SUMMARY DESCRIPTION
OF THE GEOLOGIC ENVIRONMENT
OF THE WILLISTON BASIN LIGNITE FIELDS,
NORTH DAKOTA

Donald E. Trimble, compiler

U.S. Geological Survey Open-file Report

78-920

This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards and nomenclature.

Contents

Figures

Page

Tables

SUMMARY DESCRIPTION

OF THE GEOLOGIC ENVIRONMENT

OF THE WILLISTON BASIN LIGNITE FIELDS,

NORTH DAKOTA

by

Donald E. Trimble

Lignite has been known in North Dakota since Lewis and Clark noted its presence in the journal of their traverse of the Missouri River in 1805, and it has been mined in North Dakota since 1884 (Brant, 1953, p. 57). Initially the mining activity was underground, but strip mining operations have become dominant (fig. 1) and since 1965 all lignite

---

Figure 1.--NEAR HERE

---

produced in the state has come from strip mines (Landis, 1973, p. 50). The lignite-bearing rocks of North Dakota are basin-fill deposits of Late Cretaceous and Paleocene age that occur mainly in the Williston Basin, in the western part of the state. The eastern boundary of the area discussed here (fig. 2) is, therefore, the eastern edge of outcrop

---

Figure 2.--NEAR HERE

---

of the Upper Cretaceous Hell Creek Formation in the southern third of the state and the eastern margin of the known limits of distribution of the Paleocene Tongue River Member of the Fort Union Formation north of the 47th parallel. The international and state boundaries form the northern, western, and southern limits of the discussion area, except for a small area of older rocks along the crestal part of the Cedar Creek Anticline in the extreme southwest corner of the state which is excluded.

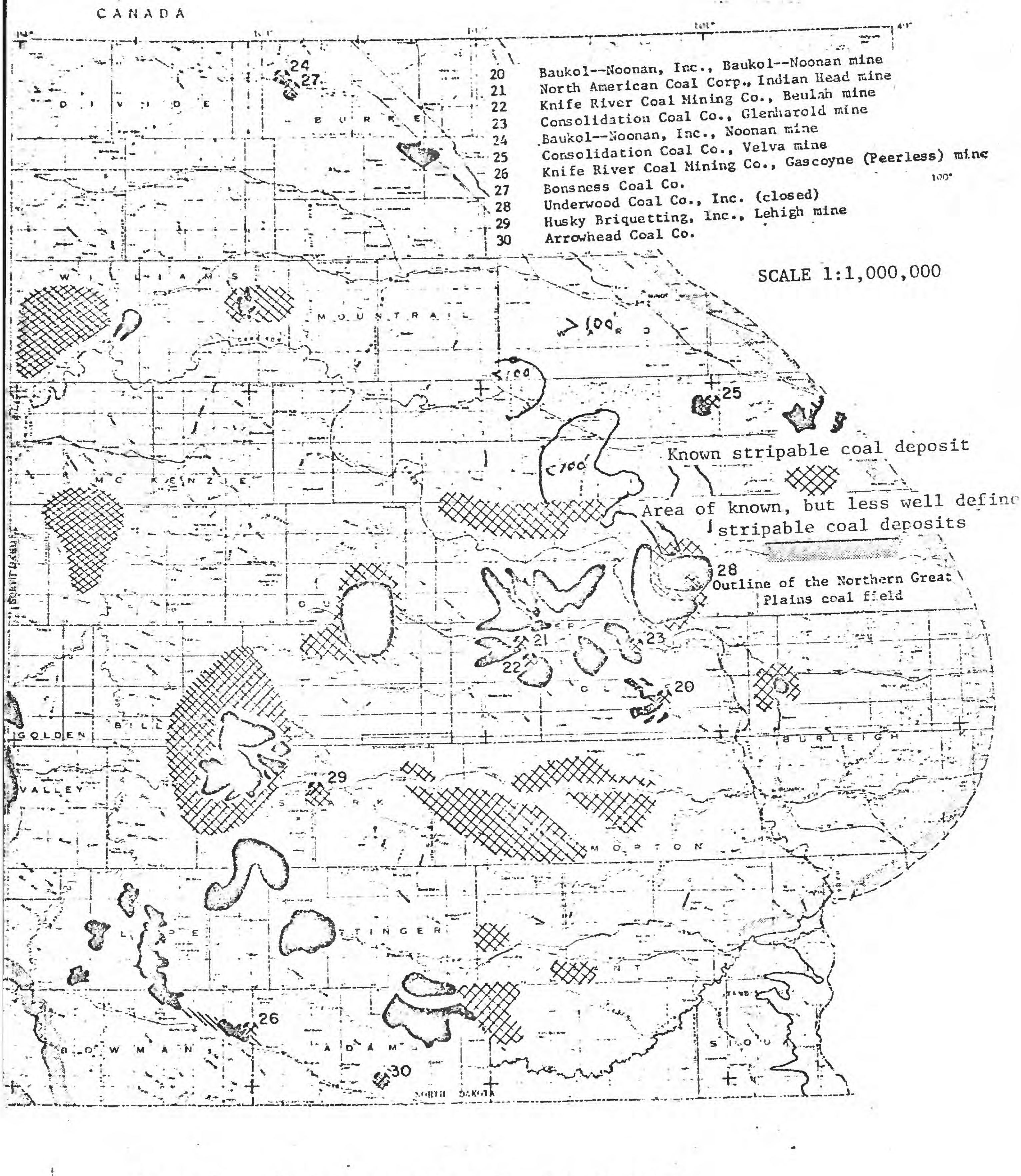

Figure 1. Stripping coal deposits of North Dakota

(From U.S. Geol. Survey Min. Field Studies Map MF-590, 1974)

EXPLANATION

Twr--White River Formation
Tgr--Golden Valley Formation
Tfs--Sentinel Butte Member of Fort Union Formation
Tft--Tongue River Member of Fort Union Formation
Tfc--Cannonball Member of Fort Union Formation
Tfl--Ludlow Member of Fort Union Formation
Khc--Hell Creek Formation
Kfh--Fox Hills Sandstone
Kp--Pierre Shale

Scale: 1 inch equals 24 miles or about 1:1,500,000.

Figure 2.--Geologic map of western North Dakota. Heavy line indicates base of Fort Union Formation. (Map modified from Carlson, 1969)

This summary description of the geologic environment of the lignite fields of the Williston Basin in North Dakota is intended to provide the geologic setting for use in the preparation of Environmental Impact Statements for proposed lignite development in the region. Inasmuch as the lignite has a narrow stratigraphic range of occurrence, the generalizations provided here should have broad regional application, and should reduce the duplication of effort that otherwise would be required in the preparation of those statements.

SOURCES OF INFORMATION

The descriptive material provided here was compiled from the existing literature and is current to 1976. The published sources are listed in the references at the end of the report. D. E. Trimble prepared the general descriptive sections on physiography, stratigraphy, and structure, but the specialized sections on resources, geologic hazards, and geochemical and geotechnical aspects have been provided by others with expertise in those fields. The many contributors are acknowledged in the sections for which they are responsible. Alphabetically listed, they are Roger B. Colton, Jon J. Connor, Norman M. Denson, C. Richard Dunrud, Robert M. Lindvall, Edward E. McGregor, Edward J. McKay, William Z. Savage, William K. Smith, and Charles W. Spencer, all of the U.S. Geological Survey.

PHYSIOGRAPHIC DESCRIPTION

The part of North Dakota described in this report is entirely within the Glaciated and Unglaciated Missouri Plateau Sections of the Great Plains except for an area at the northeastern margin that is part of the Central Lowland. A northeast-facing escarpment (the Missouri Escarpment), commonly 60-90 m high, marks the eastern edge of the Great Plains.

Central Lowland

In the Central Lowland east of the Missouri Escarpment, beds of the Paleocene Fort Union Formation are covered by 30-75 m of glacial deposits, mostly till (Lemke and others, 1965, p. 18). The easternmost part of the area within the Souris River loop, however, is covered by the deposits of a proglacial lake, Glacial Lake Souris, which formed at the margin of the receding ice front during recession of the last major advance of the ice in this area. The deposits of Glacial Lake Souris range in thickness from zero to at least 22 m (Lemke, 1960). Ice of the last major advance here was confined almost entirely to the Central Lowland, and overlapped onto the Coteau du Missouri only slightly to leave the record of its terminus as the Martin Moraine (Lemke and others, 1965, p. 24).

Great Plains

Glaciated Missouri Plateau Section.--Between the Missouri River and the Central Lowland Section, a topographically high belt of hummocky, ridged terrain is pitted by kettles and other undrained depressions. Numerous sinuous meltwater channels, many of which contain elongate lakes, wind their way across the surface of this drift-covered plateau. This complex of end moraines and stagnation moraines, whose eastern margin is the northeast-facing scarp at the east edge of the Great Plains, is called the Coteau du Missouri (fig. 3). Its southwestern

---

Figure 3. --NEAR HERE

---

margin is marked by the Alamo terminal moraine (Lemke and others, 1965). Before 1950, the entire morainal complex was called the Altamont moraine. The till on the Coteau du Missouri locally is more than 30 m thick over a large area south and west of Minot (Andrews, 1939, Plate II).

Southwest of the Coteau du Missouri, and extending to and locally beyond the Missouri River, is an area of older ground moraine characterized by low relief (less than 15 m) and numerous shallow undrained depressions. This moraine commonly is 6-15 m thick.

The maximum extent of glaciation in North Dakota is poorly defined, and is determined mainly by the outer limit of glacial erratics (Benson, 1953, p. 184-194). The glacial deposits between this poorly defined boundary and the Missouri River consist mainly of erratic boulders and a few ice-contact deposits (Lemke and others, 1965, p. 21). Bedrock commonly is exposed at the surface. Drainage is well integrated, and the general character of the terrain is not unlike that of the Unglaciated Missouri Plateau Section to the south.

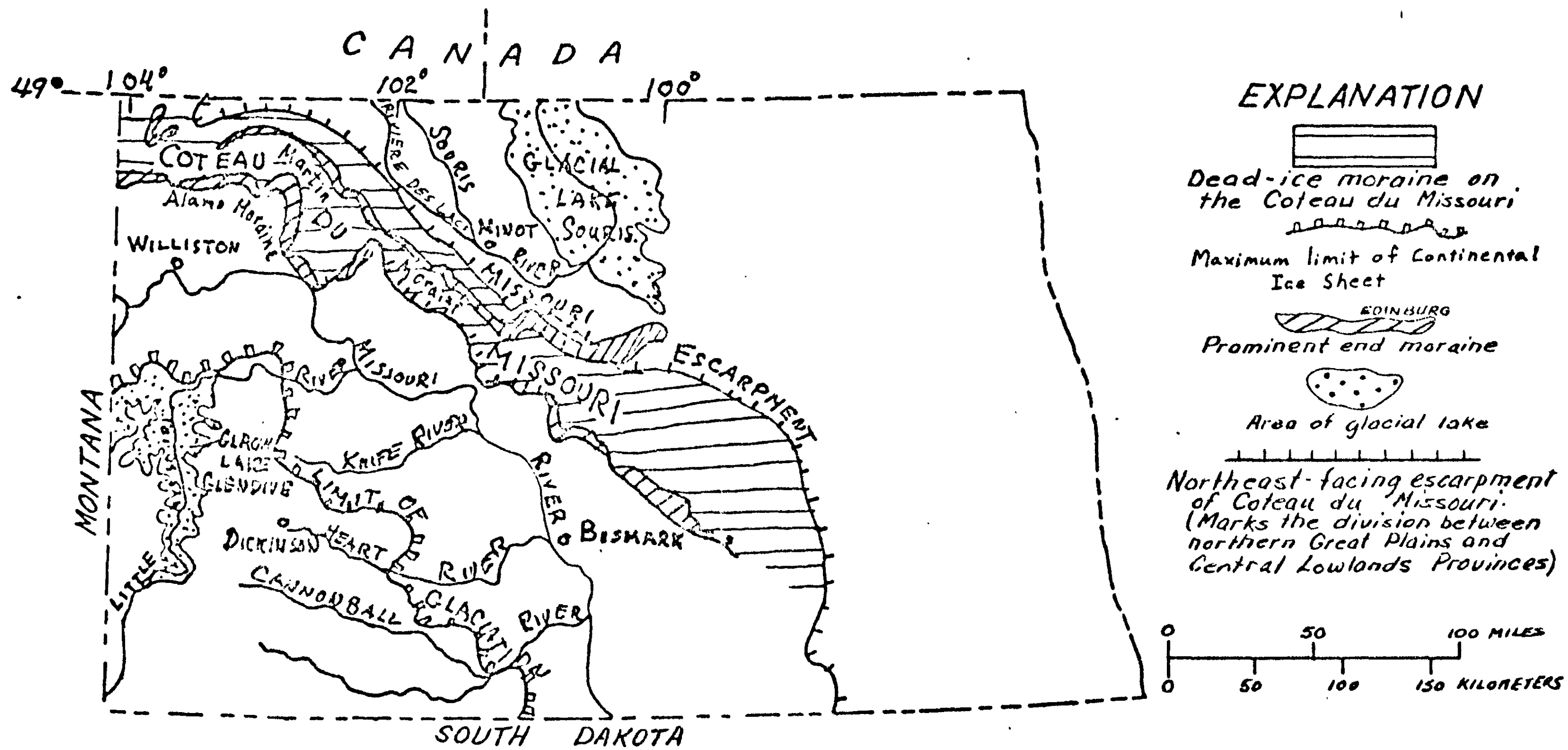

Figure 3.– Glacial map of western North Dakota. (From Lemke and others, 1965)

Before the onset of glaciation, the course of the Missouri River was far to the north of its present course, and the preglacial Missouri flowed northeasterly across the extreme northwest tip of North Dakota into Canada. The Yellowstone and Little Missouri Rivers flowed northward through northwestern North Dakota to join the Missouri north of the international boundary. Waters of the Knife, Heart, and Cannonball Rivers, however, flowed eastward and northeastward where they merged and flowed northward into Canada. These rivers were forced to adopt new courses because of blocking and damming by the advancing ice fronts, and the present course of the Missouri River (fig. 4) is essentially an ice-marginal channel that is joined successively

---

Figure 4. --NEAR HERE

---

by the Little Missouri, Knife, Heart, and Cannonball Rivers (Bluemle, 1972). The Missouri River has cut its present valley about 175 m below the upland surface.

Unglaciated Missouri Plateau Section.--Drainage in the area south of the maximum position of the ice front is much the same as it was before glaciation. The Little Missouri River flows northward to the former maximum position of the ice front, where it turns eastward following a former ice-marginal channel. The Knife, Heart, and Cannonball Rivers, whose headwaters are separated from the Little Missouri by a north-trending drainage divide, all flow eastward in preglacially established courses to join the glacially diverted south-flowing Missouri River.

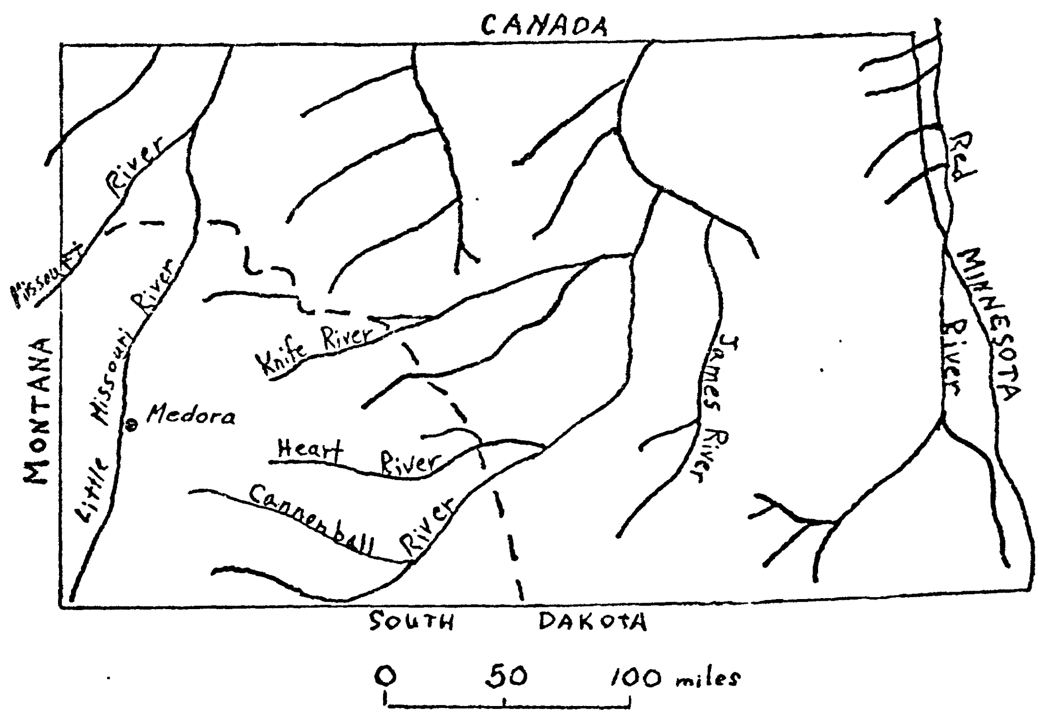

Figure 4.- Preglacial drainage in North Dakota. Dashed line represents route of present Missouri River. (Modified from Bluemle, 1972)

The north-trending preglacial valley of the Little Missouri is nearly 50 km wide at Medora, and is characterized by badlands development. Its east-trending glacially diverted course is less than 15 km wide, and is characterized by steep valley walls and many landslides.

A proglacial lake, Glacial Lake Glendive, formed in the blocked valley of the Little Missouri River. Glacial Lake Glendive apparently was short-lived, for it left little record in the way of lacustrine deposits. Recognition of the former existence and extent of the lake is based mainly on the distribution of ice-rafted erratics and the altitudes of supposed spillways (Lemke and others, 1965, p. 18).

The rest of the unglaciated Missouri Plateau in North Dakota is a gently northeast sloping plateau of little relief except where it is surmounted by isolated buttes and mesas that are the erosional remnants of higher interstream divides, or where entrenched by the Knife, Heart, and Cannonball Rivers and their tributaries, which are incised 60-90 m below the general level of the plateau. The walls of these valleys commonly are steeply sloping and have smooth, rounded forms typical of long-established drainage courses.

The general upland terrain commonly is rolling prairie, but sandstone ledges and red fused rock layers (clinker) resulting from the burning of lignite are resistant beds that form benches and locally cap small mesa-like features. Softer siltstone, mudstone, and claystone layers locally have been dissected to produce badland topography, but more commonly form smooth rounded slopes between benches.

Mountains, buttes, and mesas in western North Dakota are of different sizes and heights, ranging from the Killdeer Mountains with a total relief of about 210 m (high point 1,010 m) to Sentinel Butte, Flat Top Butte, Bullion Butte, Black Butte, Chalky Buttes, and many others with relief of about 150 m, on down to lesser buttes of 60-90 m or less of relief. White Butte, just east of Chalky Buttes, is the highest point in the state with an altitude of 1,068.63 m (3,506 ft). The Missouri River to the east is at an altitude of about 488 m where it leaves the state, so the total relief in the entire state is only about 580 m (1,900 ft).

GEOLOGIC DESCRIPTION

Stratigraphy

Nearly 5,180 m (17,000 ft) of mostly marine deposited sedimentary rocks representing every geologic system overlie the Precambrian crystalline basement rocks near the center of the Williston Basin, southeast of Williston, North Dakota (fig. 5).

Figure 5.--NEAR HERE

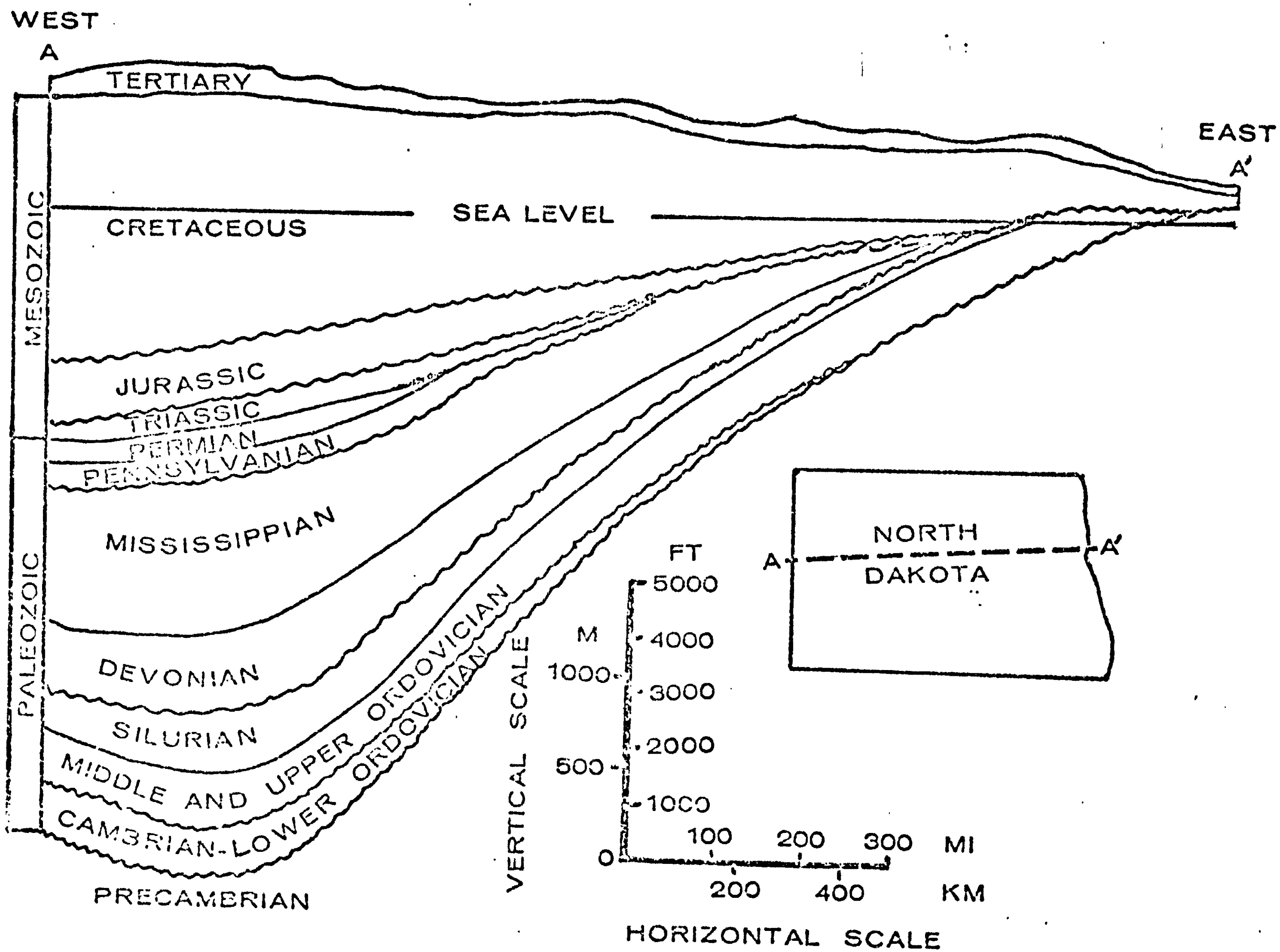

Fig. 5 -- Generalized cross-section of the Williston Basin in North Dakota.

Pre-Hell Creek strata.--Sedimentary rocks of the Williston Basin (see fig. 15) were deposited in a nearly continuously subsiding structural basin (Carlson and Anderson, 1965; Carlson and Anderson, 1973a). Although the seas persisted here throughout the Paleozoic until the end of the Permian and returned in the latter part of the Early Cretaceous, the basin became isolated at various times during the Devonian and Mississippian as well as during the Permian, and great thicknesses of evaporites were deposited in the central parts of the basin. Through much of Triassic, Jurassic, and Early Cretaceous time the basin was free of seas, or contained only highly saline isolated seas where evaporites accumulated, but late in Early Cretaceous time the basin again became part of a great inland sea that persisted to near the end of the Cretaceous. More than 1,220 m (4,000 ft) of marine sediments were deposited in the Williston Basin during the existence of this Cretaceous sea. After the sea receded, the area of the Williston Basin was a coastal plain and low flood plain where three-horned dinosaurs (Tricerotops) roamed. Sediments laid down on this coastal plain by sluggish streams form the Hell Creek Formation (Fig. 6), the youngest of the pre-Tertiary rocks of the Williston Basin.

Figure 6. --NEAR HERE

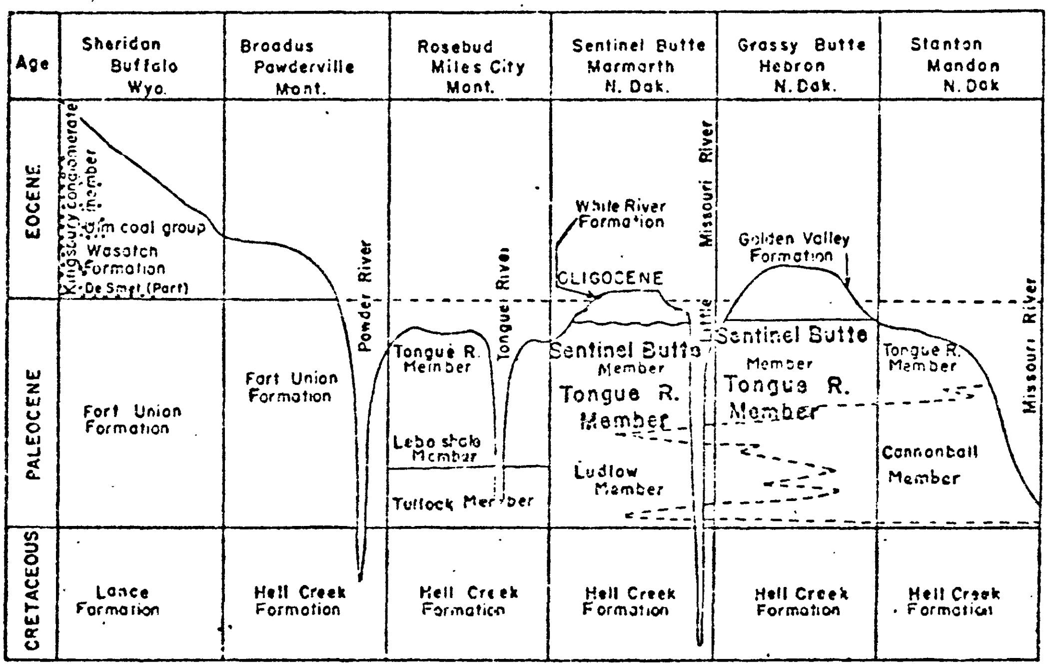

Figure 6.--Diagrammatic section through the Fort Union region. Stippled parts indicate dark zones of strata of all kinds; unstippled parts are light-colored zones (Modified from Brant, 1953, p.11).

Hell Creek Formation (Upper Cretaceous).--The Hell Creek Formation generally consists of less than 122 m (400 ft) of dark-colored carbonaceous shale and sandstone that contain some lignite seams, generally less than 0.76 m (2.5 ft) thick (Brant, 1953, p. 1). These thin lignite seams are impure and discontinuous (Landis, 1973). In southwestern North Dakota the Hell Creek is as much as 175 m (575 ft) thick (Hares, 1928, p. 47). The Hell Creek underlies the Fort Union Formation throughout the basin.

Fort Union Formation (Paleocene).--The oldest Tertiary strata in the Williston Basin compose the Fort Union Formation. The Fort Union, which locally is as much as 610 m (2,000 ft) thick (Landis, 1973, p. 48), overlies the Hell Creek Formation. Fort Union Formation is the bedrock that underlies most of the area of this report.

The Fort Union Formation in the Williston Basin is composed of four members (in ascending order)--the Ludlow, Cannonball, Tongue River, and Sentinel Butte Members. All the known commercially strippable lignite reserves in North Dakota are in the Tongue River and Sentinel Butte Members of the Fort Union Formation (Smith and others, 1973, p 53).

The Ludlow, like the Tongue River and Sentinel Butte Members, was deposited in a nonmarine environment and contains some lignite. It is the basal member of the Fort Union. The Ludlow occurs only in the southern part of the State, south of the latitude of Bismark. It is thickest and best-exposed in Bowman County, in the southwestern part of the State, where it reaches a maximum thickness of 76 m (250 ft) and contains an aggregate of almost 12 m (40 ft) of coal in one area (Brant, 1953, p. 12; Hares, 1928, p. 25-26), but it thins rapidly eastward and northward from Bowman County (Landis, 1973, p. 48). The Ludlow is equivalent to both the Tullock and Lebo Members of the Fort Union Formation of the Powder River Basin of Wyoming and Montana, but these members are not separable in the Williston Basin (Brown, 1962, p. 6). The Ludlow Member of the Fort Union Formation consists of somber shale and mudstone, light-colored sandstone, and lignite.

The Cannonball Member of the Fort Union Formation, unlike the other members, is of marine origin. It does not contain lignite. The Cannonball intertongues with the Ludlow Member in the southwestern corner of the State, and entirely replaces it along the eastern side of the Williston Basin north of Bismark.

The Cannonball is about 9-15 m (30-50 ft) thick along the northeast side of the area near Velva, where it crops out along the Souris River valley wall (Lemke, 1953). The Cannonball consists mostly of alternating thin beds of tan to brown sandstone and sandy shale, but locally is mostly shale, some of which is dark colored.

The Tongue River Member is the most widespread bedrock unit in western North Dakota, and it underlies most of the area described here. Maximum thickness of the Tongue River Member probably is more than 335 m (1,100 ft) (Brant, 1953, p. 12). In the Glen Ullin-Dengate area, where it is about 91 m (300 ft) thick (Barclay, 1973; Barclay, 1974; Smith, 1973), it consists of a lower half composed of thick light- or yellowish-gray lenticular sandstone beds, thick olive and brownish-gray mudstone and subordinate claystone beds and a few carbonaceous shale and lignite beds, and an upper half composed of yellowish-gray or light olive gray sandstone and light yellowish-orange-weathering mudstone, siltstone, and clayey siltstone, a few lignite beds, and limestone pods at two or more horizons (Barclay, 1973).

The Sentinel Butte Member of the Fort Union Formation is about 61-122 m (200-400 ft) thick. Lithologically, the Sentinel Butte is similar to the Tongue River Member, but commonly it is darker colored. It consists of alternating thick dark bentonitic mudstone and claystone and light-colored siltstone and sandstone. The basal contact in places is drawn at the base of the lowest dark bentonitic mudstone above a sequence of light-colored beds of the Tongue River Member (Barclay, 1973; Royse, 1967). In other places in western North Dakota, the contact is drawn between a locally thick lignite, the HT lignite bed of the Tongue River Member, and an overlying silty sandstone that in some places ranges from several meters to more than 30 m (100 ft) thick (Royse, 1967, p. 527).

Golden Valley Formation (upper Paleocene and lower Eocene).--Although Brown (1962, p. 20) said "The beginning of the Eocene is marked by strata of the Golden Valley Formation containing the floating fern *Salvinia preauriculata* Berry," the Golden Valley now is considered to be late Paleocene and early Eocene in age (Hickey, 1969). The Golden Valley Formation conformably overlies strata of the Fort Union Formation in high buttes in western North Dakota, and in areas of considerable size between the Knife River and the Little Missouri River west of Beulah, between the Knife River and the Heart River north and west of Hebron, between the Heart and the Cannonball Rivers south of Dickinson, and in lesser areas north of the Little Missouri River but south of the Missouri River. Golden Valley Formation evidently is not present in the southwestern part of the State. South of the Cannonball River it does not occur at HT Butte or Chalky Buttes (Moore and others, 1956).

The maximum preserved thickness of the Golden Valley Formation is 55 m (180 ft) (Hickey, 1969). The Golden Valley consists of a lower member of fluvially deposited kaolinitic claystone, siltstone, and sandstone that is 6-12 m (20-40 ft) thick, and an upper fluvial member of illitic and montmorillonitic fine-grained sediments. Bright yellow and orange colors, and leached and oxidized zones characterize the formation, which also contains thin lignite at its upper boundary.

White River Formation or Group (Oligocene).--In most places the White River has not been divided into mappable units and is designated the White River Formation. It unconformably overlies the Golden Valley Formation in many buttes and erosional remnants south of the Little Missouri River and north of the Cannonball River. South of the Cannonball and west of the Little Missouri, the White River Formation overlies the Sentinel Butte Member of the Fort Union Formation. In the Chalky Buttes area in Slope County (Moore and others, 1956) and in the White Butte area, Stark and Hettinger Counties (Soward, 1975a, 1975b, 1975c, and 1975d), however, the White River is of group rank and has been subdivided into the Chadron Formation and the overlying Brule Formation. The Brule caps a number of spires in the Chalky Buttes, but is not present in the White Butte area.

The White River consists of fluvial and lacustrine basin-fill sedimentary rocks, coarser grained near the base and finer grained in the upper parts. The combined thickness of the Chadron and the Brule is about 76 m (250 ft) (Denson and Gill, 1965, p.9).

The Chadron Formation consists of a basal conglomeratic sandstone that is as much as 7 m (23 ft) thick in the White Butte area, a middle sandy claystone (1-4.6 m thick), and an upper 4.6-12 m (15-40 ft) of interbedded calcareous claystone and limestone.

The Brule Formation, present only in the Chalky Buttes, the Little Badlands in Stark county, Rainy Buttes, and Black Butte (Denson and Gill, 1965, plate 3) is siltstone, mudstone, and claystone that elsewhere forms badlands.

The Arikaree Formation (Miocene).--The Arikaree is the youngest of the Tertiary basin-fill deposits of the Williston Basin in North Dakota. The Arikaree Formation unconformably overlies upper Paleocene and lower Eocene Golden Valley Formation in the Killdeer Mountains, south of the Little Missouri River, and overlies White River Group at Chalky Buttes, Rainy Buttes, Little Badlands, and Coffin Butte south of the Cannonball River and Black Butte, north of the Cannonball (Denson and Gill, 1965, pl. 3). It consists of sandstone, limestone, shale, and conglomerate, and has a maximum thickness of about 76 m (250 ft) (Keefer, 1974). Its areal extent is very limited.

Glacial deposits (Pleistocene).--The glacial deposits consist mainly of end moraine, stagnation moraine, ground moraine, and glaciofluvial and glaciolacustrine deposits. Although the maximum position of the ice front was far to the south of the Missouri River, the glacial deposits are confined primarily to that part of the region north and east of the Missouri River. South and west of the Missouri River they consist mostly of erratic boulders and glaciofluvial deposits of limited extent.

The glaciofluvial deposits include gravel, sand, and silt of meltwater channels, kames and kame terraces, and eskers. The glaciolacustrine deposits are thin marginal or shoreline deposits of sand or fine gravel of an arm of Glacial Lake Souris and some thin fine-grained lacustrine deposits along the Little Missouri River that were deposited in Glacial Lake Glendive.

The Coteau du Missouri, north of the Missouri River, is mantled by a morainal complex that during the recession of the ice was channeled by meltwater. The till of the morainal complex is stony silty clay that generally is less than 30 m thick, but over a considerable area west and south of Minot is more than 30 m thick, and locally more than 90 m thick (Andrews, 1939, pl. II).

The area of the Central Lowlands included in the area of this report is completely mantled by ground moraine and glaciolacustrine deposits as well as some glaciofluvial deposits. The ground moraine here too is stony silty clay, less than 45 m thick in most places (Lemke, 1953).

Alluvium (Pleistocene and Holocene).--Flood-plain and terrace deposits of the modern streams are composed mostly of sand, silt, and clay. Gravel is a minor constituent of the alluvium in most places, and it occurs mainly in point bars of the Missouri River and in some low outwash terrace deposits that may be considered part of the alluvium.

Landslide deposits (Holocene).--Landslides as a geologic hazard are discussed in more detail elsewhere in this report. Slumping and landsliding generally are common in areas underlain by clayey silty sedimentary rocks like those that characterize the basin-fill of the Williston Basin, particularly where high slopes or bluffs are undercut, or are oversteepened because of a resistant capping layer such as the clinker beds or some of the sandstone beds.

The landslide deposits are unsorted jumbled masses of the parent formation. Lithologies are varied, depending on the character of the bedrock, but the disrupted churned-up character of the internal structure of the mass is common to nearly all landslide deposits, regardless of their type. Some very large slumps maintain the integrity of their internal structure in the rotated slide block. In earthflow, the materials become thoroughly mixed.

STRUCTURE

Williston Basin

The Williston Basin is an intracratonic structural basin in western North Dakota that extends westward into Montana, southward into South Dakota, and northward into Canada (fig. 7). Its center is south of

Figure 7.--NEAR HERE

Williston, North Dakota (U.S. Geol. Survey and Am. Assoc. Petroleum Geologists, 1961). The basin was initiated structurally in the early Paleozoic, and subsided nearly continuously throughout the Paleozoic, Mesozoic, and most of the Cenozoic (Carlson and Anderson, 1965, p. 1836; Carlson and Anderson, 1973a, p. 36-37). Deposition of basin-fill sediment ended in the late Pliocene when the continental interior was epeirogenically uplifted. The Precambrian floor in the central area of the Williston Basin is more than 4,572 m (15,000 ft) below sea level (Carlson and Anderson, 1973b, p. 43). Beds in the basin dip very gently toward its center, except where interrupted by folds. The regional dip in the Fort Union strata within the basin in North Dakota generally is between 1 and 10 m per km (5 and 50 ft per mile) (Roe, 1950, p. 434) but may be as much as 35 m per km (180 ft per mile) (Brant, 1953, p. 13).

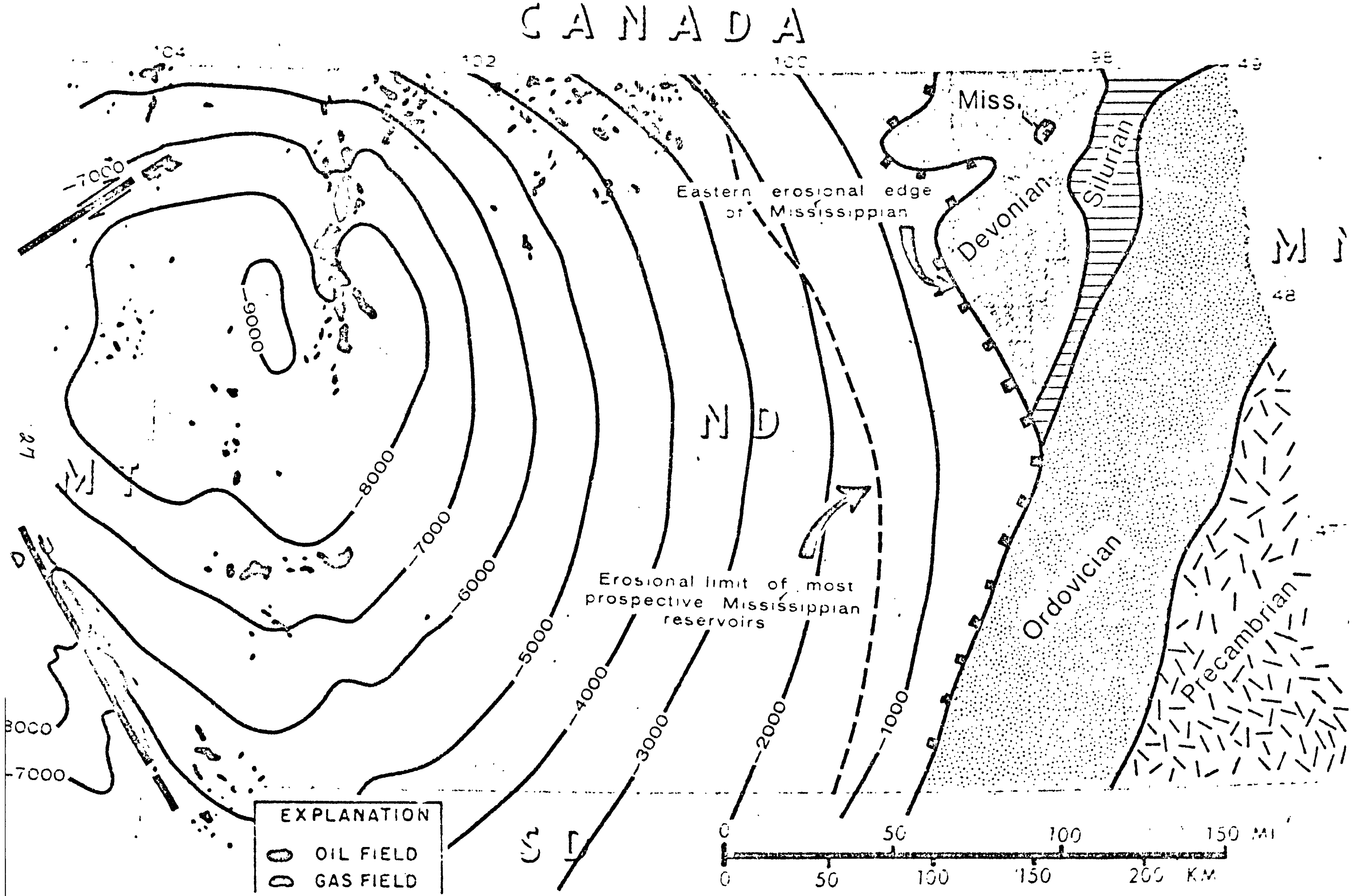

Figure 7.- Structure contour map of Williston Basin, North Dakota.

Folds.--Several major folds are imposed on the strata of the Williston Basin. The largest of these folds, the southeast-trending Cedar Creek Anticline (Dobbin and Larsen, 1936), is mostly in Montana, but it extends into Bowman County, in the extreme southwestern corner of North Dakota. East of Williston are the north-trending Nesson Anticline (Collier, 1919) and White Earth Syncline. The Keene Dome (Nevin, 1946) forms a southeast-trending branch of the Nesson Anticline south of the Missouri River. The northwest-trending Killdeer Syncline lies mostly south of the Little Missouri River. Two small northwest-trending anticlinal folds lie near the State boundary west of Flat Top Butte, in McKenzie County (U.S. Geological Survey and American Association of Petroleum Geologists, 1961). Thomas (1974, p. 1318) considers the Nesson and Cedar Creek Anticlines to be intrablock drag folds formed by forces generated by the adjustments of basement blocks subjected to simple shear during Laramide compression.

Fractures.--Faults are rare in western North Dakota, but a widespread lineament pattern (fig. 8) has been recognized by Thomas

Figure 8.--NEAR HERE

(1974). The lineaments, which are delineated by stream trends, topographic alinements, and tonal zones, form a northeast-northwest trending intersecting pattern that "is believed to be caused by the zonal arrangement of smaller fracture traces that cause differential erosion phenomena" (Thomas, 1974, p. 1306). The lineament pattern has been interpreted as a result of adjustments along basement weakness zones of a basement-block framework during Laramide time (Thomas, 1974, p. 1320). The block framework apparently adjusted laterally by simple shear to the compressive forces.

This regional fracture pattern may affect ground water movement, and is likely to be reflected in any presently unrecognized structures that offset the strata, including the lignite seams.

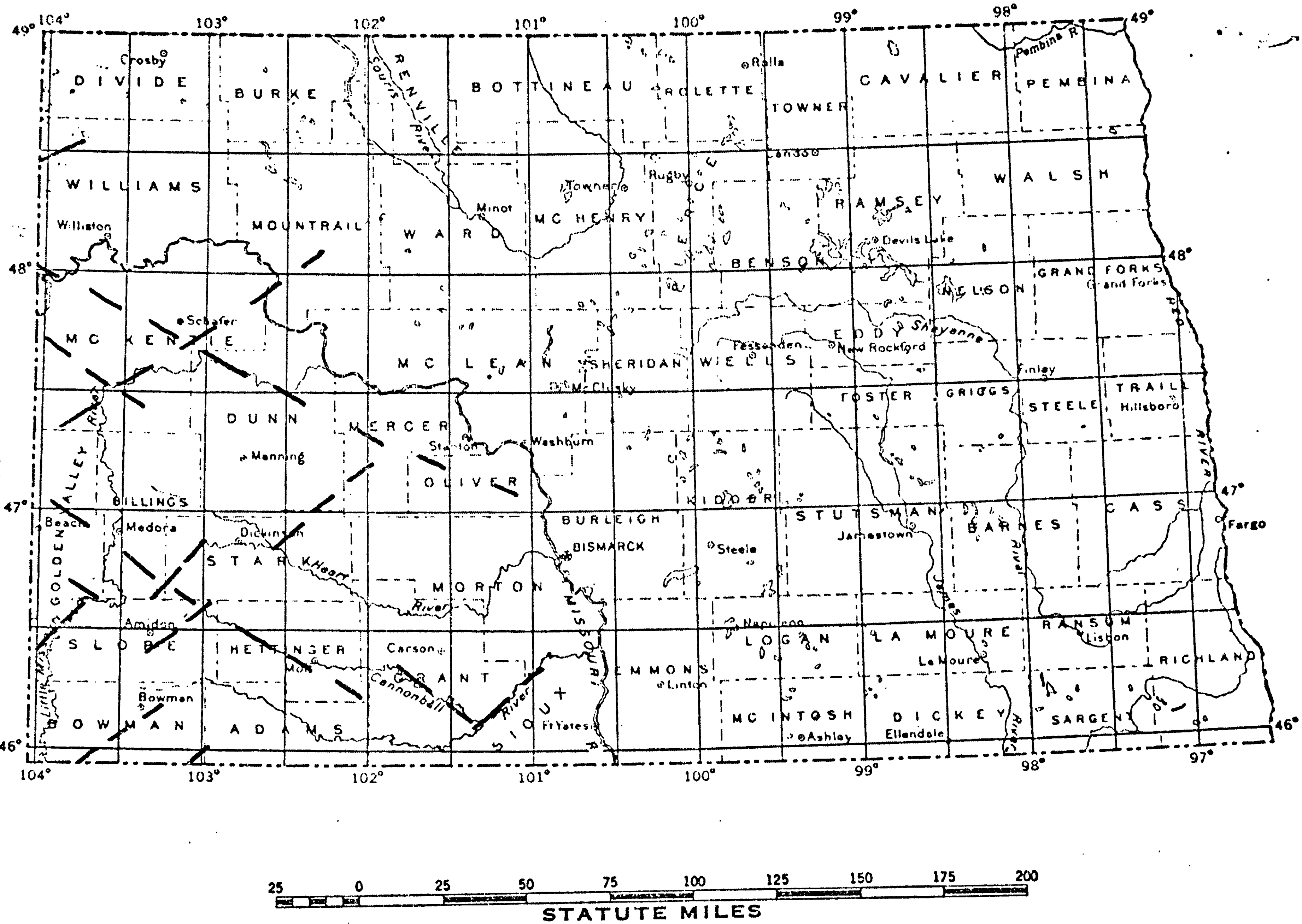

Figure 8 -- Lineament trends in western North Dakota (From Thomas, 1974).

LANDSCAPE GEOCHEMISTRY

by

Jon J. Connor

The two greatest geochemical impacts on the western landscape as a result of large-scale coal development are likely to be geochemical alteration at strip-mine sites by overturn, and geochemical alteration adjacent to electric-generating sites by the products emitted by coal combustion. The first tends to be a rather localized effect but the second may have regional impact.

Environmental interest in the chemical composition of the natural landscape is mainly concerned with the changes in chemical composition that may take place as a result of disturbing or restoring a landscape. This interest focuses primarily on the chemical potential of disturbed or restored materials to support a desirable vegetative cover, which in turn can support animal life, including animals used directly by humans.

If the area to be disturbed by mining or related activity presently supports vegetation, the chemical composition of the substrate (soil or rock) obviously meets at least the minimum requirements of this vegetation. Therefore, a primary geochemical need in impact assessment is a knowledge of the chemistry of these substrates in terms of geochemical backgrounds or baselines. Such baselines define the minimum levels of total nutrient elements, and maximum levels of toxic elements, to which this vegetation is exposed, although not necessarily to the extreme that this vegetation can endure. They also provide a basis for estimating the chemical potential of abandoned or reclaimed land to support the same vegetation.

Many studies have shown that the elemental composition of bulk soil is only weakly reflected by element levels in plant tissue. Therefore, work in plant geochemistry should focus on levels in the plant that may be toxic to wildlife or domestic animals. The plants, by their very presence, demonstrate that any current levels of elemental concentration found in the supporting soil can be tolerated by the vegetation, so the major botanical problem then becomes whether or not such plants can be expected to grow on some new kind of substrate resulting from man's activities and whether or not such growth will result in changed tissue concentrations of elements.

The first part of this question can only be answered by a study of the geochemistry of the new substrate. The chemical composition of these materials may indicate levels of nutrient elements below, or levels of toxic elements above, the concentrations found in the original (native) substrate. It is true that chemical requirements or chemical tolerances of vegetation are determined by the available amounts, not total amounts, of certain elements in the substrate, but the experimental difficulties of determining or stating in a general way the criterion of element availability without reference to species-selective membrane response make the concept very difficult or impossible to apply to native ecosystems.

While nutrient deficiencies are not uncommon in the plant and animal world, public concern over trace element impact of coal development tends to focus on element excesses (toxicities). The definition of what constitutes an excess in a landscape material is less difficult than that of the definition of availability, but it is nevertheless a difficult one. Ideally, an excess is that amount above normal, but because normal concentrations can and do vary over considerable ranges in nature, a normal concentration at one spot (or in one sample) might well be viewed as excessive at another nearby spot (or in another sample of the same or similar material).

Considerable evidence is available that shows that the range in normal concentrations in soil and plant tissue typical of the coal regions of Wyoming, Montana, and North and South Dakota is manifested largely at very local or short-range scale in nature (U.S. Geological Survey, 1974b, 1975, 1976a, 1977); that is, the range in concentration noted in a suite of samples from one localized area in the region (such as a strip mine), is likely to be similar to the range noted at other, far-distant, sites. Under such circumstances, an elemental excess may be viewed as concentrations above some upper limit typical of the normal range.

A provisional limit for selected constituents in seven ordinary landscape materials of western North Dakota is shown on Table 1. Each limit is defined as a concentration above which only about one sample in 20 is expected to fall under natural conditions. Because of vagaries inherent in some estimates, limits judged to be less reliable are given to one significant figure only and placed in parentheses. Nevertheless, these limits may prove useful in assessing geochemical impact. For example, observed ranges in concentration of elements in 30 samples of largely unreclaimed spoil materials from the Velva, Kincaid, and Beulah mines, North Dakota are as follows:

	Kincaid	Velva	Beulah
Al, %	4.7-8.7	5.5-7.4	7.0-8.7
C, %	1.8-18	1.2-8.1	.29-8.7
Ca, %	2.3-5.5	2.6-3.7	.73-2.8
F, ppm	400-1,600	400-2,900	600-1,100
Fe, %	2.2-3.7	2.1-2.6	1.7-4.7
Hg, ppm	.02-.1	.04-.05	.007-.12
K, %	1.4-2.1	1.4-1.7	1.6-2.1
Li, ppm	14-32	21-33	16-29
Mg, %	1.1-1.7	1.1-1.6	.79-1.6
Mn, ppm	290-560	200-340	110-790
Na, %	.90-1.4	.44-1.3	.57-1.5
Rb, ppm	38-76	47-75	49-87
S, %	.027-.74	.027-.16	.16-1.1
Si, %	20-30	26-31	22-34
Th, ppm	7.4-14	5.8-8.3	5.5-10
Ti, %	.21-.40	.23-.30	.32-.40
U, ppm	1.8-4.7	2.1-3.2	2.3-3.7
Zn, ppm	43-110	56-71	68-100

Mercury, in particular, seems anomalously high in these samples compared to baseline data of table 1.

Table 1.--NEAR HERE

Table 1. Probable upper limits of concentration to be expected in ordinary landscape materials of the Northern Great Plains

[The limits are estimated as those above which only about one sample in 20 of a randomly collected suite is expected to fall due to natural causes alone. Values expressed as parts per million (milligrams per liter in water) except as indicated. Limits given to two significant figures except those in parentheses, which are given to only one significant figure because they are judged to be less stable. Leaders (--) indicate data insufficient to estimate limit.]

Property	Landscape Material[1/]						
	Rock		Soil		Sediment	Ground water	Wheat[2/]
	Shale	Sandstone					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Al, %	--	--	(7)	(8)	--	70×10^{-7}	--
As	--	--	--	--	--	--	--
B	--	--	79	91	--	.91	--
Ba	--	--	--	--	--	.024	--
Be	--	--	--	2.6	--	--	--
Br	--	--	--	--	--	1.1	--
C(total), %	5.3	--	(10)	(6)	(5)	--	--
Ca, %	--	--	3.5	(15)	--	(.02)	--
Cd	--	--	--	--	--	--	(.1)
Cl	--	--	--	--	--	.012	--
Cr	--	--	--	82	--	--	(.03)
Co	--	--	11	12	--	--	(.06)
Cu	--	--	38	35	--	--	(5)
F	--	--	--	--	--	(4)	(1)

Table 1. Probable upper limits of concentration to be expected in ordinary landscape materials of the Northern Great Plains--Continued

Property	Landscape Material[1/] Rock: Shale	Rock: Sandstone	Soil	Soil	Sediment	Ground water	Wheat[2/]
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Fe, %----------	--	--	3.7	3.8	--	.0004	--
Ga-------------	--	--	17	--	--	--	--
HCO_3------------	--	--	--	--	--	1500	--
Hg-------------	--	--	(.05)	.066	--	--	(.01)
K, %-----------	--	--	(2)	(2)	--	.0012	--
La-------------	--	--	--	38	--	--	--
Li-------------	80	25	33	39	26	.12	(.2)
Mg, %----------	--	--	1.5	(4)	(2)	(.03)	--
Mn-------------	--	--	(1000)	(2000)	--	--	--
Mo-------------	--	--	5.8	--	--	--	(3)
Na, %----------	--	--	(1)	1.4	(2)	.13	--
Ni-------------	--	--	30	38	--	--	(.6)
Pb-------------	--	--	--	30	--	--	(.1)
Ra-------------	--	--	--	--	--	2.6[3/]	--
Rb-------------	300	98	(100)	(100)	91	--	--
SO_4, %---------	--	--	--	--	--	(.2)	--
Se-------------	--	--	--	--	--	--	(2)
Si, %----------	--	--	(40)	(40)	--	.0031[4/]	--
Sr-------------	--	--	--	--	--	(2.3)	--
Th-------------	--	--	(10)	--	(10)	--	--

Table 1. Probable upper limits of concentration to be expected in ordinary landscape materials of the Northern Great Plains--Continued

Property	Landscape Material[1/]						
	Rock		Soil		Sediment	Ground water	Wheat[2/]
	Shale	Sandstone					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Ti, %	--	--	1.2	1.6	--	--	--
U	--	--	(4)	(5)	(6)	(.05)	--
V	--	--	--	--	--	--	(.02)
Y	--	--	27	27	--	--	--
Zn	220	--	(100)	(87)	95	(.9)	(50)
Rad[5/]	--	--	(50)	--	--	--	--
In water only							
Alkalinity						(1000)	
Dissolved solids (180°C)						3000	
Hardness (Total as $CaCo_3$)						(2000)	
Temperature, °C						14	
pH (standard units)						8.9	
Gross						15[3/]	
Specific conductance, micromhos/cm						(4000)	
Sodium absorption ratio						(100)	

[1/] Identification of landscape materials and sources of data (references at end of footnotes).

(1) Fort Union Formation, outcrop (USGS, 1976a, table 14).

(2) Do.

Table 1. Probable upper limits of concentration to be expected in ordinary landscape materials of the Northern Great Plains--Continued

(3) "A-horizon", <2 mm fraction (USGS, 1976a, table 9, figs. 15-27).

(4) "B-horizon", <2 mm fraction (USGS, 1976a, table 9, figs. 15-27).

(5) <150 fraction (USGS, 1976a, table 3).

(6) From domestic or livestock wells, average depth 30 m (USGS, 1976a, table 13).

(7) Grains of *Triticum aestivum* and *T. durum* (Shacklette and others, 1976).

2/ Determined on dry weight.

3/ Radioactivity in picocuries per liter.

4/ As SiO_2.

5/ Radioactivity in picocuries/gram. Computed as 4.81(ppm U)+1.1 (ppm Th)+8.5(%K). From John Rosholt (U.S. Geological Survey, written commun., 1976a).

A miscellaneous collection of landscape materials from 25 counties composing the coal province in western North Dakota, however, has maximum observed concentrations greater than the upper limits of A-horizon soil (column 3, table 1) for aluminum (<10%), calcium (>10%), iron (7%), potassium (7%), magnesium (5%), sodium (3%), boron (200 ppm), cobalt (30 ppm), copper (150 ppm), gallium (70 ppm), molybdenum (15 ppm), and nickel (150 ppm). These differences suggest something of the magnitude of the geochemical impact of strip mining.

Mineral as well as chemical changes will also take place in the substrate if natural soil is replaced by or intermixed with overburden rock. Probably the most important result of such substitution arises from exposure of previously buried material to weathering, with the attendant possibility of chemical release of foreign substances into the surficial landscape. The most highly reactive materials occurring at the surface of overturned materials are expected to be fragments of coal or other highly carbonaceous strata and pyrite (found in both coal and sandstone). The bulk of such overturned material, however, will most likely be a mixture of fine-grained fragments of shale, siltstone, and claystone. The mineralogy of such a mixture would be rather simple consisting largely of quartz and clay minerals with more or less feldspar and carbonate minerals (U.S. Geological Survey, 1976a). Any chemical release from these materials under conditions of weathering is apt to be much slower than from the more reactive materials.

In addition, the potential impact on vegetative cover is suggested in an examination of the copper/molybdenum ratio in sweetclover (*Melilotus officinalis or M. alba*) growing on these materials (table 2).

Table 2.--NEAR HERE

This ratio is seen to occur around 1-2 in clover from the Velva, Kinkaid, and Beulah mines and compares with an optimal ratio in forage of about 5-7 (U.S. Geological Survey, 1976a). A browse diet formed largely of such a plant might induce symptoms of a copper/molybdenum imbalance in grazers. Grass (*Bouteloua gracilis*) in the Powder River Basin has an average ratio of 4.7 (U.S. Geological Survey, 1975, p. 17) and sagebrush (*Artemisia tridentata*) in the Green River Basin exhibits an average ratio of about 11 (U.S. Geological Survey, 1976a). Presumably such plants growing in North Dakota would have similar ratios. Wheat, although not a browse plant, has an average ratio of 4.6 (Shacklette and others, 1976).

Additional impacts have been observed in crested wheatgrass (*Agropyron desertorum* and *A. cristatum*) at the southern edge of the Powder River Basin (table 3). Expected concentrations (geometric means)

Table 3.--NEAR HERE

---

of cadmium, cobalt, fluorine, uranium, and zinc are higher in wheatgrass growing on reclaimed spoil materials than in the naturally growing control. Uranium, in particular is increased 4-fold.

Table 2. Copper and molybdenum in sweetclover (*Melilotus* sp.), and pH in spoil materials from eight coal mines in the Northern Great Plains

[Geometric mean (GM) concentrations and observed ranges expressed as parts per million in dry material; GD, geometric deviation; mines listed in order of increasing Cu:Mo ratios.]

Mines, or baseline data	Sweetclover, above ground parts: Copper GM	Copper GD	Copper Observed range[1/]	Molybdenum GM	Molybdenum GD	Molybdenum Observed range[1/]	Cu:Mo ratio GM	Cu:Mo ratio GD	Cu:Mo ratio Observed range[1/]	Mine spoils: pH Am	pH SD	pH Observed range[1/]
Big Sky------	8.2	1.16	6.5 - 9.8	13	1.23	10 -20	0.61	1.21	0.44 - 0.75	7.6	0.53	6.5 - 8.5
Utility------	6.9	1.14	5.3 - 9.0	11	1.33	6.4 -18	.62	1.29	.43 - 1.0	7.8	1.30	4.4 - 9.0
Velva--------	7.2	1.18	5.9 - 9.5	7.9	1.25	5.3 -12	.92	1.27	.63 - 1.4	7.8	.40	7.0 - 8.5
Savage-------	5.9	1.27	4.1 - 9.3	6.4	1.30	4.8 -10	.92	1.47	.50 - 1.9	8.2	.49	7.0 - 8.5
Kincaid------	9.0	1.20	6.7 -13	6.5	1.84	2.8 -18	1.4	1.70	.65 - 2.8	7.8	.71	7.1 - 9.4
Beulah-------	5.5	1.14	4.4 - 6.7	2.6	1.60	1.2 - 8.3	2.1	1.60	.63 - 3.8	7.0	.69	6.2 - 8.7
Dave Johnston	7.0	1.19	5.2 - 9.5	3.1	2.18	1.5 -14	2.3	2.34	.47 - 6.5	6.2	1.59	4.0 - 8.5
Welch--------	8.1	1.27	5.6 -11	3.4	1.68	1.9 - 9.5	2.4	1.77	1.2 - 5.0	6.6	.96	5.4 - 7.8
Baseline data[2/]	7.6	1.66	2.8 -21	2.1	2.57	.32-14	3.6	2.35	.65 -20	7.2	.46	6.3 - 8.1

1/Ranges given for baseline data are not the "observed" ranges, but the expected central 90-percent ranges as described in the text.

2/Sweetclover baseline based on eight samples collected throughout the United States; pH baseline based on 64 A-horizon soil samples collected across the Powder River Basin (U.S. Geological Survey, 1974b).

Table 3. Statistical analysis of element concentrations in the ash of crested wheatgrass from topsoil borrow areas and from reclaimed spoil areas at the Dave Johnston Mine, southern Powder River Basin, Wyoming

[Concentrations expressed as parts per million, except for Ca, Na, K, P, S, Si, and ash, which are in percent; *, component of variance tested to be significant at the 0.05 probability level; ratio, number of samples in which element was detected to total number of samples analyzed.]

Element, or ash	Analysis of variance: Total log_{10} variance	Natural variance[1/]: Between areas	Natural variance[1/]: Among samples within areas	variance due to analytical error[1/]	Summary statistics, Topsoil borrow areas: Ratio	Geometric mean	Geometric deviation	Observed range	Reclaimed spoil areas: Ratio	Geometric mean	Geometric deviation	Observed range
CA------	0.0046	<1	95*	5	20:20	4.1	1.11	3.6-5.2	20:20	3.9	1.21	2.6-5.3
Cd------	.0702	27*	<1	73	20:20	.86	1.90	.2-2	20:20	1.4	1.40	.6-2
Co------	.0991	35*	13	52	10:20	.72	1.76	<1-2	15:20	1.5	2.59	<1-8
F[2/]-----	.0240	30*	61*	9	20:20	4.5	1.17	3-6	20:20	6.2	1.46	3-10
Hg[2/]----	.0138	<1	18	82	20:20	.011	1.33	.01-.02	20:20	.011	1.29	.01-.02
X-------	.0148	<1	96*	4	20:20	.18	1.23	13-24	20:20	20	1.38	9.8-30
Li------	.1081	15	83*	2	20:20	13	2.02	4-30	20:20	22	1.93	8-65
P-------	.0267	55*	29*	16	20:20	2.1	1.16	1.8-2.4	20:20	1.4	1.38	.6-2.4
S, total[2/]	.0203	<1	97*	3	20:20	.17	1.29	.10-.27	20:20	.18	1.45	.09-.33
Se[2/]----	.0710	<1	91*	9	20:20	.23	1.91	.10-.60	20:20	.27	1.73	.10-.70
Si------	.0138	15	65*	20	20:20	20	1.22	14-26	20:20	16	1.33	9.4-26
U------	.2165	39*	54*	7	9:20	.25	2.41	<.4-1.2	19:20	1.0	3.02	<.4-10
Zn-----	.0199	59*	39*	2	20:20	310	1.20	220-460	20:20	440	1.25	300-580
Ash----	.0035	<1	94*	6	20:20	6.3	1.15	5.3-8.0	20:20	6.0	1.14	2.6-5.3

1/Expressed as percent of the total variance

2/Analyses determined on dry material, not ash; therefore expressed on dry-weight basis.

Regional geochemical impacts are likely to result mainly from windborne transport of extraneous materials. Two sources of such materials are unreclaimed or abandoned disturbed areas and stack emissions from coal-fired generating plants. Again, the focus of such impact is on potential changes in the vegetative cover. It is reasonable to suppose that powerplant emissions contain at least small amounts of every element naturally present in the lignite, but any practical assessment of their impact can only be based on elemental effects observed in the landscape adjacent to or downwind from the stack. Such effects were looked for in both sagebrush and soil lichen downwind from the Dave Johnston powerplant at the southern edge of the Powder River Basin (figs. 9 and 10). The strongest effect, as measured

Figures 9 and 10.--NEAR HERE

by regression techniques, was due to selenium, a particularly important element because of its known toxic effects to browsers. In both vegetation species, selenium concentrations appear to be increased to distances of 5-10 km beyond the powerplant. Other suspect elements include strontium, vanadium, uranium, and fluorine and, perhaps, titanium, zinc, lithium, and cobalt. Except for uranium in sagebrush and selenium in lichen, the observed concentrations thought to reflect contamination are similar to or less than the upper limits for natural conditions given in table 1. In any event, the fears aroused by such accumulations reflect less a concern with absolute amounts introduced as with the availability to plants of such emissions. Because the lichen samples were cleaned prior to analysis, the selenium accumulation noted there probably reflects biological accumulation, not simple physical entrapment.

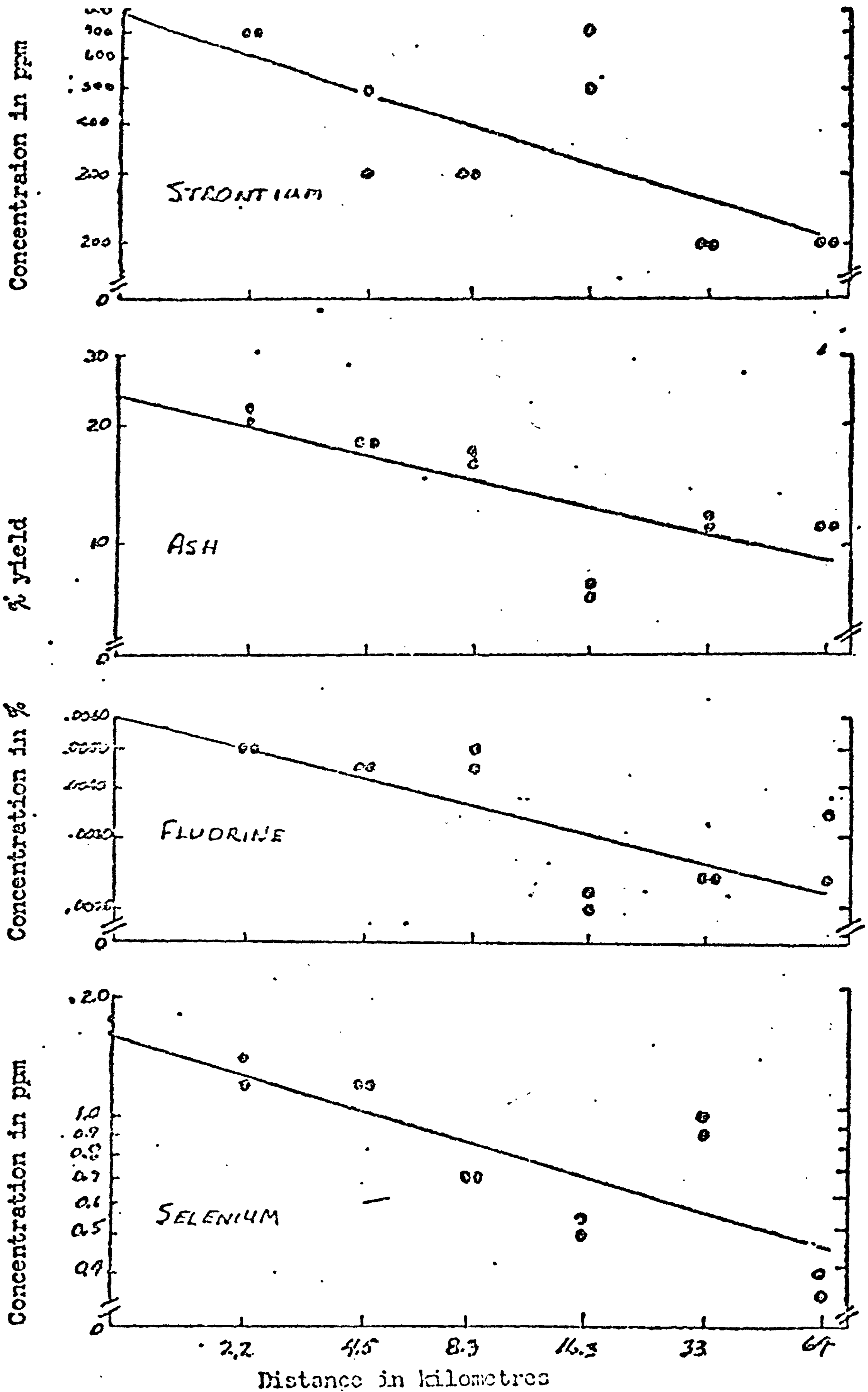

Figure 9. Regression trends in Parmelia chlorochroa for concentrations of fluorine, selenium, strontium, and ash progressing east from the Dave Johnston power plant. Slopes are significantly different from zero at the 0.01 probability level or less.

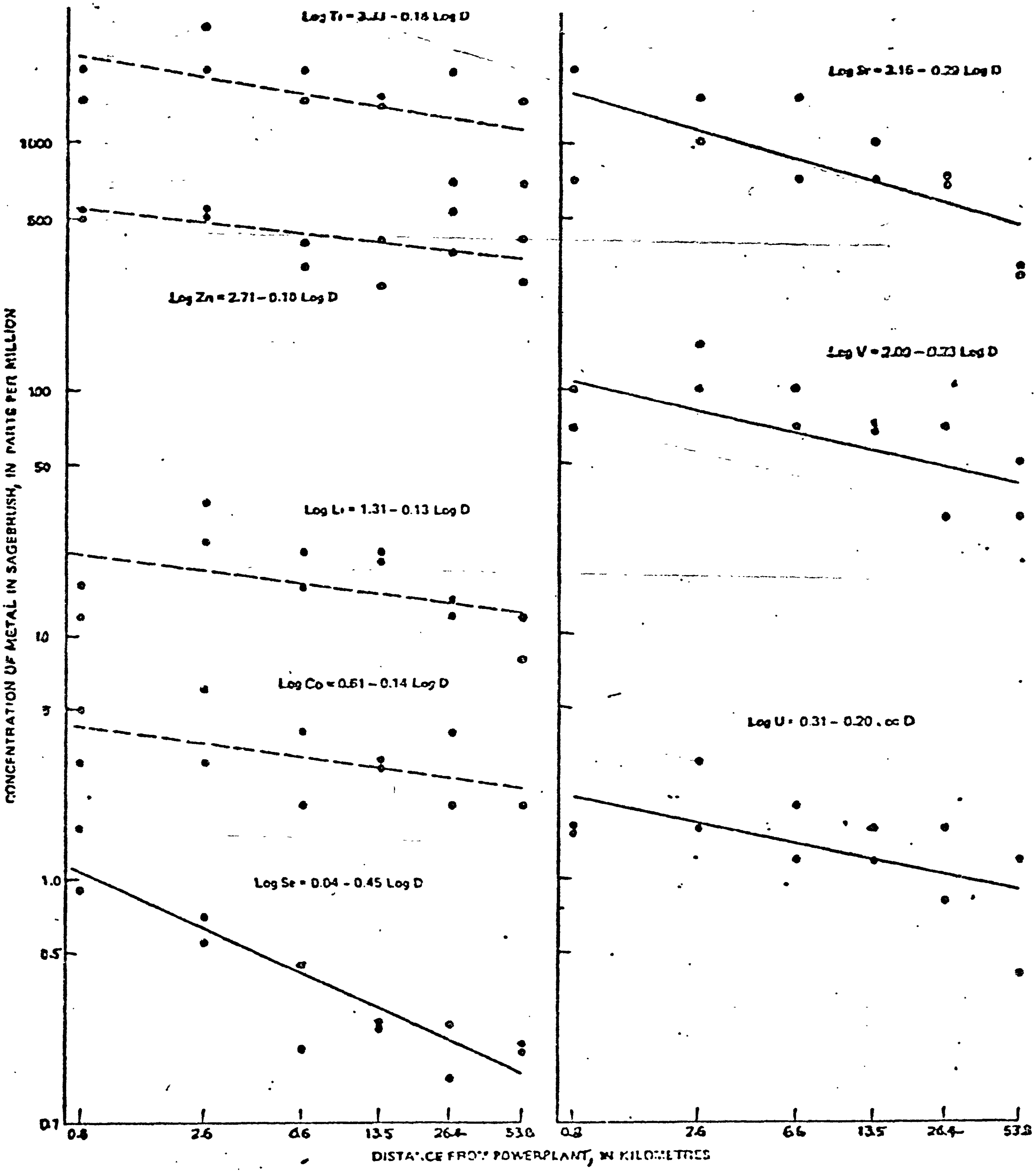

Figure 10. Metal trends in sagebrush away from powerplant. Slopes of solid regression lines are statistically significant at the 0.05 or lower probability level of dashed lines at the 0.05 to 0.10 probability levels; both define trends in concentration. Concentrations of selenium measured in dry weight; all other concentrations measured in ash weight.
(From Connor and others, 1976).

Presumably, the most abundant emissions from powerplants would be the oxides of sulfur, carbon, nitrogen, and hydrogen (water), but as essential constituents of vegetative tissue, it is unlikely that such impact on plant material could be measured as simple distance-related accumulation, although it might be measured in general terms of plant health. Interestingly, geochemical effects of power generation need not necessarily reflect only stack emissions. A sagebrush traverse north of the Jim Bridger powerplant indicated appreciable accumulations in sagebrush of iron, titanium, nickel, silicon, fluorine, and selenium, as well as, increased ash contents. All of these effects were measured before any of the generating units went on-line, and they tended to be greatest within 1-3 km of the plant. They probably reflect either a construction impact (windborne dust) or natural (substrate) fluctuations, or both (U.S. Geological Survey, 1976a).

The hydrologic impact of energy development is expected to be substantial, although the greatest changes will likely be on the quantity or flow direction of water supplies, rather than on chemical quality, at least in a regional sense. Table 1 gives some expected upper limits of a variety of geochemical properties in the shallower (about 30 m) domestic or livestock water supplies of the Northern Great Plains. Table 4 lists interim EPA standards for nine constituents in

Table 4.--NEAR HERE

primary drinking water as well as the maximum concentrations observed in the ground water study on which the data in table 1 are based. Except for measurements of radioactivity, the shallow ground water in North Dakota currently appears to be well within the interim limits.

Table 4. Maximum element concentrations observed in shallow ground water from both domestic and livestock wells of the Northern Great Plains and listing of EPA interim standards for maximum concentrations permitted in primary drinking water (from U.S. Geological Survey 1976a, tables 13 and 14, and U.S. Environmental Protection Agency, 1975a, 1975b).

[All data expressed in milligrams per liter (mg/L) except where noted as picocuries/liter (pCi/L).]

Constituent	Observed	EPA interim standard
As	0.026	0.05
Ba	.52	1.0
Cd	.001	.01
Cr	<.014	.05
Pb	<.014	.05
Hg	.0001	.002
Se	.006	.01
Gross beta, pCi/l	22	22
Ra_{226} pCi/l	4.2	3

The most difficult aspect of impact assessment on the trace-element character of the landscape, however, is that of assessing the broad-scaled regional effects. Although changes in trace-element concentrations far from mines or powerplants will almost certainly be very small, there is some concern that such changes may still pose a potential hazard to plant, animal, or human health. This is mainly because the exact roles played by many trace elements in living tissue are unclear or unknown, and the relation of the local geochemical environment on health or disease is even less well known (Hopps and Cannon, 1972; Cannon and Hopps, 1971). Moreover, such an assessment must be an interdisciplinary one. While it is the role of the natural scientist to determine the relative magnitude of man's contributions to the geochemical environment, it is the role of the medical scientist to determine what, if any, health hazard may result from that contribution.

PHYSICAL PROPERTIES OF THE FORT UNION FORMATION

by

E. E. McGregor, and W. K. Smith

Selected physical-properties tests on samples of the Fort Union Formation from four drill holes in the northern Powder River Basin in southeastern Montana show that, with few exceptions, the rocks of the Fort Union are so weak they cannot be tested as rocks but must be considered as strong soils. The rocks were tested at natural moisture conditions and, in general, the siltstones and shales at high moisture conditions behave plastically. Sandstone and silty sandstone with natural moisture either is plastic or crumbles when removed from a core barrel. Dehydrated surface exposures are cemented and hard, and do not reflect the character of the rock at depth. The rocks have very low tensile and compressive strengths, which suggests the need for careful design of slopes, mine faces, and pit floors. Mine slopes should be carefully designed even in strong rock.

Fort Union rocks from the Decker mine area in southeastern Montana also were sampled and tested to determine their quantitative engineering properties. Properties which have been determined to date for several typical lithologies from the Decker mine include bulk density, confined (both peak and residual) and unconfined compressive strengths, Young's modulus, Poisson's ratio, and Brazilian tensile strengths. Results of triaxial tests are summarized in table 5, uniaxial (Poisson's ratio) tests in table 6, and Brazilian tension tests in table 7. Details of the physical property testing are given in Fahy and Smith (1976).

Tables 5, 6, 7.--NEAR HERE

Table 5. Results of triaxial tests

Sample Number	Rock Type	Density g/cm^3	Density lb/ft^3	Confining pressure kN/m^2	Confining pressure lb/in^2	Peak strength kn/m^2	Peak strength lb/in^2	Residual strength kN/m^2	Residual strength lb/in^2	Young's modulus $10^9 N/m^2$	Young's modulus $10^6 lb/in^2$
1-1		2.38	149	0	0	7,810	1,130	0	0	0.54	0.0783
1-2		2.33	145	345	50	9,540	1,380	3,750	544	.447	.0648
1-3		2.30	144	690	100	6,270	910	-	-	.236	.0347
1A-4[1]		2.33	145	0	0	22,800	3,300	0	0	.757	.110
1-5		2.34	146	1,380	200	5,830	845	5,200	754	.215	.0312
1A-6		2.34	146	2,070	300	8,230	1,190	7,880	1,140	.351	.0509
1A-7		2.31	144	2,760	400	8,250	1,200	7,190	1,043	.336	.0487
1-8		2.33	145	3,450	500	6,040	876	5,850	848	.269	.0390
1-9		2.60	162	5,170	750	40,400	5,860	-	-	2.26	.327
1-10		2.33	145	6,900	1,000	7,060	1,020	5,800	841	.209	.0303
1-11		2.54	159	10,300	1,500	39,400	5,710	33,800	4,900	2.41	
				Cyclic loading							
1-12		2.39	149	0	0					.244	.0354
				1,720	250					.444	.0644
				3,450	500					.611	.0886
				6,900	1,000					.652	.0945
				10,300	1,500	10,400	1,510			.690	.100
3A-1		2.28	142	0	0	18,100	2,630	0	0	1.29	.187
3A-2		2.27	142	690	100	19,100	2,770	9,100	1,320	1.38	.186
3A-3		2.33	145	345	50	24,400	3,540	7,500	1,090	1.88	.272
3A-4		2.29	143	1,720	250	20,600	2,990	11,300	1,640	1.29	.187
3A-5		2.25	140	3,450	500	24,700	3,580	17,200	2,490	1.60	.232

Table 5. Results of triaxial tests--Continued

Sample Number	Rock Type	Density g/cm^3	Density lb/ft^3	Confining pressure kN/m^2	Confining pressure lb/in^2	Peak strength kn/m^2	Peak strength lb/in^2	Residual strength kN/m^2	Residual strength lb/in^2	Young's modulus 10^9N/m^2	Young's modulus 10^6lb/in^2
3A-6		2.38	149	1,380	200	15,300	2,220	10,200	1,480	1.28	.186
3A-7		2.29	143	2,070	300	27,200	3,940	13,000	1,890	1.67	.242
3A-8		2.25	140	2,760	400	25,600	3,710	15,000	2,180	1.50	.218
3A-9		2.31	144	5,170	750	31,400	4,550	16,300	2,360	1.90	.276
3A-10		2.34	146	6,900	1,000	38,100	5,530	23,100	3,350	2.12	.307
3A-11		2.30	144	10,300	1,500	36,600	5,310	26,400	3,830	1.95	.283
				Cyclic loading							
3A-12		2.28	142	0	0					1.29	.187
				1,720	350					1.84	.268
				3,450	500					2.24	.324
				5,170	750					2.53	.366
				10,300	1,500	40,200	5,830	28,300	4,100	2.94	.426
3A-14		2.33	145	0	0	19,100	2,760	0	0	1.81	.263
3A-15-1		2.38	149	0	0	16,300	2,360	0	0	1.64	.238
3B-2		2.08	130	0	0	7,750	1,124	0	0	.884	.128
3B-3-1		2.14	134	0	0	7,250	1,050	0	0	.867	.126
3B-4		2.13	133	345	50	8,310	1,210	3,150[2]	457	.879	.127
3B-5		2.04	127	690	100	9,350	1,360	5,250[2]	761	1.00	.145
3B-6		2.17	135	1,380	200	11,000	1,600	6,350[2]	921	.775	.112
3B-7		2.16	135	2,070	300	16,700	2,420	10,600	1,540	1.55	.225

Table 5. Results of triaxial tests--Continued

Sample	Rock	Density		Confining pressure		Peak strength		Residual strength		Young's modulus	
Number	Type	g/cm^3	lb/ft^3	kN/m^2	lb/in^2	kn/m^2	lb/in^2	kN/m^2	lb/in^2	$10^9 N/m^2$	$10^6 lb/in^2$
3B-8		2.11	132	2,760	400	17,500	2,540	13,100	1,900	1.71	.248
3B-9		2.08	130	3,450	500	21,600	3,130	15,000	2,180	1.98	.287
3B-10		2.11	132	5,170	750	25,000	3,630	18,400[2]	2,670	2.16	.313
3B-11		2.10	131	6,900	1,000	25,000	3,630	20,500	2,970	2.26	.328
3B-12		2.11	132	10,300	1,500	27,500	3,990	26,300	3,810	2.27	.330
				Cyclic loading							
3B-13		2.09	130	0	0					.965	.140
				1,720	250					1.91	.277
				3,450	500					2.47	.358
				6,900	1,000					3.26	.473
				10,300	1,500	28,400	4,120	27,500	3,990	4.15	.603
3B-14[1, 3]		2.09	130	0	0	4,000	580	0	0	.799	.116
3C-2		2.42	151	0	0	17,300	2,500	0	0	1.50	.218
				Cyclic loading							
3C-3		2.36	147	0	0					1.28	.186
				1,720	250					1.55	.220
				3,450	500					1.90	.276
				6,900	1,000					2.50	.360
				10,300	1,500	38,000	5,500	34,000	4,950	3.26	.472
				Cyclic loading							
3D-1[1]		2.82	176	0	0					9.98	1.43

Table 5. Results of triaxial tests--Continued

Sample	Rock	Density		Confining pressure		Peak strength		Residual strength		Young's modulus	
Number	Type	g/cm^3	lb/ft^3	kN/m^2	lb/in^2	kn/m^2	lb/in^2	kN/m^2	lb/in^2	$10^9 N/m^2$	$10^6 lb/in^2$
				1,720	250					12.2	1.77
				3,450	500					14.1	2.05
				5,170	750	97,000	14,100	48,100	6,980	12.5	1.81
3D-2		2.58	161	0	0	45,000	6,530	0	0	6.60	.957
3D-4		2.60	162	1,720	250	50,000	7,250	22,300	3,230	6.02	.874
3D-5		2.73	170	3,450	500	103,000	14,900	35,200	5,110	14.1	2.04
3D-6		2.79	174	6,900	1,000	135,000	19,600	48,500	7,030	15.3	2.22
4-4		1.34	83.6	0	0	20,000	2,900	0	0	2.20	.320
4-5		1.32	82.4	0	0	25,500	3,700	0	0	2.03	.294
4A-6		1.33	83.0	0	0	19,000	2,760	0	0	1.51	.219
4A-7		1.33	83.0	345	50	23,100	3,350	9,000	1,300	1.74	.252
4A-8		1.33	83.0	690	100	28,800	4,180	10,000	1,450	1.97	.286
4-9		1.33	83.0	1,380	200	24,400	3,540	14,100	2,040	1.68	.244
4-10		1.31	81.7	2,070	300	28,800	4,180	18,400	2,670	1.63	.236
4-11		1.31	81.7	2,760	400	31,400	4,550	20,000	2,900	1.93	.279
4A-12		1.32	82.4	3,450	500	37,800	5,480	19,400	2,810	2.24	.325
4-13		1.29	80.5	5,170	750	40,000	5,800	22,800	3,310	1.75	.254
4-14		1.32	82.4	6,900	1,000	35,900	5,210	20,000	4,350	2.16	.313
4A-15		1.32	82.4	10,300	1,500	33,100	4,800	29,700	4,310	2.02	.293

Table 5. Results of triaxial tests--Continued

Sample Number	Rock Type	Density g/cm^3	Density lb/ft^3	Confining pressure kN/m^2	Confining pressure lb/in^2	Peak strength kn/m^2	Peak strength lb/in^2	Residual strength kN/m^2	Residual strength lb/in2	Young's modulus 10^9N/m^2	Young's modulus 10^6lb/in^2
				Cyclic loading						2.17	0.315
4A-16		1.31	81.7	0	0					2.15	.311
4				1,720	250					2.25	.326
				3,450	500					2.05	.298
				5,170	750					2.05	.298
				6,900	1,000	39,100	5,670	37,200	5,400	2.05	.298
				10,300	1,500						

[1] Samples were previously loaded for Poisson's ratio (uniaxial) tests.

[2] Samples exhibited sudden increase in residual strength after post-peak drop
Residual strength recorded is the minimum stress immediately following the post-peak drop.

[3] Sample 3B-14 cored parallel to bedding.

Table 6. Results of Poisson's ratio tests

Sample Number	Field Location	Rock Type	Poisson's Ratio
1A-4	#1	Shape	0.49
1-13	#1	Shale	.56
3A-13	#3	Shale	.15
3A-15	#3	Shale	.44
3B-1	#3	Siltstone	.57
3B-14	#3	Siltstone	.36
3C-1	#3	Calcareous shale	.40
3D-1	#3	Limy siltstone	.81
3D-3	#3	Limy siltstone	.47
4-1	#4	Coal	.36
4-2	#4	Coal	.37
4A-3	#4	Coal	.43

Note: -Sample 3B-14 cored parallel to bedding; all other samples were cored perpendicular to bedding.

-The high Poisson's ratios (>0.5) are a consequence of dilatation during testing.

Table 7. Results of Brazilian Cylinder tests

Sample identification prefix	Rock type	Number of samples tested	Average tensile strength kN/m^2	lb in.^{2}	Direction to bedding
1	Shale	10	2,460	357	perpendicular
1A	Shale	5	1,390	202	oblique angle
2	Shale	4	407	59	perpendicular
3A	Shale	15	2,280	331	perpendicular
3A	Shale	6	930	135	parallel
3B	Siltstone	12	496	72	perpendicular
3B	Siltstone	6	363	53	oblique angle
3C	Calcareous shale	12	2,520	366	perpendicular
3C	Clayey limestone	4	18,600	2,700	perpendicular
3D	Limy siltstone	10	11,200	1,620	perpendicular
3D	Limy siltstone	4	10,300	1,490	oblique angle
4	Coal	15	1,760	255	perpendicular
4	Coal	3	2,000	290	oblique angle

Note: - Coal samples #4A not differentiated from #4 for Brazilian testing.

- Coal, limy siltstone, and limestone samples exhibited brittle fracture in tension.
- Shale and ordinary siltstone samples exhibited ductile fracture in tension.

GEOLOGIC HAZARDS

Slope stability of the Fort Union Formation

by

W. Z. Savage

Slope stability of rocks of the Fort Union Formation can be influenced by a number of external factors such as time of exposure of a slope, angle of slope, amount of rainfall, and collection of water in depressions above slope, and by internal factors such as natural physical properties of the rocks and overconsolidation. Upon exposure to air, many of the clay-rich rocks of the Fort Union Formation tend to dessicate and become intensely fractured near the surface of an exposed face. Cracks form on some slopes after only a few months of exposure, and the period of time a slope is required to be stable is an important design consideration.

Piping may occur if water collects in surface depressions above a slope, and may cause slumping or flowage of the slope below. Expansion of overconsolidated rocks, particularly denser clay shales, may be a contributive factor in slope failure in rocks of the Fort Union Formation. This possibility needs to be investigated further.

Slope stability calculations.--Safety factors for a typical open-pit design in the Fort Union Formation of the Powder River Basin were calculated by the conventional method of slices; that is, by the formula

$$F_s = \frac{[dN\tan \phi + cdL]}{dT}$$

where F_s is the safety factor which must be greater than 1 for the slope to be stable; dN and dT are, respectively, the normal and shear forces acting on each slice; ϕ is the angle of internal friction; c is the cohesion; and dL is the length of the slip surface on a slice. Summation is from one through the number of slices. Side forces and the effect of forces from seepage were not considered in these calculations. Material properties used for the calculations along with an idealized open-pit cross section are shown in figure 11.

Figure 11.--NEAR HERE

Potential surfaces of failure for which safety factors were calculated are shown in figure 12. The dashed line in the figure

---

Figure 12.--NEAR HERE

---

indicates the geometry after removal of a coal bench. Safety factors for both geometries were determined.

ROCK TYPE	YOUNG'S MODULUS E (10^9 N/M^2)	POISSON'S RATIO ν	STRENGTH T_B (KN/M^2)	DENSITY ρ (KG/M^3)	COHESION C (KN/M^2)	FRICTION ϕ (°)
A. SILTSTONE	0.85	0.38	430	2,300	1,700	44.8
B. SHALE	1.3	.30	1,600	2,300	4,990	32.3
C. SANDSTONE	7.0	.47	10,750	2,700	3,220	69.4
D. CLAY	.22	.49	407	2,390	642	52.0
E. COAL	1.98	.39	1,880	1,320	5,040	42.4
F. SHALE	.22	.30	3,850	2,380	642	52.0

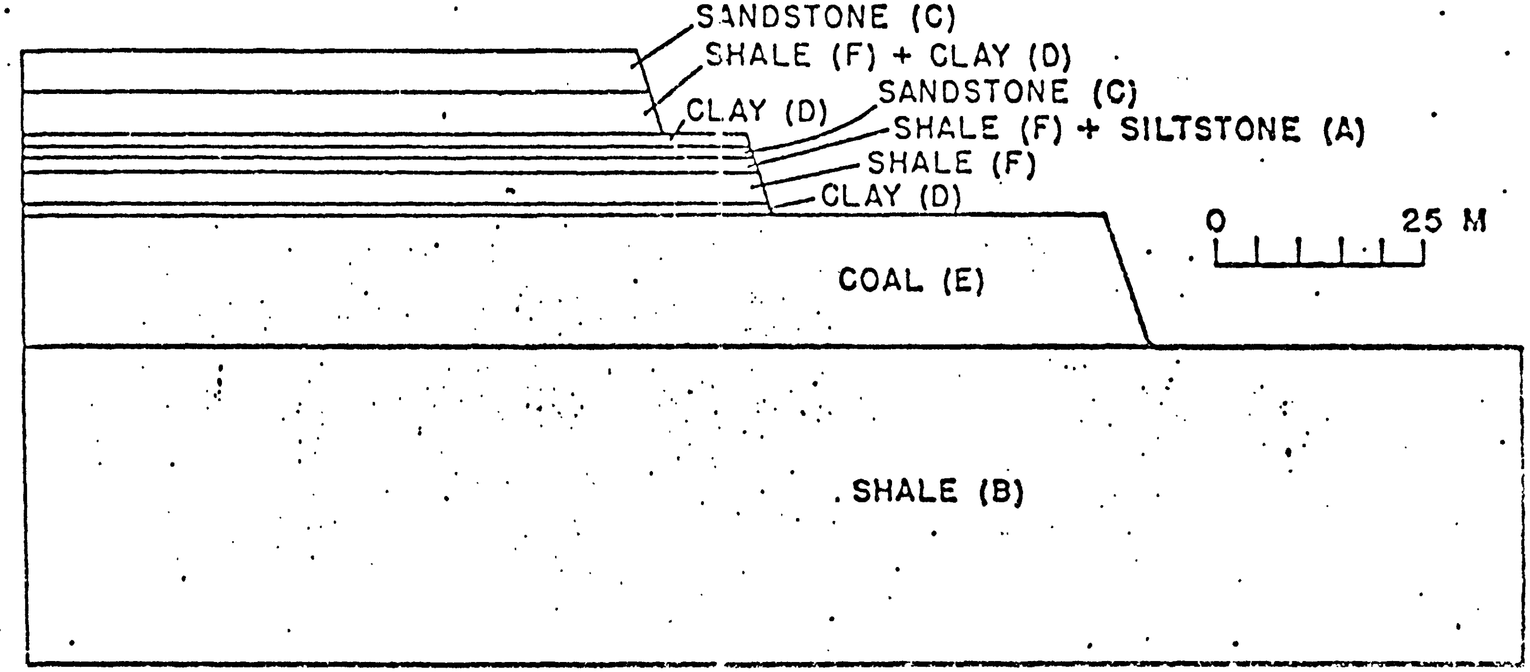

Figure 11. -- Idealized cross section through an open pit in the Fort Union Formation. The average of laboratory-determined properties for the layers are shown

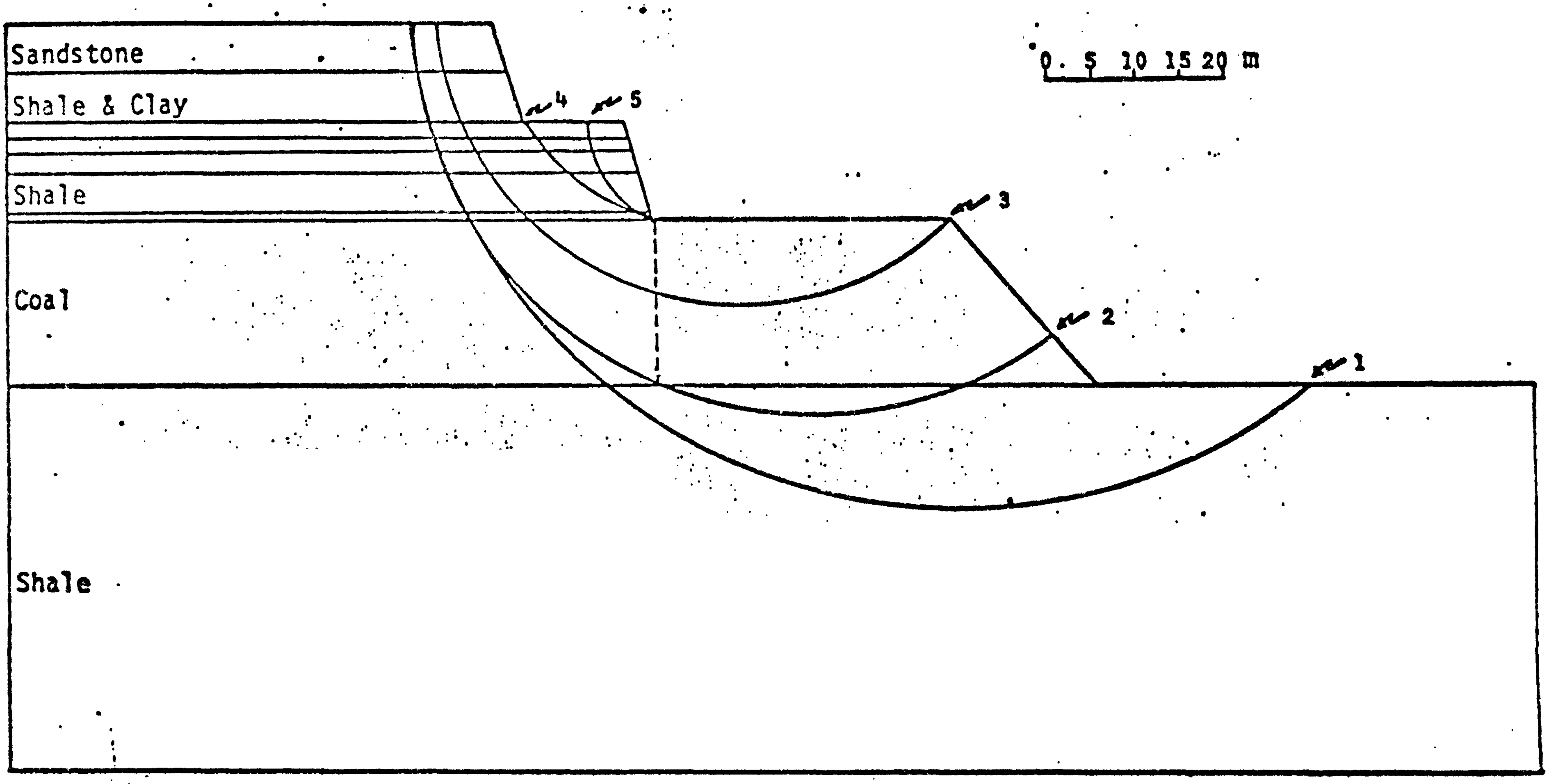

Figure 12. -- Potential surfaces of failure for which safety factors were calculated. The dashed line indicates the geometry after removal of the coal bench.

We considered the effects of changing rock properties on the safety factors. Two different cases were considered: the first case is that in which the values for the properties given in figure 11 were used; and in the second case, the cohesion of each layer was reduced to zero. This reduction was made in a rough attempt to account for the effect of fractures in the rock layers on their strength. This reduction of the cohesions to zero should be considered as an extreme case, as the actual cohesions of the rock layers will probably lie somewhere between zero and the laboratory values given in figure 11.

Safety factors for the five potential failure surfaces are given in table 8. Note that when the average laboratory values are used

---

Table 8.--NEAR HERE

(case 1), the safety factors are high for all surfaces--whether the coal bench is present or absent. On the other hand, when the cohesions are zero (case 2), safety factors are drastically reduced and we see that surfaces 2 and 5 are least stable. In fact, surface 2 is seen to be marginally stable when the coal bench is removed. The addition of seepage forces would further reduce the stability, but further study of this problem is needed.

The most critical conditions for slope stability seem to occur with removal of the coal bench, especially along failure surfaces 2 and 5. Failure along either surface during the final stages of coal-bench removal could endanger miners and mining equipment.

Table 8. Safety factors calculated by the method of slices for the five potential failure surfaces shown in Figure 12

	Coal bench present		Coal bench absent	
	Case 1	Case 2	Case 1	Case 2
Surface #1	24.28	2.21	29.55	2.07
Surface #2	43.10	1.53	24.84	1.09
Surface #3	89.77	2.13	35.39	1.55
Surface #4	24.03	2.25	24.03	2.25
Surface #5	25.35	1.28	25.35	1.28

Conclusions.--Open-pit coal mines of the Fort Union Formation that we have examined generally have stable highwalls. The highwalls do deteriorate with time, and small postmining failures commonly are observed. These would not be particularly critical unless the mining were delayed and then resumed after a period of several months. This time-dependent behavior also has implications for reclamation of highwall slopes. In conducting the geotechnical measurements for determining the optimum reclaimed highwall slope angle, the degradation of the strength paramenters with time must be taken into account.

Finally, we emphasize the role of water in highwall stability. Seepage and piping from pools that are allowed to collect above the highwall do lead to small failures and during especially wet weather could contribute to failures on surfaces such as 2 or 5 in figure 12.

Landslides

by

Roger B. Colton

Landslides are not abundant in the western part of North Dakota, but they could be a continuing cause of damage to highways, railroads, industrial operations, and other facilities. Landslide-prone areas and areas of previous landsliding can probably be identified and avoided.

Most of the large slump-type landslides in western North Dakota occur along the steep-walled valleys of the Missouri and the Little Missouri Rivers, and many involve till overlying Fort Union Formation. Others are along the Des Lacs and Heart River valley. Some landslides occur in the Fort Union on slopes below exposed coal seams, probably because of wetting by water seeping from the coal bed aquifer, or on over-steepened slopes cut on mudstone or shale below a protective cap of clinker or sandstone, as on the slopes of high buttes.

Beds of the White River Formation (or Group) form protective caps on Fort Union on the Killdeer Mountains, Sentinel Butte, and HT (Black) Butte, in Slope County, which are almost completely flanked by landslides. The White River Formation there slumps with the Fort Union. Earth flow is a common shallow type of landslide in the unglaciated upland south of the Little Missouri River and probably constitutes the major unstable ground hazard in the region.

Table 6a.--Untitled as yet.

Formation name	Lithology[1/]	Thickness m	Susceptibility to landsliding
Windblown sand	Loose sand	>9	Slumps to 30^{o}-35^{o}
Colluvium	Variable; derived from erosion of nearby outcrops by sheetwash, creep; clasts angular	>15	Fails to angle of repose
Alluvium	Sand and gravel; clasts rounded	>45	Fails to angle of repose
Outwash gravel and sand	Gravel and sand	60	Fails to angle of repose
Till	Compact mixture of all sizes of debris carried and deposited by ice		Fails along vertical prismatic jointing
Golden Valley Formation	Clay, silty clay, carbonaceous beds, silt, sand, lignite	>50	High
Sentinel Butte Member	Interbedded sand, silt, clay, shale, limestone, and lignite	150	Low to high
Tongue River Member	Interbedded sand, silt, clay, shale, lignite, and limestone	115-135	Low to high
Cannonball Member	Interbedded yellowish-brown, yellow gray and olive gray sandstones, siltstones, shales, and lenticular limestones	90-104	Moderate to high
Ludlow Member	Grayish-olive sandstone, siltstone, clay, and lignite	14-35	Moderate
Hell Creek Formation	Interbedded gray and greenish-gray shale, siltstone, and sandstone	56-104	Low
Fox Hills Sandstone	Upper fine- to medium-grained sandstone, interbedded siltstone, claystone, fine-grained sandstone	6-30 55-69	High
Pierre Shale	Gray shale		Very high

1/ Lithologic descriptions and thickness from Carlson, C. G., 1973.

Surface subsidence

by

C. Richard Dunrud

Spectacular surface subsidence features that occur in the Fort Union Formation over old underground coal mine workings near Beulah, Haynes, Lehigh, and Wilton, North Dakota are similar to subsidence effects studied recently by the U.S. Geological Survey in the western Powder River Basin. During the first half of this century, coal was mined from the Fort Union Formation in an extensive area of underground workings north of Acme, Wyoming. The surface above the old underground workings now is covered by subsidence depressions that reflect the geometry of the former mine workings. Mining was done by the room-and-pillar method, and depressions formed above the old workings where the remaining coal was not strong enough to support the weight of the overburden either because the coal pillars were partially removed or because the initial pillars were too small to support the load over a period of time. The following conclusions drawn from the Acme studies probably are generally applicable, and likely would apply equally well to the North Dakota localities.

Where the overburden is less than 23 m (5 ft thick), the depressions range in depth from 0.3-2.5 m 1-8 ft) and tend to be rectangular, like the mine workings they overlie. Where the overburden is more than 23 m (75 ft) thick, the depressions tend to be more circular or elliptical. The depressions commonly are slightly larger than the mined-out area. Tension cracks, a few centimeters to a meter or so wide, occur at the margins of the depressions, and compression ridges occur locally in the central parts of the depressions. Locally, soil and colluvium over the tension cracks has stretched without fissuring and conceals the cracks, but, in places, holes as much as 3 m (10 ft) wide have formed in the soil and colluvium over the cracks because of piping, gravity collapse, or the activities of man or animals.

Vertical-walled subsidence pits, 1-3 m (3-10 ft) wide and 3-6 m (10-20 ft) deep, have occurred in time above individual mine openings or above the intersection of two mine openings. Many of these pits occur within subsidence depressions that were formed earlier. The pits were formed by upward stoping initiated by collapse of mine roofs. Collapse of mine roofs commonly is governed by the width of the mine opening, the strength of the mine roof, and the adequacy of the roof support system used. The occurrence of pits, therefore, is dependent on the time required for the roof to collapse, the thickness and strength of the overburden, and the width of the mine opening. Pits may suddenly form with little or no warning, tens or even hundreds of years after mining.

Coal mine fires

by

C. Richard Dunrud

Coal mine fires in abandoned mine workings are threats to the environment and to adjacent coal deposits. According to Rabchevsky (unpublished Ph. D. thesis, George Washington University, April 6, 1972, 94 p.) at least 288 coal fires are burning out-of-control in the United States, of which about 70 percent are located in the western states. About 120 fires, or about 42 percent of the national total, are located in the States of Montana, Wyoming, and North Dakota. Studies by the U.S. Geological Survey and by the U.S. Bureau of Mines (D. L. Donner, oral commun., 1975) show that fires in at least three abandoned coal mines are burning out-of-control in a 400-600 hectare (1,000-1,500 acre) near Acme, Wyoming. The coal in these abandoned mine workings apparently was ignited by increased temperatures in the coal resulting from local stress increases and from the introduction of oxygen and water through open subsidence cracks in the overburden.

The increase in internal energy of the coal produced by the local increased stress levels and by oxidation of the coal and the pyrite in the coal appears to have elevated the temperatures sufficiently to ignite the coal. Field studies indicate that, once the coal ignites, the fire can support combustion and spread by drawing in fresh air through open subsidence cracks and pits in the overburden and exhausting gases via other cracks and pits. The voids created as the coal is burned produce further ground settlement, more tension cracks, and more local pits by a stoping process, which in turn provides more oxygen to the fire. Care must be taken in in-place gassification experiments to insure that subsidence cracks do not form, or controlled fires may suddenly burn out of control.

Fires were observed on old exposed highwalls. To prevent the possibility of fires occurring on final graded highwalls in modern mines, special care must be taken to insure that the highwall is adequately covered with spoil or other noncumbustible material during restoration.

A reconnaissance study of the gases that are exhausted along with steam and smoke through tension cracks and pits was conducted by the U.S. Geological Survey in the Acme mining area, north of the town of Acme, in the spring of 1976. Analyses revealed carbon disulfide, carbon oxysulfide, and an unknown sulfur compound. Methane in excess of one percent by volume was detected in a crack near one of the most intense fire areas. The exhausting gases also contain less nitrogen and more helium than normal atmosphere.

Seismic risk

extracted from von Hake, 1975

No earthquakes of intensity V or above (Modified Mercalli Scale) have occurred in North Dakota during historic time. The first instrumentally located earthquake in North Dakota occurred on July 8, 1968, but its intensity did not exceed IV. North Dakota (and the eastern half of Montana) is included in seismic risk zone I where only minor damage is expected.

ECONOMIC RESOURCES

Lignite

by

Edward J. McKay

Lignite occurs in an area of about 72,520 sq. km. (28,000 sq. mi.) in the western half of North Dakota (fig. 1) in a sequence of beds about 375 m (1,200 ft) thick in the Tongue River and Sentinel Butte Members of the Fort Union Formation of Paleocene age. Thicknesses of individual lignite beds vary within individual mines and between mined deposits, but most minable beds average about 2.4 to 3.6 m (8-12 ft) in thickness, and the Harmon bed is as much as 12 m (40 ft) thick in the Bowman deposit (North) in Slope County (Pollard and others, 1972). Some individual beds extend over wide areas (Rehbein, 1977). In addition to coal, which may occur in as many as thirteen beds in any one locality, the Fort Union Formation consists of poorly consolidated sandstone and siltstone, and minor amounts of shale. Subordinate amounts of lignite are present in the adjoining Ludlow Member of the formation.

Estimated resources of lignite in North Dakota total nearly 531 billion tons as shown in several resource categories on table 9. Included in the total is 16 billion tons of lignite in strippable deposits less than 61 m (200 ft) below the surface (table 10).

Tables 9 and 10.--NEAR HERE

Production in 1975 of 8.5 million tons of lignite in North Dakota (U.S. Bur. of Mines Annual Report) is expected to increase to about 30 million tons in 1982 (Metzger, 1976). At that increased level of production the 16 billion tons would last more than 500 years.

Table 9. Estimated original lignite resources of North Dakota[1/]

[In millions of short tons. Overburden 0-365 m (1,200 ft)[2/]. All figures are for lignite in the ground.]

County	Original reserves in the ground[3/]	Inferred resources and resources in beds less than 1.5 m (5 ft) thick	Total identified resources	Additional hypothetical resources in unmapped and unexplored areas	Total estimated resources
	(1)	(2)	(3)=(1)+(2)	(4)	(5)=(3)+(4)
Adams	266	1,591	1,857		
Billings	2,836	14,882	17,718		
Bowman	1,136	5,885	7,021		
Burke	530	6,080	6,610		
Burleigh	208	949	1,157		
Divide	792	7,472	8,264		
Dunn	2,992	68,050	71,042		
Golden Valley	1,290	7,029	8,319		
Grant	670	3,988	4,658		
Hettinger	1,847	10,806	12,653		
McHenry	40	78	118		
McKenzie	3,211	28,972	32,183		
McLean	1,923	14,555	16,478		
Mercer	4,754	24,159	29,913		
Morton	1,968	13,282	15,250		
Montrail	749	14,629	15,378		
Oliver	1,923	15,916	17,839		
Renville	59	724	783		
Sheridan	---	660	660		
Slope	4,994	15,097	20,091		
Stark	2,216	23,481	25,697		
Ward	905	9,381	10,286		
Williams	2,144	24,791	26,935		
Total	37,453	313,457	350,910	[4/]180,000	530,910

Cumulative production and losses in mining to Jan. 1,1972[5/]	280
Resources remaining in the ground, Jan. 1, 1972	530,630

1/ From Brant (1953), with minor modification of data for Hettinger County.
2/ About 98 percent of the total lignite in North Dakota is 305 m (1,000 ft) or less below the surface.
3/ Measured and indicated resources in beds 1.5 m (5 ft) or more thick.
4/ Not classified by county.
5/ Assuming past losses in mining equal past production.

Table 10. Method of recovery of lignite reserves of North Dakota,

Jan. 1, 1972

[In millions of short tons]

County	Original reserves in the ground, 0-365 m (1,200 ft) over-burden1/	Method of recovery: Surface mining2/ — Reserves in the ground3/	Surface mining2/ — Potentially recover-able4/	Surface mining2/ — Economically recover-able5/	Underground mining — Reserves in the ground3/	Underground mining — Potentially recover-able6/
	(1)	(2)	(3)	(4)	(5)	(6)
Adams	266	163	130		103	51
Billings	2,836	1,078	862		1,758	879
Bowman	1,136	785	628		351	175
Burke	530	117	94		413	207
Burleigh	208	156	125		52	26
Divide	792	137	110		655	328
Dunn	2,992	2,000	1,600		992	496
Golden Valley	1,290	278	222		1,012	506
Grant	670	115	92		555	278
Hettinger	1,847	980	784		867	434
McKenry	40	15	12		25	13
McKenzie	3,211	825	660		2,386	1,193
McLean	1,923	1,009	807		914	457
Mercer	4,754	1,986	1,589		2,768	1,384
Morton	1,968	342	274		1,626	813
Montrail	749	148	118		601	300
Oliver	1,923	629	503		1,294	647
Renville	59	8	6		51	25
Sheridan	---	---	---		---	---
Slope	4,994	2,326	1,861		2,668	1,334
Stark	2,216	1,275	1,020		941	470
Ward	905	501	401		404	202
Williams	2,144	1,130	904		1,014	507
Total	37,453	16,003	12,802	7,680	21,450	10,725

1/ From col. 1, table 9. About 98 percent of the total lignite in North Dakota is 305 m (1,000 ft) or less below the surface. Cumulative production and losses to Jan. 1, 1972 is small. Use of figures for original reserves introduces no appreciable error.

2/ From North Dakota Geological Survey, written communication, Sept. 10, 1973. See also U.S. Bur. Mines (1972).

3/ Col. 2 plus col. 5 equals col. 1.

4/ 80% of figures in col. 2.

5/ 60% of total in col. 3; not classified by county.

6/ 50% of figures in col. 5.

The effects of coal mining on land disruption and water use, and problems of reclamation are discussed in reports of the Northern Great Plains Resource Program (1975). In addition to these reports, the social, economic, and environmental effects of burning lignite within the state are the subject of continuing studies that are sponsored by the U.S. Energy Research and Development Administration and the University of North Dakota.

Lignite chemistry.--The average composition of lignite, according to Fieldner and others (1942), is 36.4 percent moisture, 26.6 percent volatile matter, 30.2 percent fixed carbon, and 0.7 percent sulfur (average BTU is 6,990). Average BTU content lignite of the Fort Union Formation in North Dakota, by county, ranges from 6,120 to 7,510 (table 11). Trace elements (less than 0.1 percent or 1,000 ppm) in samples of coal from the Fort Union Formation total slightly more than 0.1 percent (Hatch and Swanson, 1976). Minor elements (0.1 percent-1 percent or 1,000-10,000 ppm) and major elements (more than 1 percent or 10,000 ppm) are the ash-forming constituents of coal.

Studies such as those by Klein and others (1975) and O'Gorman and Walker (1972) on ash and gases resulting from coal combustion in power plants point to the need for quantitative studies of minor and trace elements in combustion products. The pre-combustion chemical properties of lignite, together with some properties obtained from ash, are shown by sample analyses published by the U.S. Bureau of Mines and the U.S. Geological Survey and are taken from the Northern Great Plains Resource Program Report of 1974. The extent to which the quantitative values of elements and oxides shown in these analyses are duplicated in emissions from individual power plants and captured by boiler slag, fly ash, flue gas, scrubbers, and electrostatic precipitators has been studied at one power plant in North Dakota by the Radian Corporation (1975), and wider aspects of the subject are dealt with by Klein and others, (1975). In particular, metals that are regarded as dangerous when in excess, such as arsenic, lead, mercury, and selenium, should be monitored (Baria, 1975).

Among the factors of economic concern to operators of power plants are the amounts of ash, sulfur, sodium, iron, and calcium in lignite, and the amounts and form of hydrogen, which largely determine the feasibility of using lignite for gasification and liquifaction purposes. Average analyses of samples taken in 21 counties of North Dakota by the Bureau of Mines are shown in tables 11 and 12. Trace element composition is shown in table 13 and major oxide composition of the ash in table 14. The most complete and current bibliography of work in this field is contained in U.S. Geological Survey (1976b).

Tables 11, 12, 13, and 14.--NEAR HERE

Table 11. Average analysis of coal by county and bed

County - Bed	Moisture A.R. 1/	Ash A.R. 1/	Ash Dry	Sulfur A.R. 1/	Sulfur Dry	Sulfur M&AF 2/	Btu A.R. 1/	Btu Dry	Btu M&AF 2/	No. of anal.
North Dakota										
Adams										
Uncorrelated	33.1	10.5	15.7	1.2	1.8	2.1	7,080	10,590	12,560	34
County total	33.1	10.5	15.7	1.2	1.8	2.1	7,080	10,590	12,560	34
Billings										
Uncorrelated	38.5	6.2	10.1	.8	1.4	1.5	6,350	10,320	11,480	6
County total	38.5	6.2	10.1	.8	1.4	1.5	6,350	10,320	11,480	6
Bowman										
Uncorrelated	43.4	6.6	11.7	.8	1.5	1.6	6,120	10,810	12,240	8
County total	43.4	6.6	11.7	.8	1.5	1.6	6,120	10,810	12,240	8
Burke										
Uncorrelated	33.4	7.9	11.9	.3	.6	.6	7,260	10,900	12,370	612
County total	33.4	7.9	11.9	.3	.6	.6	7,260	10,900	12,370	612
Burleigh										
Uncorrelated	35.1	6.2	9.7	.6	1.0	1.1	7,100	10,950	12,120	116
County total	35.1	6.2	9.7	.6	1.0	1.1	7,100	10,950	12,120	116
Divide										
Uncorrelated	32.0	7.8	11.6	.4	.7	.7	7,510	11,050	12,500	238
County total	32.0	7.8	11.6	.4	.7	.7	7,510	11,050	12,500	238
Dunn										
Uncorrelated	40.6	7.0	11.9	.6	1.1	1.2	6,310	10,630	12,060	25
County total	40.7	7.0	11.9	.6	1.1	1.2	6,310	10,630	12,060	25
Golden Valley										
Uncorrelated	41.3	5.8	9.9	.6	1.1	1.2	6,330	10,790	11,970	3
County total	41.3	5.8	9.9	.6	1.1	1.2	6,330	10,790	11,970	3
Grant										
Uncorrelated	34.5	10.4	15.9	1.6	2.5	2.9	6,840	10,440	12,410	19
County total	34.5	10.4	15.9	1.6	2.5	2.9	6,840	10,440	12,410	19
Hettinger										
Uncorrelated	39.6	8.9	14.9	1.3	2.2	2.5	6,340	10,490	12,330	13
County total	39.6	8.9	14.9	1.3	2.2	2.5	6,340	10,490	12,330	13
McKenzie										
Uncorrelated	42.7	5.0	8.9	.4	.7	.7	6,330	11,040	12,120	5
County total	42.7	5.0	8.9	.4	.7	.7	6,330	11,040	12,120	5
McLean										
Uncorrelated	38.7	6.4	10.5	.4	.8	.8	6,620	10,800	12,070	44
County total	38.7	6.4	10.5	.4	.8	.8	6,620	10,800	12,070	44
Mercer										
Uncorrelated	33.8	6.8	10.4	.5	.9	1.0	7,200	10,880	12,140	728
County total	33.8	6.8	10.4	.5	.9	1.0	7,200	10,880	12,140	728
Morton										
Uncorrelated	39.0	8.0	13.2	1.0	1.7	1.9	6,430	10,540	12,150	38
County total	39.9	8.0	13.2	1.0	1.7	1.9	6,430	10,540	12,150	38
Mountrail										
Uncorrelated	43.1	3.6	6.4	.2	.4	.4	6,440	11,310	12,080	1
County total	43.1	3.6	6.4	.2	.4	.4	6,440	11,310	12,080	1
Oliver										
Uncorrelated	36.5	10.3	16.3	.8	1.4	1.6	6,410	10,100	12,070	20
County total	36.5	10.3	16.3	.8	1.4	1.6	6,410	10,100	12,070	20
Renville										
Uncorrelated	35.2	6.3	9.8	.9	1.5	1.6	7,090	10,940	12,130	2
County total	35.2	6.3	9.8	.9	1.5	1.6	7,909	10,940	12,130	2
Slope										
Uncorrelated	42.5	6.3	11.0	1.3	2.4	2.6	5,950	10,350	11,630	1
County total	42.5	6.3	11.0	1.3	2.4	2.6	5,950	10,350	11,630	1
Stark										
Uncorrelated	41.1	8.5	14.6	1.1	1.9	2.2	6,150	10,440	12,220	14
County total	41.1	8.5	14.6	1.1	1.9	2.2	6,150	10,440	12,220	14
Ward										
Uncorrelated	37.2	5.5	8.8	.1	.3	.3	6,790	10,820	11,860	899
County total	37.2	5.5	8.8	.1	.3	.3	6,790	10,820	11,860	899
Williams										
Uncorrelated	41.0	6.3	10.8	.5	.9	1.0	6,420	10,880	12,200	38
County total	41.0	6.3	10.8	.5	.9	1.0	6,420	10,880	12,200	38
State total	35.1	6.8	10.5	.4	.7	.7	7,050	10,860	12,130	2864

1/ A. R., as received
2/ M and AF, moisture and ash free

Table 12. Proximate, ultimate, Btu, and sulfur analyses of 31 samples of lignite from western North Dakota

[All analyses, except Btu in percent; original moisture content may be slightly more than shown because samples were collected and transported in plastic bags to avoid metal contamination; Ar, as received, and MAF, moisture and ash free; (T) and (B) indicate top and bottom of bed, respectively. All analyses of mine samples by Coal Analysis Section, U.S. Bureau of Mines, Pittsburgh, Pennsylvania.]

Sample No.	USBM Lab. No.	Sample interval (m)	Moisture	Vol.matter		Fixed C		Ash	Btu		Hydrogen		Carbon		Nitrogen		Oxygen		Sulfur		Sulfate S		Pyritic S		Organic S	
			AR	AR	MAF	AR	MAF	AR	AR	MAF	AR	MAF	AR	MAF	AR	MAF	AR	MAF	AR	MAF	AR	MAF	AR	MAF	AR	MAF
NOONAN COAL BED, BAUKOL-NOONAN MINE, BURKE COUNTY, NORTH DAKOTA																										
165632	K-32669	(Tipple)	24.1	30.8	45.6	36.8	54.4	8.3	8270	12240	6.0	5.0	49.1	72.7	0.9	1.3	35.2	20.3	0.5	0.7	0.0	0.0	0.10	0.15	0.36	0.53
COTEAU BED, VELVA STRIP MINE, WARD COUNTY, NORTH DAKOTA																										
D165608	K-3266	1.8(T)	37.2	27.7	49.0	28.9	51.0	6.2	6720	11870	7.0	5.0	40.1	70.9	0.7	1.2	45.5	22.0	0.5	0.9	0.01	0.01	0.20	0.36	0.27	0.48
D165609	K-32667	1.8	38.9	26.1	45.5	31.2	54.5	3.8	6450	11780	7.0	4.7	40.8	71.2	.6	1.1	47.5	22.6	.3	.4	.01	.01	.01	.01	.24	.42
D165610	K-32668	1.8	37.2	26.3	44.9	32.4	55.1	4.1	6670	11370	6.7	4.4	41.4	70.7	.7	1.1	47.0	23.6	.1	.2	.01	.01	.00	.00	.13	.22
KUTHER (K) AND HAGEL (H), GLEN HAROLD MINE, MERCER COUNTY, NORTH DAKOTA																										
D165564	K-31589	1.2(K)	34.6	29.2	47.8	31.9	52.2	4.3	7160	11720	6.8	4.8	42.8	70.0	0.7	1.2	44.9	23.3	0.5	0.7	0.0	0.0	0.02	0.04	0.43	0.70
D165565	K-31590	2.1(H)	28.6	32.7	49.0	34.0	51.0	4.7	7820	11710	6.4	4.8	46.5	69.6	.8	1.2	41.1	23.6	.5	.8	.02	.03	.03	.05	.46	.69
D165566	K-31591	1.2	26.6	32.5	47.4	36.0	52.6	4.9	7980	11640	6.3	4.8	47.7	69.6	.9	1.4	39.6	23.4	.6	.8	.0	.0	.03	.04	.54	.79
D165567	K-31592	2.1(H)	31.4	30.6	47.7	33.6	52.3	4.4	7530	11720	6.7	5.0	44.9	69.9	.8	1.2	42.7	23.2	.5	.7	.0	.0	.03	.05	.42	.65
BEULAH BED, INDIAN HEAD MINE, MERCER COUNTY, NORTH DAKOTA																										
D165576	K-31601	3.4	31.1	26.7	45.4	32.1	54.6	10.1	7010	11900	6.0	4.4	42.6	72.4	0.7	1.2	39.9	20.8	0.7	1.2	0.0	0.0	0.43	0.74	0.26	0.45
D165577	K-31602	3.4	30.1	27.1	47.1	30.5	52.9	12.3	6870	11930	5.9	4.5	40.9	71.1	.7	1.2	37.4	18.4	2.8	4.8	.03	.05	2.39	4.15	.33	.58
D165578	K-31603	3.4	30.7	29.3	46.5	33.8	53.5	6.2	7360	11660	6.2	4.5	44.3	70.2	.7	1.1	42.1	23.4	.5	.8	.01	.01	.14	.22	.34	.53
D165579	K-31604	3.4	31.0	28.3	45.6	33.9	54.4	6.8	7110	11460	6.3	4.5	43.6	70.2	.7	1.2	42.2	23.5	.4	.6	.02	.12	.08	.14	.28	.45
BEULAH BED, SOUTH BEULAH MINE, MERCER COUNTY, NORTH DAKOTA																										
D165572	K-31597	2.4	29.8	29.1	47.3	32.4	52.7	8.7	7250	11800	6.3	4.8	42.4	69.0	0.5	0.8	39.9	21.8	2.2	3.6	0.05	0.08	1.84	3.00	0.33	0.56
D165573	K-31598	.9	32.9	28.9	46.6	33.2	53.4	5.0	7430	11960	6.8	5.0	43.9	70.7	.5	.8	43.1	22.4	.7	1.1	.01	.01	.13	.22	.52	.84
D165574	K-31599	2.4	28.4	26.5	47.5	29.2	52.5	15.9	6420	11530	5.6	4.4	40.2	72.2	.7	1.3	36.5	20.1	1.1	2.0	.0	.0	.88	1.59	.22	.39
D165575	K-31600	.9	30.1	25.1	47.2	28.0	52.8	16.8	6140	11550	5.5	4.3	38.0	71.5	.7	1.3	38.0	21.1	.9	1.8	.01	.01	.74	1.37	.21	.39
HAGEL BED, CENTER (BAUKOL-NOONAN) MINE, OLIVER COUNTY, NORTH DAKOTA																										
D165568	K-31593	3.0	34.2	27.3	45.2	33.2	54.8	5.3	7090	11720	6.6	4.6	43.1	71.2	0.7	1.2	43.8	22.2	0.5	0.8	.01	0.01	0.14	0.23	0.31	0.51
D165569	K-31596	3.0	33.8	29.2	50.4	28.7	49.6	8.3	6860	11850	6.7	5.0	40.4	69.7	.7	1.1	42.2	21.2	1.7	3.0	.03	.05	1.26	2.18	.44	.77
D165570	K-31575	3.0	33.2	29.5	47.3	32.9	52.7	4.4	7260	11650	6.6	4.6	43.5	69.8	.7	1.2	44.5	23.8	.3	.6	.02	.03	.04	.07	.29	.46
D165571	K-31596	3.0	34.7	28.9	47.4	32.0	52.6	4.4	7100	11660	6.9	4.9	42.5	69.7	.7	1.2	45.2	23.6	.3	.6	.02	.03	.04	.06	.28	.46
HARMON BED, GASCOYNE (PEERLESS) MINE, BOWMAN COUNTY, NORTH DAKOTA																										
D165976	K-34074 (1st seam)	1.2	46.2	24.9	51.5	23.4	48.5	5.5	5580	11540	7.4	4.6	33.8	69.9	0.4	0.9	52.0	22.8	0.9	1.8	0.03	0.05	0.34	0.70	0.50	1.03
D165979	K-34075 (T, 2nd seam)	1.2	37.5	30.1	55.2	24.3	44.8	8.1	6760	12410	7.2	5.6	39.3	72.2	.6	1.0	43.8	19.4	1.0	1.8	.01	.01	.50	.92	.50	.91
D165780	K-34076 (B, 2nd seam)	1.2	42.2	25.5	49.6	25.9	50.4	6.4	6180	12040	7.3	5.1	36.6	71.4	.4	.9	48.7	21.5	.6	1.1	.06	.11	.06	.11	.46	.90
D16082	K-34077 (1st seam)	1.2	44.6	24.4	47.5	27.0	52.5	4.0	6090	11870	7.5	5.0	36.3	70.7	.5	1.0	51.0	21.9	.7	1.4	.00	.00	.05	.10	.67	1.30
D165985	K-34078 (T, 3rd seam)	1.2	45.0	24.4	48.3	26.2	51.7	4.4	6010	11880	7.5	4.9	35.6	70.5	.5	1.0	51.3	22.1	.7	1.5	.00	.00	.05	.09	.70	1.38
D165986	K-34079 (B, 3rd seam)	1.2	42.3	25.0	49.6	25.6	50.4	7.1	6080	12030	7.3	5.2	35.6	70.5	.4	.9	47.8	19.8	1.8	3.6	.01	.01	.11	.22	1.70	3.37
D165989	K-34085 (T, 2nd seam)	1.2	36.5	27.1	49.1	28.0	50.9	8.4	6550	11900	6.6	4.6	38.6	70.1	.5	.9	43.0	19.0	2.9	5.4	.08	.15	2.26	4.10	.61	1.11
D165990	K-34081 (B, 2nd seam)	1.2	42.7	27.0	52.9	24.1	47.1	6.2	6320	12350	7.5	5.3	36.7	71.7	.5	1.0	48.2	20.2	.9	1.8	.01	.01	.11	.21	.82	1.60
D165992[1]	K-34082 (1st seam)	2.1	41.5	31.2	63.4	18.1	36.6	9.2	4420	8960	6.4	3.6	29.6	60.1	.7	1.4	52.5	31.6	1.6	3.3	.12	.25	.05	.09	1.48	2.99
D165993[1]	K-34083 (1st seam)	2.1	38.8	31.5	57.3	23.4	42.7	6.3	5260	9580	6.5	3.9	34.3	62.5	.8	1.4	50.9	30.0	1.2	2.2	.71	1.29	.06	.11	.44	.80

[1] Leonardite (weathered coal, largely soluble in alkaline solution).

Table 13. Quantitative determinations (in ppm) for 12 trace elements in 44 samples of lignite

[illegible]

[In thickness column (T), (B), and (M) indicate top, bottom, and middle of bed, respectively.

Values for Cd, Cu, Li, Pb, and Zn are calculated from analyses on ash of coal.]

Sample No.	Thickness of sample interval (m)	As	Cd	Cu	F	Hg	Li	Pb	Sb	Se	Th	U	Zn	Ash (percent)
NOONAN BED, BAUKOL-NOONAN MINE, BURKE COUNTY, NORTH DAKOTA														
D165632	(Tripple)	8	0.1	10.9	70	0.09	3.8	4.3	1.0	0.5	<2.0	1.0	5.8	10.7
COTEAU BED, VELVA MINE, WARD COUNTY, NORTH DAKOTA														
D165605	1.8	4	<0.1	3.4	40	0.09	1.5	2.1	0.2	0.5	<2.0	1.4	3.2	6.86
D165606	1.8	5	< .1	4.7	20	.07	2.0	2.0	.2	.4	<2.0	.8	2.3	6.76
D165607	1.8	10	< .1	8.0	<20	.23	7.0	3.0	.3	1.0	3.3	1.8	2.6	10.0
D165609	1.8	10	< .1	11.6	35	.17	7.2	4.2	.5	1.3	4.3	2.6	2.5	10.5
D165609	1.8	5	< .1	3.4	30	.08	1.5	2.0	.1	.3	<2.0	.1	1.8	6.80
D165610	1.8	4	< .1	3.4	35	.15	1.4	2.2	.1	.3	<2.0	.3	1.8	7.38
D165611	1.8	4	< .1	4.3	<20	.07	4.2	2.5	.2	.5	<2.0	< .1	2.0	8.34
D165612	1.8	4	< .1	4.0	20	.10	2.5	2.3	.2	.5	2.8	.5	1.7	7.64
D165613	1.8	5	< .1	5.7	30	.25	4.3	3.3	.2	.8	3.8	1.3	1.5	8.34
KUTHER (K) AND HAGEL (H) BEDS, GLENHAROLD MINE, MERCER COUNTY, NORTH DAKOTA														
D165564	1.2	10	<0.1	3.4	<20	0.10	1.	<1.5	0.2	0.7	9.4	2.1	1.4	7.02
D165565	2.1	5	< .1	6.4	<20	.09	1.2	<1.5	.7	.8	<2.0	1.1	2.2	7.16
D165566	1.2	15	< .1	3.6	<20	.08	.6	2.0	.4	.8	<2.0	.6	1.3	6.52
D165567	2.1	5	< .1	2.4	<20	.05	.5	<1.5	3.0	.5	<2.0	.6	2.3	5.78
BEULAH BED, INDIAN HEAD MINE, MERCER COUNTY, NORTH DAKOTA														
D165576	3.4	4	<0.1	7.5	<20	0.05	3.4	4.8	0.3	0.5	3.4	0.9	1.5	9.58
D165577	3.4	10	< .1	10.6	<20	.07	3.8	5.3	1.4	.8	4.0	1.9	9.1	10.6
D165578	3.4	10	< .1	5.6	<20	.34	2.1	3.1	.4	.9	5.2	.7	2.1	10.4
D165579	3.4	15	< .1	5.8	<20	.11	3.3	5.2	.3	1.0	5.0	.9	4.7	10.3
BEULAH BED, SOUTH BEULAH MINE, MERCER COUNTY, NORTH DAKOTA														
D165572	2.4	30	<0.1	4.7	<20	0.21	1.8	3.1	0.5	0.6	<2.0	0.7	27.7	10.2
D165573	0.9	10	< .1	3.2	<20	.19	.7	<1.5	.2	.6	2.5	.4	3.5	6.58
D165574	2.4	5	< .1	7.3	20	.10	7.6	7.6	1.1	1.2	5.5	1.6	5.4	19.1
D165575	0.9	8	< .1	11.3	50	.10	9.9	7.0	1.0	1.5	5.6	2.2	15.0	23.5
HAGEL BED, CENTER (BAUKOL-NOONAN) MINE, OLIVER COUNTY, NORTH DAKOTA														
D165568	3.0	10	<0.1	3.2	20	0.22	0.9	<1.5	0.1	1.0	<2.0	0.5	2.2	10.8
D165569	3.0	8	< .1	6.8	30	.11	1.5	4.7	.5	1.3	3.7	1.5	1.7	9.94
D165570	3.0	5	.1	2.8	<20	.05	.9	1.6	.3	1.6	<2.0	.8	1.6	6.48
D165571	3.0	5	< .1	4.3	<20	.05	.9	2.5	.3	.7	<2.0	.7	1.3	6.28
HARMON BED, GASCOYNE (PEERLESS) MINE, BOWMAN COUNTY, NORTH DAKOTA														
D165974	1.2 (T, 2nd seam)	1	<0.1	7.5	40	0.08	8.1	6.8	0.2	1.0	---	---	15.8	11.3
D165975	1.2 (1st seam)	2	< .1	4.2	<20	.05	2.5	2.2	.2	.4	---	---	6.1	6.14
D165976	1.2 (1st seam)	4	< .1	3.3	30	.15	<1.	<1.5	.2	.5	---	---	2.1	11.8
D165977	1.2 (1st seam)	4	< .1	2.3	<20	.12	1.	1.8	.2	.4	---	---	1.5	7.30
D165978	1.2 (T, 2nd seam)	1	< .1	6.7	<20	.14	3.1	3.1	.2	.8	---	---	1.9	7.74
D165979	1.2 (T, 2nd seam)	5	< .1	8.1	<20	.48	7.5	5.1	.5	1.2	---	---	<1.5	11.3
D165980	1.2 (B, 2nd seam)	2	< .1	4.2	20	.37	2.1	4.2	.2	.7	---	---	<1.5	10.4
D165981	1.2 (B, 2nd seam)	1	< .1	3.6	<20	.07	2.1	2.7	.1	.2	---	---	<1.5	7.42
D165982	1.2 (1st seam)	10	< .1	2.9	<20	.09	<1.	2.6	.1	.4	---	---	<1.5	6.40
D165983	1.2 (1st seam)	2	< .1	3.7	<20	.06	1.	3.2	.1	.4	---	---	<1.5	8.04
D165984	1.2 (T, 3rd seam)	2	< .1	4.0	<20	.40	4.5	3.9	.2	.9	---	---	<1.5	8.64
D165985	1.2 (T, 3rd seam)	2	< .1	4.7	20	.09	3.8	3.3	.5	.6	---	---	<1.5	7.38
D165986	1.2 (B, 3rd seam)	5	< .1	3.3	<20	.42	5.6	4.6	.4	.5	---	---	<1.5	10.3
D165987	1.2 (B, 3rd seam)	1	< .1	15.4	<20	.12	18.7	11.1	.4	1.1	---	---	3.0	11.7
D165988	1.2 (T, 2nd seam)	2	< .1	7.1	70	.31	5.2	<1.5	.2	.8	---	---	<1.5	11.4
D165989	1.2 (T, 2nd seam)	2	< .1	4.4	<20	.60	2.1	<1.5	.4	.9	---	---	<1.5	10.4
D165990	1.2 (B, 2nd seam)	2	< .1	5.0	30	.31	4.6	<1.5	.4	.8	---	---	<1.5	10.0
D165991	1.2 (B, 2nd seam)	2	< .1	6.3	20	.20	4.4	4.1	.4	1.0	---	---	<1.5	8.24
D165992[1]	2.1 (1st seam)	8	< .1	5.1	<20	.13	2.7	3.6	.2	.6	---	---	3.4	12.1
D165993[1]	2.1	8	< .1	4.1	<20	.11	4.1	<1.5	.2	.5	---	---	<1.5	8.84

1/ Leonardite (weathered coal, largely soluble in alkaline solution).

Table 14. Major oxide composition, in percent, of the laboratory ash of 46 samples of lignite from western north Dakota

[In sample interval column (T), (B), and (M) indicate top, bottom, and middle, respectively.]

Sample No	Sample Interval (m)	Ash	SiO_2	Al_2O_3	Na_2O	K_2O	CaO	MgO	P_2O_5	Fe_2O_3	SO_3
NOONAN BED, BAUKOL-NOONAN MINE, BURKE COUNTY, NORTH DAKOTA											
D165632	(Tipple)	10.7	31.	12.	4.13	0.74	15.	3.75	0.0	5.9	15.
COTEAU BED, VELVA STRIP MINE, WARD COUNTY, NORTH DAKOTA											
D165605	1.8 (T)	6.86	6.3	6.0	0.95	<0.10	37.	9.30	<0.05	5.5	12.
D165606	1.8 (M)	6.76	9.2	7.9	.98	< .10	34.	10.7	.15	4.9	13.
D165607	1.8 (B)	10.0	29.	11.	1.30	< .10	23.	6.95	.19	4.0	15.
D165608	1.8 (T)	10.5	27.	12.	1.38	.22	22.	6.85	.24	4.6	17.
D165609	1.8 (M)	6.80	11.	5.7	1.00	< .10	33.	9.75	.24	7.0	17.
D165610	1.8 (B)	7.38	8.	5.8	.93	< .10	38.	9.15	.95	3.8	7.9
D165611	1.8 (T)	8.34	12.	9.2	.78	< .10	35.	8.15	.20	3.7	8.4
D165612	1.8 (M)	7.64	17.	6.6	.85	< .10	30.	9.40	.09	5.1	13.
D165613	1.8 (B)	8.34	17.	9.7	.83	< .10	27.	8.35	.50	4.5	18.
KUTHER (K) AND HAGEL (H) BEDS, GLENHAROLD MINE, MERCER COUNTY, NORTH DAKOTA											
D165564	1.2 (K)	7.02	13.	2.9	8.30	<0.10	26.	5.60	<0.05	4.3	20.
D165565	2.1 (H)	7.16	19.	6.8	9.95	< .10	23.	4.90	.05	5.0	19.
D165566	1.2 (K)	6.52	6.8	4.9	10.4	.20	27.	5.40	< .05	4.4	24.
D165567	3.0 (H)	5.78	12.	4.7	9.20	< .10	28.	4.90	< .05	5.4	23.
BEULAH BED, INDIAN HEAD MINE, MERCER COUNTY, NORTH DAKOTA											
D165576	3.4	9.48	34.	11.	3.50	<0.10	22.	6.00	.97	3.0	12.
D165577	3.4	10.6	26.	11.	3.80	.15	18.	5.25	.26	7.9	22.
D165578	3.4	10.4	16.	8.	3.25	< .10	17.	4.70	.71	15.	30.
D165579	3.4	10.3	27.	11.	3.55	< .10	19.	5.25	.58	7.4	20.
BEULAH BED, SOUTH BEULAH, MERCER COUNTY, NORTH DAKOTA											
D165572	2.4	10.2	20.	9.5	3.95	0.71	12.	4.00	0.06	19.	27.
D165573	0.9	6.58	12.	10.	5.85	.55	21.	6.50	.13	7.7	27.
D165574	2.4	19.1	30.	11.	3.55	.18	21.	3.45	.06	6.5	16.
D165575	0.9	23.5	45.	13.	2.70	.76	9.9	3.05	.07	7.0	14.
HAGEL BED, CENTER (BAUKOL-NOONAN) MINE, OLIVER COUNTY, NORTH DAKOTA											
D165568	3.0	10.8	12.	3.4	1.15	<0.10	20.	6.00	<0.05	20.	35.
D165569	3.0	9.94	30.	11.	.70	1.2	18.	5.55	< .05	8.6	20.
D165570	3.0	6.48	14.	7.7	1.45	< .10	31.	8.80	< .05	4.0	17.
D165571	3.0	6.28	14.	9.0	1.40	.29	31.	8.65	.06	4.4	17.
HARMON BED, GASCOYNE (PEERLESS) STRIP MINE, BOWMAN COUNTY, NORTH DAKOTA											
D165974	1.2 (T, 2nd seam)	11.3	34.	19.	1.65	<0.10	19.	7.80	<0.05	1.1	14.
D165975	1.2 (1st seam)	6.14	7.3	9.8	.50	< .10	29.	9.10	.06	3.6	35.
D165976	1.2 (1st seam)	11.8	6.1	3.1	.25	< .10	25.	5.90	.07	20.	38.
D165977	1.2 (1st seam)	7.30	4.9	4.8	2.65	< .10	26.	8.40	.10	14.	39.
D165978	1.2 (T, 2nd seam)	7.74	29.	11.	1.05	< .10	23.	8.30	< .05	.89	24.
D165979	1.2 (T, 2nd seam)	11.3	17.	10.	.50	< .10	19.	7.80	< .05	12.	32.
D165980	1.2 (B, 2nd seam)	10.4	11.	6.3	.45	< .10	21.	7.10	.07	15.	37.
D165981	1.2 (B, 2nd seam)	7.42	14.	9.6	.50	< .10	32.	11.1	.05	1.5	28.
D165982	1.2 (1st seam)	6.40	1.0	6.7	1.20	< .10	29.	7.80	< .05	11.	20.
D165983	1.2 (1st seam)	8.04	1.9	4.7	1.55	< .10	30.	9.40	.34	9.5	33.
D165984	1.2 (T, 3rd seam)	8.64	8.5	12.	2.40	< .10	23.	8.00	.33	9.1	22.
D165985	1.2 (T, 3rd seam)	7.38	6.2	12.	2.95	< .10	27.	10.0	.12	2.0	24.
D165986	1.2 (B, 3rd seam)	10.3	8.5	9.4	2,25	< .10	21.	7.30	.05	15.	17.
D165987	1.2 (B, 3rd seam)	11.7	29.	19.	1.65	< .10	21.	6.90	< .05	.12	17.
D165988	1.2 (T, 2nd seam)	11.4	30.	7.7	1.95	< .10	21.	7.10	.36	5.2	34.
D165989	1.2 (T, 2nd seam)	10.4	15.	5.4	2.95	< .10	20.	7.10	.08	18.	27.
D165990	1.2 (B, 2nd seam)	10.0	15.	7.2	2.20	< .10	23.	8.30	.30	9.5	34.
D165991	1.2 (B, 2nd seam)	8.24	6.4	10.	3.90	< .10	29.	10.3	< .05	3.1	36.
D165992[1]	2.1 (1st seam)	12.1	2.8	5.3	2.00	< .10	23.	7.70	.06	14.	45.
D165993[1]	2.1 (1st seam)	8.84	4.5	6.4	2.65	< .10	24.	10.6	< .05	6.8	44.

1/Leonardite (weathered coal, largely soluble in alkaline solution).

Oil and gas

by

Charles W. Spencer

Figure 7 shows the present-day subsurface structural configuration of the North Dakota portion of the Williston Basin as mapped on the base of the Mississippian. Sandberg (1962) provides a regional stratigraphic and paleotectonic framework for the Williston Basin and Ashmore (1971) presents an overview of the petroleum geology of North Dakota. Phanerozoic rocks range in thickness from more than 4,570 m (15,000 ft), in the deeper parts of the basin, to less than 305 m (1,000 ft) in eastern North Dakota. Lignite deposits overlie those parts of western North Dakota having the greatest potential for petroleum and nearly all the present oil and gas fields are within this area. Consequently, any major development of the lignite resources will have to be interrelated with petroleum exploration and development.

Oil was first discovered in North Dakota as recently as April, 1951 (Carlson and others, 1960, p. 124). Subsequently 444,290,885 barrels of oil have been produced through July 1, 1975 (North Dakota Geological Survey, 1976). Most of this oil came from about 2,500 producing wells drilled in 15 western counties. At the end of 1967, North Dakota ranked 13th in the United States in proved reserves and annual production (Ashmore, 1971, p. 692). As of July 1, 1976, a total of 5,578 producing wells and dry holes had been drilled in North Dakota, primarily in the area of the lignite fields.

Oil fields in western North Dakota produce from a variety of structural, structural-stratigraphic, and stratigraphic traps. The diverse nature of traps is exemplified by the Red Wing Creek field which produces oil from Mississippian rocks in an astrobleme (Sawatzky, 1975) caused by the impact of a cosmic body during Jurassic(?) time. Figure 13 shows the location of all oil and gas fields in North Dakota

Figure 13.--NEAR HERE

and adjacent Montana and South Dakota. Early petroleum exploration in the lignite fields area emphasized surface structural mapping. However, it was soon found that, with few exceptions, surface structure did not accurately portray the structural attitude of Mississippian and older rocks. Beginning in the mid 1950's, deep structurally controlled oil pools were located by seismic methods. However, mapping of subsurface porosity and facies, using well control, is the chief means of locating Mississippian stratigraphic traps that produce oil in the northeast corner of the lignite fields area. These studies greatly reduce the need for seismic exploration.

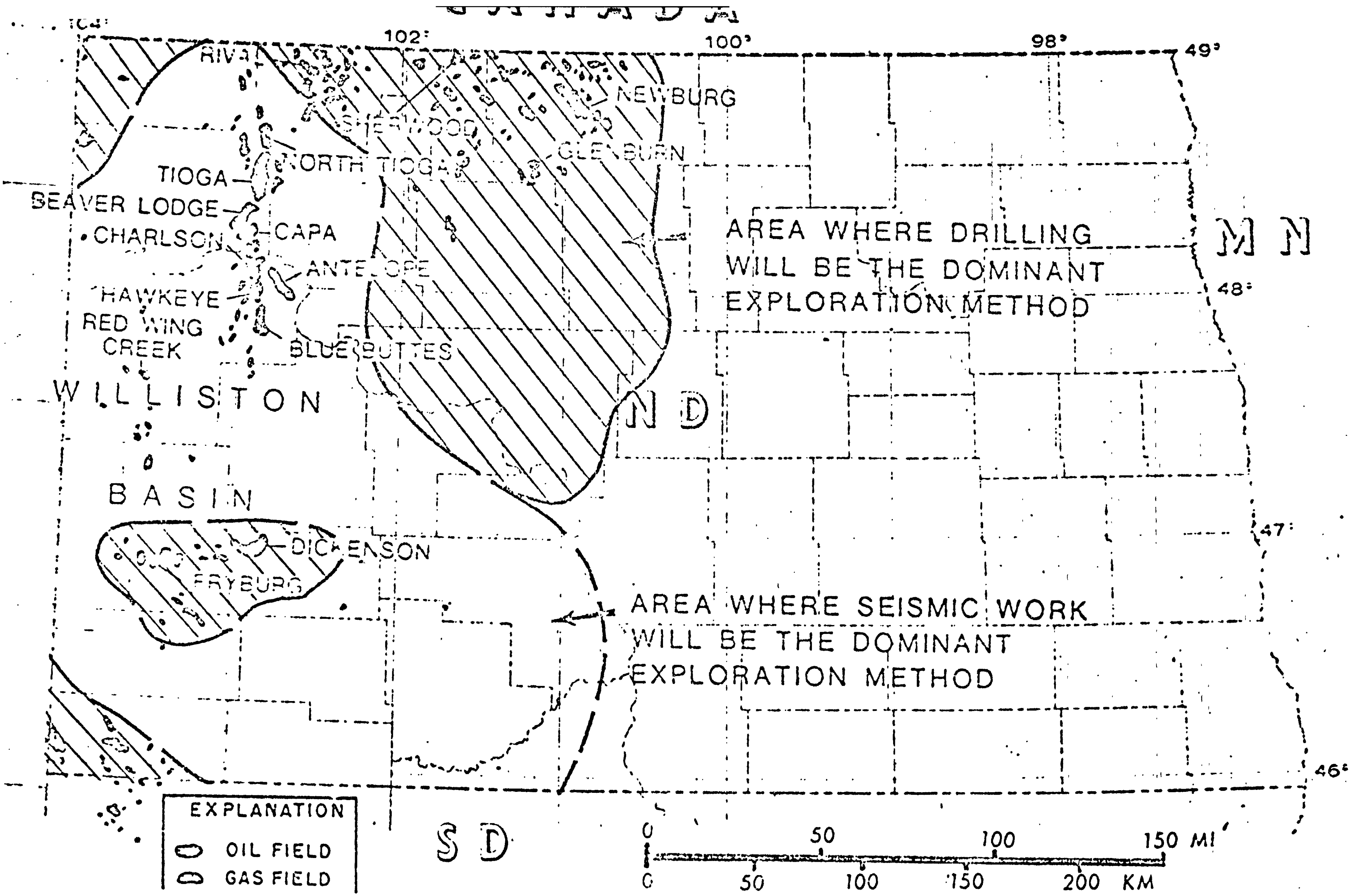

Figure 13. -- Map showing oil and gas fields of North Dakota and adjacent Montana and South Dakota, and areas in North Dakota where future exploration activity is expected to be dominated by drilling or seismic surveys.

Relation of petroleum reservoirs to tectonic features.--The major structural features of the Williston Basin in western North Dakota are shown in figure 14. Two major anticlines are present in the area, the

Figure 14.--NEAR HERE

south-plunging Nesson Anticline and the southeast end of the northwest-plunging Cedar Creek Anticline. Both of these anticlines are paleostructural features that had mild structural movement as early as Ordovician time. Much of the Cedar Creek Anticline is bounded by a high-angle reverse fault on the southwest flank, which dies out in Upper Cretaceous shales. Only minor faults are associated with the Nesson Anticline and the subsidiary southeast plunging Sannish Anticline. An extension of the Brockton-Froid fault zone is present in Montana in the northwest part of the map area. This fault may be a right-lateral wrench fault according to Stone (1970, pl. 1).

The Williston Basin has been an intracratonic basin since at least Ordovician time. At times it was connected by seaways to geosynclines to the west or north, or both. Carbonate reservoir rocks were deposited in the basin at least from Ordovician through Mississippian time, but marine deposits during Late Jurassic through early Tertiary time were mostly shale and sandstone. The paleomovement on the Cedar Creek, Nesson, and Sannish Anticlines formed local highs where porous reservoirs formed in algal and bioclastic carbonate rocks. Porosity also was produced by secondary dolomitization. All of these anticlines have multiple producing zones.

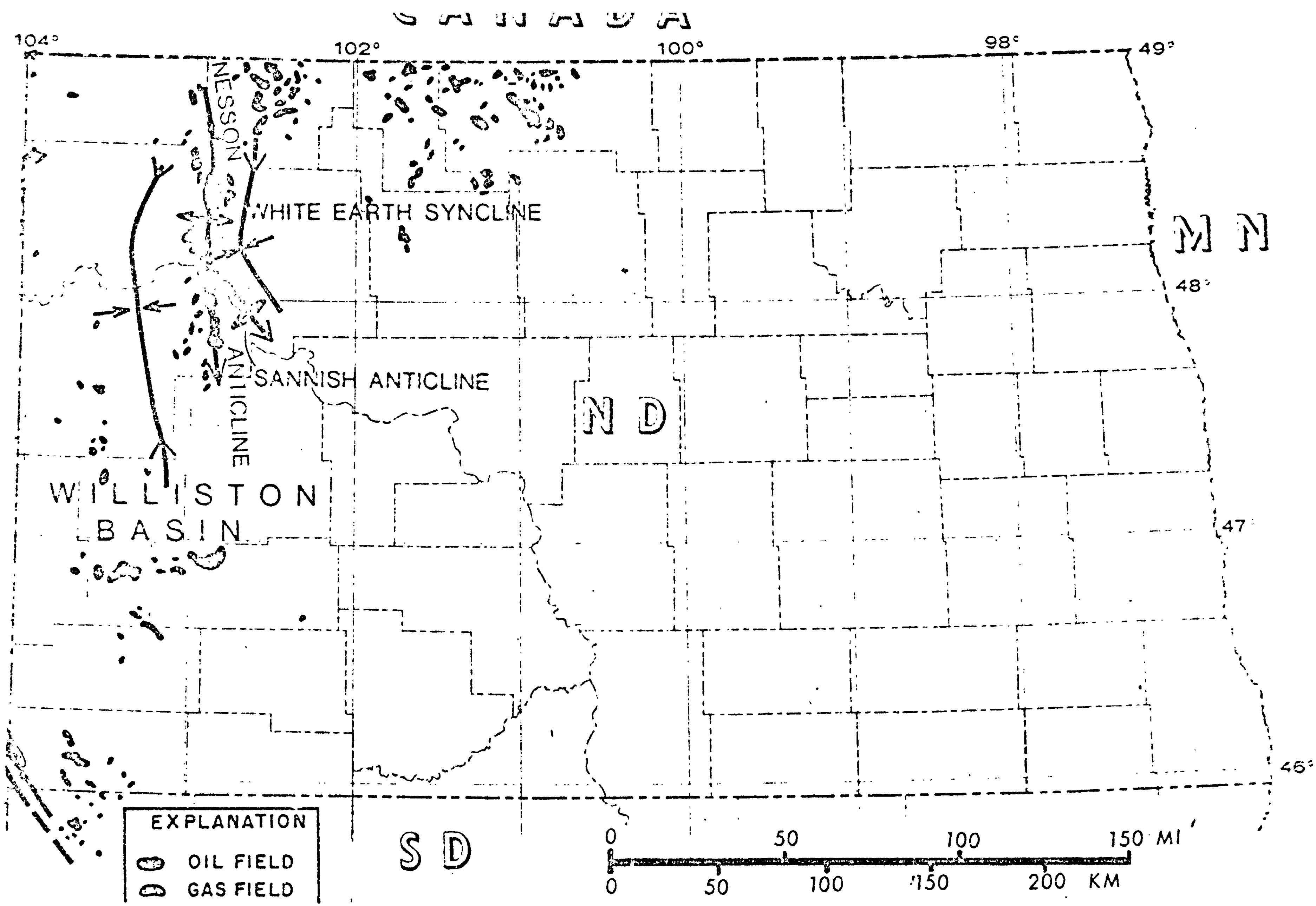

Figure 14. -- Tectonic map of the North Dakota and adjacent areas showing distribution of oil and gas fields and major subsurface structural features.

Several oil fields developed in Mississippian bioclastic and algal pellet banks are localized along the Brockton-Froid (Weldon) line of weakness (Hansen, 1966), and a future high level of drilling activity (fig. 13) may be expected in the northwest corner of the North Dakota lignite fields area. Many small oil fields with 15-30 m (50-100 ft) of closure produce from dolomites in the Ordovician Red River Formation. Whether these structures are tectonic or algal mounds is not known. Generally the structures die out in the overlying lower Paleozoic beds and consequently these structures are being located by the use of seismic isopachs of lower Paleozoic intervals to find local paleothins above the Red River Formation. This approach has resulted in a fairly high rate of discovery of small Ordovician oil pools. Because of this success, seismic activity probably will continue in parts of the lignite field (fig. 13).

Present production.--There are no individual fields in North Dakota in the giant size category; table 15 shows cumulative oil production for the twelve largest fields in North Dakota located on figure 13.

Table 15.--NEAR HERE

North Dakota is primarily an oil province and nearly all of this oil comes from Paleozoic carbonate reservoir rocks. Only a small amount is produced from Jurassic clastic rocks (Newburg field). These oil fields also produce dissolved flammable gas. Gas is produced from the Cretaceous Eagle Sandstone in several small fields on the southeast end of the Cedar Creek Anticline, in southwest North Dakota, but these gas fields are generally outside the lignite field. Some non-flammable gas is present in the Pennsylvanian and Permian Minnelusa Formation on the Nesson Anticline. Figure 15 is a stratigraphic column modified from Sandberg (1962, fig. 5) that shows nomenclature, dominant

Figure 15.--NEAR HERE

lithology, and producing formations for the North Dakota part of the Williston Basin. According to Ashmore (1971, p. 693), about 92 percent of North Dakota's recoverable oil is in carbonate rocks and 74 percent of the total oil has been found in carbonate reservoirs of Mississippian age (Ashmore, 1971, table 1).

Table 15.--Summary of selected North Dakota oil fields.

Field	Age of producing formations(s)	Type of trap	Cumulative oil production to July 1, 1975 in millions of barrels[1/]
Antelope	*Mississippian Devonian Silurian	Structural	30.4
Beaver Lodge	*Mississippian Devonian Silurian Ordovician	Structural	79.9
Blue Buttes	Mississippian	Structural-Stratigraphic	20.9
Capa	Mississippian	Stratigraphic	10.7
Charlson	*Mississippian Devonian	Structural	22.1
Glenburn	Mississippian	Stratigraphic	11.8
Hawkeye	Mississippian	Structural-Stratigraphic	11.5
Newburg	*Jurassic Mississippian	Stratigraphic	16.0
North Tioga	Mississippian	Structural-Stratigraphic	13.9
Rival	Mississippian	Stratigraphic	12.3
Sherwood	Mississippian	Stratigraphic	11.4
Tioga	*Mississippan Devonian Silurian Ordovician	Structural-Stratigraphic	56.7

1/ Data from North Dakota Geological Survey (1976). Associated gas production not shown.

* Major producing reservoir in multiple pool fields.

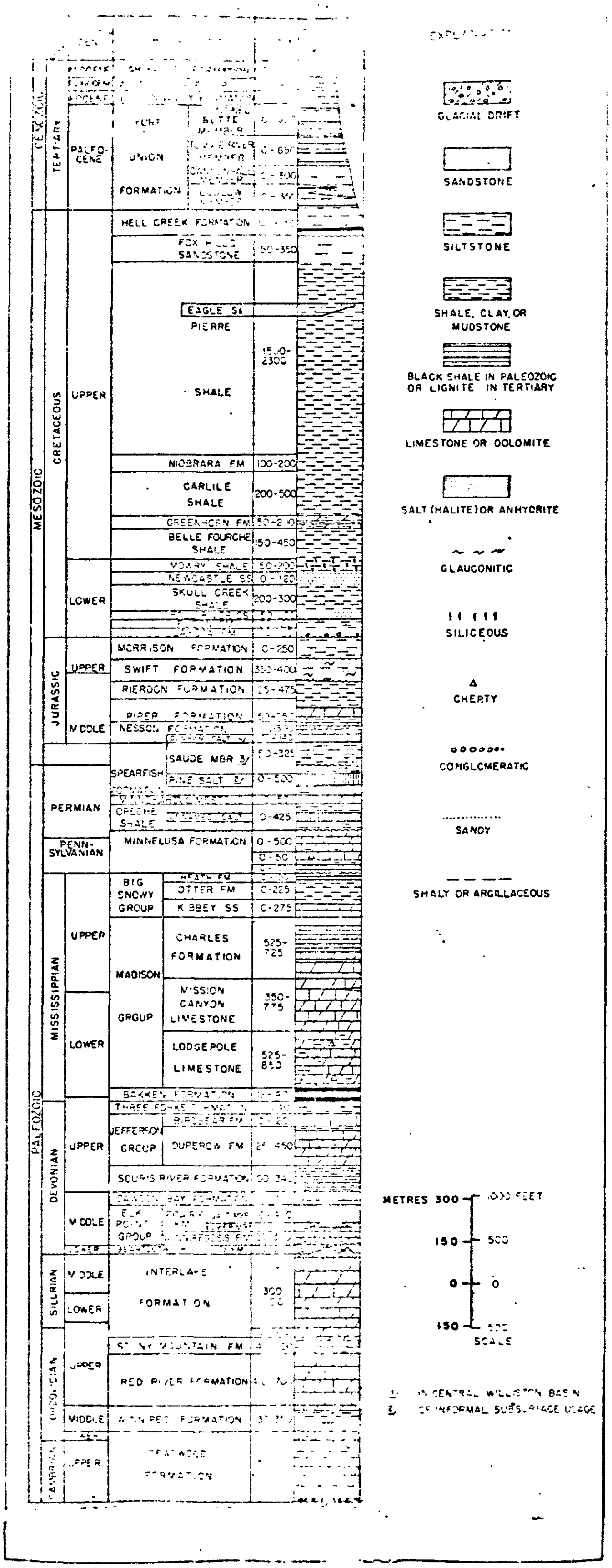

Figure 15.- Generalized stratigraphic column, North Dakota portion of Williston Basin.

Future exploration.--Future exploration will involve detailed seismic mapping to define small, low-relief structural closures on lower Paleozoic reservoirs. This work may result in the drilling of large numbers of seismic shotholes 15-61 m (50-200 ft) deep. Logs of the shotholes might be valuable for lignite resource assessment. However, some modern seismic techniques, such as Vibroseis and Dynaseis, do not use shotholes.

The western half of North Dakota will continue to be a focal point of petroleum exploration. Recent research by Rice (1975) on the occurrence of shallow biogenic (methane) gas may spur considerable shallow drilling for dry gas in Tertiary and Cretaceous sandstones over the entire state.

Uranium resources

by

Norman M. Denson

Uranium in North Dakota is largely restricted to the southwestern part of the State where it occurs in lignite and related carbonaceous materials. The carbonaceous host rocks containing the higher grade occurrences range from 0.15 to 0.6 m (6 in. to 2 ft) or more in thickness and are characterized by lenticularity, high ash contents (35-40 percent), and low heating values. The principal host rocks are nearly flat lying, and in general the stratigraphically and topographically higher carbonaceous beds in the mineralized sequence contain the most uranium. Most of the uranium-bearing host rocks in southwestern North Dakota are of early Tertiary (Paleocene) age and range from zero to about 365 m (1,200 ft) in thickness. Field relations indicate that the uranium is of secondary origin and was introduced long after the accumulation and marked regional uplift and warping of the lignite beds and associated rocks. Transportation and deposition of the uranium into the lignite is thought to have been by ground water moving downward and laterally from an overlying tuffaceous (volcanic) source rock.

The two principal areas containing uraniferous lignite in southwestern North Dakota are (1) the Little Missouri River Escarpment area in west-central Billings County and the northwestern part of Stark County, and (2) the Chalky Buttes area in the south-central part of Slope County. The Little Missouri Escarpment area covers about 780 sq km (300 sq mi) of gently rolling upland and about 260 sq km (100 sq mi) of rugged badland terrain, whereas the Chalky Buttes area comprises about 39 sq km (15 sq mi) of steep slopes flanking the prominent buttes.

Minor local occurrences of uraniferous lignite underlie Sentinel and Flat Top Buttes in south-central Golden Valley County, Bullion Butte in southwestern Billings County, and the Medicine Pole Hills in western Bowman County. The uranium content of the lignite in these low-grade occurrences is not uniform but ranges from about 0.005 to 0.02 percent. Here the uranium is inconspicuously disseminated in the carbonaceous material and individual uranium minerals have not been identified.

Many of the uranium occurrences in the Little Missouri River Escarpment area contain 0.1 percent or more uranium and are overlain at many localities by relatively thin overburden which make them amenable to strip mining. Uranium Magazine (1958, p. 13 and 26) reports that in the western Dakotas about 900,000 tons of proved reserves have been established, about half of which are in the Little Missouri River Escarpment area.

From 1962 to 1967, uraniferous lignite in southwestern North Dakota was burned in kilns or pits and the ash shipped to mills in South Dakota, Colorado, and New Mexico, where it was blended and treated along with sandstone ores. Both the burning and mining have now been discontinued, apparently because market demand could be more profitably satisfied elsewhere.

Construction materials

by

Robert M. Lindvall

Construction materials in the Williston Basin portion of North Dakota are limited chiefly to sand and gravel, although very minor amounts of crushed stone, scoria, pseudoquartzites, and glacial boulders have been produced in the state in past years.

Sand and gravel.--In North Dakota, sand and gravel production is the third largest mineral industry, surpassed only by petroleum and coal in dollar value. In 1973, $6,021,000 worth of sand and gravel was produced (Huvos, 1976). The sand and gravel is used mainly for concrete aggregate in paving and building construction, and for pit-run road metal. Minor uses include railroad ballast and fill material in construction work.

Sand and gravel deposits are widespread north and east of the Missouri River in the Williston Basin and are chiefly of glacial origin. The deposits include outwash plains, kames, kame terraces, eskers, deltas, and beaches. Most of these deposits are relatively small, and commonly are characterized by abrupt changes in quality and quantity. They may contain considerable amounts of clay and silt, and, though they provide material for local use, most are not of high commercial grade.

Deposits south and west of the Missouri River are less widespread, and consist chiefly of terraces and point bar deposits along the major and some of the minor streams. The quality and quantity of these water-deposited materials varies considerably and abrupt vertical changes in texture and sorting are common.

Information regarding the sand and gravel resources of the Williston Basin portion of North Dakota are available from maps, reports, and unpublished data from the U.S. Geological Survey, the North Dakota Geological Survey, the North Dakota State Water Commission, and the North Dakota State Highway Department. Geologic maps prepared in connection with county ground-water studies show the areal distribution of known surface deposits of sand and gravel. Maps and data from the subsurface exploration conducted for these studies are published by the North Dakota Geological Survey in their Bulletin Series, and by the North Dakota State Water Commission in the County Ground Water Study Series. Sizeable amounts of exploratory information as well as detailed analytical data on known sand and gravel deposits is available in the files of the North Dakota State Highway Department.

Stone.--Stone production in the Williston Basin area consists cheiefly of what is known commercially as "crushed and broken stone." Sources of this material include the "pseudoquartzites" and "scoria" of the area south and west of the Missouri River, and boulders from the glaciated areas.

Pseudoquartzites.--"Pseudoquartzites" occur in many areas of the southern part of the Williston Basin. These rocks are composed of siliceous siltstones and mudstones and are very hard and resistant to weathering. Present commercial use seems to be limited to rip-rap material for facing earth dams.

Scoria.--Baked clay or natural bricklike material is included in the category of "crushed and broken stone." Locally, it is called "scoria" or "clinker," but probably more correctly should be called porcellanite. "Scoria" was formed when clay and shale beds overlying lignite were baked and fused by the heat of burning coal. The resulting pink, red, and blue-black deposits are widespread over the nonglaciated portion of the Williston Basin. Scoria is used widely as road metal in areas where sand and gravel are lacking. Other uses include driveways, walkways, and decorative lawn material.

Boulders.--Boulders, occurring in glacial materials, chiefly in areas north and east of the Missouri River, have been used for rip-rap, and to some extent as decorative stone in construction.

Dimension stone.--The term "dimension stone" is applied to blocks or slabs of natural stone that are cut to definite shapes and sizes, used for building stone, walls and foundations, sidewalks, and memorials and other decorative areas. A sandstone bed in the Fort Union Formation in northwestern Billings County has been quarried for use chiefly as decorative stone in fireplaces, interior walls, barbeque pits, and patio flooring.

Other nonmetallic mineral resources

by

Robert M. Lindvall

Nonmetallic mineral resources of the Williston Basin area include clay, salt, sodium sulfate, and sulfur.

Clay.--Clay deposits both in bedrock and surficial materials are widespread in the Williston Basin area, but only those in the Golden Valley Formation (Paleocene and Eocene) are used commercially at present. Two plants manufacturing clay products were in operation in 1973 in Morton County, one producing face brick, the other lightweight aggregate.

Salt.--Salt is mined by solution methods at a depth of 2,440 m (8,000 ft) from the Charles Formation (Mississippian) at Williston in Williams County by the Hardy Salt Company. Fresh water is injected into the salt bed and the recovered brine solution is evaporated in vacuum pans. Part of the salt is pressed into blocks for use by ranchers and stockmen in cattle raising operations.

Sodium sulfate.--Sodium sulfate present in saline lakes or former lake basins that occupy undrained depressions in glacial deposits north and east of the Missouri River in the Williston Basin area. Limited development of these deposits was undertaken in 1937 and again in 1948, but little if any production has ever been recorded.

Sulfur.--Elemental sulfur is recovered as a byproduct of natural gas processing plants at Lignite in Burke County, and at Tioga in Williams County.

REFERENCES CITED

Anderson, S. B., 1974, Pre-Mesozoic paleogeologic map of North Dakota: North Dakota Geol. Survey, Misc. Map 17.

Andrews, D. A., 1939, Geology and coal resources of the Minot region, North Dakota: U.S. Geol. Survey Bull. 906-B, 84 p.

Ashmore, H. T., 1971, Petroleum potential of North Dakota, <u>in</u> Cram, I. H., ed., Future petroleum provinces of the United States--Their geology and potential: Am. Assoc. Petroleum Geologists Memoir 15, v. 1, p. 692-705.

Barclay, C. S. V., 1973, Geologic map and lignite deposits of the Glen Ullin quadrangle, Morton County, North Dakota: U.S. Geol. Survey Coal Inv. Map C-54.

_____, 1974, Geologic map and lignite deposits of the Dengate quadrangle, Morton County, North Dakota: U.S. Geol. Survey Coal Inv. Map C-67.

Baria, D. N., 1975, A survey of trace elements in North Dakota and effulent streams from combustion and gasification facilities: Engineering Experiment Station, Univ. of North Dakota, 1975-1, 64 p.

Benson, W. E., 1953, Geology of the Knife River area, North Dakota: U.S. Geol. Survey open-file rept., 323 p.

Bluemle, J. P., 1972, Pleistocene drainage development in North Dakota: Geol. Soc. America Bull., v. 83, no. 7, p. 2189-2193.

_____, 1977, Geologic highway map of North Dakota: No. Dak. Geol. Survey Ed. Series 11, Misc. Map 19.

Brant, R. A., 1953, Lignite resources of North Dakota: U.S. Geol. Survey Circ. 226, 78 p.

Brown, R. W., 1948, Correlation of Sentinel Butte shale in western North Dakota: American Association of Petroleum Geologists Bulletin v. 32, p. 1265-1274.

_____, 1962, Paleocene floras of the Rocky Mountains and Great Plains: U.S. Geol. Survey Prof. Paper 375, 119 p., 69 pls.

Cannon, H. L., and Hopps, H. C., 1971, editors, Environmental geochemistry in health and disease: Geol. Soc. America Memoir 123, 230 p.

Carlson, C. G., compiler, 1969, Bedrock geologic map of North Dakota: N. Dak. Geol. Survey Misc. Map 10.

_____, 1973, Geology of Mercer and Oliver Counties, North Dakota: No. Dak. Geol. Survey Bull. 56.

Carlson, C. G., and Anderson, S. B., 1965, Sedimentary and tectonic history of North Dakota part of Williston Basin: Bull. Am. Assoc. Petroleum Geologists, v. 49, no. 11, p. 1833-1846.

_____, 1973a, Mineral and water resources of North Dakota--stratigraphy: in Report for the Committee on Interior and Insular Affairs, United States Senate, Part I, p. 31-41.

_____, 1973b, Mineral and water resources of North Dakota--structure: in Report for the Committee on Interior and Insular Affairs, United States Senate, Part I, p. 43-44.

Carlson, C. G., Bakken, W. E., and Kume, Jack, 1960, Subsurface geology and development of petroleum in North Dakota: North Dakota Geol. Survey Bull. 34, p. 124-143 (repr. from Compass, v. 37, no. 2, p. 123-143, 1960).

Collier, A. J., 1919, The Nesson Anticline, Williams County, North Dakota: U.S. Geol. Survey Bull. 691, Part II, p. 211-217.

Colton, R. B., Lemke, R. W., and Lindvall, R. M., 1963, Preliminary glacial map of North Dakota: U.S. Geol. Survey Misc. Geol. Inv. Map I-331.

Connor, J. J., Keith, J. R., and Anderson, B. M., 1976, Trace-metal variation in soils and sagebrush in the Powder River Basin, Wyoming and Montana: Jour. Research U.S. Geol. Survey, v. 4, p. 49-59.

Denson, N. M., and Gill, J. R., 1965, Uranium-bearing lignite and carbonaceous shale in the southwestern part of the Williston Basin--a regional study: U.S. Geol. Survey Prof. Paper 463, 75 p.

Dobbin, C. E., and Larsen, R. M., 1936, Geologic and structure-contour map of the Cedar Creek Anticline, Dawson Prairie, and Wibaux Counties, Montana, and Bowman County, North Dakota: U.S. Geol. Survey Map, 1:63,360, 2 sheets.

Fahy, M. P., and Smith, W. K., 1976, Geotechnical properties of some upper Fort Union rocks from the Decker area, Big Horn County, Montana: U.S. Geol. Survey Open-file Rept. 76-596, 110 p.

Fieldner, A. C., and others, 1942, Typical analyses of coals of the U.S.: U.S. Bur. of Mines Bull. 446, 45 pages. Quoted by E. R. Landis in Mineral and Water Resources of North Dakota, N. D. Geol. Survey Bull. 63, 252 p.

Hansen, A. R., 1966, Reef trends of Mississippian Ratcliffe zone, northeast Montana and northwest North Dakota: Am. Assoc. Petroleum Geologists Bull., v. 50, no. 10, p. 2260-2268.

Hares, C. J., 1928, Geology and lignite resources of the Marmarth field, southwestern North Dakota: U.S. Geol. Survey Bull. 775, 110 p.

Hatch, J. R., and Swanson, V. E., 1976, Trace elements in Rocky Mountain coals: Proceedings, Symposium on the Geology of Rocky Mountain Coal.

Hickey, L. J., 1969, Stratigraphy of the Golden Valley Formation of western North Dakota [abs.]: Geol. Soc. America Abs. with programs for November, 1969, p. 100.

_____, 1977, Stratigraphy and paleobotany of the Golden Valley Formation (Early Tertiary) of western North Dakota: Geol. Soc. America Mem. 150, 181 p., 55 pl.

Hopps, H. C., and Cannon, H. L., 1972, editors, Geochemical environment in relation to health and disease: Annals of the New York Academy of Science, v. 199, 352 p.

Huvos, J. B., 1976, The mineral industry in North Dakota: U.S. Bur. Mines Minerals Yearbook, 1973, v. 2, Area Reports--Domestic.

Johnson, W. D., Jr., and Kunkel, R. P., 1959, The Square Buttes Coal Field, Oliver and Mercer Counties, North Dakota: U.S. Geol. Survey Bull. 1076, 91 p.

Keefer, W. R., 1974, Regional topography, physiography, and geology of the northern Great Plains: U.S. Geol. Survey Open-file Rept. 74-50, 18 p.

Klein, D. H., Anders, W. A., and Bolton, N. E., 1975, Trace element discharges from coal combustion for power production. Water, Air, and Soil Pollution, ser. 5, p. 71-77: Dordrecht, Holland, D. Reider Pub. Co.

Landis, E. R., 1973, Mineral and water resources of North Dakota, economic geology, mineral fuel resources--coal: in Report for the Committee on Interior and Insular Affairs, United States Senate, part I, p. 45-52.

Lemke, R. W., 1953, Geology of the Velva quadrangle, North Dakota: U.S. Geol. Survey Geol. Quad. Map GQ-31.

_____, 1960, Geology of the Souris River area, North Dakota: U.S. Geol. Survey Prof. Paper 325, 138 p.

Lemke, R. W., Laird, W. M., Tipton, M. J., and Lindvall, R. M., 1965, Quaternary geology of Northern Great Plains: in The Quaternary of the United States--A review volume for the VII Congress of the Int. Assoc. for Quat. Research, H. E. Wright, Jr., and David G. Frey, eds.: Princeton University Press, Princeton, New Jersey, p. 15-27.

Metzger, Charles, 1976, Governor Link's Energy Advisor quoted in Energy Era, May 29, 1976, v. 3, no. 3, p. 2f and charts.

Moore, G. W., Melin, R. E., and Kepferle, R. C., 1956, Preliminary geologic map of the Chalky Buttes area, Slope County, North Dakota: U.S. Geol. Survey Coal Inv. Map C-38.

Nevin, C. M., 1946, The Keene dome, northeast McKenzie County, North Dakota: N. Dak. Geol. Survey Bull. 21, p. 1-10.

North Dakota Geological Survey, 1976, Oil and gas production statistics, first half of 1975: Grand Forks, North Dakota, 274 p.

Northern Great Plains Resource Program, 1975.

O'Gorman, J. V., and Walker, P. L., 1972, Mineral matter and trace elements in U.S. Coals: Office of Coal Research, U.S. Dept. of Interior, Research and Development Rept. No. 2, 183 p. (G.P.O. Catalog No. 163.10:61/Int. 2).

Pollard, B. C., Smith, J. B., and Knox, C. C., 1972, Strippable coal resources of North Dakota: U.S. Bur. of Mines Info. Circ. 8537, 37 p.

Radian Corporation Staff, 1975, Coal fired power plant trace element study: prepared for Environmental Protection Agency, vols. I and II, station III.

Rehbein, E. A., 1977, Preliminary report on stratigraphy and depositional environments of the lignites in the Fort Union Formation, west-central North Dakota: U.S. Geol. Survey Open-file Rept. 77-69, 23 p.

Rice, D. D., 1975, Origin of and conditions for shallow accumulations of natural gas, <u>in</u> Geology and mineral resources of the Bighorn Basin: Wyoming Geol. Assoc. Guidebook 27th Ann. Field Conf., p. 267-271.

Roe, W. B., 1950, Geological features of North Dakota lignites: Econ. Geology, v. 45, p. 434-440.

Royse, C. F., Jr., 1967, Tongue River--Sentinel Butte contact in western North Dakota: N. Dak. Geol. Survey Rept. Inv. 45, 53 p.

Sandberg, C. A., 1962, Geology of the Williston basin, North Dakota, Montana, and South Dakota, with reference to subsurface disposal of radioactive wastes: U.S. Geol. Survey Trace Elements Inv. Rept., TEI-809, 148 p.

Sawatzky, H. B., 1975, Astroblemes in Williston Basin: Am. Assoc. Petroleum Geologists Bull., v. 59, no. 4, p. 694-710.

Shacklette, H. T., Erdman, J. A., Harms, T. F., and Papp, C. S. E., 1976, Trace elements in plant foodstuffs in Oehme, F. W., ed., Toxicity of Heavy Metals in the Environment: Marcel Dekker, New York (in press).

Smith, H. L., 1973, Geologic map and lignite deposits of the New Salem quadrangle, Morton County, North Dakota: U.S. Geol. Survey Coal Inv. Map C-62.

Smith, J. B., Pollard, B. C., and Knox, C. C., 1973, Mineral and water resources of North Dakota, strippable lignite reserves: in Report for the Committee on Interior and Insular Affairs, United States Senate, p. 52-57.

Soward, K. S., 1975a, Geologic map and coal resources of the White Butte West quadrangle, Hettinger County, North Dakota: U.S. Geol. Survey Coal Inv. Map C-69.

_____, 1975b, Geologic map and coal resources of the White Butte East quadrangle, Hettinger County, North Dakota: U.S. Geol. Survey Coal Inv. Map C-70.

_____, 1975c, Geologic map and coal resources of the White Butte NW quadrangle, Stark and Hettinger Counties, North Dakota: U.S. Geol. Survey Coal Inv. Map C-71.

_____, 1975d, Geologic map and coal resources of the White Butte NE quadrangle, Stark and Hettinger Counties, North Dakota: U.S. Geol. Survey Coal Inv. Map C-72.

Stephens, E. V., 1970a, Geologic map of the Heart Butte NW quadrangle, Morton and Grant Counties, North Dakota: U.S. Geol. Survey Coal Inv. Map C-52.

_____, 1970b, Geologic map of the Heart Butte quadrangle, Morton and Grant Counties, North Dakota: U.S. Geol. Survey Coal Inv. Map C-53.

Stone, D. S., 1970, Principal horizontal stress in the central Rocky Mountains versus California: The Mountain Geologist, v. 7, no. 2, p. 69-82.

Symposium Proceedings sponsored by ERDA and Univ. of North Dakota 1975, Technology and use of lignite, GFERC/lc-75/2, 371 p.

Thomas, G. E., 1974, Lineament-block tectonics: Williston-Blood Creek Basin: Am. Assoc. Petroleum Geologists Bull., v. 58, no. 7, p. 1305-1322.

Uranium Magazine, 1958.

U.S. Environmental Protection Agency, 1975a, Interim primary drinking water regulations: 40 Code of Federal Regulations, Pt. 141, Federal Register, v. 40, no. 51, March 14, 1975, p. 11,990-11,998.

_____, 1975b, Interim primary drinking water regulations: 40 Code of Federal Regulations, Pt. 141, Federal Register, v. 40, no. 150, August 14, 1975, 5 p.

U.S. Geological Survey, 1974a, Stripping coal deposits of the northern Great Plains, Montana, Wyoming, North Dakota, and South Dakota: U.S. Geological Survey Miscellaneous Field Studies Map MF-590.

U.S. Geological Survey, 1974b, Geochemical survey of the Western Coal Regions, 1st ann. progress report (July, 1974): U.S. Geol. Survey Open-file Rept. 74-250, 38 p.

_____, 1975, Geochemical survey of the Western Coal Regions, 2nd ann. progress report (July, 1975): U.S. Geol. Survey Open-file Rept. 75-436, 132 p.

_____, 1976a, Geochemical survey of the Western Energy Regions (formerly Geochemical survey of the Western Coal Regions), 3rd ann. progress report, July, 1976: U.S. Geol. Survey Open-file Rept. 76-729.

_____, 1976b, Minor and trace elements in coal--a selected bibliogrpahy of reports in English: U.S. Geol. Survey Open-File Rept. 76-481, 29 p.

_____, 1977, Geochemical survey of the Western Energy Regions, 4th ann. progress report, July 1977: U.S. Geol. Survey Open-file Rept. 77-872, 207 p.

U.S. Geological Survey and the Am. Assoc. Petroleum Geologist, 1961, Tectonic map of the United States.

von Hake, C. A., 1975, Earthquake history of North Dakota: Earthquake Info. Bull., v. 7, no. 6, p. 22-23.

Zeiglar, D. L., 1955, Pre-Piper Post-Minnekahta "Red Beds" in the Williston Basin: North Dakota Geol. Soc. Guidebook, Black Hills Field Conf.