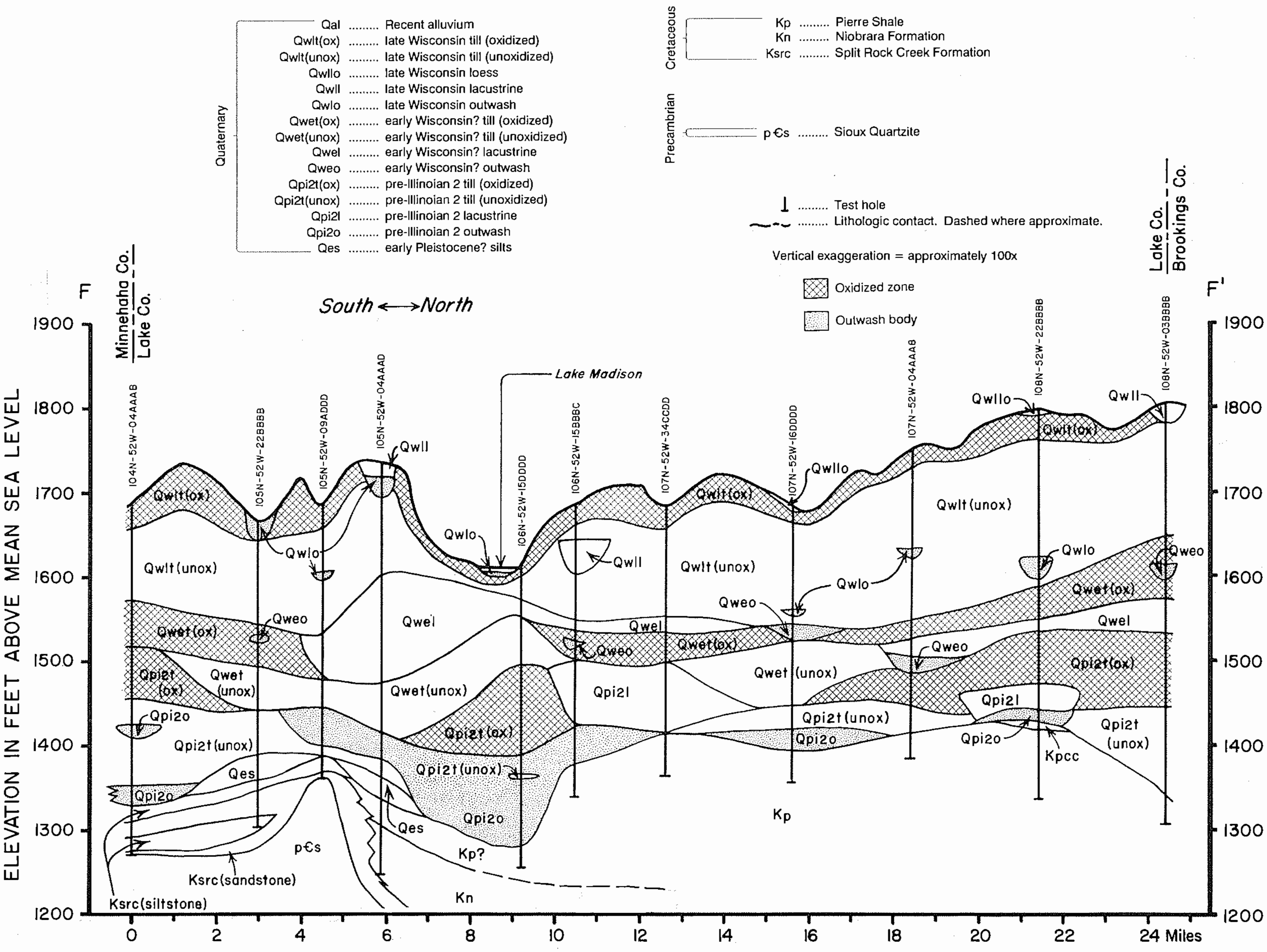


Figure 13. Geologic cross section G - G'. See Figure 6 for location.

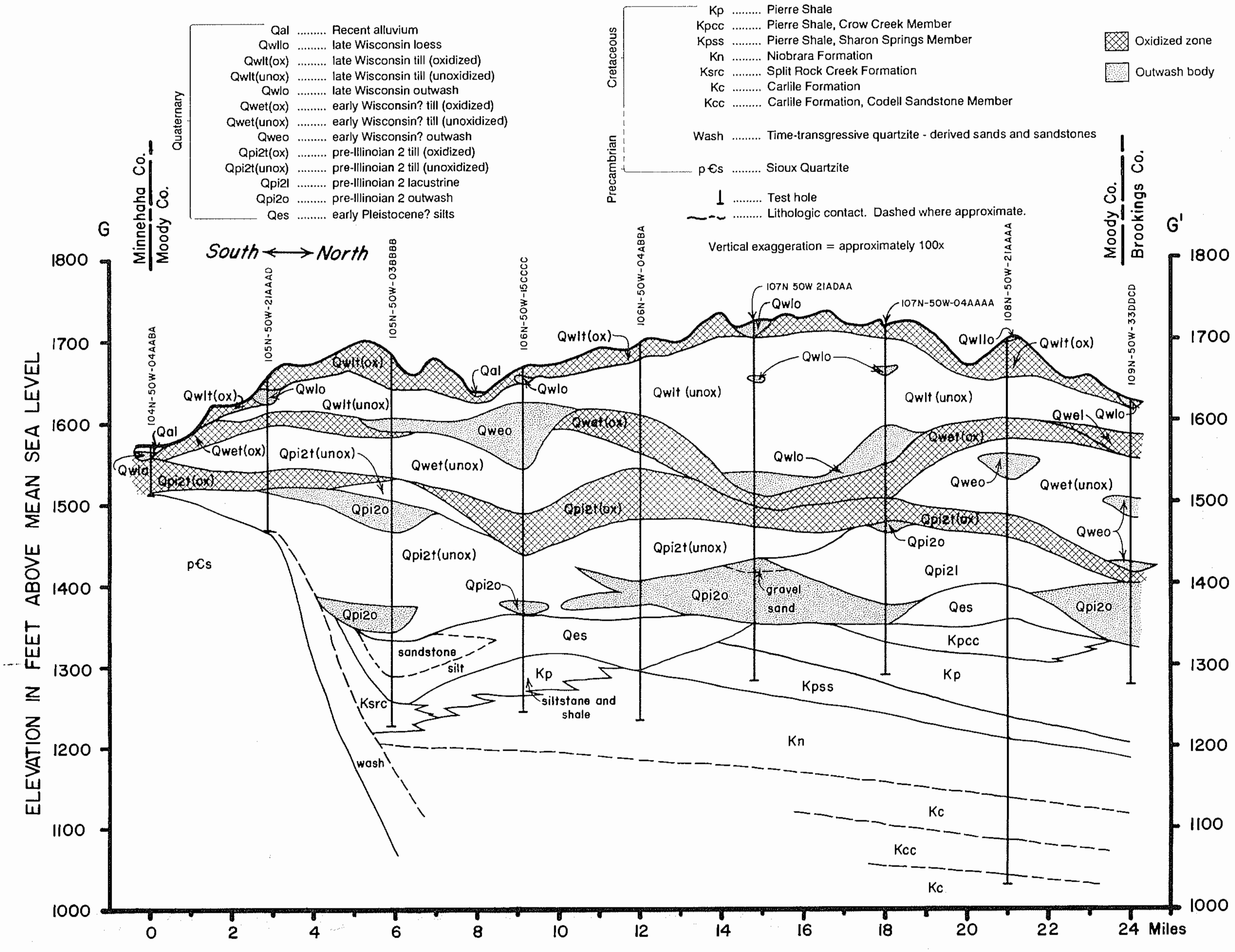
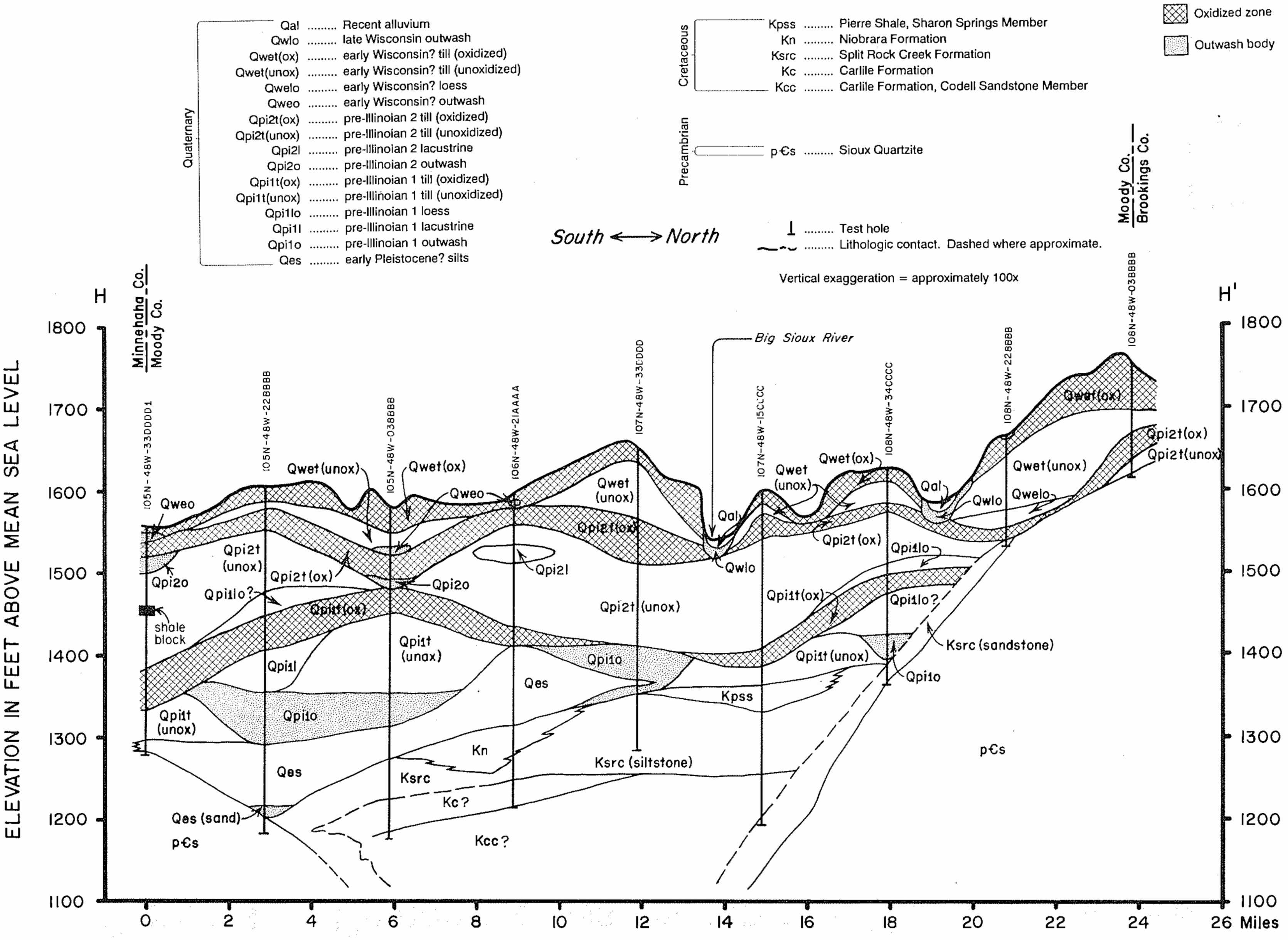


Figure 14. Geologic cross section H - H'. See Figure 6 for location.



The lower sands of the Nishnabotna Member were likely deposited by meandering streams in a terrestrial environment (Witzke and others, 1983). Worldwide elevation of sea level during the period (Haq and others, 1987) caused deposition of finer sediments of the Woodbury Member in shoreline and marine environments along the coast of what had become a shallow sea, the Western Interior Seaway. Marine conditions persisted in the area surrounding the Sioux Ridge during the remainder of Late Cretaceous time.

GRANEROS SHALE

Conformably overlying the Dakota Formation is the Graneros Shale, a gray-brown, waxy, noncalcareous claystone containing abundant septarian concretions and countless thin, wavy-bedded, fine sandstones. The mudstones of the upper Dakota Formation and the Graneros are nearly identical, making the contact between the two formations difficult to identify. The contact has traditionally been marked "at the first relatively continuous sand below the Greenhorn Limestone" (Schoon, 1971). In the Sioux Ridge area, this indicator has been found to be inconsistent and impractical. Sand lenses often constitute a large proportion of the sediments upward through rocks belonging to the Graneros Shale interval into the base of the Greenhorn Limestone (Holtzheimer, 1987). However, geophysical logs of most drill holes in the area display a consistently smooth electric and natural gamma signature in an interval up to 65 feet thick immediately below the Greenhorn Limestone. In this report, the suite of rocks producing this distinctive signature will be recognized as the Graneros Shale. In the southern and eastern parts of the study area, the Graneros Shale pinches out against the Sioux Ridge.

GREENHORN LIMESTONE

The Greenhorn Limestone is typically 20 to 30 feet of interbedded gray, silty calcareous shale, calcarenite, and hard skeletal limestone containing abundant foraminifera and <u>Inoceramus</u> fragments. It is a key marker bed throughout the western interior due to its distinctive electric-log signature, abundant temporally-distinct macrofauna, and widespread occurrence. Sharp unconformities separate the Greenhorn from both overlying and underlying rocks. The Greenhorn Limestone laps unconformably onto the flank of the Sioux Ridge in southern and eastern parts of the study area.

CARLILE SHALE

The Carlile Shale is composed of the basal Fairport Member, the Blue Hill Shale Member, the Codell Sandstone Member, and in places is capped by an unnamed shale. Dark-gray mudrock is the dominant lithology of the lower two members of the Carlile. The Fairport Member is a mildly calcareous, organic-rich shale. It is easily recognized by relatively high natural gamma values on bore hole geophysical logs. The Blue Hill Shale Member is typically a greasy, concretionary, noncalcareous, organic-rich shale with occasional thin sandstone lenses. In northwest Lake County, the Blue Hill Shale Member grades to a hard, fissile, silicious shale. The Fairport Member and Blue Hill Shale Member have an aggregate thickness of up to 140 feet.

The medium- to coarse-grained yellow to brown sandstones and gray-brown siltstones overlying the Blue Hill Shale Member in eastern South Dakota have been historically correlated with the Codell Sandstone Member of Kansas (Barkley, 1952). Recent work in Nebraska (Degraw, 1987) suggests that upper Carlile sands in northern Nebraska and southeastern South Dakota may be stratigraphically distinct from the Codell Sandstone Member of Kansas.

In South Dakota, these sands form a relatively continuous blanket wrapping around the west end of the Sioux Ridge (Hedges and others, 1982, pl. 9). In the Ramona area of northwest Lake County, up to three sandstone tongues were found with a combined sand thickness of over 60 feet.

In northwest Lake County up to 40 feet of gray, greasy shale has been found between the top of these "Codell" sands and the base of the overlying Niobrara Formation.

NIOBRARA FORMATION

Disconformably overlying the Carlile is the Niobrara Formation. In eastern South Dakota it is composed of interbedded chalk, calcarenite, and chalky shale, punctuated in the upper part with several bentonite seams. The Niobrara Formation varies in thickness from under 100 feet in north-central Lake County to about 150 feet in the southern half of the study area. This thickening towards the Sioux Ridge is caused by progressively greater clastic deposition nearer that highland. Insoluble-residue tests performed during this study demonstrated that the Niobrara in northwestern Lake County contains less than 25 percent clastic materials. Clastic dilution of the carbonates increase to about 90 percent in the thicker section near the Sioux Ridge.

PIERRE SHALE

The Pierre Shale, the uppermost bedrock unit, underlies the northwest three-quarters of the two-county area. The Pierre has been divided into a number of members in the type area along the Missouri River in central South Dakota (Gries, 1954), but only three have been recognized in this area. The Sharon Springs Member, a black, highly organic, noncalcareous, bentonitic claystone, is the basal member of the Pierre. It contains the thick, widespread Ardmore bentonite beds and displays a series of distinctive high spikes on natural-gamma logs, making it an easily recognized marker bed. It ranges up to 35 feet thick in the study area.

The Sharon Springs Member is overlain by up to 90 feet of medium-gray, interbedded, calcareous and noncalcareous shales. These shales, which belong to the Gregory Member, underlie the Crow Creek Member, a buff marl interbedded with calcareous shales and locally containing a thin basal sandstone. The Crow Creek Member is normally about 20 feet thick and is bounded on the top and bottom by sharp unconformities.

Dark-gray, bentonitic, fissile to massive shales make up the rest of the Pierre Shale. Occasional bentonite beds, marine shellfish and tan concretionary beds are scattered throughout the upper part of the formation.

The Pierre reaches thicknesses of nearly 200 feet in portions of northern Lake County. Its upper surface, however, is heavily eroded, suggesting that the formation was probably once much thicker.

SPLIT ROCK CREEK FORMATION

The Split Rock Creek Formation is a suite of embayment fill and other nearshore facies deposited along the irregular paleoshore of the Sioux Ridge (Ludvigson and others, 1981). The formation is a lateral equivalent to all of the marine Cretaceous formations previously described in this chapter (fig. 4). Sediments assigned to the Split Rock Creek Formation within embayments opening to the north side of the Sioux Ridge in southern Lake and Moody Counties have been correlated with the Graneros, Greenhorn, Carlile, Niobrara, and Pierre Formations based upon microfaunal assemblages and bentonite bed correlations (Holtzheimer, 1987).

The lower 200 to 300 feet of the formation often consists primarily of pink, coarse to medium, subangular wash derived from the adjoining quartzite highlands. Several beds of siltstone, laminated claystones, and lignite, up to 20 feet thick, separate these sands into irregular depositional units.

A distinct lithology of opaline spiculites, carbonaceous claystones, bedded cherts, calcium bentonites, pink quartz sandstones, and sandy siltstones forms the uppermost part of the formation. This lithology occurs at depositional sites which were well protected from harsh open shoreline processes. Abundant, well-preserved, terrestrial plant and animal fossils in this sequence suggest that a significant part of the Sioux Ridge remained emergent even during periods of extremely high sea levels.

The Split Rock Creek Formation produces an erratic, high-amplitude, electric-log signature on SP, natural-gamma, and resistivity logs. This is primarily a function of the interbedding of widely diverse rock types, ranging from clean, quartz sands to highly organic claystones.

Laterally, the Split Rock Creek Formation records a near-continuous range of depositional regimes from quiet-water embayments to wave battered rocky shoreline to shallow shelf marine environments, dominated by coarse terrestrial diamictite. The contact of the Split Rock Creek Formation with its equivalents away from the Sioux Ridge is typically picked where the normal marine sequence can be first recognized in hand samples or electric logs.

Bedrock-Surface Topography

Present-day relief on the bedrock surface is nearly 400 feet (fig. 15). Part of this relief is attributed to the presence of the Sioux Quartzite highland. The higher bedrock surfaces in the southern and eastern portions of the study area consist of Sioux Quartzite, a rock exceedingly resistant to erosion.

The remainder of the bedrock surface rests upon Cretaceous age rocks. Much of the bedrock relief in this area has resulted from pre-Pleistocene drainage development. Erosion by glacial ice and meltwaters has undoubtedly further modified the bedrock surface.

Quaternary Stratigraphy

Quaternary sediments form the surface deposits in Lake and Moody Counties, reaching over 400 feet in thickness in northwestern Lake County. The great bulk of these sediments were emplaced during the Pleistocene Epoch, though alluvium along many of the streams and a veneer of loess over much of the landscape has been deposited since that time.

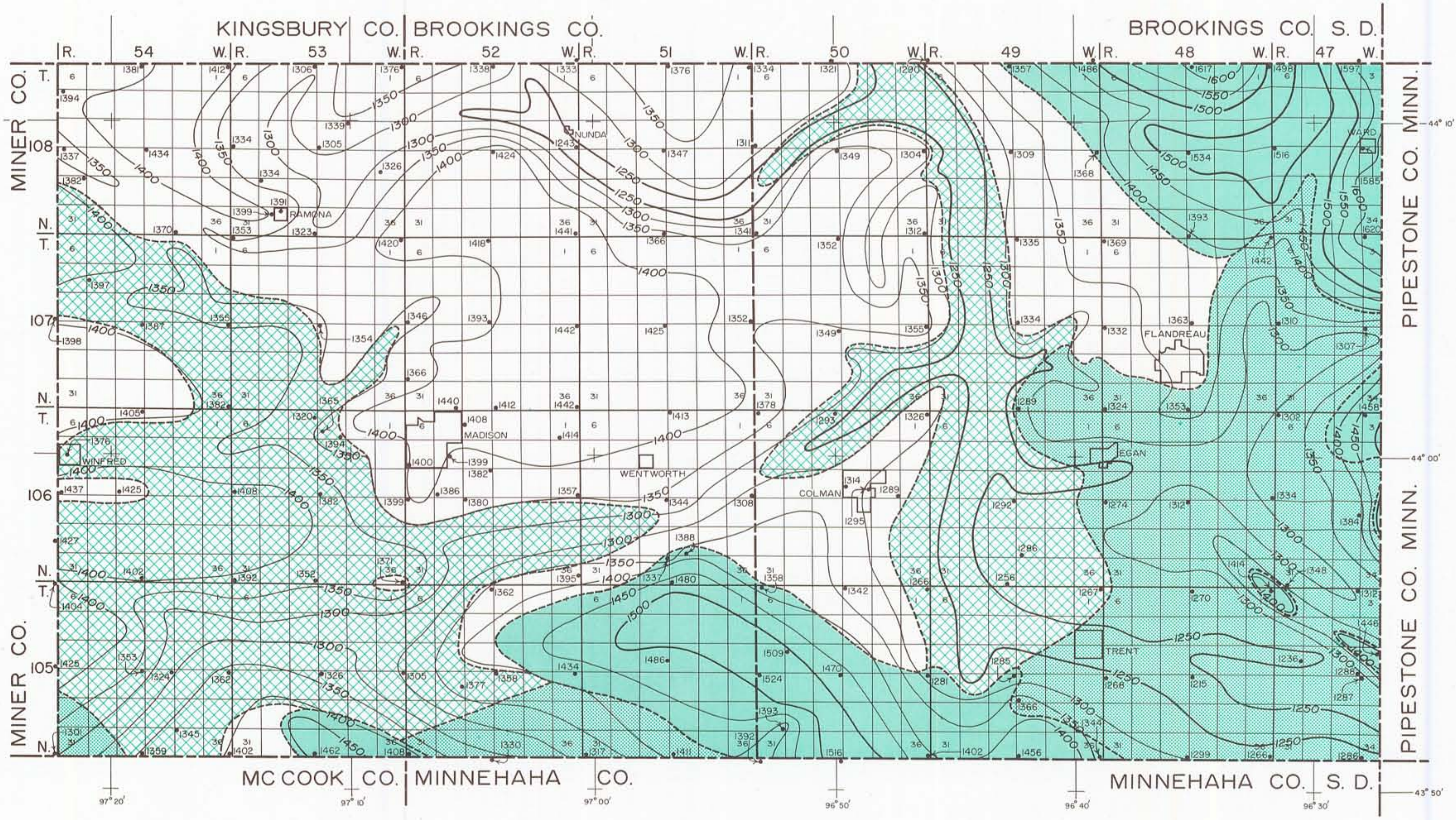
The glacial history of the area has been substantially reinterpreted since the studies previously cited. Advances during the last two decades in Pleistocene climatology and stratigraphy have forced a redefinition of the North American stratigraphic framework (Hallberg, 1986). Before that time, four major glacial stages, separated by relatively long interglacial periods, were recognized in the midwest (Kay and Apfel, 1929). Few good stratigraphic sections and coring tests containing more than one drift sheet were available. Furthermore, the sediments deposited by the various glaciations are often lithologically similar. Correlations were therefore often made primarily by counting major depositional packages back from the surface or from known stratigraphic markers.

The Pleistocene glacial history is now known to be much more complex. Presently, 11 distinct glacial cycles have been identified on the North American continent which have been matched with 11 major cold cycles recorded in ocean sediments deposited during the past 900,000 years. At least eight temporally distinct drift sheets have been noted in the upper midwest (Richmond and Fullerton, 1986).

The recognition of multiple volcanic ash beds in the region has also been of major importance to the redefinition of the glacial chronology. The Pearlette Ash, a regionally important marker bed to early stratigraphers, was discovered to be three distinct beds, representing volcanic events separated by more than 1.3 Ma (Boellstorff, 1978). The Pearlette ash beds have been fission-track dated at .61 Ma (Pearlette "O"), 1.27 Ma (Pearlette "S"), and 2.01 Ma (Pearlette "B") (Izett, 1981). Stratigraphic studies at the type sections of the classic Nebraskan, Kansan, and Aftonian sediments and other key sections containing the various Pearlette markers have revealed a hopelessly entangled set of improper correlations. These now ambiguous terms have been abandoned in the stratigraphic nomenclature, replaced by the broad term "pre-Illinoian, undifferentiated" until a new stratigraphic framework can be developed (Hallberg, 1986). That convention has been adopted in this study.

At least five drift sheets have been found within drill holes in Brookings County, which borders Lake and Moody Counties to the north (Jarrett, Johnson, Lehr, in preparation). Four of

Figure 15. Bedrock map of Lake and Moody Counties.

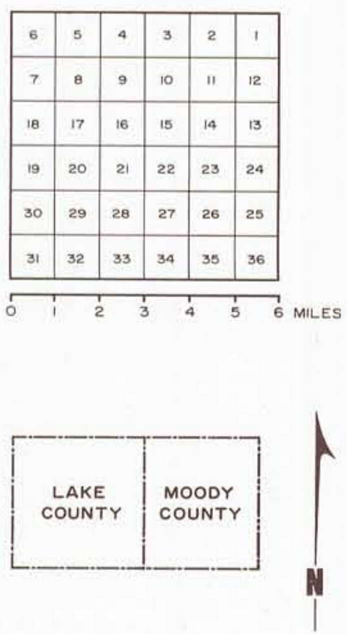


1393● Control point. Number is elevation, in feet, above mean sea level.

1450 1500 Contour line on bedrock surface. Number is elevation, in feet, above mean sea level. Contour interval = 50 feet.

- - - - Approximate formation boundary

Cretaceous	☐	Pierre Shale
Cretaceous	▨	Niobrara Formation
Cretaceous	▒	Split Rock Creek Formation
Precambrian	■	Sioux Quartzite



the five were also found within this study area. The stratigraphy of the youngest drift, the late Wisconsin, is relatively well defined. The exact age and stratigraphic position of the older deposits are less certain.

Pre-Wisconsin Stratigraphy

The youngest of the Pearlette Ash markers, now known as the Pearlette "O" ash bed (Izett and Wilcox, 1982) crops out 20 miles south of this study area near Hartford. This ash, locally known as the Hartford Ash, separates till previously identified as Illinoian from the underlying drift then thought to date from Kansan and Nebraskan time (Steece, 1965). Boellstorff (1978) has correlated Steece's Illinoian drift at the Hartford site with the classic Kansan till by lithologic analysis as well as its stratigraphic relationship to the Hartford Ash (table 1). He also found both tills underlying the Hartford Ash to be younger than the classic Nebraskan till. Analyses of the tills included heavy mineral separations, Chittick carbonate analysis, lithologic analysis of the 1 to 2 mm size fraction and paleomagnetic studies.

Materials suitable for absolute dating of pre-Wisconsin sediments have not been found during the course of this study. Stratigraphic analysis of the drift sheets in Lake and Moody Counties is therefore primarily based upon the redefined stratigraphy at the nearby Hartford outcrops. The drift sheet directly overlying the ash at the Hartford outcrops has been traced to Lake and Moody Counties by closely spaced drill hole information, supplemented by geomorphic analysis of surface deposits. This drift will be identified simply as pre-Illinoian 2 (pi-2) in this report. The lowermost drift (pre-Illinoian 1) in the Lake-Moody area is discontinuous both within the study area and in northern Minnehaha County (between the present study area and the Hartford outcrops). This drift therefore could be a composite of two or more older pre-Illinoian drift sheets which were indistinguishable by the methods employed here.

Wisconsin Stratigraphy

Wisconsin stage nomenclature in this report is modified from that proposed by Lemke and others (1965). They divided the Wisconsin stage into two major time-stratigraphic divisions: early Wisconsin from 70,000 to 22,000 years before present (B.P.) and late Wisconsin ranging from 22,000 years B.P. to 10,000 years B.P.

They suggested that one glacial advance occurred in the Dakotas during the early Wisconsin, based primarily upon geomorphology. The reassessment of pre-Wisconsin stratigraphy noted above and of the extent of early Wisconsin glaciation (Clark, 1986; Richmond and Fullerton, 1986) has cast some doubt upon the actual age of these sediments. The drift sheet labeled early Wisconsin by Lemke may actually be much older. Radiocarbon dates of greater than 30,000 years B.P. were obtained on samples from the "early Wisconsin" drift sheet in Brookings County (Lemke and others, 1965, table 2). The maximum age for the glaciation is as yet constrained only by the age of the underlying pre-Illinoian drift.

TIME DIVISIONS (HALLBERG, 1986)		TIME SCALE (RICHMOND AND FULLERTON, 1986)	BOELLSTORFF IOWA-NEBR. SECTIONS (1978)	HARTFORD SECTION (BOELLSTORFF, 1978)	HARTFORD SECTION (STEECE, 1965)	THIS STUDY	MAGNETIC POLARITY
LATE PLEISTOCENE							
LATE MIDDLE PLEISTOCENE	ILLINOIAN	132,000					NORMAL
MIDDLE MIDDLE PLEISTOCENE	PRE-ILLINOIAN	302,000					
			A_1 CLASSIC "KANSAN"	A_1	ILLINOIAN	pi2	
		610,000	PEARLETTE "O"	— — —	— — —		
EARLY MIDDLE PLEISTOCENE			A_2	A_2	KANSAN	pi1	
			A_3	A_3	NEBRASKAN	NOT PRESENT	
EARLY PLEISTOCENE		788,000					REVERSED
			A_4				
			B TILLS				
		1,270,000	PEARLETTE "S"				
PLIOCENE		2,010,000	PEARLETTE "B"				
		2,140,000	C TILLS NORMAL REVERSED				
		2,480,000					

Table 1. Classifications and correlation of pre-Wisconsin glaciations.

Due to this uncertainty, the term early Wisconsin? will be tagged with a question mark in this report. Early Wisconsin? drift underlies nearly the entire two-county area and forms the land surface in the eastern one-third.

Five distinct glacial advances were postulated by Lemke to have occurred during the late Wisconsin. Drift from only one, however, has been detected in Lake and Moody Counties, extending over the western two-thirds of the two-county area. Though no radiocarbon dates have been established during this study, a date of 12,200±400 years B.P. (W-801) has been determined in neighboring Miner County (Lemke and others, 1965, table 2).

Pleistocene Deposits

Early Pleistocene Deposits

EARLY PLEISTOCENE? SILTS

An unnamed deposit of pale-green, pale-gray, pale-pink, and white alluvial and lacustrine silts mantle the bedrock surface adjacent to the Sioux Ridge in southern Lake and Moody Counties. Up to 90 feet of these alternately fine sandy and clayey silts are mapped on figures 7, 9, 10, 12, 13, and 14. Weak stratification was noticed in some samples. Examination under the microscope has revealed them to be composed of colorless subround to round quartz grains enclosed in a white matrix of very fine clayey material. A few root casts were the only fossils detected. X-ray analysis showed the cuttings to be composed of quartz, feldspar, calcite, dolomite, and kaolinite.

These discontinuous deposits occupy topographically lower areas on the bedrock surface and probably represent normal stream and lake deposition during part of the early Pleistocene but may indeed be much older. The maximum age of these deposits is constrained only by the age of the underlying Pierre Shale.

Similar deposits have been found in Clark County (Christensen, 1987) in similar stratigraphic positions but no data suitable for assigning an age to these sediments have yet been found.

PRE-ILLINOIAN 1 DEPOSITS

Till

The till making up most of the oldest pre-Illinoian drift sheet (pi-1) occurs in the areas of lower bedrock surface elevations in the northern portions of the mapped area, and in scattered locations in southern Moody County overlying the early Pleistocene? silt. This till ranges up to 120 feet thick in SDGS test holes.

The pi-1 till consists of a very compact, blocky, calcareous clay-rich matrix with sand- to boulder-sized clasts throughout. A wide range of clast petrology is present, including chalk, limestone, dolomite, shale, chert, and several igneous and metamorphic rock types. Euhedral to subhedral selenite crystals up to one-half inch long are commonly imbedded in the till matrix.

This till is generally olive-gray to pinkish-gray below a weathering zone which exceeds 50 feet at a few locations. In the oxidized upper portions of the till, distinctive red, reddish-brown, yellow-brown, and brown oxidation coloration make the surface of the till sheet easy to map even where it is deeply buried.

Intense fracturing or jointing below the oxidized zone is postulated by the presence of cuttings containing mottled and oxidized-unoxidized contact sediments from well below the depth of total oxidation. Tabular aggregations of euhedral selenite which apparently are joint fillings also suggest the presence of jointing. These observations suggest that a transition zone of unoxidized till with deep oxidized fractures and joints occurs well below the oxidized zone. This phenomenon has been directly observed in younger tills cored during the course of this and other SDGS studies and can be confidently inferred to occur in this even more intensely weathered till.

Outwash

Outwash occurs within and beneath pi-1 till primarily in the southeastern portions of the two-county area (fig. 10). These outwash bodies are composed of clean, round to subangular sand and fine gravel. White, red and green quartz and feldspar with some dolomite, limestone, shale, pink quartzite and undetermined dark-colored clasts are the primary grain types.

At some locations, the sands lying at or near the base of the pi-1 drift consisted almost entirely of well-sorted, green, pink and white quartz and feldspar. This lithology is similar to fluvial sediments deposited in the valleys of streams which once transversed the state from west to east but have since been diverted by Pleistocene glaciation along the present-day course of the Missouri River (Flint, 1955). Accordingly, sands of this type found buried in valleys beneath the drift in eastern South Dakota are usually informally referred to as "western derived." Though these clean sands found at or near the base of the drift in Lake and Moody Counties are also often referred to as "western derived," pre-Pleistocene drainage patterns (fig. 15) suggest that they may be at least in part derived from the Precambrian highlands in nearby Minnesota.

Lacustrine Sediments

Several occurrences of glacial-lake deposits within the lowermost pre-Illinoian drift were noted during drilling for this investigation. Lithologies were generally light- to dark-gray clays and silts with occasional black, organic-rich bands. Varves were logged in scattered test holes.

These sediments probably accumulated in water ponded for a short time along the margin of advancing or retreating ice. Many other smaller lake and fine-grained glaciofluvial deposits undoubtedly exist in those areas mapped as till but were either not penetrated by the drill or were judged too thin (less than 10 feet) to be a mappable unit.

Loess

One test hole in southern Moody County (NW¼ sec. 33, T. 105 N., R. 48 W.) penetrated 28 feet of tan, silty, clayey loess lying on oxidized pi-1 till. The sediments were slightly calcareous, very compact and contained small red-brown root casts and small scattered black carbonaceous specks.

Other widely scattered lenses of this loess may occur in the area but were undetected by the rotary drill. Removal of much of the loess by subsequent glacial erosion except in areas shielded by bedrock highs, such as at the above location, may largely account for the lack of other occurrences.

PRE-ILLINOIAN 2 DEPOSITS

Till

Pre-Illinoian 2 (pi-2) till underlies much of the area mapped for this project and is the uppermost till in a portion of southwestern Moody County (fig. 3). A broad moraine-like accumulation of pi-2 till up to 230 feet thick is a notable feature of this drift. It underlies a large area forming a broad arc from the vicinity of Lake Herman, along the north escarpment of the Sioux Ridge (fig. 5), east and north to the northeast corner of Moody County.

This till is a calcareous, silty clay containing abundant sand, gravel and rocks. It is very compact, blocky, and extensively jointed. Selenite crystals are crowded in the joints as well as scattered through the matrix. As in the underlying drift, clast petrology includes chalk, limestone, dolomite and shale as well as a wide variety of igneous and metamorphic types.

An upper weathered zone composed of yellow to gray-brown till locally reaches 90 feet in thickness. The degree of weathering decreases gradually downward into dark-gray to gray unweathered till. The upper distinctly colored material is quite continuous, making the top of this drift sheet relatively easy to recognize in drill holes and to correlate between data points.

The small pi-2 outcrop area in southern Moody County is easily distinguished from adjacent till plains by its deeply dissected surface. This well-drained surface shows few details of its original configuration, having been substantially modified by a long period of erosion and largely concealed by subsequent loess deposition.

Outwash

A large sand deposit, partially enclosed by pi-2 till and partially at its base, subcrops over 50 percent of the combined two-county area (figs. 7 through 14; Hansen, 1986a, fig. 15). This outwash forms the Howard aquifer (Hansen, 1986a), an important source of ground water in parts of Sanborn, Miner, Kingsbury, and Brookings, as well as Lake and Moody Counties. It reaches over 100 feet in thickness in both northwest Lake County and southwest Moody County. This deposit is variable in thickness due both to its infilling of a rugged underlying surface and considerable erosional relief on its upper surface.

The grains are primarily white and light green, quartz-rich, well-rounded, coarse to medium sands. Compared to other sand and gravel deposits in the area, this sand is uncharacteristically clean, well-sorted, and contains few local shale and chalk grains. These anomalies may be due to the incorporation and redeposition of nonglacial "western derived" sands by relatively clean glacial ice and meltwater; the diversion of a large nonglacial stream (Flint, 1955, p. 42-43) by encroaching ice; or more probably, a combination of the two phenomena.

Other sand and gravel deposits derived from the pi-2 glaciation occur primarily in the eastern part of the mapped area and in the upper portions of the drift sheet (fig. 14). These sediments contain a suite of constituents more rich in shale, chalk and northern exotics than the above-described outwash. The clasts are also often faceted, broken, and poorly sorted, unlike those in the Howard outwash body.

Lacustrine Sediments

Several lacustrine deposits were noted within the pi-2 drift sheet. Most are under 30 feet thick and are commonly in contact with outwash. The sediments are composed of dark-gray, light-gray, or yellow-brown silts and clays, sometimes varved. A few test holes penetrated lake sediments containing small fragments of fossil shells. These sediments undoubtedly were deposited in lakes formed by temporary ice damming of meltwater drainageways and in ice-walled lakes in stagnant-ice masses.

Loess

Loess deposited on the pi-2 drift surface subcrops small areas of southwestern Lake and eastern Moody Counties. These patches of reddish-brown clayey silt, locally over 20 feet thick, are undoubtedly erosional remnants of a much larger loess blanket which once covered the pi-2 till surface. The lower half of the loess which mantles the area mapped as Qpi2t (fig. 3) is part of this loess blanket, separated from younger loess by a weak paleosol.

Late Pleistocene Deposits

EARLY WISCONSIN? DEPOSITS

Till

Early Wisconsin? drift, unlike the older drift sheets, was found throughout the mapped area, overlying even the highest surfaces of the Sioux Ridge. Loess mantled early Wisconsin? till forms the land surface in that part of the study area roughly between Interstate Highway 29 and the

Minnesota border (fig. 3). In the remainder of Lake and Moody Counties, the early Wisconsin? is covered by late Wisconsin drift.

In western Lake County, early Wisconsin? till over 200 feet thick forms the core of a massive moraine bordered on the west by the East Fork Vermillion River. Elsewhere, this drift sheet ranges between 20 and 120 feet thick with an upper oxidized fringe normally about 40 to 50 feet thick. The oxidized till thickness is quite variable in Moody County due to deep erosion in the outcrop area.

The early Wisconsin? till is composed of a calcareous, silty, sandy, pebbly clay. It is normally dark-gray to gray, weathering to yellow-brown to gray-brown in the upper oxidized portion. Euhedral to subhedral selenite line deep, oxidized joints and fractures in a mottled transition zone between the upper oxidized and lower unoxidized parts of the till. Core from the SW¼ of sec. 27, T. 106 N., R. 49 W. also contained two intervals of poorly sorted sandy silts with crude cross-stratification and convolute bedding. These apparently constitute local units of ice contact stratified drift which are undoubtedly common in the drift.

The lithology of the coarse sand contained in some till samples were examined during the course of this study, including several intervals of the above-mentioned core. The lithology of the 1 to 2 mm clasts contained in till has been used by some workers to distinguish till sheets in the region (Matsch, 1971; Van Zant, 1973; Lucas, 1977; and Schroeder, 1979). So called "pebble counts" performed for this study, following Schroeder's techniques, found early Wisconsin? till to contain 8 to 13 percent shale, and late Wisconsin till to be greater than 20 percent shale. "Pebble counts" by Schroeder (1979, app. C) found pre-Wisconsin till in Moody County to contain under 5 percent shale clasts, early Wisconsin? till to contain about 10 percent shale, and late Wisconsin to contain 17 to 25 percent shale.

In the area where the early Wisconsin? till is the uppermost drift, the surface is a smoothly-sloped, well-drained surface. Only an occasional hint of its original configuration is still unhidden by erosion and loess.

Numerous igneous and metamorphic boulders dot the surface of the exposed early Wisconsin? till. One of the larger erratics exposed in South Dakota is locally known as Lone Rock in the NW¼ sec. 15, T. 106 N., R. 47 W. Lone Rock, composed of pink granite, is about 20 feet in diameter. In comparison, a 17-foot diameter boulder near the James River was the largest measured by Waring (1949) in his study of South Dakota glacial erratics.

Outwash

Numerous discrete channels of outwash exist within the early Wisconsin? drift sheet (figs. 7 through 14). Most of these units are composed of sandy, fine to medium gravel, but locally may be very coarse gravel or fine sand. Rock composition spans a wide variety of igneous, metamorphic, and sedimentary rock fragments, including shale, chalk, chert, granite, limestone, and ferrous concretions. Several scattered test holes in southern and western Moody County contained reddish-brown coarse sand lightly cemented with finely crystalline selenite.

An unusually clean, white to orange, fine to medium sand lies on the early Wisconsin? till surface in secs. 4, 9, 10, and 11, T. 107 N., R. 48 W. (fig. 3, Qweo). This sand occupies a gentle swale on the upland till surface parallel to the trench now occupied by the Big Sioux River. It is composed largely of subround, polished quartz with less than 10 percent gray ovoid shale particles and other occasional dark-colored grains. A weak soil is developed at the top of the sand in some locations in the center of section 10.

Lacustrine Sediments

Lake deposits in the early Wisconsin? were, in general, less common and thinner than in other drift sheets. Dark-gray, gray, and olive lake silt and clay deposits were generally less than 20 feet thick. Test-hole drilling found only one, in west-central Lake County (fig. 9), of notable thickness (80 feet).

Some early Wisconsin? lake deposits are exposed at the land surface in Moody County. Most (such as NW¼ sec. 14, T. 105 N., R. 49 W.) are round, occasionally boulder rimmed kettles, formed by the in situ melting of large stagnant ice blocks. Eight of these ice-block lakes were identified during surface mapping of the southern two-thirds of the early Wisconsin? outcrop area (fig. 3). Many others undoubtedly exist elsewhere on that surface, hidden by the loess which covers most of the early Wisconsin? drift.

Loess

Some yellow-brown to gray clayey silts underlying the late Wisconsin and overlying early Wisconsin? drift are mapped on figures 7 through 14 as early Wisconsin? loess. Though actually deposited primarily during the interglacial period following the early Wisconsin? glaciation, these sediments are derived from and closely associated with the early Wisconsin? drift; they will be labeled accordingly in this report.

The silt is somewhat sandy at a few locations, is quite calcareous, and contains occasional root tubules and small black specks.

These loess deposits are over 20 feet thick at the NE¼ of sec. 24, T. 105 N., R. 53 W.

That part of the study area not overlain by late Wisconsin sediments is largely covered by eolian silt, clay, and sand. This wind-blown material, covering the early Wisconsin? and pi-2 till plains, have been assigned for the purposes of this report to early Wisconsin? time based upon stratigraphic correlation with nearby subsurface loesses in western Moody County. Though no internal weathering zones were noted within this deposit during this study, parts of the loess sheet were certainly formed during late pi-2 or late Wisconsin time.

Because this loess sheet mantles and smooths an undulatory till surface, and is arranged at some locations into crude longitudinal dunes, its thickness is highly variable. At many locations, particularly on the northwest (upwind) slope of moraines or surfaces deeply eroded by modern processes, loess is not present. Conversely, eolian deposits may be quite thick on moderately sloped, southeastward (downwind) facing surfaces. Several locations were found to contain greater than 10 feet of loess.

The composition of the eolian sediments also varies from place to place. A number of sand dunes scattered throughout the area contain orange to light brown, well-sorted, fine to medium quartz sand. On the other hand, the loess, which makes up by far the major portion of the eolian deposits, is composed of yellow-brown to light-gray, calcareous, clayey silts.

LATE WISCONSIN DEPOSITS

Till

Most of the surface deposits in the western two-thirds of the study area are composed of late Wisconsin till (figs. 2 and 3). This till is more than 250 feet thick in southwestern and north-central Lake County (fig. 11), but averages slightly over 100 feet.

The upper several feet of the late Wisconsin till has been altered by oxidation to yellow-brown and brown colors from the dark-gray and gray hues encountered lower in the till units. Late Wisconsin till typically has a thinner upper oxidized fringe than the older till sheets, seldom exceeding 30 feet in thickness. The depth of oxidation in a drift sheet is thought to be controlled primarily by the lowest level that water-table conditions has reached (Hallberg and others, 1978). Duration of weathering, till lithology, climate, till-sheet morphology and other factors, therefore, are indirect controls upon average oxidized zone thicknesses.

The late Wisconsin till is a calcareous, silty, sandy, pebbly clay which contains numerous sand or gravel lenses and abundant rocks and boulders. Boulders dot the till surface, especially on steeper slopes where erosion has removed the finer components of the till and concentrated these large clasts at the land surface. Late Wisconsin till contains more shale, when compared with earlier till sheets, as indicated by "pebble counts" of the 1 to 2 mm faction. As described in an earlier section, over 20 percent of the clasts examined from late Wisconsin till in Lake and Moody Counties were found to be composed of shale. Schroeder (1988) utilizing systematic sampling techniques, found similarly high shale values for late Wisconsin tills in neighboring Miner County. The high shale pebble content of this drift (in comparison to older tills in the area) is thought to be a result of the westerly path traversed by the late Wisconsin glacier, over more shale-rich terrain than earlier advances.

The late Wisconsin till surface is poorly drained, rugged and capped with a discontinuous thin loess blanket.

Outwash

Outwash deposits derived from the melting of late Wisconsin ice occurs at the base, within, and at the surface of the late Wisconsin drift sheet. Outwash deposits are evident along most of the larger stream valleys throughout the area, even forming the bulk of the surface outwash in the early Wisconsin? terrain of eastern Moody County (fig. 3). This older surface formed a convenient drainageway for meltwater issuing from late Wisconsin ice encroaching upon the Coteau des Prairies from both the west (James lobe) and from the east (Des Moines lobe).

As with earlier glacial deposits, the composition of the late Wisconsin outwash resembles that of clasts found in contemporaneous till. A variety of lithologies including shale, chert, chalk, granite, limestone, quartzite, ferruginous concretions, and occasionally coal is found in the outwash. Grain size ranges from boulders to fine sand. Individual clasts are typically angular to subround and sometimes faceted. Sorting is generally poor, especially in locations where transport by running water was brief, such as along Battle Creek in northeastern Lake County.

Outwash units buried at the base and within the late Wisconsin drift are rare and difficult to trace from drill hole to drill hole. The outwash appears to be relatively continuous only in the southwestern corner of Lake County. More detailed information concerning these buried outwash bodies is available in Hansen (1986a).

Lacustrine Sediments

Though most of the late Wisconsin drift is till, lake sediments are relatively common in this area. These sediments occur within two geomorphically distinct types of lake plains. The first, flat-lying features occupying valleys and depressions in the present day land surface, were formed during the late stages of deglaciation. Lake sediments well above the present strandline of Milwaukee Lake (fig. 2) are examples of this type of deposit.

The second type of lake deposit, common throughout the area mapped as stagnation moraine (fig. 2), is the ice walled lake plain. These are circular, flat-topped features, often more than a mile in diameter, usually elevated well above the surrounding land surface. These ice walled (sometimes referred to as perched) lake plains were formed as a result of material being deposited in a lake completely surrounded by stagnant ice.

The sediments found in both types of lake are similar, normally ranging in grain size from fine sand to clay. Sediment color is black, gray, occasionally white, and sometimes varved into distinct horizontal beds. Rare small shell fragments were noted during drilling, though none were complete enough for identification.

An interesting assemblage of coarser-grained material was noted at one ice walled lake plain in Lake County. A concentrate of pebble- to cobble-sized, ironstone concretions and clayballs crop out in a roadcut at the base of a lake plain near the northwest corner of sec. 30, T. 108 N.,

R. 53 W. These sediments were undoubtedly transported from a position on or near the lake margin during the waning phases of the lake.

Eolian Sediments

Although not mapped on figures 2 and 3, late Wisconsin loess forms a discontinuous thin blanket over much of the two-county area. Because these wind-transported sediments are typically 2 feet or less in thickness, only rarely exceeding 5 feet, and patchy in nature, the loess was not regarded as a mappable unit at the scale of these maps. Where thicker loess was penetrated by test holes, however, it was recorded upon the cross sections (figs. 7 through 14).

These wind-blown deposits have multiple source areas. Some of the loess on the early Wisconsin till surface east of the Sioux River are derived from late Wisconsin outwash in Brookings County, the Big Sioux valley in Moody County, and the valley now occupied by Skunk Creek in Lake County. Loess overlying the late Wisconsin drift of Lake County is derived from outwash in the nearby James Basin.

These sediments are composed of unstratified yellow to yellow-brown calcareous, clayey to sandy silt. Small calcareous loess kindchen, reddish-brown root tubules, and tiny black organic specks are abundant.

The loess overlying the late Wisconsin surface displays numerous examples of large scale polygonal shaped patterns previously noted by Christensen (1987) in Clark County, South Dakota and Schroeder (1988) in Miner County, South Dakota. These polygons, often over 1 mile across, are prominent features on air photos of western Lake County. The features are commonly associated with periglacial environments and areas of once permanently frozen ground. The patterns seem to be best developed in areas of thicker loess, though patterns are distinguishable in areas with little or no loess.

RECENT DEPOSITS

Alluvial Sediments

Many streams in the study area are flanked by alluvial sediments deposited during Holocene (Recent) time. These include black and dark-brown organic silt, clay, and fine sand within the flood plain of the various creeks and rivers. Although some alluvium occurs sporadically in the more youthful late Wisconsin terrain (notably in the valley of the East Fork Vermillion River), it is much more prevalent on the well-drained, more mature early Wisconsin? landscape in Moody County. A considerable amount of material has been eroded, transported, then deposited in Recent times along the Big Sioux valley and its larger tributaries. Alluvium thickness locally exceeds 15 feet in the Big Sioux valley; it rarely exceeds 5 feet in thickness in the late Wisconsin terrain.

Lacustrine Sediments

Holocene lake deposition has also been a landscape-altering process. Infilling of lakes primarily by erosion of surrounding land has resulted in the natural process of lakes reverting to sloughs and swamps then to dry lake beds. Such former lakes dot the late Wisconsin landscape by the score, containing up to 25 feet of black to olive clay and silt, much undoubtedly deposited during the Holocene.

Eolian Sediments

Eolian silts and clays are a third type of sediment deposited since the end of Pleistocene glaciation. Loess dunes, at places over 3 feet deep, bury fence lines and other artifacts within the study area. These yellow-brown to dark-brown sediments are nearly indistinguishable from older loess deposits in the area.

Quaternary History

Pre-glacial Geography

Figure 15 shows the present configuration of the bedrock surface in this study area, and is probably a close approximation of the area's topography immediately before the onset of Pleistocene glaciation. The bedrock surface has certainly been eroded and modified to a degree by the four or more glaciations of the area. Though the exact amount and location of glacial erosion is unknown, its overall effect upon large-scale features, such as river valleys and large highlands are probably minor. Indeed, elevated plateaus of erosion-prone bedrock such as that between the present-day towns of Madison and Nunda (fig. 15) have retained relatively complete preglacial weathering profiles, despite being overridden by glacial ice. The major features presently displayed on the bedrock surface are therefore thought to be reasonably intact relicts of pre-Pleistocene time.

Immediately prior to Pleistocene glaciation, the area appeared distinctly different than present landscapes. Lake and Moody Counties were located near a major drainage divide, far from the major preglacial streams to the northwest (Christensen, 1977) and to the south Christensen, 1967). Gently rolling shale hills were carved by small streams, some headed in the Sioux Quartzite highlands to the south and east (fig. 16). The quartzite in these highlands sometimes rose abruptly above the surroundings plains in spires and vertical cliffs much like those found today in nearby Palisades State Park in Minnehaha County. Over half of the 405 feet of total bedrock relief detected during this study lies within these quartzite highlands (fig. 15).

No major pre-Pleistocene stream valleys were found in the study area. Only one part of the drainage net shown on figure 16 may have extended far beyond the borders of Lake and Moody Counties. The extent of that valley, which reaches eastward into Minnesota from Trent, is yet unknown. Those extending outside the study area into bordering South Dakota counties blend into

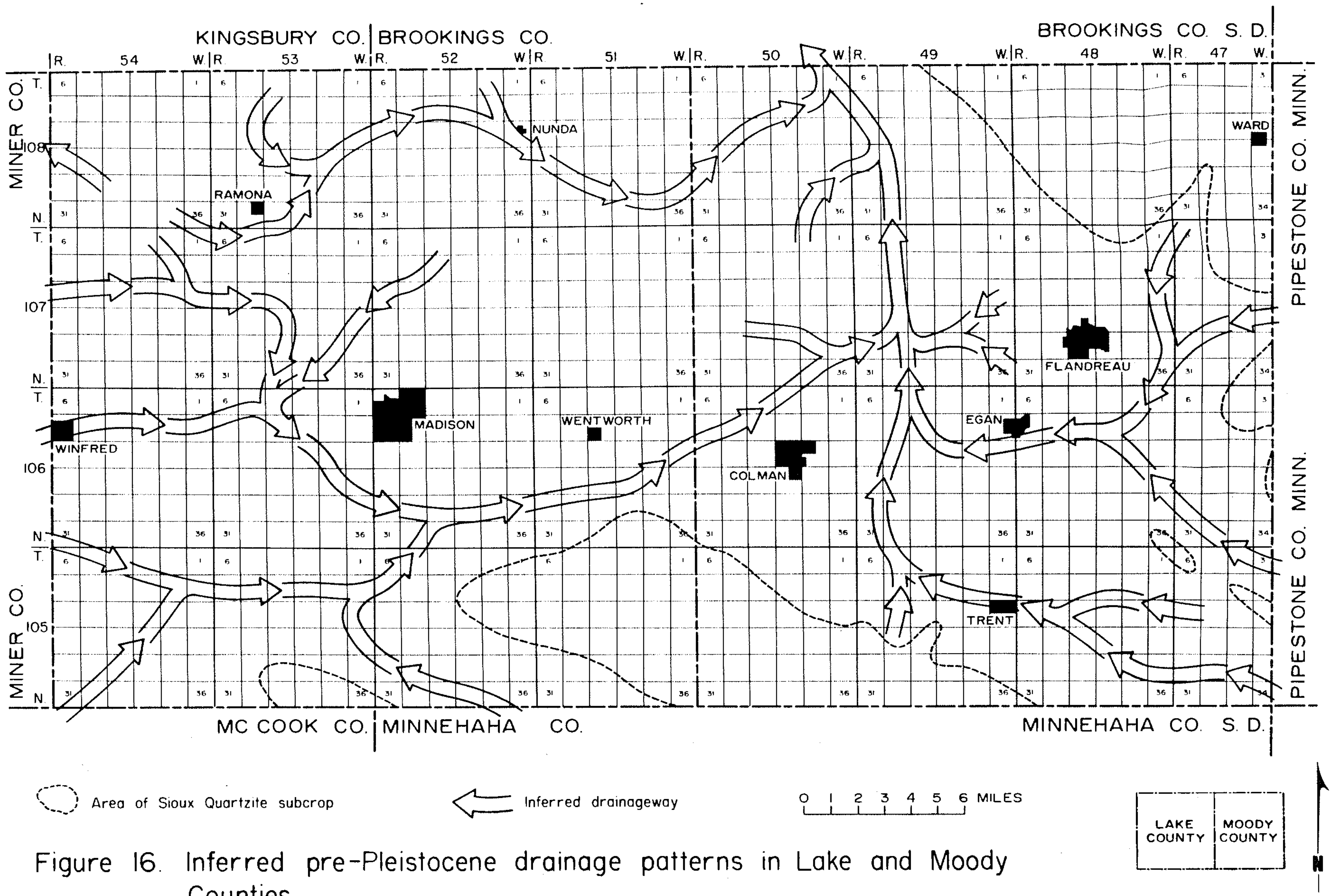


Figure 16. Inferred pre-Pleistocene drainage patterns in Lake and Moody Counties.

the surrounding highlands within several miles. Almost the entire surface of the two-county area apparently was drained through a northward trending valley into Brookings County.

The valleys comprising this drainage net were locally incised over 100 feet into the surrounding landscape. Interfluves outside of the quartzite highlands were composed of Pierre Shale while valley bottoms were incised into the Niobrara Formation, the Split Rock Creek Formation, and the Carlile Shale (fig. 15).

Pastel colored fluvial sediments composed of silts, clays and sands were deposited in these valleys over a period of time sometime between the end of the Cretaceous and the encroachment of ice during early Pleistocene time.

Pre-Illinoian 1 Glaciation

Regional studies of Pleistocene geology suggest that multiple pre-Illinoian glacial advances reached parts of eastern South Dakota (Richmond and Fullerton, 1986). At least two of these traversed Lake and Moody Counties.

Early Pleistocene glaciations are thought to have approached South Dakota from a northeastern direction, a hypothesis supported both by the distribution of drift in eastern South Dakota and studies in surrounding areas. However, the distribution of drift in the study area suggests that ice flow of the pi-1 glacier may have been locally diverted to a southward flow path along the large north-south preglacial valley extending from Deuel County to southeastern Moody County (Hedges and others, 1982, pl. 1).

The pi-1 drift, capped by intermittent loess and a well defined weathering zone, partially fills the valleys incised into the underlying bedrock. The configuration of the loess and weathering zone on the pi-1 drift surface (fig. 10) indicates that subsequent glaciations probably modified the pi-1 surface only to a minor extent. Pi-1 drift was therefore primarily deposited in the valleys and "pinched out" on the adjacent interfluves, smoothing and infilling the previously well incised landscape.

The influence of preexisting valleys on glacial deposition, relatively thin pi-1 drift, and a lack of evidence that similar drift exists to the south and west suggests that this glaciation may not have extended far beyond Lake and Moody Counties.

Deposits of loess on the pi-1 till surface are locally over 20 feet thick. These materials indicate that high winds and unvegetated local sediment sources such as barren outwash plains existed after the retreat of glacial ice from the area.

Pre-Illinoian 2 Glaciation

A long period of weathering after the retreat of the pi-1 glacier formed a thick (up to 90 feet) oxidized zone in the upper part of the pi-1 drift. The subsequent reglaciation of the region to the north of the study area caused major alteration of the drainage patterns of the upper midwest. A combination of older drift sheets and pi-2 glaciation occupied the path of the major regional streams which channeled water from western North and South Dakota (and beyond) to Hudson Bay. The presence of the "western-derived" sand in the study area indicates that these streams were diverted by the ice as far south as Lake and Moody Counties. This stream meandered eastward, depositing the "western-derived" sands in a poorly developed valley over more than half of the two-county area. Eventually, meltwater from advancing pi-2 ice deposited poorly sorted, angular outwash over the surface of these "western derived" fluvial sands.

As pi-2 ice overran the study area, it deposited a broad moraine against the edge of the quartzite highlands (figs. 9, 10, and 14), before eventually overriding the Sioux Ridge and spreading to the south. Distribution of the drift as well as glacial striations on quartzite surfaces exposed in windows through pi-2 drift near Dell Rapids (Flint, 1955, pl. 3) indicate at least a lobe of pi-2 ice flowed due south from the study area.

The emplacement of the pi-2 drift sheet changed the physiography of the area substantially. In the Sioux Ridge area, pi-2 drift, locally over 200 feet, thick added considerable mass in the early development of the Coteau des Prairies. The subsequent highland influenced the movement of later glaciations over a broad area.

The pi-2 glaciation also greatly modified drainage patterns in eastern South Dakota. The streams carrying exotic, quartz-rich, "western-derived" sands were apparently permanently diverted from east-central South Dakota. Lithologies of this type are not found in younger sediments of the area.

After the retreat of the pi-2 ice sheet, loess deposition resumed over the newly formed land surface. Finally, a reddish-colored soil such as that found in a drill hole at the SE¼ of sec. 13, T. 106 N., R. 51 W. was developed on the drift surface.

Early Wisconsin? Glaciation

Early Wisconsin? glaciation is also thought to have encroached upon eastern South Dakota from a northeastern direction. Observations in the vicinity of Lake and Moody Counties suggest a continuation of this trend across the study area. Glacial striations on nearby quartzite surfaces in early Wisconsin? terrain (Flint and others, 1959; Winchell, 1882), orientation of moraines in western Lake County (fig. 8), and asymmetrical erosion of the oxidized zone on the pi-2 drift (figs. 9 and 10) suggest a general southwest flow.

The early Wisconsin? ice is thought to have reached only a short distance beyond Lake and Moody Counties (Schroeder, 1988) and was probably relatively thin in this area. Only minor modification of the local landscape was achieved by early Wisconsin? ice. A relatively uniform blanket of till, outwash, and lake deposits generally reproduce the geomorphic expression of the underlying drift.

Though early Wisconsin? drift is exposed in the study area, details of its depositional history are difficult to interpret. Most of the features once displayed on the drift surface have been altered by erosion and masked by loess cover. In a few scattered localities, primarily in southern Moody County, ice-block lakes and kames indicate that the receding glacier left areas of stagnant ice (fig. 3).

Loess deposition and erosion of the drift surface again followed deglaciation of the area.

Late Wisconsin Glaciation

Changes in global climate during late Wisconsin time shifted the center of glaciation westward from earlier glacial advances. The late Wisconsin ice therefore approached eastern South Dakota from the north rather than from the northeast (Hallberg and Kemmis, 1986).

Near the border between North and South Dakota the southward-flowing ice sheet was diverted by the Coteau des Prairies bedrock highland, which had become a nearly insurmountable obstacle by the accumulation of pre-late Wisconsin drift. The southward-flowing ice split on the wedge-shaped highland and continued southward as two distinct lobes, now called the Des Moines lobe and James lobe after the present-day streams which occupy the two areas.

The Des Moines lobe was diverted to the southeast into southern Minnesota and Iowa. Though Des Moines lobe ice did not enter this study area, meltwaters emanating from ice only a few miles to the northeast eroded channels now occupied by Pipestone, Spring, and other unnamed creeks in eastern Moody County. This meltwater deposited a large volume of outwash within those valleys. The Des Moines lobe ice also contributed substantial amounts of meltwater and meltwater-borne debris to the interlobate drainageway now occupied by the Big Sioux River. The outwash in the valley of the Big Sioux is a remnant of meltwaters of both Des Moines lobe and James lobe ice which flanked the Coteau des Prairies.

Meanwhile, the James lobe was diverted into a lowland previously created by a major stream flowing northward through what is now Spink and Brown Counties, South Dakota (Christensen, 1987). The ice flowed southward, eventually reaching the far southeastern corner of the state at its maximum extent.

As the ice flowed southward, it also encroached upon the bordering highlands of the Coteau des Prairies. This encroachment was not uniform and even but rather occurred in surges and sublobes, responding to changes in glacier dynamics and breaches in the western rim of the Coteau des Prairies highland. Examination of figures 7 through 10 shows that the early Wisconsin? land surface already sloped from west to east across Lake County to a central lowland near the present location of the Big Sioux River. Figures 11 through 14 show that the rim of the highland indeed contained swales and valleys in the surface of the early Wisconsin? drift, providing channels for the flow of glacial ice into the study area from the ice mass to the west.

Geomorphic analysis of the late Wisconsin drift surface suggests that at least three sublobes flowed across the study area from the James lobe. Ice initially flowed into Lake and Moody Counties along a sag in the early Wisconsin? surface extending from the far northwest corner of Lake County to near Colman (fig. 17a). The maximum extent of this ice is marked by a low rocky end moraine arcing from near Lake Campbell at the Brookings County border southward to near Chester in southeastern Lake County (figs. 2 and 3).

As dynamics in the ice sheet to the west shifted, this sublobe retreated and established equilibrium for a sufficient time to build a recessional moraine near the present-day valley of Battle Creek (fig. 17b). Another abrupt decrease in glacial energy abandoned a large expanse of ice in northern Lake County (fig. 17c). Later adjustments diverted ice flow southward in far southwest Lake County. The present-day course of the East Fork Vermillion River marks the edge of this active ice (fig. 17d). The ice to the west of that line remained active along the flank of the Coteau des Prairies. That mass of ice to the east of the East Fork Vermillion River stagnated and melted in place. Some of the meltwater from these stranded sublobes flowed along the sublobe boundaries and cut meltwater channels now occupied by the East Fork Vermillion River, North Skunk Creek, and Battle Creek (Hansen, 1986a, fig. 8). Outwash deposited within these channels as well as Lake Madison, Lake Herman, and most of the other lakes and sloughs in the area date from this period of stagnant-ice wasting. These lakes occupy depressions in the land surface formed by ice blocks persisting during most of the melting process.

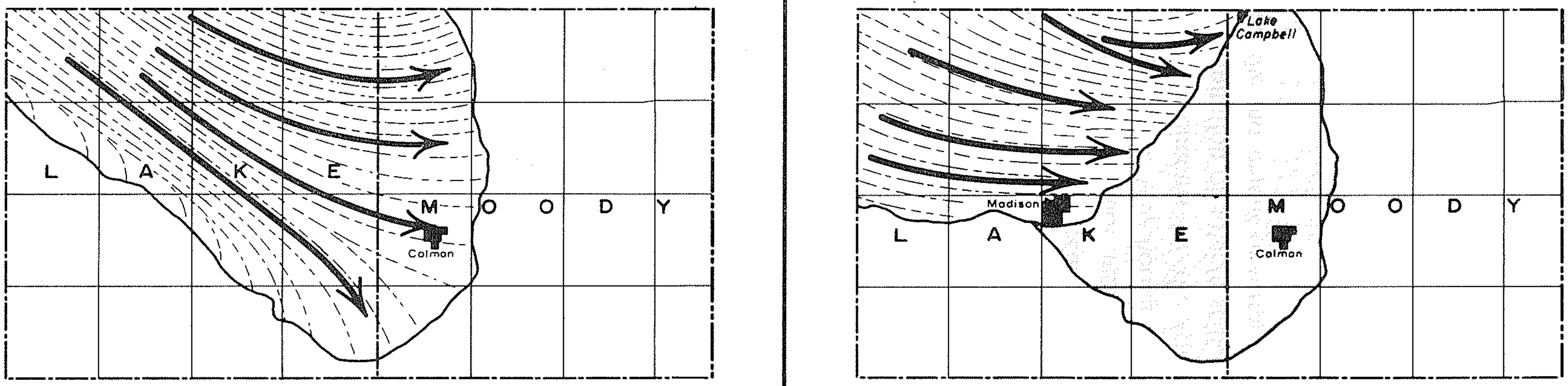
Recent History

The geologic history of the area since the end of the Pleistocene Epoch has been dominated by processes still active today. Erosion by running water is gradually moving sediments from the highlands to areas topographically lower thereby infilling lakes and sloughs. Wind continues to sweep dust from areas with little or no vegetation and redeposit it elsewhere. Landslides and other forms of mass movement continue to occur in areas rendered unstable by both natural and man-made action. Weathering of the uppermost several feet of each surface drift sheet have modified these sediments by the formation of a dense pattern of jointing as well as oxidation and precipitation of soluble salts. These modifications, presumably still active today, have likely affected the movement of water in the area since deglaciation (Barari and Hedges, 1985).

Economic Geology

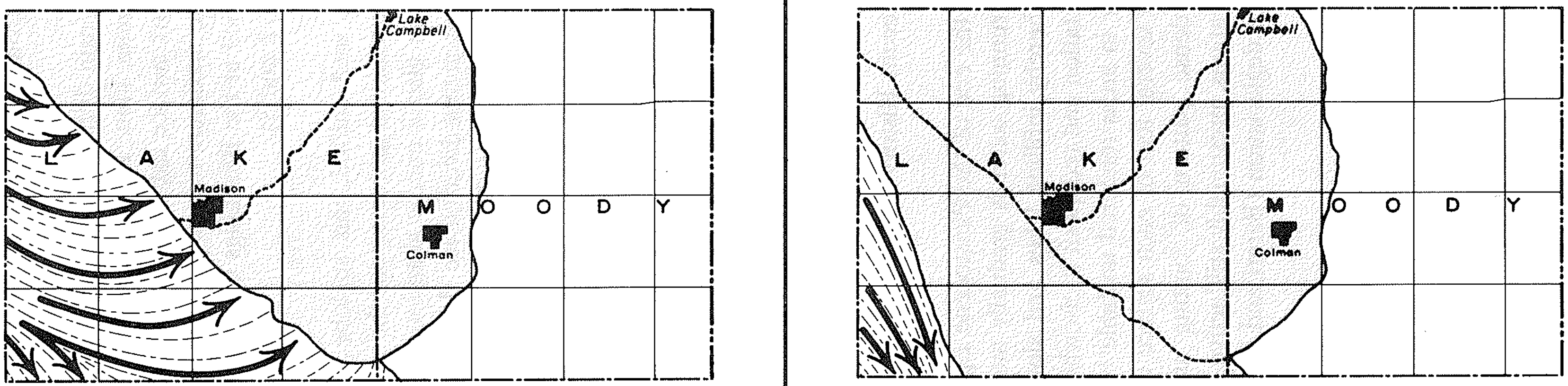
Water

Water is the most important mineral resource yet found in Lake and Moody Counties. A separate volume (Hansen, 1986a) describes in detail the water resources available in the study area. The major findings of the hydrological study are also summarized in Hansen (1986b).



A Initial sublobe of late Wisconsin ice flowed from the northwest corner of the study area southeastward to near Colman.

B Glacier retreated, then reestablished equilibrium for a time, building moraine between Madison and Lake Campbell areas.



C Further rapid retreat of the late Wisconsin glacier abandoned a large expanse of ice in northwest Lake County. Shifting energy patterns in the glacier caused ice to flow onto the highland farther to the south.

D Glacial equilibrium adjusted, southeast flow is established along the west flank of the ice–covered highland.

Active ice. Arrows indicate direction of movement

▨ Stagnant ice

Former ice margin

0 6 12 MILES

N

Figure 17. Patterns of late Wisconsin glacial flow in Lake and Moody Counties.

Sand and Gravel

Sand and gravel is another important mineral commodity in Lake and Moody Counties. These resources, used chiefly in the maintenance of the area's roads, were also mapped and described as a part of this study. Those with an interest in these resources are referred to Tomhave (1987a, 1987b).

Oil and Gas

No commercial quantities of oil or gas have been found in the area. Geologic conditions necessary for the accumulation of petroleum appear to be absent in Lake and Moody Counties.

Other Minerals

Although no economic mineral deposits have yet been found, this area has attracted considerable exploration in recent years. The Sioux Quartzite has been suggested as a possible host for unconformity vein-type uranium deposits (Cheney, 1981). Some test coring subsequently was conducted in Moody County as well as in several neighboring counties, though no economic deposits have been reported.

The Sioux Quartzite underlying neighboring counties in Minnesota has been recently proposed to possibly contain paleoplacer gold deposits. David L. Southwick of the Minnesota Geological Survey has reported interest in the idea by several exploration companies (Southwick, written communication, 1985). Areas in southeastern South Dakota, including Lake and Moody Counties, may have similar possibilities.

Lake and Moody Counties are within an area suggested as an exploration target for stratiform-manganese deposits (Cannon and Force, 1983). Cretaceous age rocks fringing the Sioux Ridge display many characteristics commonly associated with some of the world's most valuable manganese deposits (Hammond, 1988). Exploration of the area for this strategic metal is currently under way.

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APPENDIX - List of test holes used in compiling this report. Logs for these holes are on file at the South Dakota Geological Survey offices, Vermillion, South Dakota.

Location	Test-Hole Name	Ground-Surface Elevation	Total Depth
NE NE NE NE sec. 03, T. 104 N., R. 48 W.	CO-81-33	1572	27
NW NE NW NE sec. 02, T. 104 N., R. 49 W.	CO-82-55	1495	26
NW NW NE NW sec. 02, T. 104 N., R. 49 W.	CO-82-67	1500	26
NE NE NW NW sec. 02, T. 104 N., R. 49 W.	CO-82-54	1500	26
NE NE NE NE sec. 03, T. 104 N., R. 49 W.	CO-82-53	1500	26
NE NW NW NE sec. 03, T. 104 N., R. 49 W.	CO-82-60	1508	26
NE NE NW NW sec. 04, T. 104 N., R. 49 W.	CO-114-85	1600	154
NE NW NE NE sec. 04, T. 104 N., R. 50 W.	LM-11-80	1573	58
SW SW SW SE sec. 04, T. 104 N., R. 50 W.	MA-78-1	1570	50
SW SW SW SE sec. 04, T. 104 N., R. 50 W.	CO-81-41	1567	36
NE NW NW NW sec. 06, T. 104 N., R. 50 W.	LM-81-6	1655	265
NW NE NE NE sec. 04, T. 104 N., R. 52 W.	LK-06-80	1688	412
NE NE NE NE sec. 04, T. 105 N., R. 47 W.	LM-81-18	1568	530
NE NE SE NE sec. 15, T. 105 N., R. 47 W.	R1-82-146	1620	171
SE SE SE SE sec. 16, T. 105 N., R. 47 W.	LM-81-17	1600	327
NE NE NE SE sec. 18, T. 105 N., R. 47 W.	R1-82-147	1578	585
NW NW NW NW sec. 22, T. 105 N., R. 47 W.	LM-52-80	1597	380
SW SW SW SW sec. 34, T. 105 N., R. 47 W.	LM-51-80	1602	368
NE NE NE NE sec. 01, T. 105 N., R. 48 W.	R1-82-100	1616	205
NW NE NE NE sec. 01, T. 105 N., R. 48 W.	R1-82-101	1616	208
NW NW NW NW sec. 03, T. 105 N., R. 48 W.	LM-33-81	1578	400
NW NW NW SW sec. 18, T. 105 N., R. 48 W.	CO-82-22	1506	17
NW NW SW SE sec. 18, T. 105 N., R. 48 W.	CO-82-71	1510	26
NE NE SE SE sec. 18, T. 105 N., R. 48 W.	CO-82-70	1510	26
NE NE NE NE sec. 19, T. 105 N., R. 48 W.	MY-78-11	1508	35

SE SE NE NE sec. 19, T. 105 N., R. 48 W.	CO-82-69	1510	26
NW NW NW NW sec. 19, T. 105 N., R. 48 W.	LM-81-13	1498	744
NW NW NW NW sec. 19, T. 105 N., R. 48 W.	CO-82-72	1496	26
SW SW NW SW sec. 19, T. 105 N., R. 48 W.	CO-82-73	1492	36
NE NE SE SE sec. 19, T. 105 N., R. 48 W.	CO-82-68	1505	36
SW SW SW SW sec. 20, T. 105 N., R. 48 W.	CO-82-20	1507	17
NW NW NW NW sec. 22, T. 105 N., R. 48 W.	LM-53	1601	420
SE SE SE SE sec. 33, T. 105 N., R. 48 W.	LM-50-80	1554	273
SE SE SE SE sec. 33, T. 105 N., R. 48 W.	CO-81-29	1554	40
NE SE SE SE sec. 36, T. 105 N., R. 48 W.	LM-81-15	1550	524
NE SE SE SE sec. 36, T. 105 N., R. 48 W.	LM-81-16	1550	50
NE NE NE NE sec. 01, T. 105 N., R. 49 W.	R1-82-103	1598	395
SE SE SE SE sec. 04, T. 105 N., R. 49 W.	CO-82-17	1526	37
NW NE NE NE sec. 10, T. 105 N., R. 49 W.	CO-82-18	1518	27
SE SE SE SE sec. 11, T. 105 N., R. 49 W.	CO-82-19	1499	27
NE NE NE NE sec. 21, T. 105 N., R. 49 W.	LM-81-12	1614	360
SE SE NE NE sec. 22, T. 105 N., R. 49 W.	LM-81-19	1610	236
SE SE NE SE sec. 23, T. 105 N., R. 49 W.	SR-39-141	1550	440
SE SE SW NE sec. 25, T. 105 N., R. 49 W.	CO-82-23	1499	37
SE SE SE SE sec. 25, T. 105 N., R. 49 W.	CO-82-21	1493	17
SE SE NE SE sec. 26, T. 105 N., R. 49 W.	CO-82-63	1520	26
SW SW SE SW sec. 27, T. 105 N., R. 49 W.	DR-145	1575	230
SW SW SW SW sec. 34, T. 105 N., R. 49 W.	MD-49	1529	74
NE NE NE SE sec. 34, T. 105 N., R. 49 W.	CO-82-61	1509	36
SE SE NE SE sec. 34, T. 105 N., R. 49 W.	CO-82-59	1508	26
NE NE NE NE sec. 35, T. 105 N., R. 49 W.	MY-78-12	1509	20
NW NW NE NE sec. 35, T. 105 N., R. 49 W.	CO-82-65	1510	36
NW NW NW NE sec. 35, T. 105 N., R. 49 W.	CO-82-62	1520	46
NE SE NE SE sec. 35, T. 105 N., R. 49 W.	CO-82-66	1500	26
SE SE SE SE sec. 35, T. 105 N., R. 49 W.	CO-82-24	1493	17

NW SW SW NE sec. 36, T. 105 N., R. 49 W.	SR-39-66	1490	37
SE SE SE SE sec. 36, T. 105 N., R. 49 W.	LM-81-14	1529	186
NE NW NE NE sec. 01, T. 105 N., R. 50 W.	R1-82-118	1650	440
NW NW NW NW sec. 01, T. 105 N., R. 50 W.	R1-82-132	1650	380
NW NW NW NW sec. 03, T. 105 N., R. 50 W.	LM-12-80	1683	455
NW NW NW NW sec. 06, T. 105 N., R. 50 W.	R1-82-123	1719	362
NW NW NW NW sec. 19, T. 105 N., R. 50 W.	LM-81-8	1624	102
SE NE NE NE sec. 21, T. 105 N., R. 50 W.	LM-10-80	1662	193
NE NE NE NE sec. 24, T. 105 N., R. 50 W.	LM-81-10	1637	355
NW NW NW NW sec. 29, T. 105 N., R. 50 W.	MY-78-13	1585	55
SE SE SE SE sec. 36, T. 105 N., R. 50 W.	LM-48	1582	181
NW NW NW NW sec. 09, T. 105 N., R. 51 W.	LK-79A	1608	55
SW SE SW SW sec. 11, T. 105 N., R. 51 W.	WR-79-3	1610	55
SW NW NW SW sec. 16, T. 105 N., R. 51 W.	WR-79-4	1611	80
SW NW NW SW sec. 16, T. 105 N., R. 51 W.	LK-79D	1611	30
NE NE NE SE sec. 16, T. 105 N., R. 51 W.	LK-08-80	1610	125
NE NE NE SE sec. 16, T. 105 N., R. 51 W.	LM-9-80	1610	160
NE SE SE NE sec. 17, T. 105 N., R. 51 W.	LK-63A	1605	41
SE SE SE SE sec. 19, T. 105 N., R. 51 W.	LK-79E	1631	65
NE NE NE SE sec. 23, T. 105 N., R. 51 W.	LM-81-9	1582	60
SW SW SW SW sec. 31, T. 105 N., R. 51 W.	LM-81-5	1650	600
SW SW SW SW sec. 34, T. 105 N., R. 51 W.	LM-07-80	1651	451
SE NE NE NE sec. 04, T. 105 N., R. 52 W.	LM-18-80	1740	494
SE SE SE NE sec. 09, T. 105 N., R. 52 W.	R1-82-160	1685	319
NE NE NE SE sec. 20, T. 105 N., R. 52 W.	R1-82-161	1692	440
NW NW NW NW sec. 22, T. 105 N., R. 52 W.	LM-05-80	1661	360
NE NE NW NE sec. 24, T. 105 N., R. 52 W.	LM-81-3	1650	217
SW SW SW SW sec. 31, T. 105 N., R. 52 W.	LM-81-2	1723	322
SE SW SW SW sec. 36, T. 105 N., R. 52 W.	R2-83-130	1648	441
SW NW NW NW sec. 22, T. 105 N., R. 53 W.	LM-4	1790	791

NW NE NE NE sec. 24, T. 105 N., R. 53 W.	LM-81-1	1791	665
NW NW NW NW sec. 31, T. 105 N., R. 53 W.	LK-67A	1552	101
SE SE SE SE sec. 33, T. 105 N., R. 53 W.	LM-81-4	1785	324
NW NW NW NW sec. 14, T. 105 N., R. 54 W.	LK-79F	1629	155
NW NE NE NE sec. 21, T. 105 N., R. 54 W.	LK-01-80	1660	365
NE NE NE NE sec. 22, T. 105 N., R. 54 W.	R2-82-146	1630	602
NE NE NE NE sec. 24, T. 105 N., R. 54 W.	R1-82-159	1630	335
SE NE NE NE sec. 28, T. 105 N., R. 54 W.	Knudson	1660	378
SW SW SE SE sec. 33, T. 105 N., R. 54 W.	LM-2-80	1645	305
NW NW NW NW sec. 35, T. 105 N., R. 54 W.	R2-82-145	1650	368
SE SE SE SE sec. 36, T. 105 N., R. 54 W.	R2-82-159	1620	597
NE NE NE NE sec. 01, T. 105 N., R. 55 W.	R-3	1652	290
SE SE SE SE sec. 13, T. 105 N., R. 55 W.	R-22	1625	230
SE SE SE SE sec. 36, T. 105 N., R. 55 W.	R-10	1579	215
SE SE SE SE sec. 36, T. 105 N., R. 55 W.	R2-82-160	1575	428
NW NW NW NW sec. 03, T. 106 N., R. 47 W.	LM-81-36	1642	186
NW NW NW NW sec. 06, T. 106 N., R. 47 W.	R1-82-98	1674	428
NE SE SE NE sec. 21, T. 106 N., R. 47 W.	LM-35-81	1604	473
SE SE SE SW sec. 31, T. 106 N., R. 47 W.	R1-82-157	1635	349
SW SW SW NE sec. 05, T. 106 N., R. 48 W.	FE-81-14	1550	43
NE NE SW SW sec. 05, T. 106 N., R. 48 W.	CO-82-12	1218	37
SW NW SW NW sec. 07, T. 106 N., R. 48 W.	CO-82-13	1546	27
SE NE SE SE sec. 07, T. 106 N., R. 48 W.	CO-82-14	1525	37
SE SE SE SE sec. 13, T. 106 N., R. 48 W.	R1-82-99	1648	430
NW NW NW NW sec. 19, T. 106 N., R. 48 W.	R1-82-104	1595	350
NE NE NE NE sec. 21, T. 106 N., R. 48 W.	LM-81-34	1597	380
SE SE SE SE sec. 15, T. 106 N., R. 49 W.	MY-78-8	1519	30
NE NE NE NW sec. 19, T. 106 N., R. 49 W.	D.O.E.-Huron	1670	352
NE NE NE NE sec. 21, T. 106 N., R. 49 W.	LM-81-31	1597	395
NW NW NE NW sec. 26, T. 106 N., R. 49 W.	CO-82-15	1520	27

SE SE SW SW sec. 27, T. 106 N., R. 49 W.	R2-82-157	1601	345
SE SE SW SE sec. 33, T. 106 N., R. 49 W.	LM-32-81	1557	380
NE NE NE NW sec. 35, T. 106 N., R. 49 W.	MY-78-9B	1510	20
SE SE SE SW sec. 35, T. 106 N., R. 49 W.	CO-82-16	1508	27
NE NE NE NE sec. 01, T. 106 N., R. 50 W.	R1-82-119	1664	410
NE NW NW NE sec. 04, T. 106 N., R. 50 W.	LM-33-80	1698	464
NW NW NW NW sec. 06, T. 106 N., R. 50 W.	R1-82-121	1668	380
SE SE SE SE sec. 14, T. 106 N., R. 50 W.	Sioux Valley	1680	650
SW SW SW SW sec. 15, T. 106 N., R. 50 W.	LM-13-80	1670	425
SW SW NE SE sec. 15, T. 106 N., R. 50 W.	Colman-Norbeck	1695	636
NW NW NW NW sec. 03, T. 106 N., R. 51 W.	LM-32-80	1650	294
SW SE SE SE sec. 13, T. 106 N., R. 51 W.	R1-82-122	1690	410
NW NE NE NE sec. 21, T. 106 N., R. 51 W.	LK-14-80	1700	400
SW SW SE SW sec. 27, T. 106 N., R. 51 W.	Reiff	1712	331
SE NE NE NE sec. 33, T. 106 N., R. 51 W.	LM-15-80	1680	344
NW NW SW SW sec. 34, T. 106 N., R. 51 W.	LM-17-80	1650	173
SE SE SE SW sec. 01, T. 106 N., R. 52 W.	Elertson	1699	1103
NW NW NW SW sec. 04, T. 106 N., R. 52 W.	MD-81-9	1710	337
SW SW SW SW sec. 07, T. 106 N., R. 52 W.	MD-81-1	1686	305
NE NE NE SW sec. 08, T. 106 N., R. 52 W.	Well 10	1657	275
SE NE NE SW sec. 08, T. 106 N., R. 52 W.	Grimshaw-Stach	1640	268
NW SE NE SW sec. 08, T. 106 N., R. 52 W.	Well 11	1655	260
NW SE NE SW sec. 08, T. 106 N., R. 52 W.	MD-81-14	1657	260
NW SE NE SW sec. 08, T. 106 N., R. 52 W.	MD-81-16	1657	260
NE NE NE SE sec. 08, T. 106 N., R. 52 W.	MD-81-7	1655	110
NE NE NE SE sec. 08, T. 106 N., R. 52 W.	MD-81-8	1655	335
SE SE SE SE sec. 13, T. 106 N., R. 52 W.	R1-82-124	1691	380
SW NW NW NW sec. 15, T. 106 N., R. 52 W.	LM-19-80	1690	350
NE SE SE SE sec. 15, T. 106 N., R. 52 W.	R1-82-133	1620	365
NE NE NE NE sec. 16, T. 106 N., R. 52 W.	MD-81-12	1690	332

SE SW SW SW sec. 17, T. 106 N., R. 52 W.	MD-81-3	1680	320
NE NW NW NW sec. 19, T. 106 N., R. 52 W.	MD-81-2	1737	495
NW NW NW NW sec. 21, T. 106 N., R. 52 W.	MD-81-4	1640	338
NE NE SE SE sec. 36, T. 106 N., R. 52 W.	R1-82-130	1633	255
NE NE SE SE sec. 36, T. 106 N., R. 52 W.	R1-82-131	1633	50
NE SW NW SW sec. 03, T. 106 N., R. 53 W.	R1-82-88	1695	371
NW SE NW SW sec. 03, T. 106 N., R. 53 W.	R1-82-87	1690	305
NW NW SW SW sec. 03, T. 106 N., R. 53 W.	R1-82-134	1701	110
SW NE SE SW sec. 03, T. 106 N., R. 53 W.	MD-81-15	1680	50
SW SE SE SW sec. 03, T. 106 N., R. 53 W.	R1-82-158	1718	350
SE SW SE SE sec. 03, T. 106 N., R. 53 W.	MD-81-13	1680	305
NE SE SE NE sec. 04, T. 106 N., R. 53 W.	LM-27C-80	1700	410
SE NE SE NE sec. 11, T. 106 N., R. 53 W.	MD-81-10	1669	50
SE NE SE NE sec. 11, T. 106 N., R. 53 W.	MD-81-11	1669	50
SE SW SW SW sec. 15, T. 106 N., R. 53 W.	LM-20-80	1700	335
SW NW SW SW sec. 18, T. 106 N., R. 53 W.	R2-82-152	1795	550
SW SW SW SW sec. 31, T. 106 N., R. 53 W.	R1-82-128	1730	368
SE SE SE SE sec. 33, T. 106 N., R. 53 W.	LM-21-1980	1782	470
SE SE SE SE sec. 36, T. 106 N., R. 53 W.	R1-82-129	1803	530
NE NE NE NE sec. 04, T. 106 N., R. 54 W.	LM-24-80	1793	425
SE NW NE SW sec. 07, T. 106 N., R. 54 W.	Winfred	1711	436
SW SW SW SW sec. 09, T. 106 N., R. 54 W.	LK-67B	1643	49
SW SE SW SW sec. 16, T. 106 N., R. 54 W.	LM-23-80	1660	263
SW SW SW SW sec. 18, T. 106 N., R. 54 W.	R-34	1689	285
NW NE NE NE sec. 29, T. 106 N., R. 54 W.	R1-82-165	1692	365
NE SE SE SE sec. 33, T. 106 N., R. 54 W.	LM-22-80	1632	245
NE NE NE NW sec. 01, T. 106 N., R. 55 W.	R-2	1670	320
NE NE NE SE sec. 25, T. 106 N., R. 55 W.	MR-05-78	1671	275
NW NW NW NW sec. 03, T. 107 N., R. 47 W.	Dykstra	1740	550
SW SW SW SW sec. 16, T. 107 N., R. 47 W.	MY-78-4	1580	35

SW NW SW SW sec. 18, T. 107 N., R. 47 W.	R1-82-91	1620	535
NW NW NW NW sec. 22, T. 107 N., R. 47 W.	LM-81-37	1640	417
NE NE NE NE sec. 01, T. 107 N., R. 48 W.	R1-82-96	1662	264
NW NW NW NW sec. 06, T. 107 N., R. 48 W.	R1-82-95	1625	391
NE NE NE NE sec. 08, T. 107 N., R. 48 W.	CO-82-9	1552	21
SW SW SW SW sec. 15, T. 107 N., R. 48 W.	R1-82-92	1604	410
NE NE NE NE sec. 16, T. 107 N., R. 48 W.	CO-82-10	1542	27
NW NW NW NW sec. 19, T. 107 N., R. 48 W.	R1-82-94	1652	410
NE NW sec. 23, T. 107 N., R. 48 W.	Red Wing	1555	369
NW NW NW NW sec. 25, T. 107 N., R. 48 W.	MY-77-6	1545	65
NE NE NW NW sec. 26, T. 107 N., R. 48 W.	CO-82-11	1537	47
SW SE SW SW sec. 29, T. 107 N., R. 48 W.	FE-81-19	1525	36
SW SW SW SW sec. 31, T. 107 N., R. 48 W.	R1-82-105	1597	335
SE SE SE SE sec. 33, T. 107 N., R. 48 W.	R1-82-97	1650	365
SW NW NW NW sec. 03, T. 107 N., R. 49 W.	R1-82-113	1645	425
SW SW SW SW sec. 15, T. 107 N., R. 49 W.	R1-82-96	1638	380
SW SW SW SW sec. 34, T. 107 N., R. 49 W.	R1-82-114	1573	320
NE NE NE NE sec. 04, T. 107 N., R. 50 W.	LM-35-80	1719	430
NE NE SE NE sec. 21, T. 107 N., R. 50 W.	LM-34-80	1715	432
NE NE NE NE sec. 24, T. 107 N., R. 50 W.	R1-82-115	1685	365
SE SE SE SE sec. 13, T. 107 N., R. 51 W.	R1-82-120	1702	410
NW NE NE NE sec. 21, T. 107 N., R. 51 W.	LM-31-80	1670	311
NW NE NE NE sec. 04, T. 107 N., R. 52 W.	LM-30-80	1750	365
SE SE SE SE sec. 16, T. 107 N., R. 52 W.	LM-29-80	1680	324
SW SW SW SW sec. 18, T. 107 N., R. 52 W.	LM-29-81	1740	412
NE NE NE NE sec. 24, T. 107 N., R. 52 W.	R1-82-126	1660	395
NW SW SW SW sec. 30, T. 107 N., R. 52 W.	MD-81-5	1708	362
SW SW SE SE sec. 32, T. 107 N., R. 52 W.	MD-81-6	1710	335
SE SE SW SW sec. 34, T. 107 N., R. 52 W.	LM-28-80	1690	323
SE SE SE SE sec. 36, T. 107 N., R. 52 W.	R1-82-125	1600	440

NE NE sec. 01, T. 107 N., R. 53 W.	Phelps	1780	769
SW NW NW NW sec. 22, T. 107 N., R. 53 W.	LM-26-80	1760	443
NW NW NW NW sec. 03, T. 107 N., R. 54 W.	LK-40-80	1793	590
NW NW NW NW sec. 03, T. 107 N., R. 54 W.	LM-81-22	1800	755
SW NW NW SW sec. 08, T. 107 N., R. 54 W.	Hageman	1730	685
SE NE NE NE sec. 21, T. 107 N., R. 54 W.	LM-25-80	1825	474
NE NE NE NE sec. 24, T. 107 N., R. 54 W.	R1-82-142	1835	545
SE SE SE SE sec. 36, T. 107 N., R. 54 W.	R1-82-143	1792	454
NE NE NE NE sec. 01, T. 107 N., R. 55 W.	MR-76-07	1761	410
SE SE SE SE sec. 13, T. 107 N., R. 55 W.	R-44A	1677	305
SW NW NW NW sec. 19, T. 108 N., R. 47 W.	R1-82-82	1672	160
NW NW NW NW sec. 22, T. 108 N., R. 47 W.	R1-82-79	1760	176
NE NE NE NE sec. 01, T. 108 N., R. 48 W.	R1-82-81	1720	222
NW NW NW NW sec. 03, T. 108 N., R. 48 W.	R1-82-84	1745	129
SW SW SW SW sec. 19, T. 108 N., R. 48 W.	CO-82-07	1550	28
NW NW NW NW sec. 22, T. 108 N., R. 48 W.	R1-82-83	1662	128
SW SW SW SW sec. 29, T. 108 N., R. 48 W.	CO-82-8	1701	37
SW SW SW SW sec. 34, T. 108 N., R. 48 W.	R1-82-92	1629	262
NE NE NE NE sec. 04, T. 108 N., R. 49 W.	R1-82-89	1620	264
NW NW NW NW sec. 05, T. 108 N., R. 49 W.	CO-82-3	1571	27
SE SE NE SE sec. 06, T. 108 N., R. 49 W.	CO-82-2	1571	27
NW NW SW NW sec. 07, T. 108 N., R. 49 W.	CO-82-1	1597	27
SW NW SW NW sec. 10, T. 108 N., R. 49 W.	CO-82-04	1564	37
SW SE SW SE sec. 15, T. 108 N., R. 49 W.	CO-82-6	1555	27
SW SW SW SE sec. 18, T. 108 N., R. 49 W.	I-29 R.A.	1650	295
NE NE NE NE sec. 21, T. 108 N., R. 49 W.	R1-82-106	1559	410
NE NE NE NE sec. 21, T. 108 N., R. 49 W.	R2-82-167	1559	500
NW NW NW NE sec. 21, T. 108 N., R. 49 W.	CO-82-05	1572	27
NE NE NE NE sec. 24, T. 108 N., R. 49 W.	R1-82-86	1623	340
SW SW SW SW sec. 18, T. 108 N., R. 50 W.	R1-82-110	1586	305

NE NE NE NE sec. 21, T. 108 N., R. 50 W.	LM-36-80	1706	676
NE NE NE NE sec. 24, T. 108 N., R. 50 W.	R1-82-107	1656	410
SW SW SW SW sec. 31, T. 108 N., R. 50 W.	R1-82-111	1661	350
SE SE SE SE sec. 36, T. 108 N., R. 50 W.	R1-82-112	1692	410
NE NE NE NE sec. 01, T. 108 N., R. 51 W.	R1-82-109	1612	305
SW NW NW NW sec. 03, T. 108 N., R. 51 W.	LM-38-80	1684	392
NE NE NE NE sec. 21, T. 108 N., R. 51 W.	LM-39-80	1682	371
SE SE SE SE sec. 33, T. 108 N., R. 51 W.	LM-42-80	1650	335
NW NW NW NW sec. 03, T. 108 N., R. 52 W.	LM-44-80	1808	500
SE SE NE NE sec. 08, T. 108 N., R. 52 W.	R1-82-166	1772	95
SW NE sec. 13, T. 108 N., R. 52 W.	Nunda	1760	735
SE SE SE SE sec. 13, T. 108 N., R. 52 W.	LM-81-20	1743	575
NW NW NW NW sec. 22, T. 108 N., R. 52 W.	LM-43-80	1800	463
NW NW NW SW sec. 31, T. 108 N., R. 52 W.	LM-81-30	1737	365
SE SE SE SE sec. 36, T. 108 N., R. 52 W.	R1-82-127	1723	320
NE NE NE NE sec. 01, T. 108 N., R. 53 W.	LM-26-81	1782	470
NE NE NE NE sec. 04, T. 108 N., R. 53 W.	LM-45-80	1769	508
NW NW NW NW sec. 14, T. 108 N., R. 53 W.	R2-82-168	1739	415
SW SW SW SW sec. 15, T. 108 N., R. 53 W.	LM-46-80	1774	550
SE SW SW SW sec. 18, T. 108 N., R. 53 W.	LM-24-81	1780	560
SW NE SW SW sec. 24, T. 108 N., R. 53 W.	R2-82-150	1720	1090
NW NW NW NW sec. 29, T. 108 N., R. 53 W.	R1-82-163	1788	500
SW SW SW SW sec. 31, T. 108 N., R. 53 W.	LM-23-81	1810	485
SE SE NW NE sec. 32, T. 108 N., R. 53 W.	Ramona-Kuehl	1810	871
NE NE SE NW sec. 32, T. 108 N., R. 53 W.	Ramona-Grimshaw	1811	847
SE SE SE SE sec. 33, T. 108 N., R. 53 W.	LM-41-80	1788	486
NE NE NE NE sec. 01, T. 108 N., R. 54 W.	LM-25-81	1750	410
NE NE NE NE sec. 04, T. 108 N., R. 54 W.	LM-21-81	1748	441
NW NW NW NW sec. 06, T. 108 N., R. 54 W.	R1-82-164	1730	560
NE NE SE SE sec. 06, T. 108 N., R. 54 W.	R2-83-127	1730	380

NW NW NE NW sec. 07, T. 108 N., R. 54 W.	R2-83-128	1732	380
SE SW SW SE sec. 11, T. 108 N., R. 54 W.	Nelson	1792	465
SE SE NE NE sec. 19, T. 108 N., R. 54 W.	R2-83-125	1752	425
NW NE NW NW sec. 19, T. 108 N., R. 54 W.	LM-81-20	1754	665
NW NE NW NW sec. 19, T. 108 N., R. 54 W.	R2-83-126	1757	500
NW NW NW NW sec. 22, T. 108 N., R. 54 W.	LM-47-80	1770	417
SE SE SE sec. 23, T. 108 N., R. 54 W.	Bloom	1760	801
NE NE NE NE sec. 30, T. 108 N., R. 54 W.	R2-83-108	1770	485
SW SW SW SW sec. 35, T. 108 N., R. 54 W.	R1-82-151	1812	605
NE NE NE NE sec. 01, T. 108 N., R. 55 W.	R-57	1730	560
NE NW NE NE sec. 01, T. 108 N., R. 55 W.	R2-83-129	1752	455
SW SE SE SE sec. 13, T. 108 N., R. 55 W.	R-56	1755	402
SE SE SW SW sec. 25, T. 108 N., R. 55 W.	MR-76-06	1692	350
SE SE SE SW sec. 33, T. 109 N., R. 47 W.	B6-78H	1726	65
SE SE SE SE sec. 33, T. 109 N., R. 47 W.	R1-82-80	1737	141
SW SW SW SW sec. 31, T. 109 N., R. 49 W.	R1-82-108	1568	410
SW SW SW SW sec. 31, T. 109 N., R. 49 W.	R2-82-166	1568	305
SE SW SE SE sec. 36, T. 109 N., R. 49 W.	R1-82-85	1700	215
SE SW SE SE sec. 33, T. 109 N., R. 50 W.	LM-37-80	1629	350
SW SW SW SE sec. 35, T. 109 N., R. 50 W.	LM-38-81	1625	170
SW SW SE SE sec. 35, T. 109 N., R. 50 W.	LM-39-81	1570	78
SE SE SE SE sec. 36, T. 109 N., R. 52 W.	LM-27-81	1782	500
NW NW NW NW sec. 33, T. 109 N., R. 53 W.	R2-84-77	1765	405
NW NW NW NW sec. 36, T. 109 N., R. 53 W.	R2-84-78	1786	495
NE SE NE NE sec. 32, T. 109 N., R. 54 W.	R1-84-52	1716	380
NE NW NE NE sec. 34, T. 109 N., R. 54 W.	R1-84-54	1735	155
NE NE NE NE sec. 32, T. 109 N., R. 55 W.	R2-83-97	1710	335
NW NW NW NW sec. 36, T. 109 N., R. 55 W.	R2-83-98	1731	365