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Alan E. Kehew

REPORT OF INVESTIGATION NO. 73

NORTH DAKOTA GEOLOGICAL SURVEY

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ABSTRACT

Most of the area surrounding Minot, North Dakota is underlain by deposits of Late Wisconsinan glacial advances. Bedrock of the Fort Union Group (Paleocene) is exposed only near the bottoms of the Souris and Des Lacs Valleys. Evidence for glaciations older than Late Wisconsinan includes till exposures in the valleys and a major buried valley delineated by State Water Commission test drilling. The Souris lobe, the segment of the Late Wisconsinan glacier active in the Minot area, deposited two tills that are lithologically similar; a thick lower till, Unit B, exposed at the surface south of the Souris Valley and detected in the subsurface north of the Souris Valley, and a thin upper till, Unit A, exposed at the surface and overlying Unit B north of the Souris River. During glacial retreat, glacial meltwater cut shallow channels into the till surface and deposited coarse-grained fluvial sediment. After the last glacial advance, huge discharges of water released during the draining of Glacial Lake Regina, in Saskatchewan, flowed through the Souris and Des Lacs Valleys, thereby eroding them to elevations below their present depths. Alluvial, lacustrine, and landslide deposits of the Oahe Formation (Holocene) up to 150 feet thick occur in the Souris and Des Lacs Valleys, in smaller channels on the uplands bordering the valleys, and in closed depressions (sloughs) on the uplands.

Major groundwater resources occur in aquifers within the Coleharbor Group consisting of buried channel, buried outwash, and surficial outwash deposits, and in aquifers within alluvium of the Oahe Formation deposited in the Souris and Des Lacs Valleys.

Engineering properties of each geologic map unit, compiled and extrapolated from existing data, are combined with other information such as depth to water table, flood potential, erosion potential, and slope angles to illustrate geotechnical conditions. A map showing geotechnical conditions related to foundation design, using landforms as generalized geotechnical mapping units, indicates most severe limitations for Oahe Formation sediments in the Souris and Des Lacs Valleys. A similar map showing conditions pertaining to waste disposal delineates areas within both the Oahe Formation and Coleharbor Group units, which have high potentials for groundwater contamination.

INTRODUCTION

Purpose and Objectives

Minot, North Dakota (fig. 1) is a city of 32,886 people (1980 census) located in north-central North Dakota (fig. 2). Along with other cities and towns in central and western North Dakota, Minot is growing. This growth, in part a response to energy development, requires accurate geological, hydrogeological, and geotechnical information for design and construction of buildings, roads, and utility lines. Geological conditions influence the type and cost of structures that can be built and determine the safety or risks of damage to the structure by active geological processes such as flooding or landsliding. Growth also necessitates the location and development of water supplies, deposits of materials used in construction, and sites which can be used for waste disposal. The geological setting of an area is the key to meeting the requirements of expansion and development.

This study was undertaken to compile existing information on the geology and geotechnical conditions of the Minot area, to obtain additional, more detailed information on the surface and subsurface geology of the area, and to present the information as a usable package for those involved in land-use decisions in the Minot and surrounding areas.

The first two major sections of the report deal with the geological setting and groundwater resources of the Minot area. The surface geology is shown on plate I. Plate I has another very important purpose, however, which is to present the engineering properties of the materials included in geological map units. Engineering data are not usually included on a geological map for several reasons. First, many geological studies are not concerned with practical applications of the geology. In addition, available engineering data are usually limited to sites investigated for specific projects; these studies are not overly concerned about the engineering conditions beyond the site. The construction of plate I, therefore, involved the extrapolation of site-specific engineering data to larger areas with similar geological conditions. The advantages and disadvantages of this approach are discussed in more detail later in the report.

The third main section of the report is an attempt to generalize the geological conditions and engineering properties of materials over larger areas and thereby construct maps with a smaller number of map units which show generalized geotechnical conditions. These maps will be useful in making preliminary evaluations of land-use alternatives. They are not suited for determining geotechnical conditions at a particular site.

Methods

The study area comprises 16 townships (576 square miles) with Minot approximately at the center. The area was mapped at a scale of 1:62,500 (1 inch to 1 mile) by airphoto and ground methods. New subsurface information was generated by augering 29 shallow test holes ranging from 13 to 72 feet in depth with a truck-mounted power auger. Nine additional holes with a maximum depth of 12 feet were made with a hydraulic soil probe. Locations of holes are shown on plate V and descriptive logs are given in the appendix.

All available existing geologic, hydrogeologic, and engineering data were gathered from a variety of organizations and publications. Existing data locations are also shown on plate V. Engineering properties of materials from test data were integrated with the results of geological mapping to complete plate I. The groundwater resources map (pl. II) and the geological cross sections are primarily interpretations of previously published data. The geotechnical maps showing conditions pertaining to construction and waste disposal were made by interpretation of all other data collected in the study.

Setting and Climate

Most of Minot lies within the Souris Valley, a large proglacial lake spillway (fig. 3). One of the city's biggest problems, flooding, has occurred repeatedly in the past because of the large percentage of the city that is built on the flood plain of the Souris River. Expansion of the city has occurred on both the north and south sides of the valley and is now continuing on the undulating upland surface both north and south of the valley. The

Figure 1. Aerial view of Minot looking north. Photo by Garth Anderson.

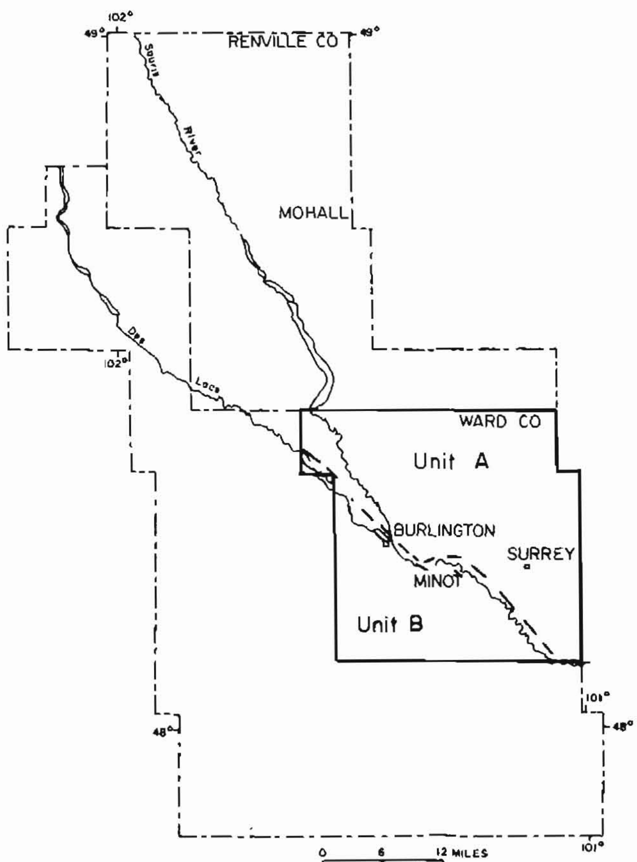

Figure 2. Location and size of study area.

Figure 3. Aerial view of Souris Valley looking north. Junction of Souris (right) and Des Lacs (left) Valleys near Burlington, North Dakota shown near top of photo. Photo by Garth Anderson.

Souris Valley branches into two large valleys, the Souris and the Des Lacs Valleys, northwest of Minot near the town of Burlington. The Souris Valley meets the Glacial Lake Souris Plain southeast of Minot.

The uplands north and south of the Souris Valley near Minot are gently undulating to rolling surfaces used mainly for agriculture. Minot Air Force Base lies about 15 miles north of the city.

The sides of the Souris and Des Lacs Valleys slope steeply down to the flat valley bottom and are deeply dissected by narrow, deep coulees occupied by intermittent streams. Coulees near the city are popular for medium to high cost single family residential development.

GEOLOGY

Fort Union Group

Sediments of the Fort Union Group (Paleocene) are exposed in places along the lower side slopes of the Souris and Des Lacs Valleys and their major tributaries within the map area (pl. I), (fig. 4). For this report, the sediments were mapped as Fort Union Group undifferentiated, although they probably belong primarily to the Bullion Creek Formation (Clayton, 1980). Marine sediments of the Cannonball Formation (Paleocene) are exposed in road cuts just east of the map area near Sawyer (Lemke, 1960). The Bullion Creek Formation consists of alternating beds of sand, silt, clay, and lignite. These sediments were deposited in low-lying fluvial and lacustrine environments present east of the developing Rocky Mountains in Paleocene time. Later, the Paleocene sediments were uplifted and stripped of overlying deposits by erosion that took place prior to Pleistocene glaciation.

Surficial Units

Coleharbor Group

Sediments deposited during Pleistocene glaciations in North Dakota are assigned to the Coleharbor Group (Bluemle, 1971). These sediments include till, fluvial sand and gravel, and lacustrine silt and clay. Test drilling done for the county groundwater study (Pettyjohn, 1968; Pettyjohn and Hutchinson, 1971) indicates that the glacial history of the Minot area is complex. Multiple till

Figure 4. Typical exposure of contact (position of pick handle near center of photo) between bedrock of the Fort Union Group (below pick) and till (above pick). Pick handle approximately 3 feet long. Exposure located near bottom of Des Lacs Valley (SE¼SE¼sec 33, T156N, R84W).

sheets are separated by either glaciofluvial and glaciolacustrine sediments or boulder pavements. River channels comparable in size to the Souris Valley were cut into older glacial sediments and preglacial bedrock and then buried by the sediment of subsequent glaciations (pl. VI).

The surficial glacial sediments throughout most of the Minot area date from the Late Wisconsinan glaciation, the final glacial advance and retreat in North Dakota, which occurred between 25,000 and 12,000 years before present (Clayton and others, 1980). The Coleharbor Group has been divided into ten map units (pl. I). Units 6, 7, 7a, and 8 represent till deposited as sediment present within and on the surface of a stagnating glacier (superglacial sediment). This material was gradually let down to ground level as the glacial ice melted. The resulting collapse topography is characterized by a hummocky surface of mounds and depressions (Clayton and others, 1980). The map units indicate differences in slope angle and local relief. The differences in topography were caused by differences in thickness of the superglacial sediment. Greater thicknesses of superglacial sediment resulted in greater local relief and slope angle (Clayton and others, 1980). Unit 7a is exceptional in that it shows an area of high relief and elevation projecting above the surrounding topography. This landform was probably formed by processes that occurred prior to the last glacial retreat. Unit 7a consists of a northwest-trending ridge north of the Souris River Valley. Its topographic form suggests that it may be a glacial thrust mass (Clayton and others, 1980) overridden by ice during the last advance. Previous workers have interpreted the ridge as an end moraine (Lemke, 1960). Although the ridge does lie near an ice margin position mapped by Clayton and others (1980), existing stratigraphic evidence is not sufficient to fully account for this feature. Hilly, collapsed till (map unit

Figure 5. Coarse, poorly sorted gravel of terrace--point-bar complex exposed in gravel pit in Souris Valley west of Minot (NE¼ sec 21, T155N, R83W). Pick handle approximately 3 feet long.

8) is present only in the extreme southwestern part of the map area, on the Missouri Coteau.

Three map units (9, 10, 11) represent fluvial deposits of sand and gravel from the last deglaciation. Map unit 9 depicts deposits of small areal extent located in narrow, shallow channels that were cut during deglaciation. The material of unit 9 consists of bodies of plane-bedded sand and gravel 5-20 feet thick deposited in point bars by the streams that cut the channels. Although the deposits are generally similar, the channels have several different origins. Channels such as Egg Coulee and Little Deep Creek, which trend southeast in the northeast part of the map area (pl. I) form the first group. A number of such channels occur in the Souris River area. They terminate in delta or fan-like deposits where they join the Glacial Lake Souris basin east of the map area. Since they trend perpendicular to the regional northeasterly slope, it is likely that the trend of the channels was controlled by the presence of active or stagnant glacial ice. As the channels are followed upstream to the northwest, most of them show increasing evidence of collapse as they gradually merge into hummocky collapse topography. In their lower reaches, they are cut into the surface till and show no evidence of collapse. The most likely explanation for most of the channels is that they flowed off stagnant ice onto recently deglaciated ground in front of the glacier. The deposits mapped as unit 9 occupy point-bar positions along the valley sides above the present valley floors. In most places less than 1 foot of Holocene sediment occurs on the surface of the bars, in contrast with thicker Holocene sediment in the valley bottoms. Livingston Creek had a somewhat different origin because its valley is broader than the typical channel described above and contains esker-like ridges in T156N, R83W consisting of poorly sorted, faulted gravel and sand. This valley probably functioned as a subglacial drainage channel prior to glacial stagnation and deglaciation of the area.

Map unit 10 consists of deposits of gravel and sand located in the valleys of the Souris and Des Lacs Rivers. The deposits generally consist of plane-bedded, poorly sorted very coarse grained gravel (fig. 5). Boulders as much as 8 feet in diameter include resistant lithologies such as Precambrian glacial erratics and petrified wood fragments from the Fort Union Group, as well as non-resistant lithologies such as boulders composed of till or lignite. A 2-ton lignite chunk was recovered from a deposit just west of Minot in sections 21 and 22, T155N, R83W (Laird and others, 1958). The presence of non-resistant boulders coupled with the grain size, sorting, and bedding suggests a short distance of transportation, high current velocity, and rapid deposition. Deposits of the unit usually occupy point-bar positions with respect to valley meanders. They form mounds of gravel extending 30 to 80 feet above the present valley floor along the valley side at inside bends of valley meanders. The surfaces of the deposits are generally flat to gently undulating and they are frequently mantled with boulders 2 to 8 feet in diameter. The deposits are interpreted as terrace-point-bar complexes formed during the rapid erosion of the Souris and Des Lacs Valleys by water draining catastrophically from Glacial Lake Regina in Saskatchewan to Glacial Lake Souris (Kehew and Clayton, 1982). In addition to the terrace--point-bar complexes described above, two other types of large-scale features were formed. One type consists of longitudinal ridges of gravel at the valley center, and the other type consists of erosional terraces along the valley side mantled by a thin lag deposit of coarse boulders and sand. A longitudinal bar mapped as unit 10 is located in section 23, T156N, R83W. An example of the erosional type is located in sections 29, 30, 31, and 32, T154N, R81W.

The Souris and Des Lacs Valleys are classified as spillways because they formed by drainage from a glacial lake. During the erosion of the Souris spillway, discharge was too high for the capacity of the channel. One mile east of Minot the floodwater breached the side of the channel and flowed out of the channel. The water eroded the channel side, forming a gap in the Souris Valley side and, in addition, eroded a complex maze of shallow channels east of Minot (Kehew, 1979, in press).

The third map unit showing fluvial deposits of the Coleharbor Group, unit 11, represents ice-contact features. These deposits are characterized by well-sorted and cross-bedded sand and gravel. Faulted and distorted bedding indicates deposition in contact with glacial ice followed by subsidence or slumping as the supporting ice melted. The topographic form of the deposits ranges from sinuous ridges (eskers) to irregular masses of sand and gravel. The ice-contact fluvial deposits seem to be concentrated in the vicinity of the Minot Ice Margin (Clayton and others, 1980), although there is no continuous outwash plain associated with this ice margin. Isolated bodies of sand and gravel mapped as unit 11 occur throughout the map area.

Sediment deposited in glacial lakes (map unit 12) occurs only in the extreme southwest corner of the map area. Such basins are common on the Missouri Coteau, which extends beyond the south margin of the map area.

The final two map units of the Coleharbor Group represent two types of post-depositional erosion. Unit 13 shows areas underlain by till of the Coleharbor Group which were eroded by rivers flowing during deglaciation. This type of topography is common along the southeast-trending channels in the northeast part of the area and in the area east of Minot where water spilled out of the Souris spillway and flowed east to Glacial Lake Souris. The topography is characterized by numerous shallow channels and by a lack of typical collapsed topography adjacent to the channels. This eroded or washed topography is distinct and unmistakable in places, but in other areas the evidence of erosion is less evident as washed topography grades into non-washed topography.

The second type of erosional topography (map unit 14) is classified as slopewash-eroded topography. This unit occurs along the sides of the Souris and Des Lacs Valleys and along the valleys of their major tributaries. These steeply sloping valley sides have been dissected by water flowing in rills, gullies, and coulees, which have developed since the spillways formed during deglaciation. The erosion of these slopes is a discontinuous process most evident during heavy showers or thunderstorms when sediment is eroded and transported through the system of gullies and coulees by intermittently flowing streams. With time, the gullies become deepened and lengthened by headward erosion. This process has been more active southwest of the Souris and Des Lacs Valleys because the land slopes northeastward from the higher elevations of the Missouri

Coteau to the Souris Valley, thus forming a natural topographic gradient for the intermittent streams.

Oahe Formation

The Oahe Formation includes sediment deposited during Holocene time, the geologic time period beginning at the end of glaciation about 10,000 years ago, and continuing to the present. The Oahe Formation is divided into four map units. Map unit 1 is a composite unit consisting of organic clay and silt deposited in the shallow channels eroded during deglaciation. This sediment may overlie sand and gravel of the Coleharbor Group. The sediment was deposited by Holocene streams, intermittent runoff from valley sides, and wind. Sediment deposited in sloughs is also present. The unit is generally thin and confined to valley bottoms.

Map unit 2 includes Holocene alluvium deposited by the Souris and Des Lacs Rivers and their major tributaries. This unit is restricted to valleys which contain a recognizable flood plain. The sediment is dark, fossiliferous, obscurely bedded material of clay to sand size representing both channel and overbank deposition. The valleys of the Souris and Des Lacs Rivers contain a maximum of 150 feet of this type of sediment in combination with that of map unit 3 (pl. VI). As is typical with fluvial environments, the surface and subsurface sediment is highly variable both laterally and vertically. Some test holes in the valleys indicate the presence of more uniform fine-grained sediment suggesting that shallow lakes occupied portions of the valleys from time to time. An example is the Souris Valley upstream from its confluence with the Des Lacs River. Test holes drilled for the Burlington Dam project (Corps of Engineers, 1978) and for this study encountered thick silty clay deposits of possible lacustrine origin.

Sediment deposited in the Souris and Des Lacs Valleys by intermittent streams flowing in gullies or coulees tributary to the main valley are assigned to map unit 3. These deposits are commonly known as alluvial fans because of their fan-like depositional pattern formed where the tributary coulee meets the main valley. The sediment is similar to alluvial sediment of unit 2, but it is generally coarser in grain size. This type of deposit constitutes a significant part of the thick alluvial valley fill in the Souris and Des Lacs Valleys. As the modern rivers meander laterally across their flood plains, they can erode and rework alluvial fan sediment. Alluvial fan deposition, on the other hand, from large coulees, can force the river toward the opposite side of the valley and occasionally dam the main valley. The Souris River may have been intermittently dammed by the Des Lacs River during Holocene time in this manner.

Fine-grained, organic-rich sediment in sloughs is mapped as unit 4. Closed depressions (sloughs) occur in glacial collapse topography (shown as map units 6, 7, and 8), as a result of the uneven subsidence of superglacial debris as the stagnant glacial ice slowly melted beneath. Runoff from surrounding higher ground transports sediment to the slough basin. Additional sediment is contributed by wind and by the decomposition of the abundant vegetation which grows in the wet environment.

The final map unit of the Oahe Formation, unit 5, consists of landslide deposits involving material from the Coleharbor and Fort Union Groups. Landslides have occurred along the valley sides, especially where the bedrock-glacial contact is close to the surface (pl. VI). The landslides probably occurred during or soon after the rapid erosion of the Souris and Des Lacs Valleys as the bedrock materials were subjected to a loss of lateral support. Because the geologic history of the Fort Union Group sediments has resulted in the engineering condition known as overconsolidation, exposure during erosion or excavation causes rebound, or volume expansion of the sediments with accompanying loss of strength (Corps of Engineers, 1978). Other factors, such as bedding composed of alternating coarse- and fine-grained sediments and aspects of groundwater flow influence the stability of slopes in the Fort Union Group. In the Des Lacs Valley, northwest of the study area, the bedrock-till contact occurs well above the present valley floor. Abundant landslides and slumps ranging from old to presently active, characterize the valley and tributary slopes. Smaller landslides in till are rare, but they do occur within the map area.

The landslides mapped commonly

consist of parallel slump ridges and slump blocks. Material within the slump blocks remained mostly intact and relatively undisturbed. With several exceptions, landslides within the map area appear to be inactive. Cuts or excavations in these deposits could cause reactivation of old planes of failure.

Glacial Stratigraphy

Introduction

One objective of this study was to characterize and differentiate till units using quantitative lithologic parameters and to relate tills to ice marginal positions representing specific glacial advances. Differences in lithology are to be expected in tills deposited during glacial advances of different ages and from different directions. The methods used for till characterization included hand specimen appearance, field stratigraphic relationships, weight percentages of sand, silt, and clay fractions of the till matrix, and lithology of the very coarse sand fraction (1-2 mm). Laboratory grain-size analyses were done by standard sieve and hydrometer methods. The specific laboratory procedure used by the North Dakota Geological Survey for till samples is described by Perkins (1977). The very coarse sand lithology is determined by counting individual grains under the binocular microscope. These were divided into groups including Precambrian igneous and metamorphic, carbonate, shale, lignite, secondary precipitates, and miscellaneous categories. Percentages of lignite, secondary precipitates, and miscellaneous groups were based on the total grain count. Percentages of igneous and metamorphic, carbonate, and shale grains were calculated by normalizing the sum of these groups as 100 percent. Finally, the ratio of igneous and metamorphic to igneous and metamorphic plus carbonate grains was calculated. Of the two laboratory techniques, grain-size distribution is most useful for tills of vastly different provenances. This technique was of very limited usefulness for differentiating tills in the Minot area. Very coarse sand lithology has proved to be an effective stratigraphic tool in localized stratigraphic studies in areas such as northeastern North Dakota (Harris and others, 1974; Hobbs, 1975) and has been used as an aid to regional stratigraphic correlation (Moran and others, 1976). In the Minot area as well, coarse sand lithology is an effective stratigraphic tool.

The very coarse sand grain counts indicate a combination of local and distant sources. Igneous and metamorphic grains include Canadian Shield Precambrian sources as well as local sources derived from Fort Union bedrock. Carbonate grains are derived from distant exposures of Paleozoic limestone and dolomite formations. The shale content of the till is probably derived principally from Cretaceous marine shales exposed east and northeast of central North Dakota. Some grains derived from Fort Union bedrock may be included in this fraction. The source of the lignite is the Paleocene Fort Union Group. The relative proportions of the various very coarse sandy groups give a relative indication of the direction of glacial advance. For example, tills with high shale content were probably derived from glaciers advancing from the east or northeast. In contrast, tills low in shale must have been deposited by south- or southeast-moving glaciers.

The most current compilation of ice-marginal correlations in North Dakota (Clayton and others, 1980) indicates 13 ice marginal positions in the state. Although age dating of most North Dakota glacial deposits is lacking, it appears that most of the ice margins represent advances and readvances of the Late Wisconsinan Laurentide ice sheet. During the late phases of Late Wisconsinan deglaciation, glacial advances and readvances occurred by the movement of thin ice lobes into low lying areas. Two such lobes may have flowed southward around the Turtle Mountains into North Dakota, the Leeds Lobe east of the Turtle Mountains, and the Souris Lobe around the west side (Lemke, 1960). The area mapped for this study lies entirely within the extent of the Souris Lobe. One mapped ice marginal position (margin 13, Clayton and others, 1980) crosses the study area (fig. 6). This margin represents the last readvance of the Souris Lobe southeastward into North Dakota. Evidence for the existence of ice margin 13 (the Minot ice margin) includes such criteria as the lobate pattern of the Souris River Valley in North Dakota and indistinct ice marginal features such as thrusts

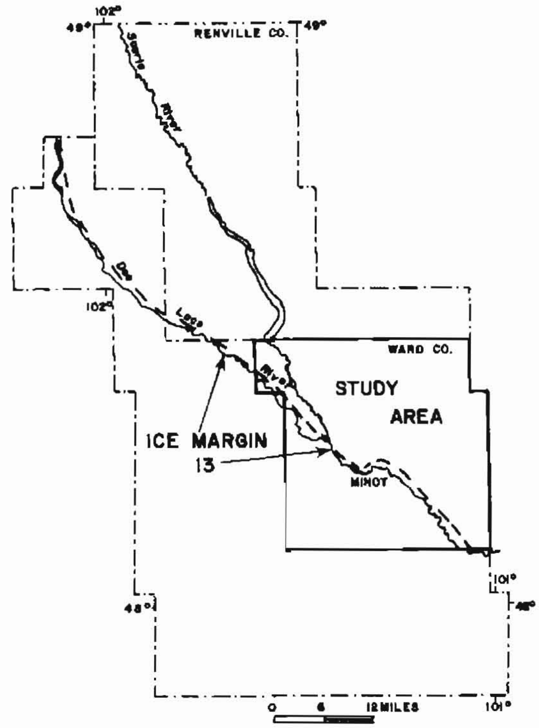

Figure 6. Location of ice margin 13 (Clayton and others, 1980) in the study area.

(Clayton and others, 1980), ice contact deposits, and outwash channels leading away from the margin. An objective of this study was to determine if the position of the Minot ice margin could be stratigraphically determined.

Samples for lab analysis were taken from surface exposures and auger holes drilled during the study. Auger samples included samples brought to the surface during auger rotation as well as split-barrel penetration samples. The maximum depth reached was usually about 75 feet. Therefore, only the upper portion of the glacial section could be studied by this method. Some samples obtained in the county groundwater study drilling program were analyzed. These rotary-drilled samples were of variable quality for this type of analysis. Deeper samples were often contaminated by overlying material, particularly when a sand layer was penetrated.

Results

On the basis of the lab analyses, two stratigraphic units were recognized in the upper portion of the till section. Lab data for these units are shown in table I. Unit A, the uppermost unit, is assumed to be the till deposited by the glacier which advanced to ice margin 13. Unit B consists of surface till samples beyond margin 13 and samples of the till below unit A behind margin 13 (fig. 6). The contact between units A and B in the subsurface is usually recognized by the presence of a sand lens or boulder concentration between the two units. Stratigraphic relations between units A and B are shown on plate VI. Although units A and B are similar in texture, small but consistent differences were noted in the two tills. Unit B is higher in igneous and metamorphic grains, lower in carbonate, and slightly higher in shale. Unit B is also higher in lignite. The lignite percentage cannot be used as a precise indicator because of the tendency of lignite fragments to easily break apart during sieving and other lab procedures. Lignite is useful as a general indicator of till lithology. The difference in lignite content between units A and B is real although the percentages are not accurate. Unit A does contain lignite, but the percentages were less than 0.5% and therefore rounded off to zero in table I.

The basic similarity between units A and B in both texture and coarse sand lithology suggests that unit A represents a readvance of the same glacier which deposited unit B after

TABLE I.--Summary of lab data for till samples.

		Texture[1]			very coarse sand (1-2 mm)[2]				
Unit	No. of Samples	Sand (%)	Silt (%)	Clay (%)	Ig. & Met. (%)	Carb. (%)	Sh. (%)	Lig. (%)	Norm. Ig. & Met.
A	63	$\bar{X}$=33.3 $\bar{S}$= 4.25	$\bar{X}$=38.7 $\bar{S}$= 3.1	$\bar{X}$=28.0 $\bar{S}$= 2.6	$\bar{X}$=68.5 $\bar{S}$= 4.3	$\bar{X}$=28.3 $\bar{S}$= 7.3	$\bar{X}$= 3.3 $\bar{S}$= 1.4	$\bar{X}$=0 $\bar{S}$=0	$\bar{X}$=.71 $\bar{S}$=.04
B	94	$\bar{X}$=33.5 $\bar{S}$= 6.5	$\bar{X}$=39.7 $\bar{S}$= 3.8	$\bar{X}$=27.0 $\bar{S}$= 5.8	$\bar{X}$=74.3 $\bar{S}$= 4.1	$\bar{X}$=21.3 $\bar{S}$= 3.8	$\bar{X}$= 4.3 $\bar{S}$= 2.5	$\bar{X}$=3.8 $\bar{S}$=6.2	$\bar{X}$=.78 $\bar{S}$=.04
Older Till Samples	9	$\bar{X}$=30.8 $\bar{S}$=10.0	$\bar{X}$=37.2 $\bar{S}$= 4.8	$\bar{X}$=32.2 $\bar{S}$= 7.0	$\bar{X}$=39.4 $\bar{S}$=17.3	$\bar{X}$=25.9 $\bar{S}$= 6.5	$\bar{X}$=34.6 $\bar{S}$=18.6	$\bar{X}$=0 $\bar{S}$=0	$\bar{X}$=.59 $\bar{S}$=.09

[1]The sum of sand (2.0 mm to 0.0625 mm), silt (0.625 mm to 0.0039 mm), and clay (less than 0.0039 mm) is equal to 100%.

[2]The sum of igneous and metamorphic rock fragments, carbonate rock fragments, and shale grains is equal to 100%. Lignite is expressed as a percentage of total very coarse sand (1-2 mm) grains. Normalized igneous and metamorphic fraction is equal to ig. & met./ig. & met. + carbonate. Percentages of other lithologic types present in small quantities are not listed in data summary.

only a short retreat. Unit B is correlated with ice margin 11 or 12 (Clayton and others, 1980). These margins represent the maximum advance of the Souris Lobe (Lemke, 1960) in North Dakota. Ice margin 13, correlated with unit A, forms a lobate shape behind margins 11 and 12, indicating a readvance of the Souris Lobe.

One explanation for the differences in very coarse sand lithology between units A and B can be formulated from the stratigraphic relations in the Minot area. Exposures near the bottom of the Souris Valley near Minot indicate that unit B often rests directly upon bedrock. This suggests that, as the Souris Lobe was advancing to margins 11 and 12, it incorporated material from the local bedrock into the till. Sand and lignite from the Fort Union Group increased the crystalline and lignite percentages in the very coarse sand fraction and diluted the carbonate content to some extent. After retreat of the Souris Lobe, the glacier began to advance to margin 13. During this advance, the glacier would have been traveling over the thick till of unit B and therefore would not have been influenced as much by local bedrock. As a result, unit A is lower in crystalline and lignite grains and slightly higher in carbonate content.

In several places in the Souris and Des Lacs Valleys, portions of older till crop out above bedrock. These exposures are common northwest of the map area in the vicinity of Donnybrook. Tills in the Donnybrook area were described by Lemke (1960). Average values of nine samples from these older tills are shown in table I for comparison with units A and B. While textures again are not significantly different, there is a major difference in shale content. The older tills contain much higher amounts of shale in the very coarse sand fraction. The high variation in the older tills indicates that more than one till is present. These tills have not been differentiated. The shale percentages suggest that the advances which deposited the older tills came from the east and northeast, where they obtained a high content of shale from Cretaceous bedrock formations. During deglaciation, the ice sheet thinned and became segmented into topographically controlled lobes near the ice margin. As the lobes flowed around topographic obstacles, they advanced over different bedrock formations and therefore deposited lithologically different tills. The Souris

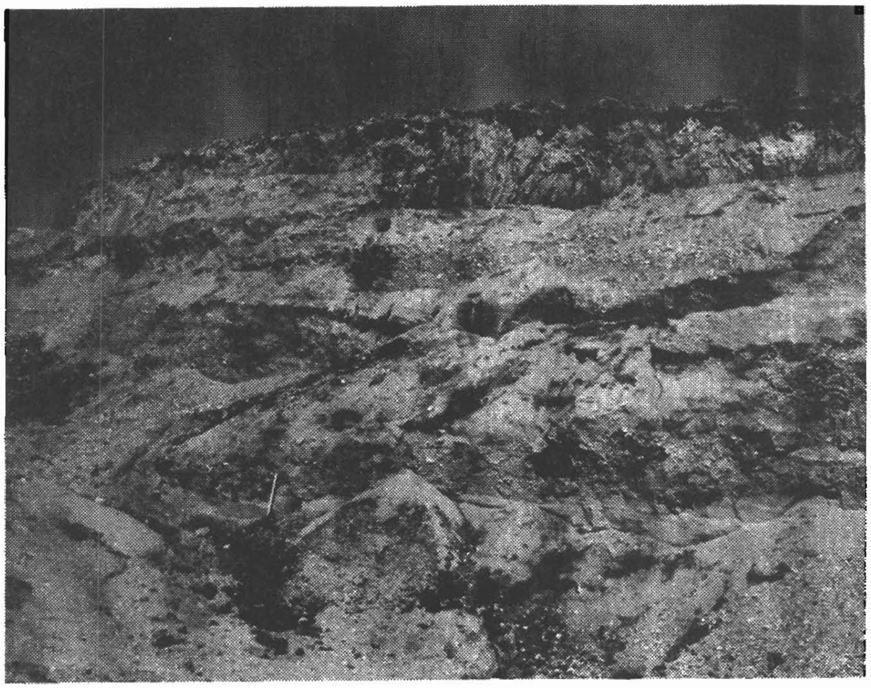

Figure 7. Exposure of sand and gravel bed at contact between units A and B. Several feet of till overlie sand and gravel near top of photo. Pick handle approximately 3 feet long. Location: NW¼sec 20, T155N, R82W.

Lobe flowed around the west side of the Turtle Mountains and deposited the shale-deficient tills of units A and B in the Minot area. These tills contrast with those of the Leeds Lobe, which flowed around the east side of the Turtle Mountains and deposited shale-rich tills (Hobbs, 1975).

Knowledge of till stratigraphy is useful in construction and development. While the engineering properties of till units in the Minot area are not significantly different, the distribution of till units is important. For example, a sand and gravel bed is commonly found at the contact between units A and B. This material is sufficiently thick in the North Hill area of Minot to form a groundwater aquifer. Where the contact between units A and B is exposed in the Souris Valley, the sand and gravel bed is quarried for construction material (fig. 7). Therefore, the stratigraphy of the tills can be related to groundwater and construction aggregate resources. Since unit A is found behind ice margin 13, this boundary forms the limit of both the groundwater and the sand and gravel resources associated with the contact between units A and B. Careful mapping and study of till stratigraphy can aid in the determination of location and distribution of economic resources. In addition, relationships such as the one described above can place limitations on other land uses such as construction and waste disposal projects.

GROUNDWATER RESOURCES

Introduction

The groundwater resources of the Minot area have been extensively studied during the past 30 years in order to meet the water supply needs of Minot's growing population. Minot has never had a dependable water supply. The discharge of the Souris River is insufficient during much of the year to provide an adequate source of water for the city. Therefore, it has been necessary to develop groundwater aquifers in order to maintain a sufficient water supply. Numerous test holes and wells have been drilled by the North Dakota State Water Commission during exploration, evaluation, and development of new aquifers. Most of the groundwater information on which this section of the present report is based was obtained from previously published reports (Pettyjohn, 1968, 1970; and Pettyjohn and Hutchinson, 1971) and unpublished data supplied by the North Dakota State Water Commission. Samples on file at the North Dakota Geological Survey obtained from some of the original test holes in the Minot area were examined. In addition, some of the test drilling done for this project was pertinent to the interpretation of groundwater conditions of the Minot area.

Bedrock Formations

Sediments of the Fort Union Group underlie glacial deposits throughout the map area. Beds of sand and lignite in these sediments often yield small to moderate amounts of groundwater to wells. The chemical quality of the water is variable depending on the particular formation from which it was obtained (Pettyjohn and Hutchinson, 1971). In general, the water is high in dissolved solids and very soft. Some formations contain groundwater high in chloride content. Groundwater from bedrock formations is less desirable for human consumption than water from Quaternary deposits, although it is commonly used for livestock supply.

Quaternary Deposits

All significant aquifers in the Minot area are found within the Coleharbor Group and Oahe Formation. Glaciers advanced and retreated across the Minot area many times. During each retreat, water from the melting glaciers transported and deposited large quantities of sand and gravel. Many of these deposits were buried by glacial sediments of later advances. Therefore glacial deposits contain aquifers both at and below the surface. The chemical quality of groundwater from these aquifers is generally good. Because glacial sediment contains abundant carbonate minerals, groundwater from these deposits is hard, but low in dissolved solids. Iron concentrations are sometimes unfavorably high. The locations of the aquifers discussed below are shown on plate II.

Meltwater Channel Aquifers

Meltwater from the last glacial retreat eroded many small channels north and east of Minot. Some of these channels contain sufficient thicknesses of saturated coarse-grained fluvial sediment to form minor aquifers. In places where such gravel deposits are fairly thick and continuous, adequate supplies for town, stock, and domestic wells have been developed. Some channels, however, contain no coarse-grained sediment or only isolated patches of water-bearing gravels. Only the most promising areas for water-well development are shown on plate II. Even in the channels shown, saturated gravel may not be continuous.

Yields in these aquifers have been reported to reach as high as 80 gpm during pump tests (Pettyjohn and Hutchinson, 1971). Average yields would be much lower. Groundwater from meltwater channel aquifers is generally of good quality. The water is calcium bicarbonate type with low dissolved solids content. One major problem with these aquifers is the high potential for contamination. The high water table and the shallow position of these aquifers allows contaminants such as nitrogen from surface waste sources to rapidly reach the water table and migrate in the aquifers. Wells should not be installed in the meltwater channel aquifers near landfills, sewage lagoons, septic tanks, or feed lots. High nitrate concentrations, which can be hazardous to health, can be expected in these locations.

North Hill Aquifer

The North Hill Aquifer is a buried deposit of sand and gravel north of Minot (Pettyjohn, 1970). This sand deposit is present between stratigraphic units A and B as described earlier (pl. II, pl. VI). Unit A is the uppermost till deposit. The sand and gravel unit is exposed in gravel pits just east of Minot in the vicinity of Livingston Creek (fig. 7). The aquifer ranges in thickness from 1 to 20 feet, and in depth from 26 to 66 feet below land surface (Pettyjohn, 1970). The aquifer can yield adequate amounts of water for domestic or commercial uses but the water is of poor chemical quality in most places.

Souris Valley Aquifer

Sediments of the Oahe Formation, deposited in the Souris and Des Lacs Valleys following the last glaciation, contain the Souris Valley Aquifer. In previous reports, this aquifer is divided into local aquifers named after the valley section in which they occur. These include the Burlington, Minot, and Lower Souris Aquifers (Pettyjohn, 1970; Pettyjohn and Hutchinson, 1971).

The distribution of sediment types within the Oahe Formation in the Souris and Des Lacs Valleys is extremely complex (pl. VI). The valleys were eroded by several episodes of water discharging from Glacial Lake Regina. During erosion of the valley, patches of coarse gravel of the Coleharbor Group were deposited as point bars in certain places along the valley sides. Oahe Formation sedimentation included deposition by the post-glacial Souris and Des Lacs Rivers, intermittent streams along valley sides, and intermittent shallow lakes on the valley floor. The aquifer portions of this complex sequence consist of the coarser units such as fluvial channel sediment. These coarser sediments are interbedded with finer overbank and lacustrine sediment. The deposits of Coleharbor Group gravel may be in hydraulic connection with the aquifers in many places. The Souris Valley Aquifer provides the major groundwater supply for the city of Minot. Water level declines in past years led to attempts to artificially recharge the aquifer and develop new groundwater supply sources (Pettyjohn and Hutchinson, 1971). The aquifer ranges from unconfined to confined conditions with the water table generally close to land surface (Pettyjohn and Hutchinson, 1971).

Groundwater quality in the Souris Valley Aquifer is generally good with occasional undesirable levels of hardness and iron. The shallow stratigraphic position and importance of this aquifer should make prevention of contamination a major priority. Any type of unlined waste disposal facility located on the floor of the Souris Valley has a significant potential for degrading the local groundwater quality. Disposal of wastes in the Souris River may also affect aquifer water quality because of the hydraulic connection between the river and the shallow aquifer.

Sundre Aquifer

The Sundre Aquifer (Pettyjohn, 1970) is a high-yielding aquifer that occurs in fluvial deposits of sand and gravel lying within a buried valley similar in size to the Souris Valley. The valley was eroded into Fort Union Group bedrock and was buried by glacial sediment of Unit B (Plate VI). The buried valley represents drainage during an interglacial period long enough to allow complete filling of the valley with fluvial sediments. The valley crosses beneath the Souris Valley at two points within the study area (plate II), and receives recharge from the overlying Souris Valley Aquifer at those locations.

The stratigraphy of the buried valley sediments consists of sand and gravel deposits interbedded with deposits of silt and clay. The thickness of sand and gravel ranges from 9 to 275 feet (Pettyjohn, 1970).

Yields from the Sundre Aquifer are very high, particularly where it crosses beneath the Souris Valley Aquifer. Transmissivities among the highest known in the state have been measured by pumping tests in these areas (Pettyjohn, 1970). Considerable hydraulic connection between the two aquifers exists in the areas where they intersect which leads to recharge of the Sundre Aquifer from the Souris Valley Aquifer and indirectly from the Souris River.

Quality of the water from the Sundre Aquifer is generally good with localized zones of relatively high concentrations of iron, sulfate, and chloride (Pettyjohn, 1970). High chloride concentrations probably result from recharge from the Cannonball Formation.

The quality and quantity of water available from the Sundre Aquifer make it the key to increased groundwater development in the Minot area.

GEOTECHNICAL CONDITIONS

Engineering Properties of Materials

Introduction

One of the primary objectives of this study was to collect available engineering data from the Minot area and relate these data to the geologic map units shown on plate I. If this task can be accomplished successfully, the geologic map becomes a much more useful tool for the engineer and planner. Unfortunately, this approach leads to problems derived from the nature of geologic maps as well as from the nature of engineering field and laboratory data. It is important to briefly discuss these problems and the process used to determine the values of engineering parameters shown on plate I so that interpretations made from the engineering properties given will not exceed the limits of accuracy inherent in the map.

Geologic map units are designed to show differences in materials, topography, age, origin, or other properties of rocks and soils. Engineering properties of the materials are not usually included in the definition of a geologic map unit. Frequently, geologic map units may include materials with highly variable engineering characteristics. This situation can occur when map units consisting of similar materials in different topographic positions result in differences in water-table depth, slope stability, or erosion potential, and when map units contain a variety of materials such as alluvium. Therefore, geologic map units may not always be useful for engineering purposes.

Engineering data are site specific. Engineering investigations are made of a particular site with a particular project in mind. Engineering studies are rarely made of large areas for which no specific project is planned. The problem that was faced in this study, therefore, was to take the available site-specific engineering data and extrapolate the values to provide reasonable estimates of each parameter for the geologic map units. There were basically two difficulties in this approach. First, at many locations where engineering data were available, the type of data available was very different from other sites. For example, lab tests which determine strength and compressibility parameters are expensive and are therefore performed only for large projects and, even then, only on a small number of samples. For most of the map units, no actual values of some of the engineering parameters were available. The second major difficulty in the procedure was that other engineering parameters, such as standard penetration test (SPT) values, were available in large numbers and showed a large amount of variation. For example, an SPT value of 100 blows per foot in till (map units 6, 7, 8, 13, and 14) probably indicates that a boulder was encountered during the test; not that the till matrix soil was that hard.

Because of problems such as those discussed above, most engineering or environmental geology studies report engineering properties only in relative terms such as high, moderate, and low. In this study, an attempt was made to use actual or estimated representative values that are more specific than high, moderate, and low. The values shown on plate I are presented as averages, where sufficient data were available, or as ranges, where data were lacking. These are estimated ranges of commonly expected values based on properties of similar materials in other map units or reported in the literature.

Caution is advised in the use of the values of engineering parameters shown on plate I. Values of these parameters should fall within the ranges given in most places; however, values which fall outside the given range may occur at a given site. Plate I cannot, under any circumstances, be used as a substitute for site investigations for any engineering project. Its potential value lies instead in that it shows generalized engineering conditions over large areas. This type of information can be extremely useful in initial comparisons of areas for different types of development. Further information will be presented later on individual engineering parameters and their designated values.

Sources of Engineering Data

Engineering data are available from a variety of firms and agencies. These include private engineering firms, as well as government agencies such as the State Highway Department, the U.S. Army Corps of Engineers, and the Soil Conservation Service. As much information as possible was collected from these sources for compilation in this report.

Discussion of Engineering Properties

Unified Classification System

The Unified Soil Classification System is the most widely used engineering classification of materials. The system is based on the grain-size distribution and plasticity of the soil sample; determinations are made by standard field and laboratory tests. Each soil class is designated by a two-letter identifier. The first letter refers to the basic soil type such as gravel, sand, silt, clay, or organic soil (G, S, M, C, O). The second letter refers to grading characteristics for non-plastic soils (W-well, P-poor), content of fines for coarse soils (M-silty, C-clayey), and the plasticity of plastic soils (H-high, L-low). Details of the classification system are found in many engineering texts and manuals.

The soil types corresponding to geologic map units are shown in plate I, column 1. Some map units have several soil types, which increases the variation in the values of the other engineering properties within that unit. The most variable map units are those containing primarily alluvial soils such as units 1 and 2. These soils are characterized by rapid lateral and vertical changes in grain size. Consequently, detailed site investigations are required for any type of construction project. Map unit 5, consisting of landslide deposits, is difficult to characterize because the materials involved in the landslides may be either bedrock (Fort Union Group) or surficial (Coleharbor Group) units. Therefore, each landslide area must be considered individually with regard to soil type. Map units composed of till (6, 7, 7a, 8, 13, 14) are usually classified as clay with low plasticity (CL). The grain size and composition of these units has been discussed previously. Beds or lenses of sand and gravel, which are often interbedded with till, may have important effects on construction projects. The coarse-grained soils comprising map units 9, 10, and 11 are also quite variable. The effect of this variation in grain size upon other engineering properties, however, is not as great as the alluvial materials described earlier. Bedrock materials of the Bullion Creek Formation are also quite variable with respect to engineering characteristics. These variations in soil type can be extremely important in slope-stability problems.

Consistency

The consistency of a soil refers to its in-place condition or its ability to bear increased loads in its natural state. Consistency is described by terms which indicate the firmness or density of the soil. With granular soils, consistency refers to the density of packing of the soil grains, and is described by terms such as loose, medium, and dense. In the case of cohesive soils, consistency is a function of a number of variables such as type and amount of clay, water content, and Atterberg limits. These soils are described by terms such as soft, medium, stiff, and hard. For both cohesive and granular soils, geologic history is an important factor in the present condition of the soil.

The in-place condition, or consistency of a soil is the factor that most strongly influences foundation design and construction. The field test which is used to determine consistency is the one that measures resistance of the soil to penetration. The Standard Penetration Test (SPT) is conducted by driving a standard sample spoon into the soil with a 140-pound hammer falling 30 inches. The standard penetration resistance (N) is reported in blows per foot. Because of the importance of this test to foundation design, penetration resistance data are the most common type of engineering data available. In some investigations, however, different penetration tests are used (Corps of Engineers, 1978).

N values and consistency descriptions for the geologic map units (pl. I), are shown in columns 2 and 3. Map units 1 and 2 constitute the softest and loosest soils in the map area for which significant testing has been done. These map units include recent alluvial sediment in the Souris and Des Lacs Valleys and their tributaries, as well as similar materials in other channels in the map area. The soft nature of the soils is the result of recent fluvial deposition and light natural loading. The combination of the consistency of the materials in map units 1 and 2 and other problems such as high water table make these areas among the most troublesome and expensive with respect to foundation construction. Spread footings on map units 1 and 2 must be designed for low bearing pressures and, for larger buildings, various types of deep foundations are necessary to limit settlement. A large part of Minot is built on the soils of these map units.

Map unit 3 consists of soils similar to units 1 and 2; however, these soils tend to be coarser grained and denser than the materials in units 1 and 2.

Unit 4 consists of fine-grained sediment deposited in sloughs on the uplands north and south of Minot. No test data were available for these soils, but they are assumed to be very soft. Construction of most types would not be feasible on such soils without removal of the soft soils and replacement with an acceptable fill.

Map units 6, 7, and 8 are composed of till and differentiated on the basis of topography. The geotechnical properties of till are determined by the mineralogic composition, mode of deposition, and post-depositional history. Till can be deposited in several different ways (Boulton, 1976). These include deposition from the base of glaciers (lodgement till) as well as melting from the top of stagnant glaciers (ablation till). When a significant non-uniform thickness of ablation till accumulates on the top of a stagnant glacier, mass movement occurs producing characteristic hummocky topography (Clayton and Moran, 1974). Most of the surficial till within the map area is interpreted to have been deposited by mass movement from the top of a stagnant glacier. SPT values, which are very low in comparison with some reported tills (Dreimanis, 1976), support this interpretation. Post-depositional events, which can influence geotechnical properties of till, include desiccation and consolidation by subsequent glacial advances.

The consistency of most near-surface till in the Minot area falls into the medium and stiff categories with SPT values commonly between 10 and 30. Several factors can result in reported blow counts which are unusually high and not representative of the till itself. The most common of these is the presence of a boulder encountered during the test resulting in extremely high blow counts. Sand and gravel lenses can also produce higher blow counts.

Penetration resistances usually show an increase with depth in most test holes. This increase can be the result of several factors. Perhaps the most likely is increasing consolidation with depth from the weight of overlying material. Penetration of till from an older glaciation would also be expected to show higher SPT values because of consolidation from the weight of the overriding glacier.

Dry Density and Void Ratio

Soil density is critical to the construction and performance of all structures. Soils of low density are troublesome for construction because of their tendency to settle or consolidate with the application of load. Foundations in such soils must be proportioned to provide large surface areas to reduce contact pressure and potential settlement of the soil. Depending on the type of soil and building, alternate types of foundations such as piles or caissons must be used. Construction in areas of low density soils can add considerably to the costs of site investigation, lab testing, and construction itself.

Soils of low density in the Minot area include soils that were deposited by modern and glacial rivers, in glacial lakes, and in modern lakes and sloughs. Alluvium of the Souris and Des Lacs Valleys and their tributaries is a good example of low density soil. In the Souris Valley, postglacial sediment (map unit 2) consists of alternating units of alluvium and lacustrine sediments (Corps of Engineers, 1978) as much as 150 feet thick. Much of Minot is built on this material. In addition to its low density, this material is highly compressible. The estimated settlement beneath the proposed Burlington Dam is 11 feet (Corps of Engineers, 1978).

The two parameters considered in this report which relate to soil density are dry density and void ratio. Map units 1 through 4, consisting of postglacial alluvium and slough sediment have low densities and high void ratios. These values are typical of young, near-surface alluvial and lacustrine sediment. Pleistocene sediments, which are also fairly loose, include map units 9 and 11 (sandy outwash sediment) and map unit 12 (fine-grained glacial lake sediment). The relatively low density of outwash is less critical because of its lower compressibility. Map unit 12, however, is composed of fine-grained lake sediment and would probably pose settlement problems.

In contrast to materials of alluvial and lacustrine origin discussed above, materials in map units representing till and bedrock are considerably denser. Density of till is basically a function of mode of deposition. Till deposited from the top of a glacier (ablation till) is commonly less dense than subglacially deposited till (lodgement till) even though fluid pressure in sediment beneath a glacier may prevent consolidation of the subglacial till to a degree corresponding to the weight of the overlying ice (Boulton, 1976; Clayton and Moran, 1974). Most of the till in the Minot area is interpreted as resulting from deposition in the manner described by Clayton and Moran (1974); that is, by mud flows as superglacial sediment became saturated and flowed into depressions formed on the melting stagnant glacier. Although this process would initially produce a deposit of low density, consolidation of the clayey till would occur by desiccation after complete melting of the glacier (Boulton, 1976). Thus, the till deposits in the Minot area are the densest materials present, characterized by high dry densities and low void ratios. Grain-size distribution is also a factor in the high density of the till.

Map unit 14 is often somewhat denser than near-surface till. This unit is composed of till exposed by erosion of the Souris and Des Lacs Valleys and later by slopewash erosional processes. Because of the greater thickness of overlying material, tills exposed near the base of the valleys tend to be stiffer and denser than the near-surface tills. These tills have undergone greater consolidation under the overburden weight or under the weight of glaciers which deposited the overlying till. Another aspect of map unit 14 is the presence of thin slopewash deposits in coulee bottoms and sides. These deposits are formed from material eroded from higher elevations. In contrast to the eroded till in these areas, the slopewash sediment is soft and loose. This makes careful site investigations necessary within this map unit. Often, foundation modification or removal of soil and replacement with fill is necessary for some structures.

Fort Union Group bedrock materials (map unit 15) in the Minot area are present in a moderately dense, overconsolidated state, because of past sediment and glacial loads. These materials are subject to rebound in deep excavations (Corps of Engineers, 1978). When the pressure of overlying material is removed, expansion and loss of strength occurs.

Atterberg Limits

The Atterberg limits are soil index properties which are useful in classification and as an indication of many types of soil behavior. The limits constitute water contents at which particular soils pass into various consistency states. The Atterberg limits are not generally considered to be accurate indications of in-place consistency because they are conducted on remolded samples. The factors which most influence the Atterberg limits are the amount and type of clay present in the soil. Atterberg limit parameters included in plate I are the liquid limit and the plasticity index, which is defined as the liquid limit minus the plastic limit. High values of liquid limit and plasticity index correlate with many undesirable aspects of soil behavior.

The clayey soils in the Minot area can be divided into three main groups. Map units consisting primarily of sandy sediment are assumed to be non-plastic and, therefore, not assigned Atterberg limit values. A first group of map units, including units 2, 4, and 12, is characterized by high liquid limits and plasticity indices. These are alluvial, lacustrine, and slough sediments with high clay content and high organic content (unit 4). Map unit 2 is expected to have quite variable Atterberg limits corresponding to the lateral and vertical variations in material in this unit. Interbedded lacustrine horizons should have the highest Atterberg limits. On the other hand, the alluvium also contains lenses of sand and gravel which would have lower Atterberg limits.

Map units 1 and 5 have intermediate Atterberg limits. Unit 1 consists of several different types of material deposited in small channels eroded during or after the last glaciation. The Atterberg limits of these sediments will depend on their grain-size distribution and organic content, which range from silt and sand in wind-deposited and slopewash sediment to organic clays in slough sediment. Map unit 15 consists of sediment with beds of clay high in montmorillonitic clay minerals, resulting in moderate to high Atterberg limits.

A final group of units, 3, 6, 7, 8, 13, and 14, have the lowest Atterberg limits in the map area. These units consist of alluvial fan sediment (unit 3), which contains more sand than other alluvial units, and till (units 6, 7, 8, 13, 14), which is composed of 20 to 30 percent clay.

Shrink-Swell Potential

The shrink-swell potential of a soil refers to its tendency to undergo volume changes caused by changes in moisture content. The process of volume change in soils is a function of type and amount of clay minerals present and the moisture content of a soil. Montmorillonite is the clay mineral most susceptible to shrink-swell behavior. This mineral is common in the Fort Union Group bedrock of the Williston Basin area, and it is also found in the till and alluvium derived from these sediments.

Shrink-swell behavior can cause considerable damage, particularly with lightly loaded structures, roads, and underground utility lines. In certain areas, special foundation design is required for some structures. Potential shrink-swell behavior can be predicted by the Atterberg limits of a soil and soils can therefore be classified as to shrink-swell potential. The USDA Soil Conservation System classification is based on liquid limit and plasticity index. Under this system, soils with liquid limits less than 30 and plasticity indices less than 10 are classified as having low shrink-swell potential. Soils in the Minot area which meet these criteria include the sandy glacial fluvial sediments in map units 9, 10, and 11. Soils with moderate shrink-swell potential (LL, 31-40 and PI 11-20) include map units 3, 6, 7, 8, 13, 14, and 15. These units represent alluvial fan sediment and all the till and bedrock units. Soils with high shrink-swell potential (LL > 40 and PI > 20) include map units 1, 2, 4, and 12. These are the alluvial, slough, and glacial lake sediments.

Permeability

Permeability, or hydraulic conductivity, is the ability of saturated sediment to transmit fluids. This parameter is extremely important in the location of waste disposal sites such as landfill, septic tanks, and sewage lagoons. The ranges of values given on plate I were obtained from lab tests when available, and also by correlation with values determined for similar materials (Fetter, 1980).

Compressibility

Compressibility refers to the tendency for decrease in volume which occurs when a soil is subjected to an increase in load. The factors which influence compressibility include mineral composition, grain size and grain-size distribution, clay content, mode of deposition, initial void ratio, and stress history. In general, clay-rich, plastic soils are much more compressible than cohesionless sand and gravel soils. One parameter used to evaluate compressibility is the compression index (C_c), which is a quantity derived from laboratory compression tests. It is the slope of a portion of the curve obtained by plotting change in void ratio against the log of pressure applied during the test. Alternatively, the compression index can be estimated by empirical equations using soil index properties such as initial void ratio, water content, and liquid limit (McCarthy, 1977).

In the Minot area, map units can be combined into several groups with respect to compression index. The cohesionless sediments of units 9, 10, and 11 are not given values for compression index because of the lack of tests on these types of materials. These are the least compressible materials in the map area. The map units which represent the next lowest values of compression index, units 6, 7, 8, 13, 14, and 15, show areas underlain by till and Fort Union Group bedrock. The low compression index of till in the Minot area is the result of its low void ratio and high dry density, in addition to its well-graded grain-size distribution. As mentioned previously, the near-surface till is not interpreted to have been deposited from the base of an active or stagnant glacier. The till does exist in an overconsolidated state, however, because of desiccation following deposition. Map unit 14 is assigned a wider range for compression index since this unit includes slopewash sediment in patches throughout its map area. This material is more compressible than till and must be treated with caution during construction. The low compression index of Fort Union Group bedrock material is the result of the heavily overconsolidated nature of these units. The geologic history of these sediments includes burial by a much greater thickness of material than present in combination with the loading effect of repeated glacial advances during Pleistocene time.

Alluvial sediments, shown by map units 1, 2, and 3, average about five times as compressible as till, as indicated by compression index values. These materials have the potential for excessive settlement for many types of structures and usually require deep foundations for larger buildings. Construction costs, therefore, are relatively greater for projects built on the Souris Valley floor in comparison to the upland areas both north and south of the valley.

A final group of units includes units 4 and 12, slough and glacial lake sediment, respectively. No values of compression index were available for these units in the map area, but they are assumed to be composed of materials of high plasticity and high in organic content. Therefore, compressibility would be very high. Where water contents are low in glacial lake sediments, compressibility would be at the low end of the range given because of desiccation.

Unconfined Compressive Strength

Unconfined compressive strength is the amount of compressive stress applied at failure to an unconfined sample of cohesive material in a standard lab test. The value determined can be used as a guide for determination of acceptable foundation loads. Values for unconfined compressive strength (Q_u) were obtained from actual unconfined compression tests and, in addition, were calculated from triaxial test results. For mixed soils, which have properties of both cohesive and cohesionless materials, the formula $Q_u = 2C \tan (45 + \emptyset/2)$ was used, where C is the value of cohesion derived from Q tests (unconsolidated--drained triaxial tests) and $\emptyset$ is the angle of internal friction obtained from the test. Unconfined compressive strength, in addition to SPT values, can be used as an indicator of safe allowable design loads.

When map units are grouped according to unconfined compressive strength, groups are similar to those described for previous engineering properties. The alluvial sediments of map units 1, 2, and 3 have the lowest Q_u values. Units including till are intermediate in strength. Bedrock material can be somewhat greater in strength, although substantial variation exists. Sandy and gravelly sediments in map units 9, 10, and 11 are considered to be high in strength in relation to other materials, although the unconfined compressive strength test cannot be performed on cohesionless sediments.

Foundation Conditions

Introduction

Geologic conditions influence the design and construction of foundations in numerous ways. The types of materials present and their engineering properties are obviously important. This information is presented on plate I. Also important, however, are other factors which are related to the stratigraphy, topography, and hydrogeology of the site. Plate III was constructed in an attempt to integrate these factors with the materials information. The map units chosen for this map are landforms because similar landforms generally have similar geologic, topographic, and hydrogeologic characteristics. Therefore, landforms serve well as generalized geotechnical mapping units. Variations in materials and engineering properties within each mapping unit are to be expected, but these variations are predictable, based on the definition and description of the landform.

Several additional comments must be made so plate III can be used correctly. Foundations must be designed based on actual surface and subsurface conditions. In most real situations, these conditions are too variable to predict without a site investigation at the actual position of the foundation. Every geologic map (or map derived from a geologic map) presents information that is generalized to some extent. Thus, the geologic map or any similar type of materials map can never by used as a substitute for site investigations. The approach chosen in the construction of plate III is to present units that contain major variations in materials and other geologic conditions. The advantage of this map is that the variations are predictable based on the nature and description of the map unit and can be anticipated prior to the planning of site investigations. This can allow savings in time and money because potential sites can be compared relative to foundation design and construction method prior to the expenditure of funds for site explorations.

Map Unit Information

The description of each map unit on plate III includes estimates of slope, maximum advisable bearing value, flood potential, erosion potential, slope stability, depth to the water table, and additional comments. The relationship of these factors to foundation design will be summarized below.

The slope angles for each map unit were obtained from topographic maps. This information is important to founda-

TABLE II.--Relationship between N and angle of internal friction (from McCarthy, 1977).

Value of N	Relative condition of soil	Approx. value of Ø (degrees)
10	loose	30
20	med. dense	32
30	med. dense to dense	35
40	dense	38
50	dense to very dense	40
60	very dense	42

tion design because the amount of slope is one factor in the prediction of erosion and slope stability. In addition, the bearing capacity of footings on sloping ground is reduced from that on level ground with similar materials. Footing design methods are available to take the slope factor into account (McCarthy, 1977).

Determination of footing bearing pressure can be made by using bearing capacity formulas, empirical correlations with penetration resistance and other data, and by using soil types and building codes. Descriptions of bearing capacity formulas can be found in most soil mechanics textbooks (McCarthy, 1977; Hough, 1969). These formulas require soil properties such as effective unit weight, angle of internal friction, and cohesion. These properties can be obtained from lab tests on samples from the foundation site or by estimation from material type and other data. Effective unit weight can be derived from the properties given in plate I in combination with the water table depth shown on plate II. Of course, borings from the site are better for determining these conditions. Cohesion can be estimated as one-half the value of unconfined compressive strength on plate I. The angle of internal friction for cohesionless and mixed soils is not given on plate I, but can be estimated from the SPT values. Table II gives the relationship between penetration resistance and angle of internal friction.

Not many SPT data for the map units with cohesionless material are available for the Minot area. Use of bearing-capacity formulas gives an ultimate bearing-capacity value for the soil. This value is usually reduced by use of an appropriate safety factor such as 3. If highly accurate information is needed, a settlement analysis must also be done, with consideration of soils below the footing level.

Presumptive bearing values for footing design can also be derived from direct empirical correlations with penetration resistance (Hough, 1969) and unconfined compressive strength (Peebles, 1962). These correlations are less satisfactory for cohesive soils because of considerations involving settlement and therefore should not be used (McCarthy, 1977). SPT values should also be corrected for depth (McCarthy, 1977). The values given on plate II for presumptive bearing capacity were determined by empirical correlations as discussed above. Since they apply to generalized map units and are correlated from average values of penetration resistance and other properties, they can be considered to be general guidelines only.

Flood potential is high in several of the map units. The low-lying flood plain of the Souris and Des Lacs Rivers and their major tributaries (unit 7) is the most important flood-prone portion of the map area. The floods in the main valleys of the Souris and Des Lacs and their effect on Minot are well known. Extensive flood control measures have been taken by the U.S. Army Corps of Engineers to protect Minot from flood damage, and an even bigger project, the Burlington Dam, is under consideration. Intermittent tributaries of the Souris and Des Lacs Rivers should also be considered as

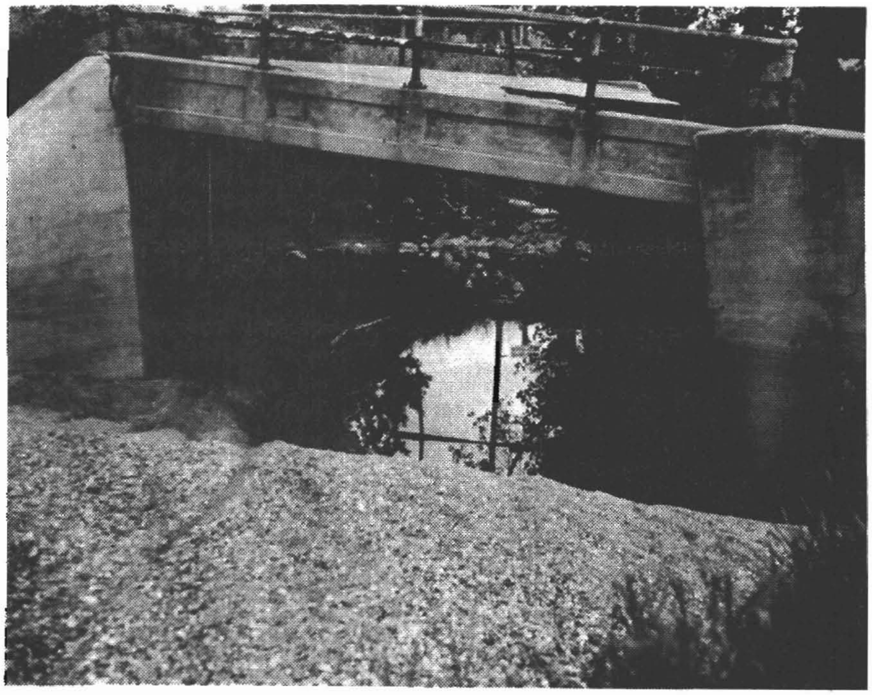

Figure 8. Damage to bridge crossing Second Larson Coulee by flooding. Location: NE¼NE¼sec 5, T154N, R82W.

posing a serious flood threat. Floods in these coulees occur as rapid, high-discharge events, or flash floods, in the summer thunderstorm season or during spring snowmelt. One flood of this nature in 1979 caused serious damage to a bridge at the mouth of Second Larson Coulee, southeast of Minot (fig. 8). A test hole near the mouth of Gassman Coulee encountered 6 feet of coarse gravel at a depth of 2 feet below the surface, indicating a large flood event in that drainage within the recent past. Map unit 6, indicating the side slopes of the Souris and Des Lacs Valleys, includes many small coulees, which are also subject to periodic flash floods. Structures built within these map areas can sustain serious damage during these floods. Bridges and culverts built in coulees within map units 6 and 7 should be designed to withstand events of high discharge and low frequency. Map unit 5, shallow glacial valleys, also has a significant flood hazard, but because these valleys are generally shallow and have low gradients, the most serious flood potential is associated with spring snowmelt. Flash floods as described above are a possibility in some cases, however. Other map units generally have low flood potential.

Erosion potential is influenced by the degree of slope and the nature of surface drainage. Map units with high flood potential also have high erosion potential. Map unit 6, which includes the side slopes of the Souris and Des Lacs Valleys, has high erosion potential in the coulees that dissect the slope. In the sloping areas between coulees, however, erosion potential by sheet, rill, and gulley processes is high, particularly when the natural vegetation cover has been removed during construction.

The stability of a natural or cut slope is the result of several factors such as slope angle, soil type, and groundwater conditions. Slope stability in the Minot area is generally good. Cuts in map units 1, 2, and 3 are usually not a problem. Special conditions, such as groundwater discharge within a cut, could lower slope stability to the point where slope failure would occur. The properties of till in the Minot area such as its well-graded grain-size distribution, high density, and low plasticity, give it favorable strength and slope-stability characteristics.

Each of the remaining map units has potential slope-stability problems within its area of occurrence. Unit 4 includes inactive landslide deposits. These features are limited to the Souris Valley. Characteristically, they are composed of closely spaced ridges parallel to the main valley side slopes. The landslides involve both till and bedrock, but the presence of bedrock is probably one of the major contributing factors in the landslide activity. In the northern portions of the Des Lacs Valley, where more bedrock is exposed in the valley walls, landslides are ubiquitous. In the Minot area, bedrock is less commonly present in the valley side slopes. The landslides that do occur near the Minot area, however, are closely associated with the bedrock exposures or proximity to the surface of bedrock. Map unit 6, the main valley side slopes, is considered to have potential slope-stability problems only where the till-bedrock contact is exposed or near the surface.

The depth-to-water table estimates were derived from subsurface information obtained from previous sources and from drilling done for this project. In the latter case, the depth-to-water table was estimated at the color change between yellow-brown, oxidized sediments above the water table and gray, unoxidized material below.

Additional comments are also included for each map unit. These include specific conditions relating to foundation design as well as comments concerning areas within map units which are exceptions to the most common characteristics of the map unit.

Spread foundations are commonly used throughout the map area with the exception of map unit 7. Within this map unit, deep foundations for moderate to heavy structures are usually required. The materials in this area have low bearing capacity and high compressibility. Water problems are also significant within this map area.

Conditions Pertaining to Waste Disposal

Introduction

The location of suitable sites for waste disposal is one of the most serious problems facing many communities today. Septic tanks have traditionally been used for disposal of household sewage in unsewered areas. Until recently, little regard has been shown for the subsurface conditions which affect the functioning of these systems. Many communities utilize waste stabilization lagoons for the disposal of sewage. This method depends upon a combination of biological decomposition, infiltration, and evaporation for disposal of wastes. Municipal solid wastes are usually disposed of in sanitary landfills. With this method, waste is dumped into trenches or natural depressions and covered daily with soil. Recent environmental regulations, which prevent open dumping and uncontrolled burning have led to an increase in the amount of waste deposited in landfills.

In general, landfills and impoundments have been constructed with little consideration for geological conditions. The main factors in selection have been accessibility, cost of land acquisition, and environmental factors such as surface water contamination, noise, odor, blowing papers and dust, appearance, and pest control. In recent years, the geological aspects of site selection have become the most important criteria in some areas as instances of sickness, death, and loss of water supplies associated with groundwater contamination from waste disposal facilities have been increasingly discovered and publicized. Environmental regulations concerning groundwater and waste disposal practices have been growing and can be expected to continue to grow in the future.

Contamination of water supplies from waste disposal facilities can affect both surface and groundwater supplies. Pollution of surface water can occur when landfills and lagoons are placed in flood-prone areas or in drainageways such as coulees (ravines). Steeply sloping coulees have high erosion potential because of the high runoff from heavy precipitation events. This drainage can erode the cover soil as well as the solid waste itself and transport it down valley toward larger streams. The present Minot landfill is located in a ravine of this type southwest of the city. Rapid erosion of newly completed sections of this landfill has already been observed (Anderson, 1979).

The prevention of contamination of groundwater from waste disposal sites requires detailed site investigations and careful construction procedures. Groundwater contamination from lagoons and septic tank leach fields occurs when liquid wastes infiltrate through the bottoms of lagoon cells and moves downward to the water table. In the case of landfills, precipitation percolating through the solid waste leaches soluble waste constituents and carries them to the water table. Some landfills are even excavated down to or below the water table, thus allowing moving groundwater to directly leach the solid waste. Other instances of groundwater contamination result from leaky sewer pipes, industrial processes, and agricultural activities.

Waste Disposal Conditions in the Minot Area

The information needed for preliminary planning of waste disposal facilities is presented on plate III. The types of information needed include topographic and hydrogeologic conditions. For the purposes of generalization and simplification, the map units used are topographic features similar to those in the geotechnical conditions map. The topographic conditions are described by the map unit description and the slope amount. Flood and erosion potentials are related to topography. Hydrogeologic conditions are indicated by depth to water table, groundwater resource potential, and the relative permeability of near-surface materials. The distribution of geologic materials and their permeabilities is shown on plate I. The groundwater resource potential is based on available information summarized earlier concerning aquifers present in the Minot area. Additional comments are included to mention exceptional areas within the map units and to emphasize the relevance of certain properties of the map units to specific waste disposal problems and procedures.

Map units 1 and 2 consist of glacial sediments, which generally have few limitations for waste disposal. Map unit 3 has the same surface material as units 1 and 2 but is known to be underlain by a thin aquifer at a fairly shallow depth (Pettyjohn, 1971). Map units 4 and 5 contain highly permeable materials in places and would require extensive engineering safeguards for proper waste disposal. Map unit 6 is characterized by high slope angles, which result in the erosion problems discussed earlier. Map unit 7 is probably the most critical unit for waste disposal problems. In addition to flood potential, the Souris and Des Lacs Valley bottoms contain highly variable sediments, which comprise Minot's most important groundwater aquifers. These aquifers are shallow and highly susceptible to pollution from waste disposal. To insure protection of these critical water supply sources, waste disposal should be prevented, if at all possible, in these areas. If alternative sites are not feasible elsewhere, extreme caution must be used.

Construction Materials

Sources of materials used in construction, here limited to sand and gravel deposits, can be located by reference to map units 9, 10, and 11 or plate I. Map unit 9, indicating river deposits in small glacial meltwater channels, consists of thin (usually less than 20-foot-thick) accumulations of fine gravel and sand. Water-table depth is usually quite shallow in these deposits. The deposits of map unit 10 contain the coarsest gravels in the map area and are limited to the valleys of the Souris and Des Lacs Rivers. Some exposures of these materials consist of one to two boulders in a matrix of finer materials (fig. 5). Finer gravel and sand may also be found in some areas of unit 10. Materials of unit 11 are mainly sand with some gravel, and usually occur as isolated deposits on the uplands north and south of the Souris Valley.

The only source of sand and gravel not shown on plate I consists of the stratigraphic zone between units A and B (pl. VI, fig. 7). The only known exposures of this unit are presently being mined for sand and gravel along the north side of the Souris Valley near the junction of Livingston Creek and the Souris River.

SUMMARY AND CONCLUSIONS

The future of Minot and all other cities, like their pasts, will be greatly influenced by their geological settings. The growth and expansion of a city is dependent on an adequate supply of natural resources such as water and construction materials. Two major factors in the safety and quality of life of its citizens are protection from natural hazards like flooding and landslides, and protection from health hazards resulting from improper waste disposal. All of these concerns are related to the cities' geological setting.

This report provides information on the geological setting as well as the engineering aspects of the geology. The most important elements of Minot's geological setting, from an engineering standpoint, were determined during the glaciations of Pleistocene time. Repeated advances of glaciers across north-central North Dakota eroded soft Paleocene sediments and redeposited them as till. As the glaciers melted and retreated, meltwater flowed off the ice into temporary lakes along the ice front. The sand and gravel that was deposited by these outwash streams now constitute sources of groundwater and construction materials. The proglacial lakes eventually drained, cutting huge channels between lake basins. The Souris and Des Lacs Valleys were pre-existing channels that were enlarged to their present size by the drainage of Glacial Lake Regina in Saskatchewan. This event, about 12,000 years B.P., marked the end of the glaciation in the Minot area. The major processes occurring in the Souris Valley since that time have been the erosion of the valley sides by intermittent streams and the deposition of sediments on the valley floor by both the intermittent streams and by the modern Souris River. These sediments contain important groundwater aquifers.

The events of the geological past, as well as active geological processes, constitute the geological setting presented to planners and engineers. In this report, engineering properties of materials were included on the geological map. The materials, as well as factors such as topography and groundwater conditions, were combined in generalized geotechnical maps concerned with construction and waste disposal conditions. Landforms proved to be useful map units for these maps because of their predictable geotechnical conditions.

With this report, sites within a large area surrounding Minot can be evaluated with respect to resource potential and geotechnical conditions. This evaluation will allow preliminary estimates of project design and cost for alternate locations under consideration. When a final site, or sites, is selected, the detailed site investigation can proceed with a general understanding of site conditions.

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APPENDIX

APPENDIX

Lithologic logs of testholes drilled for this study within study area are presented below. The holes were drilled with a truck-mounted power auger. Hole numbers refer to a computerized file of subsurface information maintained by the North Dakota Geological Survey.

Hole Number	Location	Depth (feet)	Material	Stratigraphic Unit
4000	T155N, R83W,sec 31ddd	0-20	Till; silty, pebbly, yellow-brown, lignite abundant	Coleharbor Group
		20-22	Sand; yellow-brown, wet	Coleharbor Group
		22-37	No returns; sand and lignite on auger flights; very wet	Coleharbor Group and/or Fort Union Group
4001	T154N, R84W,sec 16ddd	0-22	Till; silty, pebbly, yellow-brown, abundant lignite	Coleharbor Group
		22-32	Till; brownish-gray, mottled, texture as above	Coleharbor Group
		32-55	Till; olive-gray, as above	Coleharbor Group
		55-62	Sand and gravel; wet, poor returns	Coleharbor Group
4002	T155N, R83W,sec 16ad	0-17	Till; silty, pebbly, yellow-brown	Coleharbor Group
		17-25	Sand and gravel; coarse, wet	Coleharbor Group
		25-32	Till; sandy, yellow-brown	Coleharbor Group
		32-47	Till; silty, olive-gray, wet, poor returns, possibly some sand and gravel	Coleharbor Group
4003	T156N, R82W,sec 16aaa	0-22	Till; silty, pebbly, yellow-brown	Coleharbor Group

APPENDIX--(Continued)

Hole Number	Location	Depth (feet)	Material	Stratigraphic Unit
		22-39	Till; silty, pebbly, gray-brown, boulders 35-39	Coleharbor Group
		39-47	Till; sandy, brown, mottled, yellow nodules	Coleharbor Group
		47-65	Till; olive-gray, wet	Coleharbor Group
		65-72	Sand; water-bearing, poor returns	Coleharbor Group
4043	T157N, R81W,sec 25aba	0-29	Till; silty, pale-brown to light-yellowish-brown	Coleharbor Group
		29-39	Sand; fine- to medium-grained, gray to gray-brown	Coleharbor Group
		39-42	Till; silty, gray	Coleharbor Group
4044	T157N, R82W,sec 27aab	0-30	Till; silty, light-yellowish-brown to light-olive-gray, boulders 28-30	Coleharbor Group
		30-74	Till; olive-gray	Coleharbor Group
4045	T157N, R83W,sec 28ba	0-10	Till; silty, pale-brown to pale-olive	Coleharbor Group
		10-17	Sand; poor returns	Coleharbor Group
		17-42	Till; light-gray, wet	Coleharbor Group
4046	T157N, R84W,sec 22aaa	0-22	Till; pale-olive to light-olive-gray	Coleharbor Group

APPENDIX--(Continued)

Hole Number	Location	Depth (feet)	Material	Stratigraphic Unit
		22-35	Till; clayey, light-olive-gray to olive-gray, lignitic, orange oxidized nodules	Coleharbor Group
		35-42	Sand; clayey, poorly sorted, olive-gray	Coleharbor Group
		42-52	Till; clayey, olive-gray	Coleharbor Group
4047	T156N, R83W,sec 7bbb	0-12	Till; silty, pale-olive, some lignite	Coleharbor Group
		12-32	Till; clayey, pale-yellow to light-gray, lignite common, orange oxidized nodules	Coleharbor Group
		32-52	Till; silty, light-olive-gray	Coleharbor Group
4048	T155N, R82W,sec 3ddd	0-12	Till; silty to clayey, pale-yellow to pale-olive, some lignite	Coleharbor Group
		32-35	Sand; fine- to very fine grained	Coleharbor Group
		35-67	Till; clayey, light-gray to gray, lignitic	Coleharbor Group
4049	T156N, R82W,sec 18daa	0-27	Till; silty, yellow-brown to olive-gray, occasional lignite grains, boulders 25-27	Coleharbor Group
		27-42	Till; gray	Coleharbor Group

APPENDIX--(Continued)

Hole Number	Location	Depth (feet)	Material	Stratigraphic Unit
4050	T155N, R81W,sec 11aaa	0-32	Till; silty, pale-yellow to light-olive-gray, occasional lignite	Coleharbor Group
		32-38	Sand (?); very wet, poor recovery	Coleharbor Group
		38-42	Till; clayey, gray	Coleharbor Group
4051	T154N, R82W,sec 16cd	0-23	Till; clayey, pale-yellow to pale-olive, lignite common, orange siltstone pebbles common	Coleharbor Group
		23-25	Sand; wet, poor sample returns	Coleharbor Group
4052	T154N, R83W,sec 23ccd	0-38	Till; clayey, pale-yellow to gray, lignite abundant, orange oxidized nodules and siltstone pebbles common	Coleharbor Group
4053	T154N, R81W,sec 14ddd	0-22	Till; silty, pale-olive	Coleharbor Group
		22-32	Sand; fine- to medium-grained, light-olive-gray, water bearing	Coleharbor Group
		32-37	Till; silty, gray (bit sample)	Coleharbor Group
4054	T155N, R83W,sec 3ca (Hole near base of approximately 12-foot road cut)	0- 7	Till; clayey, pale-yellow, lignite common	Coleharbor Group
		7-12	Sand; fine- to medium-grained, yellow-brown	Coleharbor Group
		12-37	Till; silty, light-gray to gray-lignite present	Coleharbor Group

APPENDIX--(Continued)

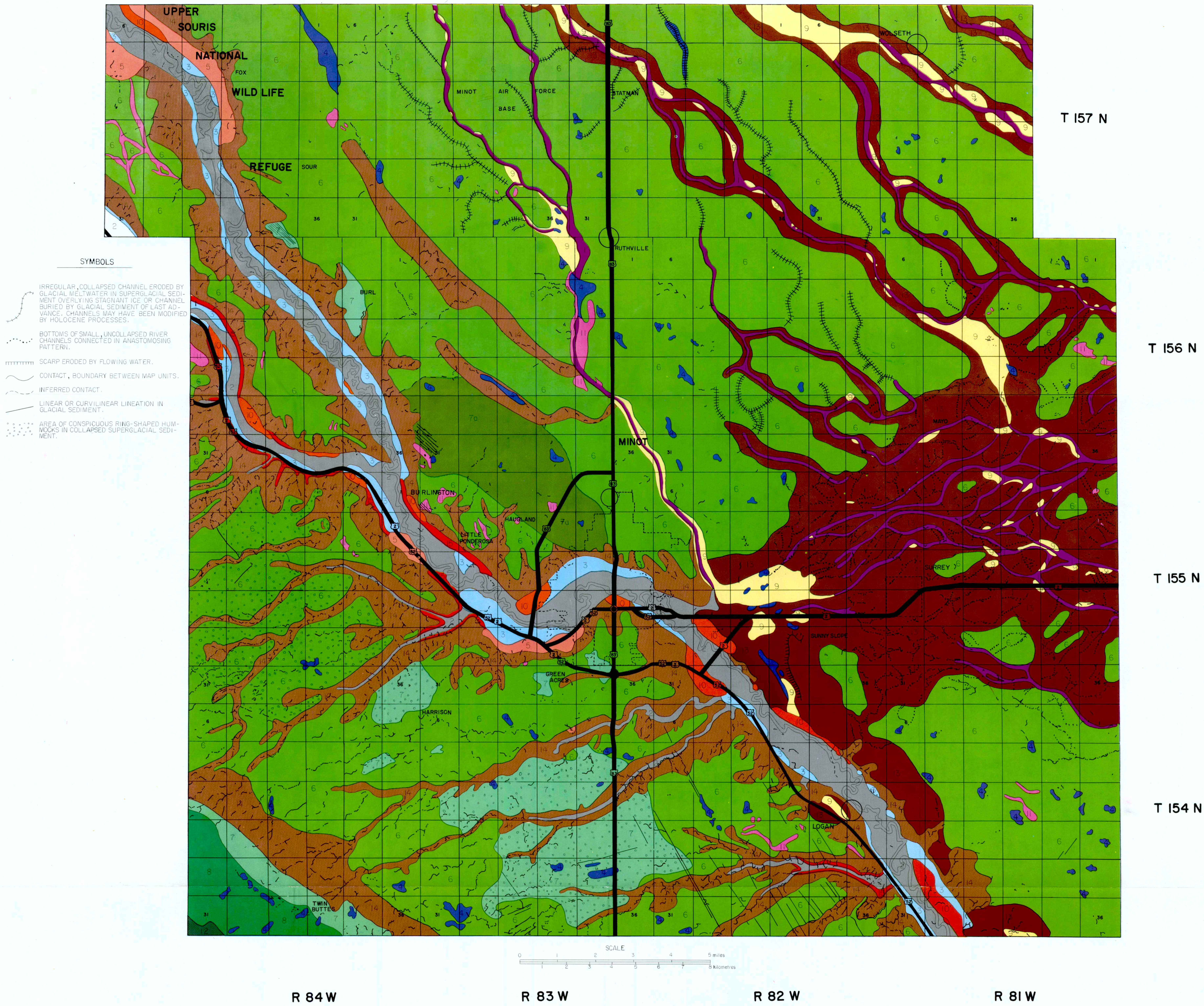
Hole Number	Location	Depth (feet)	Material	Stratigraphic Unit
4055	T155N, R83W,sec 28aac	0-10	Sand; silty, fine-grained, poorly sorted, yellow-brown	Oahe Formation
		10-28	Sand; medium- to coarse-grained	Oahe Formation
		28-38	No returns; water bearing	Oahe Formation
4056	T155N, R83W,sec 20cba	0- 2	Clay; silty, dark-gray	Oahe Formation
		2- 8	Gravel; very coarse, large pebbles	Oahe Formation
		8-12	Clay; silty, pale-yellow	Oahe Formation
		12-34	Sand (?); poor returns, water bearing	Oahe Formation
4057	T155N, R84W,sec 26bcb	0-37	Till; clayey, pale-yellow to olive-gray, mottled, lignite abundant, orange oxidized nodules	Coleharbor Group
		37-52	Sand (?); poor returns, water bearing	Coleharbor Group
4058	T155N, R84W,sec 14bba	0- 7	Sand; pale-yellow	Coleharbor Group
		7-22	Till; pale-yellow to gray, mottled, lignite abundant, orange oxidized nodules	Coleharbor Group
4059	T155N, R84W,sec 1bcc	0-13	Silt; sandy, pale-olive	Oahe Formation
4060	T156N, R84W,sec 5aa	0- 2	Sand; clayey, poorly sorted, yellow-brown	Oahe Formation

APPENDIX--(Continued)

Hole Number	Location	Depth (feet)	Material	Stratigraphic Unit
		2-12	Till; silty, pale-olive	Coleharbor Group
		12-37	Till; pale-olive, mottled, lignite abundant, orange oxidized nodules	Coleharbor Group
		37-46	Siltstone; gray	Fort Union Group
		46-48	Sandstone; silty, gray	Fort Union Group
4061	T157N, R84W,sec 34ccd	0-47	Clay; gray to dark-gray, high organic content, fossiliferous	Oahe Formation
4062	T157N, R84W,sec 34ccc	0- 5	Sand; pale-yellow, alternating with silty clay beds	Oahe Formation
		5-17	Till; pale-olive, lignitic, orange oxidized nodules	Coleharbor Group
		17-19	Sandstone; silty, thin lignitic claystone beds	Fort Union Group
4063	T156N, R84W,sec 5abb	0- 7	Sand; silty	Oahe Formation
		7-19	Poor returns; lithology uncertain, very wet	(?)
4064	T156N, R84W,sec 5aab	0- 9	Sand; clayey, poorly sorted	Oahe Formation
		9-43	Till; pale-olive to light-gray, clayey, lignite abundant	Coleharbor Group
		43-49	Sand (?); poor returns, wet	Coleharbor Group
4065	T156N, R84W,sec 6aab	0-14	Till; clayey, pale-yellow to pale-	Coleharbor Group

APPENDIX--(Continued)

Hole Number	Location	Depth (feet)	Material	Stratigraphic Unit
			olive, lignite common, orange oxidized nodules	
		14-27	Sand; medium-grained, silty, yellow-brown	Coleharbor Group
		27-32	Till; clayey, light-olive-gray, mottled	Coleharbor Group
		32-38	Sand; water bearing, poor returns	Coleharbor Group
		38-44	Till; silty, light-gray to pale-olive, mottled	Coleharbor Group
4070	T155N, R84W,sec 13aac	0-17	Sand; silty, pale-yellow, alternating silt and silty clay beds	Oahe Formation
		17-38	Till (?); silty, clayey, pale-yellow to pale-olive, lignitic	Coleharbor Group (?)
4071	T155N, R84W,sec 12bd	0- 7	Sand; silty, clayey, yellow-brown	Oahe Formation
		7-28	Lithology uncertain; till or silty, clayey, pebbly sand, poor recovery, possibly siltstone 23-28	(?)



GEOLOGY AND ENGINEERING PROPERTIES[1] OF NEAR SURFACE[2] MATERIALS; MINOT, NORTH DAKOTA

MAP UNIT	FORMATION OR GROUP	DESCRIPTION	TOPOGRAPHY[3]	ORIGIN	UNITED CLASSIFICATION SYSTEM	CONSISTENCY	SPT (BLOWS/FOOT)	LIQUID LIMIT (LL) (%)	PLASTICITY INDEX (%)	WATER CONTENT (%)	DRY DENSITY (PCF)	VOID RATIO	COMPRESSION INDEX	UNCONFINED COMPRESSIVE STRENGTH (PSF)	PERMEABILITY (CM/S)	SHRINK SWELL POTENTIAL
1	Oahe Formation	Dark, obscurely bedded clay and silt; may overlie Sand and Gravel of Coleharbor Group.	Gently Undulating.	River, slope wash, pond, and wind-blown sediment, undivided, deposited in partially collapsed to non-collapsed stream channels.	CL, OL	Soft to medium	10-20	40-50	20-30	20-30	90-110	.5-1.0	.15-.3	2000-4000	10^{-7}-10^{-4}	High
2	Oahe Formation	Dark, obscurely bedded clay and silt; occasionally overlying cross-bedded sand and gravel. Wood, shells, and bone fragments present.	Gently Undulating.	Overbank sediment deposited on flood plains of modern streams; contains some channel sediment.	CL, CH, ML, SM, SP	Soft to medium, loose to firm	$\bar{X}$ = 12 N = 361	$\bar{X}$ = 45 N = 112	$\bar{X}$ = 25 N = 112	$\bar{X}$ = 23 N = 195	$\bar{X}$ = 99 N = 75	$\bar{X}$ = .87 N = 89	$\bar{X}$ = .248 N = 26	$\bar{X}$ = 2852 N = 51	10^{-9}-10^{-3}	High
3	Oahe Formation	Dark, obscurely bedded sandy to silty clay.	Gently Undulating to undulating.	River sediment deposited by ephemeral streams on sloping surfaces (alluvial fans) near the mouths of coulees.	SC, SM, SP ML, CL	Loose to firm, soft to stiff	10-20	25-35	15-25	20-30	90-110	.5-1.0	.1-.2	2000-6000	10^{-5}-10^{-3}	Moderate
4	Oahe Formation	Dark, obscurely bedded clay and silt.	Gently Undulating.	Pond and slough sediment.	CL, CH, OL, OH	Very soft to medium	2-10	75-85	35-45	35-45	80-90	1.0->2.0	.5-.7	<1000	10^{-9}-10^{-6}	High
5	Oahe Formation, Coleharbor Group, Fort Union Group undivided	Bedded sand, silt, clay, and lignite and/or non-bedded sand, silt, clay, and gravel (till). Bedding may be disturbed or distorted. Exposures may be out of place stratigraphically.	Undulating to rolling; often occurs as a series of parallel ridges or blocks along valley sides.	Landslide deposits.	CL, SM, SC, ML	Medium to hard	10-30	Highly Variable	Highly Variable	Highly Variable	Highly Variable	Highly Variable	Highly Variable	Highly Variable	Highly Variable	Moderate to High
6	Coleharbor Group	Non-bedded and poorly sorted sand, silt, clay, pebbles, cobbles, and boulders (till).	Gently Undulating to undulating.	Glacial sediment deposited by collapse from stagnant melting glaciers.	CL	Medium to stiff	$\bar{X}$ = 19.3 N = 372	$\bar{X}$ = 32 N = 49	$\bar{X}$ = 16.1 N = 49	$\bar{X}$ = 17.4 N = 157	$\bar{X}$ = 112 N = 34	$\bar{X}$ = .44 N = 17	$\bar{X}$ = .053 N = 9	$\bar{X}$ = 3920 N = 22	10^{-6}-10^{-4}	Moderate
7	Coleharbor Group	Same as unit 6.	Undulating to rolling.	Same as unit 6.	CL	Medium to stiff	10-30	25-35	10-20	14-20	105-115	.3-.6	.03-.07	2000-6000	10^{-6}-10^{-4}	Moderate
7a	Coleharbor Group	Same as unit 6.	High elevation because of glacial processes prior to last advance.	Glacial sediment draped over topography formed previous to or during last advance.												
8	Coleharbor Group	Same as unit 6.	Hilly.	Same as unit 6.	CL	Medium to stiff	10-30	25-35	10-20	14-20	105-115	.3-.6	.03-.07	2000-6000	10^{-6}-10^{-4}	Moderate
9	Coleharbor Group	Bedded sand and gravel.	Gently Undulating to undulating.	River sediment deposited in bars usually located along inside bends of channel meanders.	SM, SP, SC, GP	Firm to compact	>30	Non-plastic	Non-plastic	Low	90-110	.6-.8	Very low	High	10^{-3}-10^{-1}	Low
10	Coleharbor Group	Plane-bedded gravel and sand; mostly poorly sorted gravel containing large boulders.	Undulating to hilly.	River channel sediment deposited in large bars in Souris and Des Lacs Valleys.	GP	Compact to very compact	$\bar{X}$ = 54 N = 17	Non-plastic	Non-plastic	Low	90-110	.6-.8	Very low	High	10^{-3}-10^{-1}	Low
11	Coleharbor Group	Cross-bedded sand and gravel; bedding disrupted and contorted.	Undulating to rolling.	River sediment deposited in contact with glacial ice.	SW, SP, SM	Firm to compact	>20	Non-plastic	Non-plastic	Low	85-100	.6-.8	Very low	High	10^{-3}-10^{-1}	Low
12	Coleharbor Group	Laminated clay and silt.	Rolling to hilly.	Glacial lake sediments deposited in contact with glacial ice.	ML, CL, CH	Soft to medium	5-15	65-75	45-55	35-45	80-90	1.0-1.5	.4-.6	1000-2000	10^{-6}-10^{-4}	High
13	Coleharbor Group	Same as unit 6.	Undulating to rolling; consists of anastomosing channel pattern in places.	Glacial sediment eroded by rivers.	CL	Medium to stiff	10-30	25-35	10-20	14-20	105-115	.3-.6	.03-.07	2000-6000	10^{-6}-10^{-4}	Moderate
14	Coleharbor Group	Non-bedded and poorly sorted sand, silt, clay, pebbles, cobbles, and boulders; contains patches of bedded sand and silty sand.	Rolling to hilly.	Glacial sediment eroded by slope wash with patches of slope wash sediment in bottoms of ravines.	SM, CL	Soft to stiff	10-35	25-40	10-20	14-25	100-120	.3-.8	.03-.1	2000-8000	10^{-6}-10^{-4}	Moderate
15	Fort Union Group	Alternating beds of sand, silt, clay, and lignite.	Exposed in cuts near bottoms of Souris and Des Lacs Valleys and valleys of their tributaries.	River, lake, and swamp sediment.	SM, SC,	Stiff	20-50	40-50	15-25	20-30	95-110	.6-.8	.02-.04	4000-8000	10^{-9}-10^{-4}	Moderate

1. Values of engineering properties are not site specific and cannot be used in place of on-site investigations.
2. Engineering properties considered to be representative of material to a depth of approximately 50 feet.
3. Slope angles; gently undulating (1°-2°), undulating (2°-4°), rolling (4°-8°), hilly (8°-15°).

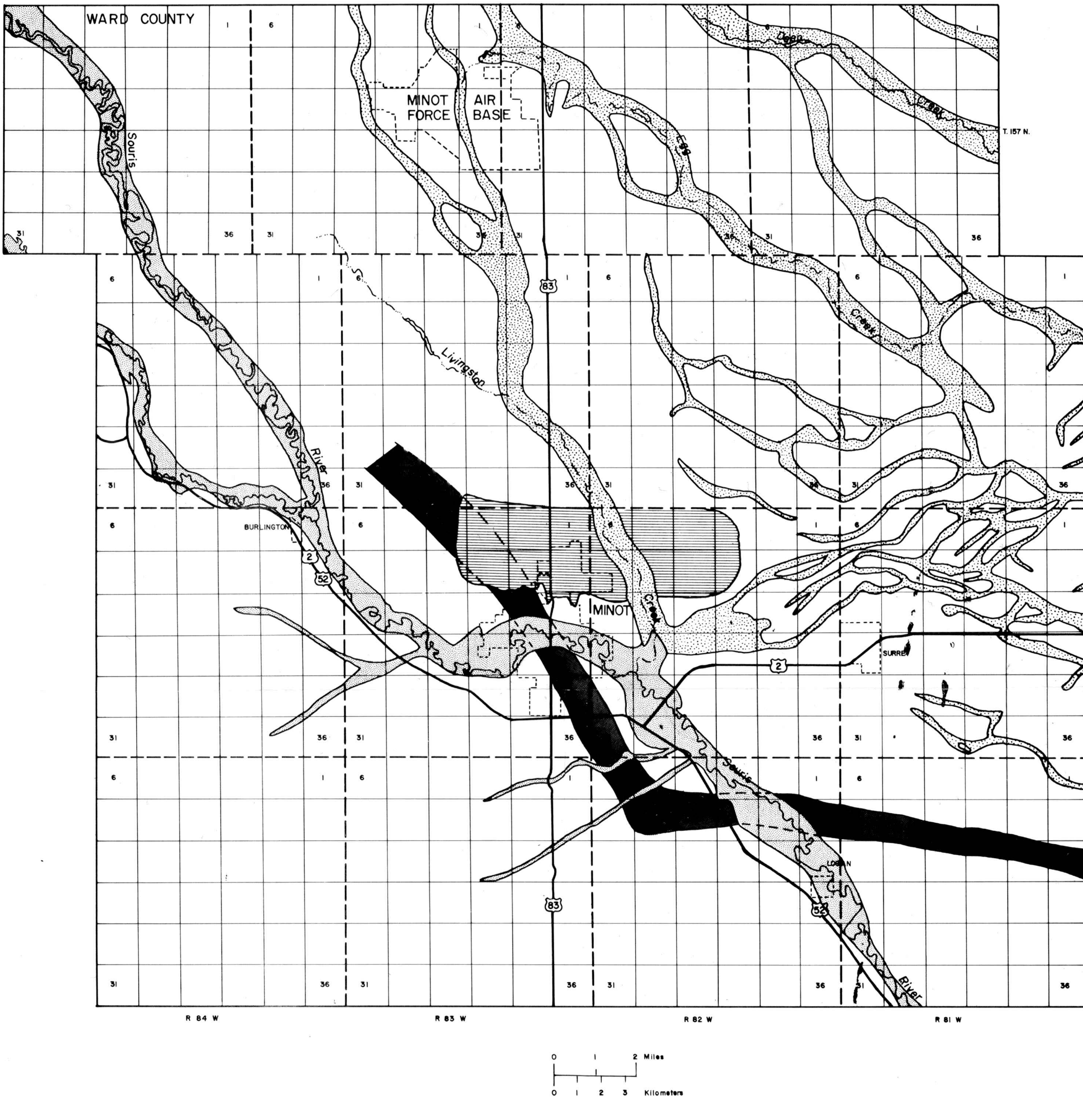


PLATE II GROUNDWATER AQUIFERS IN QUATERNARY DEPOSITS

MODIFIED FROM PETTYJOHN, 1970 AND PETTYJOHN AND HUTCHINSON, 1971

EXPLANATION

MELTWATER CHANNEL AQUIFERS

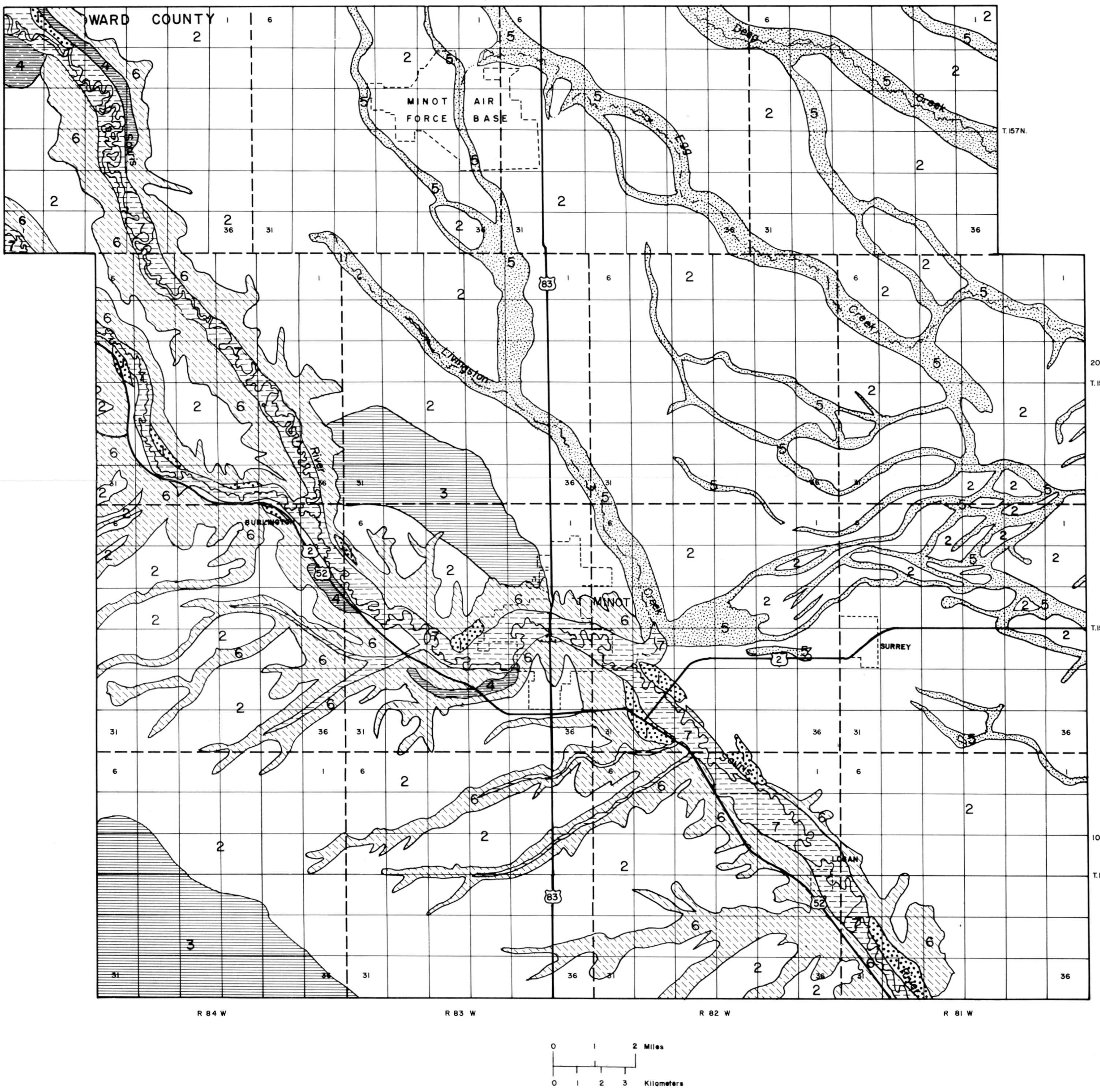
NORTH HILL AQUIFER

SOURIS VALLEY AQUIFER

SUNDRE AQUIFER

PLATE III

GENERALIZED GEOTECHNICAL CONDITIONS

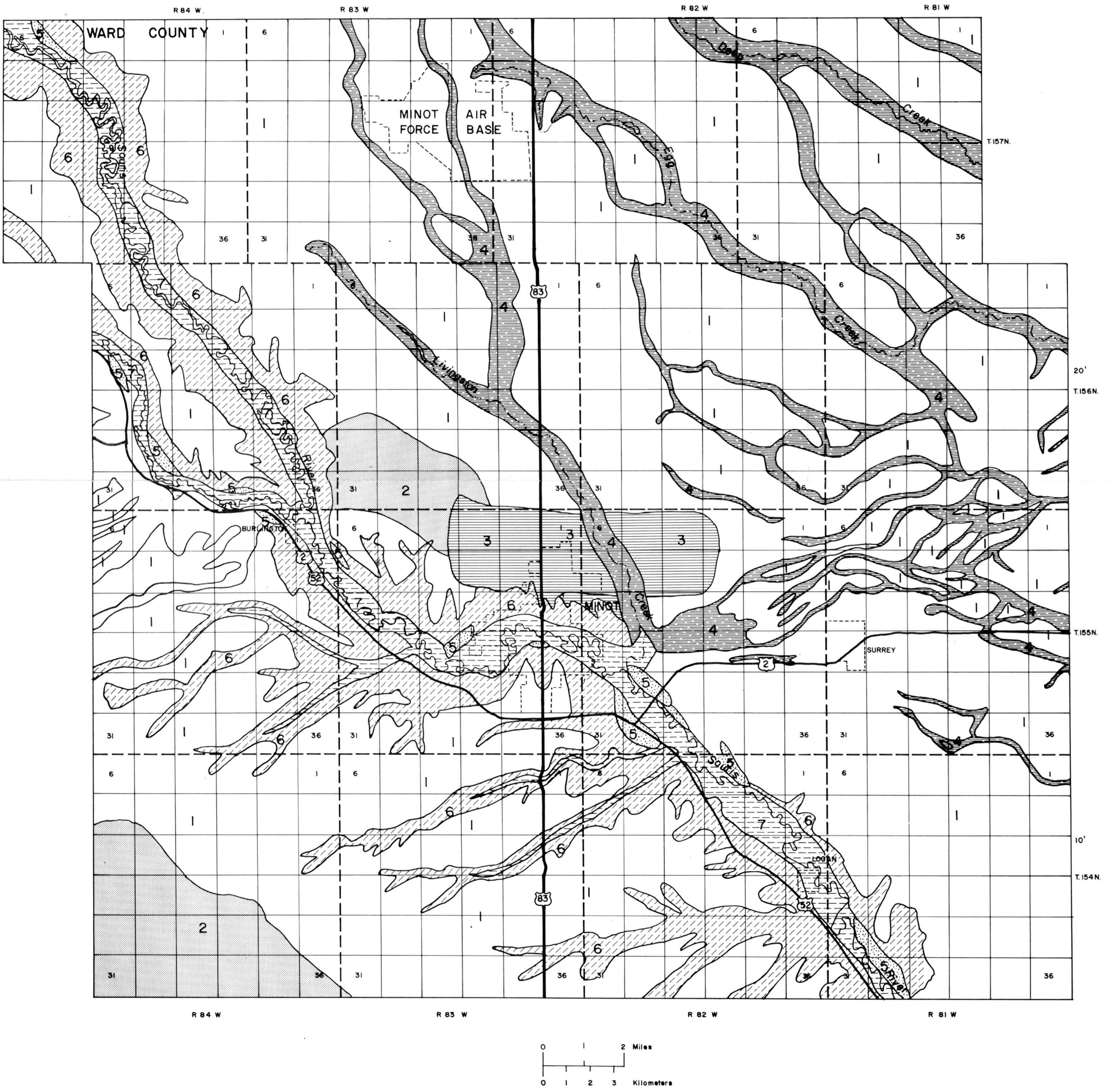


EXPLANATION

MAP UNIT	LANDFORM	SLOPE	Qa (lb/ft^2)	FLOOD POTENTIAL	EROSION POTENTIAL	SLOPE STABILITY	DEPTH TO WT	COMMENTS
1	River Terrace	Top: 0° to 2° Sides: 5° to 15°	8,000 to 12,000	Low	Low to moderate	High	20 to 60 Feet	Valuable as source of construction aggregate material.
2	Gently undulating glacial plain	0° to 2°	2,000 to 6,000	Low	Low	Moderate to high in shallow cuts	20 to 30 Feet	Spread footings generally possible; perched water common in sand and gravel lenses above WT; contains small shallow depressions with high WT and low bearing capacity.
3	Undulating to rolling glacial plain	2° to 8°	2,000 to 6,000	Low	Low to moderate	Moderate to high in shallow cuts	20 to 30 Feet	Spread footings generally possible; perched water common in sand and gravel lenses above WT; contains small shallow depressions with high WT and low bearing capacity.
4	Landslide deposits, parallel ridges along sides of Souris and Des Lacs Valleys	Variable	1,000 to 4,000	Low	Moderate	Potentially low in places	20 to 40 Feet	Old failure planes could be reactivated if slopes are steepened by excavation.
5	Shallow glacial melt-water valley bottoms	0° to 2°	1,000 to 8,000 depending on material.	Moderate to high	Moderate to high	Moderate to low	0 to 10 Feet	Drainage problems likely; waterproofing or site improvement may be necessary. Slide slopes of valleys have higher bearing capacity, fewer water problems.
6	Side slopes of Souris and Des Lacs Valleys and their major tributaries	5° to 15°	2,000 to 6,000	Low to High	High	Moderate to high	20 to 60 Feet	Bottoms of coulees eroded into valley sides covered with deposits of low bearing capacity. Coulees have high flood and erosion potential from periodic flash floods.
7	Bottoms of Souris and Des Lacs Valleys and their major tributaries	0° to 2°	1,000 to 4,000	High	High	Moderate to low	0 to 10 Feet	Deep foundations necessary for heavy structures; drainage and waterproofing necessary.

PLATE IV

GEOLOGIC AND HYDROGEOLOGIC CONDITIONS PERTAINING TO WASTE DISPOSAL



EXPLANATION

MAP UNIT	TOPOGRAPHY	SLOPE	DEPTH TO WATER TABLE	FLOOD POTENTIAL	EROSION POTENTIAL	GROUND WATER RESOURCE POTENTIAL	PERMEABILITY OF NEAR SURFACE MATERIALS	COMMENTS
1	Gently undulating glacial plain	0° to 2°	20 to 30 Feet	Low	Low	No known aquifers within upper 100 feet	Low	Contains shallow sinuous or circular depressions (sloughs) with high water table.
2	Undulating to rolling glacial plain	2° to 8°	20 to 30 Feet	Low	Low to moderate	No known aquifers within upper 100 feet	Low	Contains shallow sinuous or circular depressions (sloughs) with high water table.
3	Gently undulating to rolling glacial plain	0° to 8°	20 to 30 Feet	Low	Low to moderate	Minor aquifer present within upper 50 feet	Low	Contains small sinuous or circular depressions (sloughs) with high water table.
4	Shallow glacial melt-water valley bottoms	0° to 2°	0 to 10 Feet	High	High	Minor aquifer sometimes present within upper 25 feet	Low to high	Unlined sewage lagoons, landfill and septic tanks have high potential for contamination of aquifers where present.
5	River Terrace	Top < 2° Sides 5° to 15°	20 to 40 Feet	Low	Low	Major aquifer sometimes present within upper 50 feet	High	Permeability allows rapid downward movement of contaminants from waste disposal facilities.
6	Valley sides of Souris and Des Lacs Valleys and their main tributaries	5° to 15°	20 to 60 Feet	Low to moderate	High	No known aquifers within upper 50 feet	Low	Slope makes construction of lagoons and septic tanks difficult. Landfills subject to surface erosion problems and drainage problems.
7	Bottoms of Souris and Des Lacs Valley	0° to 2°	0 to 10 Feet	High	High	Major aquifer usually present within upper 50 feet	Low to high	Unlined sewage lagoons, landfills, and septic tanks have high potential for contaminating aquifers, where present.

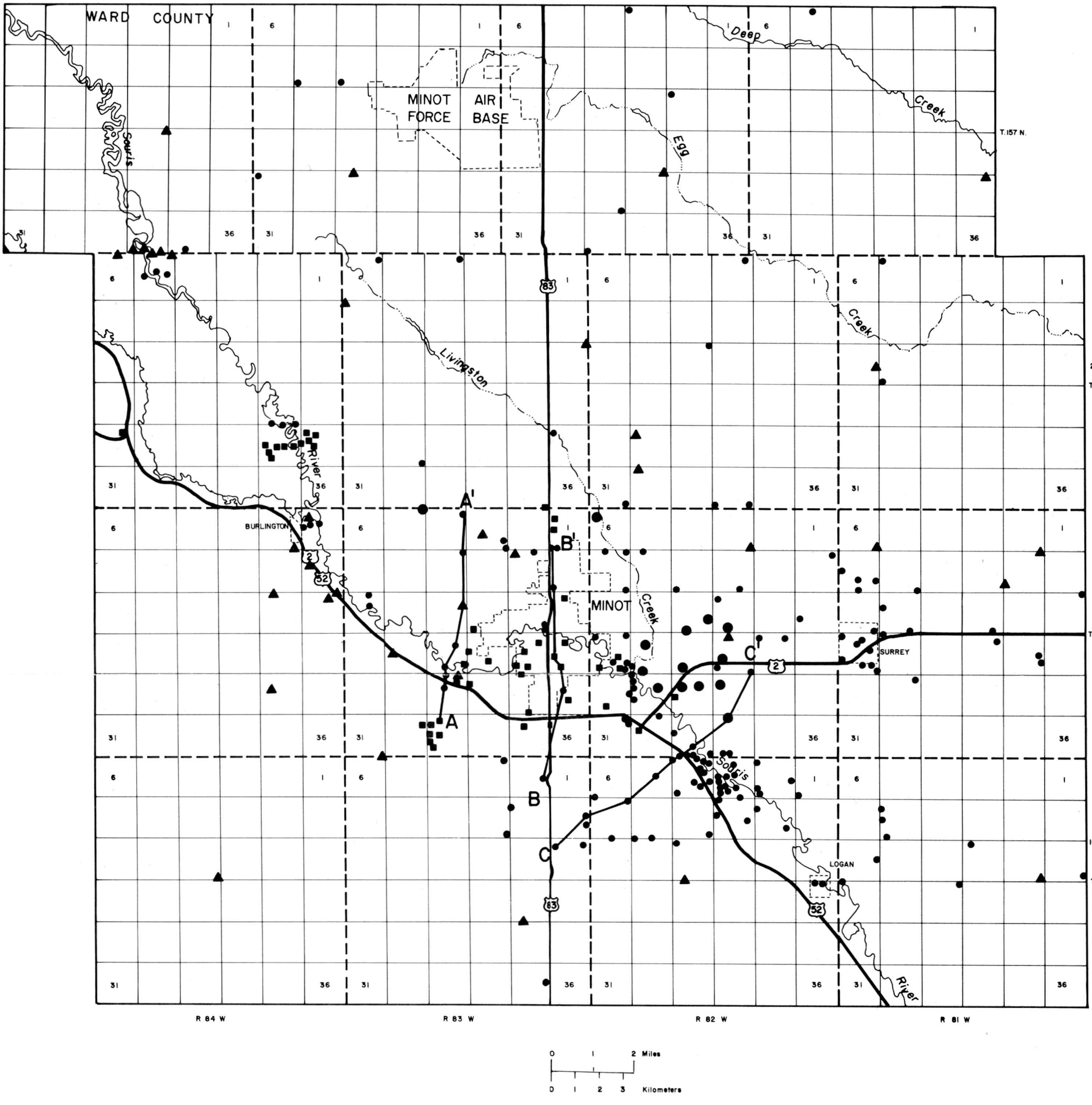


PLATE V SUBSURFACE DATA SOURCES

EXPLANATION

- ■ ENGINEERING DATA. SOURCES: PRIVATE FIRMS, N.D. STATE HIGHWAY DEPT., U.S. ARMY CORPS OF ENGINEERS.
- • STRATIGRAPHIC TEST HOLES AND WATER WELL LOGS. SOURCES: PETTYJOHN, 1968, N.D. STATE WATER COMMISSION.
- ▲ STRATIGRAPHIC TEST HOLES DRILLED FOR THIS PROJECT.
- ● STRATIGRAPHIC TEST HOLES. SOURCE: ANDERSON, 1979.

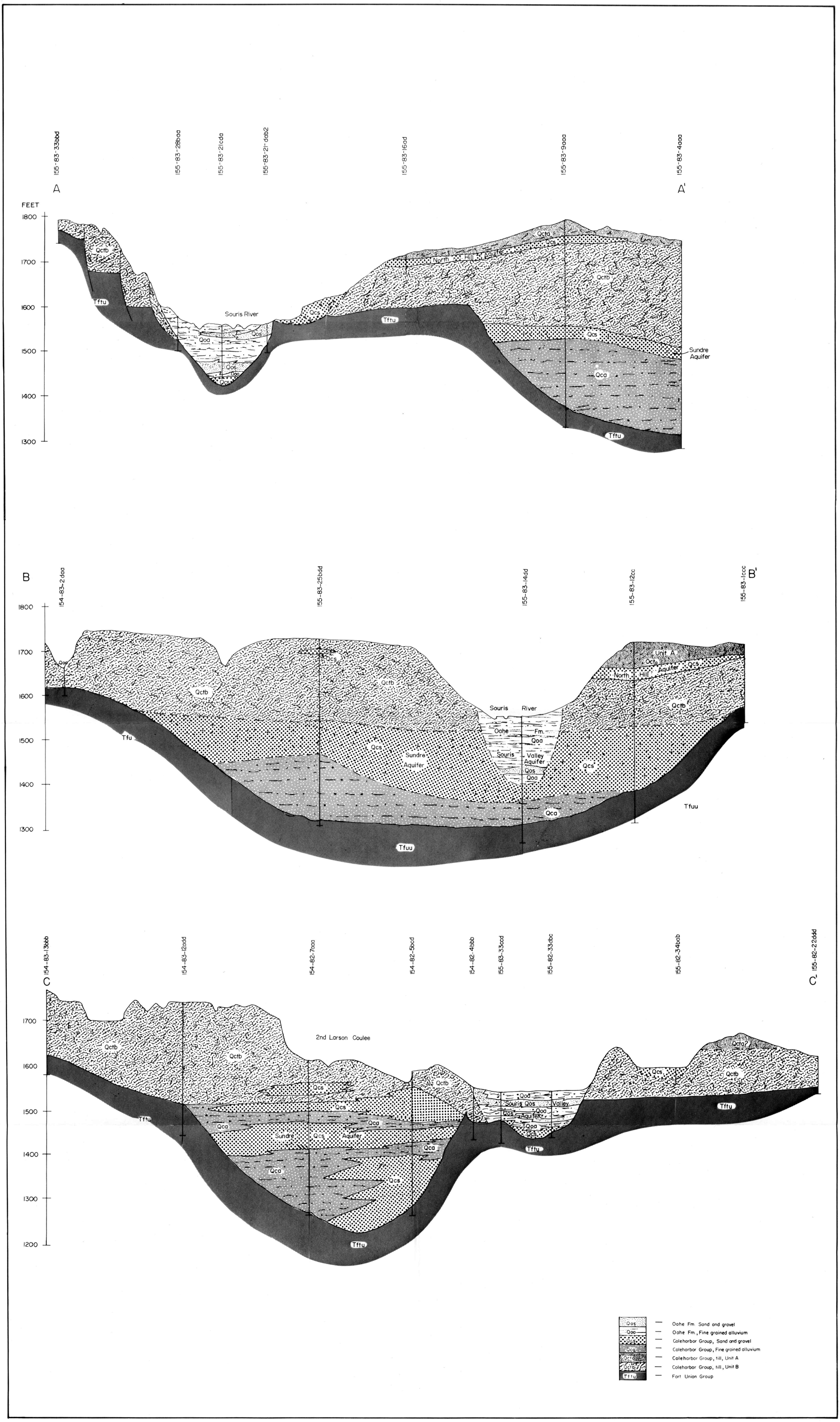


PLATE VI GEOLOGIC CROSS SECTIONS

Horizontal Scale 2.64 inches = 1 mile

Vertical Scale 1 inch = 100 feet

Location of cross sections and sources of data shown on Plate V