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The Flaxville alluvial plain : a cartographic spatial analysis

David Middleton

The University of Montana

The Flaxville Alluvial Plain:
A Cartographic Spatial Analysis

By

David Middleton

B.A., Eastern Washington University, 1986

B.A., Humboldt State University, 1979

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Numerous gravel-capped plateaus are found in northeastern Montana which are collectively known as the Flaxville formation. These appear to be the remnants of a once continuous alluvial plain which extended from the Rocky Mountains across eastern Montana and beyond.

Cartographic "reconstruction" of this presumed landform was accomplished by generalizing the present land surface at the level of the Flaxville formation. Representations of the former surface included topographic maps, block diagrams, trend surfaces, and a slope profile. A spatial analysis of these maps and diagrams provided a means to evaluate the existence of a Flaxville alluvial plain, and the possible processes involved in its development. Statistical analyses provided a comparative measure of how closely the reconstructed landform matched an idealized model which was based on a composite of existing alluvial landforms.

Both cartographic and statistical analyses of the Flaxville surface provided valid evidence to conclude that present remnants were parts of an alluvial plain. However, the Flaxville Plain was probably not continuous throughout the study area. This is suggested by the spatial distribution of remnants which appear to be principally associated with the ancestral courses of the Missouri and Yellowstone Rivers.

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** (Figure 11 in pocket on back cover.)

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I would also like to express my appreciation to my parents, Robert and Margaret, for their support and concern, and to my future wife Deanna for her continued patience and understanding.

CHAPTER 1

INTRODUCTION

Problem Statement and Hypothesis

The Flaxville gravels formation is a prominent feature of northeast Montana. Named after a town built on these gravels, the larger tracts appear as smooth-topped plateaus rising abruptly from 100 to more than 300 hundred feet (30 to 100 meters) above the surrounding terrain. The problem is to determine if these plateaus known collectively as the Flaxville formation, represent the remnants of a once continuous landform. This project addresses the hypothesis that these now distinct upland surfaces were once part of a continuous alluvial plain which extended from the east slope of the Rocky Mountains to the plains of North Dakota and Saskatchewan.

Purpose Of The Study

Although eastern Montana does not have the dramatic relief of the western portion, it is by no means flat. Irregularities include mountain outliers, isolated buttes and ridges, plateaus, river canyons, and badlands. Because of this topographic complexity, cartographic methods are needed to generalize the surface in order to detect and effectively portray regional trends. The resulting generalized representations might provide evidence for the theorized former Flaxville Plain. To this end a number of contour maps, block diagrams and a slope profile will be developed and evaluated.

Eastern Montana has been studied and mapped extensively for purposes of discovery and exploitation of coal and oil reserves. The Flaxville formation however, with one exception, has received only limited attention.[1] No previous attempts have been made to cartographically "reconstruct" the parent plain surface represented by present remnants. This approach could provide a better understanding of the geomorphic history of the region. Because the Flaxville gravel lies uncomformably on the eroded surfaces of older formations, it buries a former landscape.[2] Mapped information about this gravel would provide clues to the drainage network it buries and hence, to potentially large regional aquifers. Further, because of the Flaxville formation's broad areal extent and its fossil contents, it can be dated. Such maps would aid in stratigraphic correlation throughout the region of surrounding states and provinces. While this mapping project alone does not provide conclusive proof of the former Flaxville Plain, it

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[1]Arthur J. Collier and W.T. Thom, Jr. " The Flaxville Gravel and Its Relation To Other Terrace Gravels of the Northern Great Plains," U.S. Geological Professional Paper 108 (1918): 179.

[2]Arthur J. Collier, "Geology of Northwestern Montana," U.S. Geological Survey Professional Paper 120-B (1918): 35.

may contribute evidence to support this notion.

Study Area

The study area will encompass much of eastern Montana and western North Dakota (Figure 1[3]). Although the Flaxville formation does extend north of the international border,[4] this area was not included because Canadian maps are not compatible with those selected for study. It was decided to include a large area of North Dakota despite little direct evidence of Flaxville gravel, because present topography appears to reflect a natural extension of the proposed plain surface. Thus 100 degrees west longitude was chosen as the eastern boundary of the study area, which roughly corresponds to an eastern break in slope. The southern boundary follows the course of the lower Yellowstone River in Montana, below which evidence of the Flaxville formation becomes scant. In North Dakota the line of 47 degrees north latitude was used, because no occurrences are reported to the south. The 109th meridian bounds the study area in the west. Beyond that, erosion removed all but scattered areas of the gravel near the Rocky

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[3]Map source: "Boundaries of Counties and County Equivalents As of January 1, 1970", United States Department of Commerce, Bureau of the Census, Geography Division.

[4]David Arthur Howard, "Cenozoic History of Northeastern Montana and Northwestern North Dakota With Emphasis On the Pleistocene," U.S. Geologic Survey Professional Paper 326 (1960): 4.

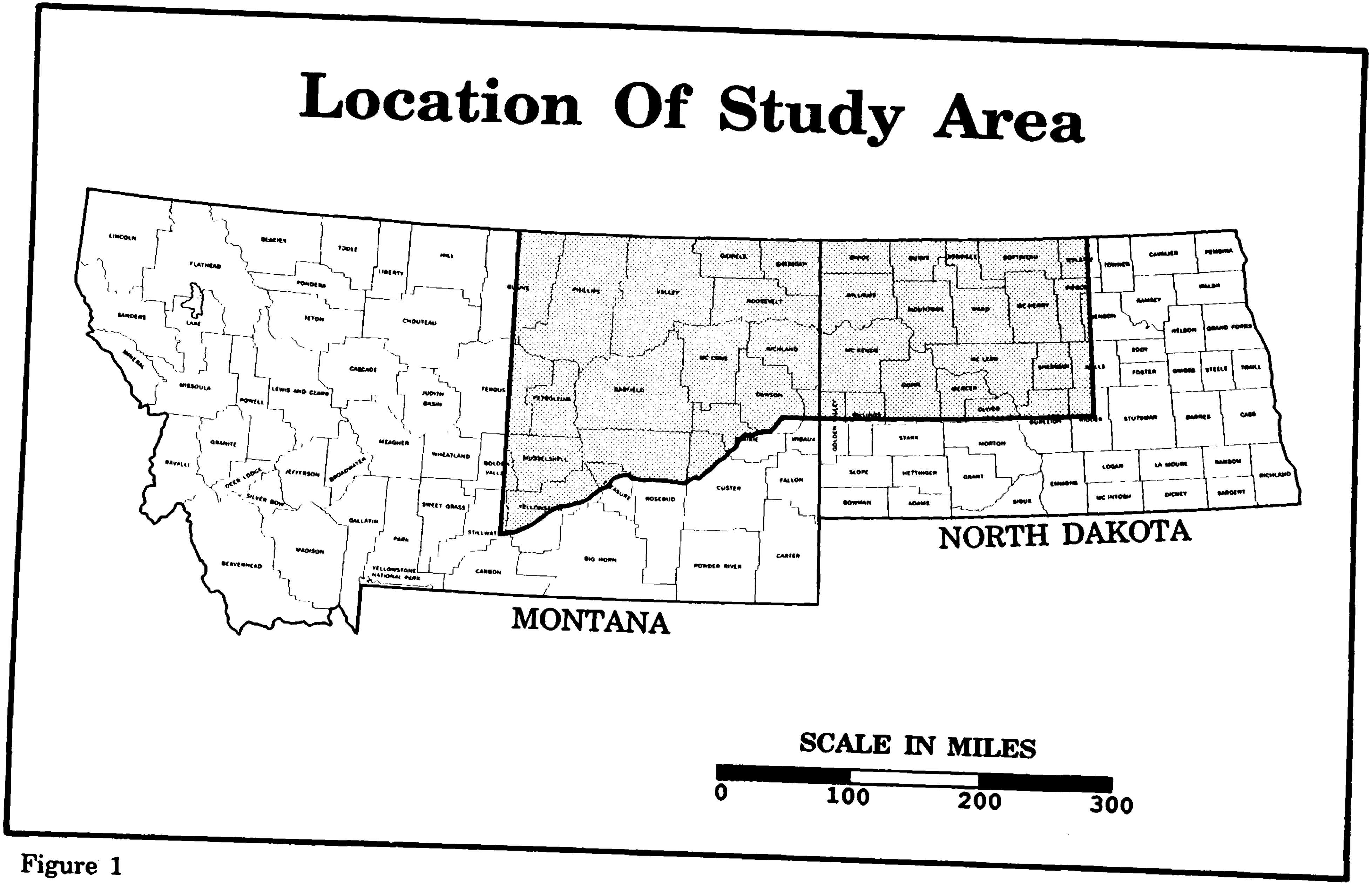
Location Of Study Area
MONTANA
NORTH DAKOTA
SCALE IN MILES
0
100
200
300

Figure 1

Mountain front.[5]

Geographic Setting

The study area is mostly within the Missouri Plateau in the west; the remainder is in the Drift Prairie in the extreme northeast (Figure 2[6]). These are portions of the regional physiographic provinces of the northern Great Plains and the Central Lowlands respectively. The regional surface slopes northeast, hence it is not surprising to find the highest elevation of 5600 feet (1723 meters) in the Little Rocky Mountains near the western boundary, and the lowest elevation of 1450 feet (446 meters) along the lower Souris River in the northeast corner. Elevations generally range from 2000 to 3500 feet (615 to 1077 meters) throughout the study area.

In the west, the gently rolling surface of the Missouri Plateau is interrupted by isolated groups of mountains well east of the main chain of the Rockies, known as mountain outliers. Farther east are numerous flat-topped plateaus, ridges, and buttes, which rise several hundred feet above the surface of the Missouri Plateau. The largest of these are the plateaus of the Flaxville formation. Near the North Dakota

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[5]William C. Alden, "Physiography and Glacial Geology of Eastern Montana and Adjacent Areas." U.S. Geological Survey Professional Paper 174 (1932): 18.

[6]Map source: Landforms of the United States, Erwin Raisz, 1957.

Landforms

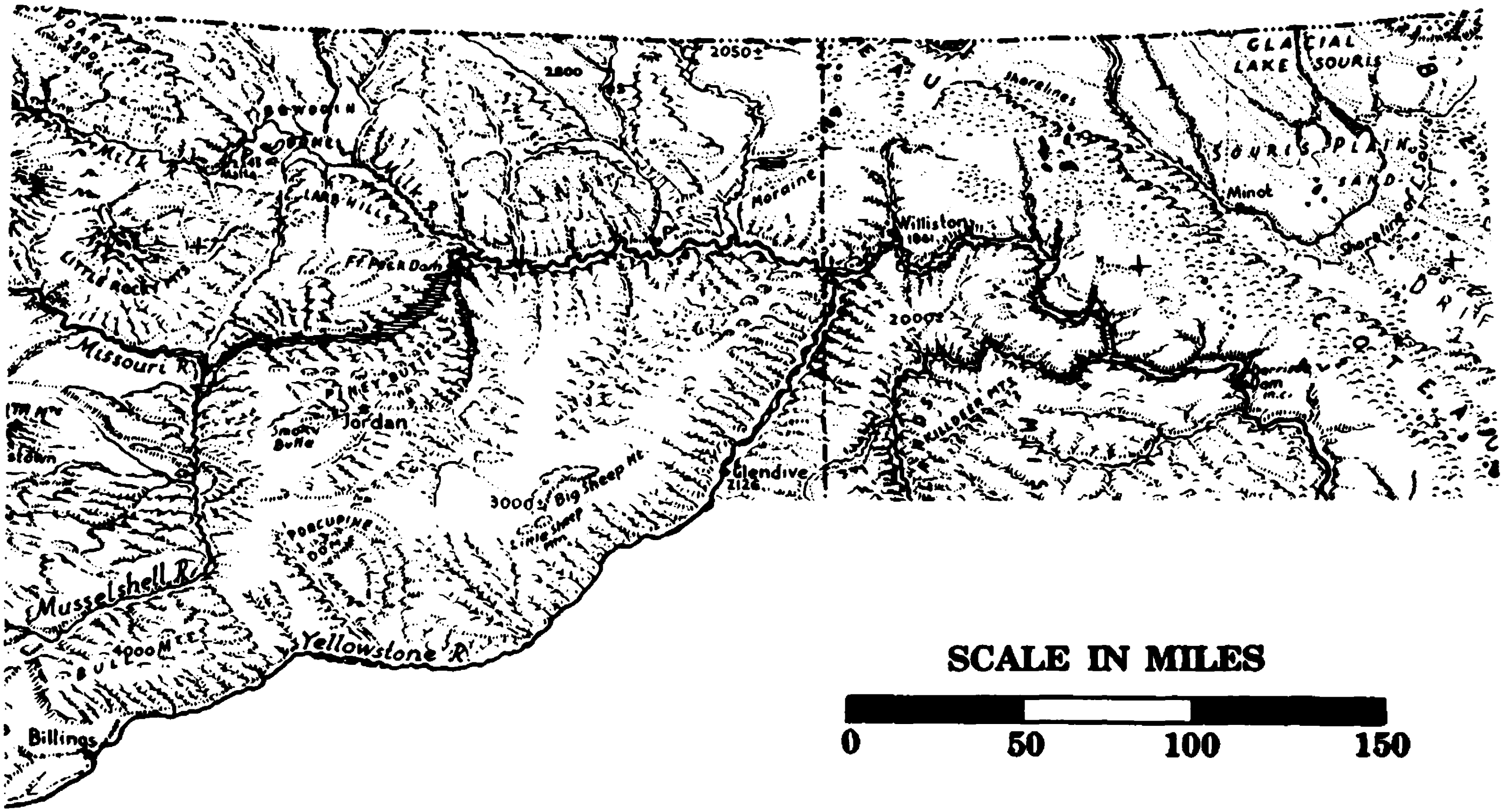

Figure 2

border are extensive tracts of badlands, generally near larger stream courses, with local relief as much as 500 feet (154 meters). In north central North Dakota, trending northwest is a belt of morainal hills without connected drainage known as the Coteau Belt. This 20 to 50 mile (32 to 80 kilometers) wide band of hills is also called the Altamont Moraine. Paralleling the Coteau Belt is the Missouri Escarpment, a 300 to 400 foot (92 to 123 meter) break in slope that marks the boundary between the higher Missouri Plateau and the flat-bottomed Drift Prairie. In the extreme northeast corner of the study area lie the Turtle Mountains which are actually an erosional remnant of the Missouri Plateau, now some 70 miles (113 kilometers) distant.[7]

Drainage

The regional dendritic pattern of drainage is the result of flat-lying, uniformly erodable, sedimentary rocks which underlie the study area. Exceptions include the roughly circular mountain outliers which possess a radial pattern. A portion of the Lake Basin in the southwest corner of the study area, and the Coteau Belt of North Dakota, are areas of internal drainage. In addition, streams perpendicular to the northeast trending Sheep Mountains, flow parallel to one

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[7]A.W. Gauger et al., "Geology and Natural Resources of North Dakota," University of North Dakota Bulletin 11 (1930): 20.

another.

The drainage system is dominated by two large, through-flowing exotic rivers, the Missouri and the Yellowstone. Following the regional slope, they trend northeast across Montana and join near the North Dakota border. There is some reason to believe that ice age glaciers displaced them from earlier courses which continued northeast into Canada. Currently, the Missouri River cuts southeast across the regional trend of North Dakota to empty into the Mississippi system. The valleys of the Missouri and Yellowstone are relatively narrow, bounded by cliffs or breaks from 100 feet (31 meters) to more than 300 feet (100 meters) above their floodplains.

Draining into the Missouri River from the north are the principal tributaries of the Milk and Poplar Rivers, Big and Little Muddy Creeks, and the White Earth River. The southern tributaries are the Musselshell, Yellowstone and Little Missouri Rivers. In the northeast corner of the study area, the Souris River drains north to Hudson Bay.

The climate throughout the study area is semi-arid and most streams are intermittent. Drainage density is generally low, except in the badlands which lack a protective soil and vegetative cover. Rapid runoff produces an extremely high drainage density in these areas.

Annual precipitation, which varies greatly from year to year, averages 12 to 16 inches (30 to 41 centimeters) across the study area. This is insufficient to support trees on most interfluve uplands. Only at the higher elevations of the mountain outliers in the west does annual precipitation approach 20 inches (51 centimeters).

Stratigraphic History

The stratigraphic history of the study area will be confined to those formations which are presently exposed. Thus the discussion begins with the late Cretaceous period. See geologic time scale (Figure 3[8]), and stratigraphic table (Figure 4[9]). During this time the entire study area was slightly below sea level.[10] A shallow epicontinental sea extended to the base of the Northern Rocky Mountains. Marine sediments deposited at this time would become the Bearpaw shale of eastern Montana and the Pierre shale, primarily of North Dakota. This was followed by an accumulation of sand

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[8]Diagram source: Geological Map of Montana, Robert Taylor and Joseph Ashley, Department of Earth Sciences, Montana State University.

[9]Diagram source: adapted from Table 2, "Statigraphy of Exposed Formations of eastern Montana and western North Dakota", David Howard, Cenozoic History of Northeastern Montana and Northwestern North Dakota With Emphasis on the Pleistocene, U.S. Geologic Survey Professional Paper 326 (1960): 16.

[10]Harold L. Levin, The Earth Through Time, Second ed. (New York, N.Y.: Saunders College Publishing, 1983): 365.

GEOLOGIC TIME SCALE

	PERIOD	EPOCH	TIME Million Years Ago
CENOZOIC	QUATERNARY	Holocene	.01
		Pleistocene	1.6
	TERTIARY	Pliocene	5.3
		Miocene	23.7
		Oligocene	36.6
		Eocene	57.8
		Paleocene	66.4
MESOZOIC	CRETACEOUS		144
	JURASSIC		208
	TRIASSIC		245
PALEOZOIC	PERMIAN		286
	PENNSYLVANIAN		320
	MISSISSIPPIAN		360
	DEVONIAN		408
	SILURIAN		438
	ORDOVICIAN		505
	CAMBRIAN		570
PRECAMBRIAN	PROTEROZOIC		2500
	ARCHEAN		3800

Figure 3

Stratigraphy of Exposed Formations

In Eastern Montana

and Western North Dakota

				Eastern Montana	Western North Dakota
Cenozoic	Quaternary	Recent		Alluvium, eolian sands and silts, slope wash, and products of mass movements	
		Pleistocene		Till, stratified drift, eolian sands and silts, slope wash, and products of mass movements	
	Tertiary	Pliocene or Miocene		Flaxville gravel: Thickness, 30 ft average. Fluvial sands and gravels. Pebbles waterworn and stained with iron oxide. Almost exclusively quartzite and chert north of Missouri River, but includes silicified igneous rocks in Yellowstone drainage basin. One probable occurrence reported in North Dakota.	
		Miocene or Oligocene		Rimroad gravel: Thickness, 30 ft average. Fluvial sands and gravels capping high divide between Yellowstone River and Redwater Creek. Similar to Flaxville gravel.	Not reported in North Dakota.
		Oligocene		White River formation: Thickness, 250 ft. Clays, shales, sands, limestone; fluvial and lacustrine.	
		Eocene		Not reported in easternmost Montana.	Golden Valley formation: Thickness, 100 ft. Micaceous sands and silts and clay lenses, underlain by gray carbonaceous shales and white and yellow-orange clays.
		Paleocene	Fort Union formation	Sentinel Butte member: Thickness ranges from 210 ft in Montana to 550 ft in North Dakota. Somber sandstones, shales, clays, and lignite coal; some bentonite. Lower part interfingers with upper part of Tongue River member.	
				Tongue River member: Thickness ranges from 700 ft in Montana to 300 ft in North Dakota. Light-gray, calcareous sand, silt, clay, and numerous lignite beds; weathers yellow to buff; loglike concretions as much as 30 ft thick.	
				Lebo shale member: Thickness, 400 ft. Dark shale and thin beds of white sandstone and sandy clay.	Ludlow (250 ft) and Cannonball (300 ft) members: The continental shales, sandstones, and lignite of the Ludlow grade eastward into the marine sands and clays of the Cannonball.
				Tullock member: Thickness 165 ft. Light and dark shales and sands, locally yellowish; coal seams in dark shales.	
Mesozoic	Cretaceous	Upper Cretaceous		Hell Creek formation: Thickness ranges from 575 ft to 100 ft, west to east. Largely shale in Montana but some sandstone in lower part and a persistent coal seam at top. Gray to brown bentonitic sandstone and shale in North Dakota.	
			Montana group	Fox Hills sandstone: Colgate sandstone—thickness, 80 ft. Brown sandstone with concretions. Basal member—thickness 60-200 ft. Yellow clay, silt, sand.	Fox Hills sandstone: Thickness, 180-320 ft. Brown to gray sandstone.
				Bearpaw shale: Thickness, 1,200 ft. Dark-gray shale; layers of bentonite.	Pierre shale: Thickness, 2,300-930 ft, west to east. Dark-gray bentonitic shale with ironstone concretions and selenite. Present also in the Cedar Creek anticline in eastern Montana.

Figure 4

known as the Fox Hills sandstone. See geologic map (Figure 5[11]).

As the Rockies began to rise, the sea gradually retreated eastward. This occurred over many millions of years as a complex series of advances and retreats. Thus this sequence of strandline positions in eastern Montana is recorded as the interbedded marine and terrestrial shale, sandstone, and conglomerate of the Hell Creek formation.[12] Terrestrial portions of this formation have yielded many of the fine dinosaur fossils for which Montana is famous. Farther east, these same sediments are thinner and were deposited mostly seaward of the retreating strandline in the eastern portion of the study area.[13] The boundary marking the close of Cretaceous and beginning of Tertiary time, is the sudden extinction of the dinosaurs.

The Fort Union formation of Paleocene time resembles the Hell Creek formation except in its lack of dinosaur fossils.[14] During Paleocene time most of Montana remained slightly above sea level. Great marshes existed in the

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[11]Map source: Geologic Map of the United States, U.S. Geologic Survey, 1974.

[12]David Alt and Donald Hyndman, Roadside Geology of Montana (Missoula,MT.: Mountain Press Publishing, 1986): 364.

[13]Harold L. Levin, The Earth Through Time, Second ed. (New York, N.Y.: Saunders College Publishing, 1983): 427.

[14]David Arthur Howard, "Cenozoic History of Northeastern Montana and Northwestern North Dakota With Emphasis On the Pleistocene," U.S. Geologic Survey Professional Paper 326 (1960): 15.

Geology

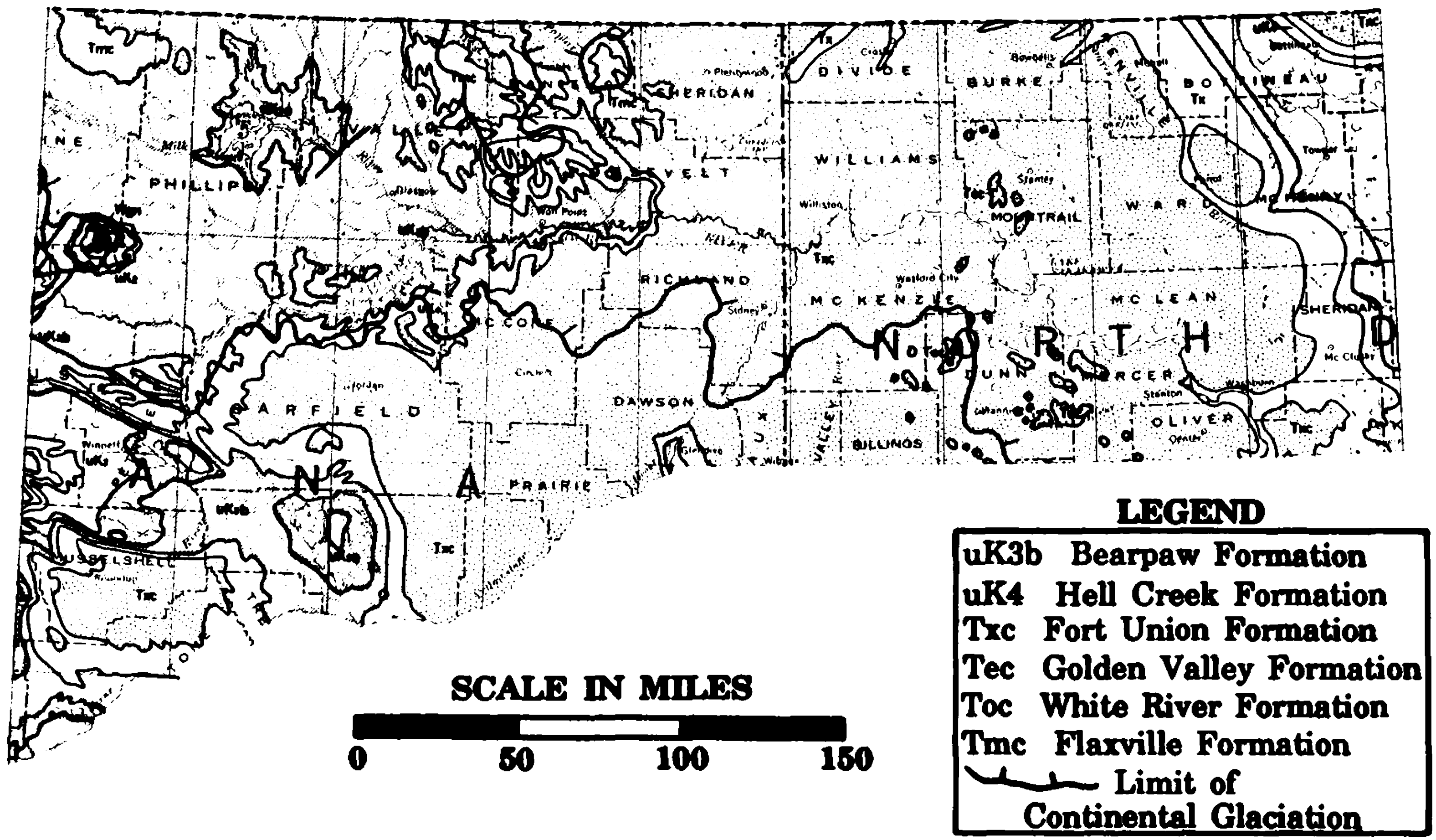

Figure 5

coastal lowlands and along river floodplains.[15] Peat deposits laid down in them were buried beneath other sediments, and became coal seams interbedded with the sandstones and mudstones of the Fort Union formation. Throughout Paleocene time as the thick sedimentary sequence of the Fort Union formation was being constructed, it is likely that all of the study area was undergoing gentle regional uplift. Following the Fort Union deposition was a period of at least ten million years during which no sedimentation occurred in eastern Montana. This also marks the end of the comformable stratigraphic sequence.

In general, Eocene streams were apparently capable not only of transporting detritus, but also of eroding the Paleocene surface. Lying uncomformably on the Fort Union formation are the relatively thin fluvial sediments of the Golden Valley formation in North Dakota. Within the present landscape of the study area, this formation is found outcropping in isolated buttes and mesas, most notably the Killdeer Mountains and the Blue Buttes. Isolated igneous intrusions were emplaced along the western boundary of the study area in central Montana during Eocene time. They deformed the overlying strata, raising Paleozoic sedimentary formations to the level of the modern landscape. Steeply-dipping Paleozoic rock, notably the Madison limestone,

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[15]David Alt and Donald Hyndman, Roadside Geology of Montana (Missoula,MT.: Mountain Press Publishing, 1986): 364.

surrounds the Eocene igneous cores of the Little Rockies and Judith Mountains. Erosion has not exposed the presumed plutonic core of the Little Snowy Mountains dome.

During late Eocene time, the climate over the entire study area grew increasingly arid. It has been suggested this was in response to the continued uplift of the Rocky Mountains.[16] As the mountains rose, erosion increased the amount of sediment available for removal while at the same time, the transporting ability of streams decreased. The thinning plant cover allowed greater soil erosion, causing widespread stream aggradation. The resulting White River beds of Oligocene age are a heterogeneous mixture, mostly fine-grained rocks composed of sand and silt. They also contain interbedded shale, clay, volcanic ash, coal, and limestone.[17] Coarser gravels were probably deposited in stream channels. Mackin comments about this formation,

> numerous erosional disconformities in the Great Plains sediments, and the lenselike character and variable thickness of the stratigraphic units indicate that during the accumulation of the sequence, the delicate balance in the graded condition of the streams was repeatedly shifted from deposition to erosion, from time to time, and from place to place.[18]

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[16]J. Hoover Mackin, "Erosional History of the Big Horn Basin, Wyoming," <u>Geological Society of America Bulletin</u> 48, pt.1 (1937): 892.

[17]David Alt and Donald Hyndman, <u>Roadside Geology of Montana</u> (Missoula,MT.: Mountain Press Publishing, 1986): 21.

[18]J. Hoover Mackin, "Erosional History of the Big Horn Basin, Wyoming," <u>Geological Society of America Bulletin</u> 48, pt.1 (1937): 821.

At the conclusion of White River deposition in late Oligocene or early Miocene time, a broad apron of sediments probably covered much of the study area.[19] Locally the White River formation rests uncomformably on the Fort Union formation, elsewhere on the Golden Valley formation. Subsequent erosion has left the caprock on the Killdeer Mountains of North Dakota as the only remnant within the study area.[20]

In middle Miocene time the climate became humid.[21] Streams deeply eroded the study area, removing most of the Oligocene deposits. Later sediments were laid down largely on pre-Oligocene deposits. After approximately two million years, in late Miocene time, the climate again became arid.[22]

Remnants of fluvial sands and coarse gravels known as the Rimroad gravel, have been found capping the Sheep Mountains of eastern Montana but at no other location at a corresponding elevation.[23] This formation does not contain fossils and does not overlie Oligocene deposits, but resembles nearby Flaxville deposits. However, because it lies 400 to 500 feet (123 to 154

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[19]David Alt and Donald Hyndman, Roadside Geology of Montana (Missoula,MT.: Mountain Press Publishing, 1986): 20.

[20]Terence T. Quirke, "The Geology of the Killdeer Mountains, North Dakota," Journal of Geology 26 (1918): 264.

[21]David Alt and Donald Hyndman, Roadside Geology of Montana (Missoula,MT.: Mountain Press Publishing, 1986): 22.

[22]Ibid., 23.

[23]David Arthur Howard, "Cenozoic History of Northeastern Montana and Northwestern North Dakota With Emphasis On the Pleistocene," U.S. Geologic Survey Professional Paper 326 (1960): 60.

meters) above the Flaxville gravel, it is assumed to be older and perhaps represents a separate erosional level.[24]

The last widespread deposit is the Flaxville formation of late Miocene and Pliocene age (Figure 6[25]). The Flaxville formation is generally composed of weakly consolidated fluvial sands and coarse stream-rounded gravels. It rests uncomformably on the Fort Union, Hell Creek, and Bearpaw formations. It varies greatly in thickness because it buries an erosional surface.[26] Although it is presumed to have covered much of North Dakota,[27] large tracts of Flaxville gravel are presently found as isolated plateaus in the western half of the study area. A more detailed discussion appears in a later section.

Flaxville deposition may have continued until earliest Pleistocene time. Alden cited a fossil in the upper part of the formation and the relation of the Flaxville surfaces to the earliest known Pleistocene deposits near the Rockies as evidence in support of that idea.[28] However, the present level of the Missouri Plateau is at least 300 feet (100

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[24]Ibid.

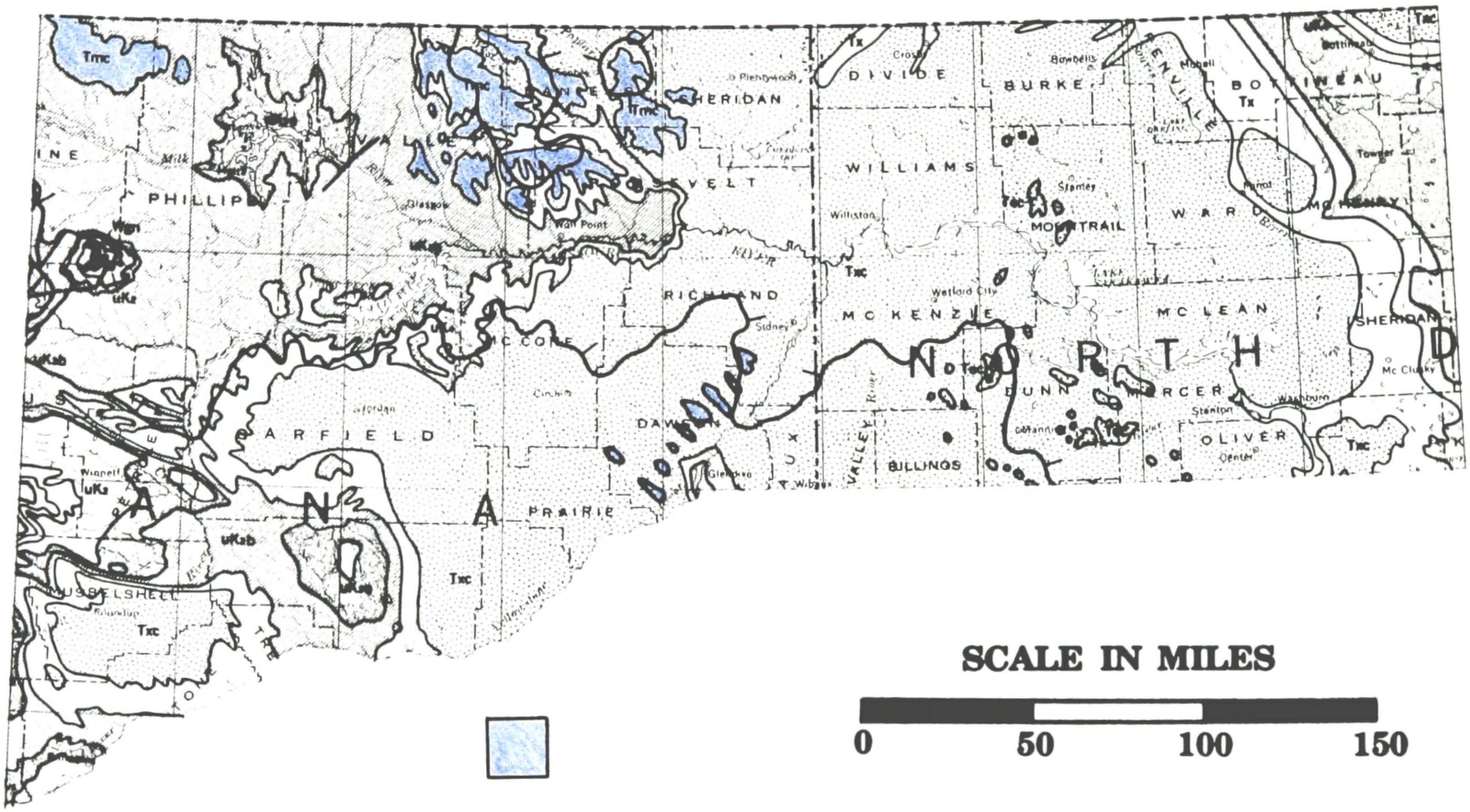
[25]Map source: Geologic Map of the United States, U.S. Geologic Survey, 1974.

[26]David Alt and Donald Hyndman, Roadside Geology of Montana (Missoula,MT.: Mountain Press Publishing, 1986): 25.

[27]Ibid., 26.

[28]William C. Alden, "Physiography and Glacial Geology of Eastern Montana and Adjacent Areas." U.S. Geological Survey Professional Paper 174 (1932): 31.

Principal Flaxville Deposits



Flaxville Deposits

SCALE IN MILES

0 50 100 150

Figure 6

meters) below the assumed Flaxville-age valley bottoms over most of the study area, which would indicate that some widespread degradation had already taken place by the onset of Pleistocene time. This is also suggested by the indiscriminate deposition of Wisconsin drift on highlands, terraces, and valleys in northeast Montana.[29] It is possible that the mountain glaciers of the cordilleran which responded quickly to Pleistocene climatic changes, were already mantling the westernmost Flaxville surfaces with till and outwash while in eastern Montana and North Dakota the Flaxville was still being actively eroded.

It is certain that with the beginning of Pleistocene time a profound climatic shift took place triggering widespread and repeated glaciations of the region. Within the study area this resulted in most of the drainage being diverted from the northeast-trending slope into Canada to the catchment of the Mississippi River.[30] The former channel of the Missouri River, presently occupied by the Milk River, was repeatedly overrun by the continental ice sheet. This forced the Missouri River to flow along a variable ice-margin. At times large ice-margin lakes were formed and drained, releasing enormous amounts of water across the study area which contributed to

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[29]David Arthur Howard, "Cenozoic History of Northeastern Montana and Northwestern North Dakota With Emphasis On the Pleistocene," U.S. Geologic Survey Professional Paper 326 (1960): 61.

[30]Ibid., 63.

the degradation of the region.[31] Stratigraphically this period is represented by numerous moraines and a varying amount of glacial drift throughout the northern portion of the study area. Drift is commonly 100 to 300 feet (31 to 92 meters) thick in the Drift Prairie region of North Dakota and in the Turtle Mountains.[32] Depths of 50 to 100 feet (15 to 31 meters) are more common in northeast Montana, although several Flaxville uplands are driftless.[33] The largest of the moraines, the Altamont or Coteau Belt, has approximately 100 feet (31 meters) of local relief.

The sedimentary rocks of the study area, including the Flaxville gravels, remain primarily in their original flat-lying orientation, and have a slight regional eastward dip which approximates the present land surface. This in combination with the erosional history outlined above, has produced a landscape of modest relief.

Regional Geologic Structure

Several domes in eastern Montana include the Bowdoin,

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[31]David Alt and Donald Hyndman, Roadside Geology of Montana (Missoula,MT.: Mountain Press Publishing, 1986): 270.

[32]A.W. Gauger et al., "Geology and Natural Resources of North Dakota," University of North Dakota Bulletin 11 (1930): 10,20.

[33]A.D. Howard, G.B. Gott, and R.M. Lindvall, "Late Wisconsin Terminal Moraine In Northeastern North Dakota," Geological Society of America Bulletin 57 no. 12 (1946): 1204,1205.

Porcupine, and Poplar Domes with approximate diameters of 60, 20, and 15 miles (97, 32 and 24 kilometers) respectively. They are roughly circular areas of older rocks surrounded by outcrops of younger rocks, but do not contribute much to local relief (Figure 7[34]). However, Collier has suggested that the Bowdoin Dome may be responsible for the absence of Flaxville deposits between the Boundary Plateau and the plateau at Opheim, based on the assumption that an uplifted portion of plateau surface would be more easily eroded.[35] Another roughly circular feature, the Williston Basin, is about 350 miles (563 kilometers) in diameter and centered under the town of Williston in northwest North Dakota. It is an area of persistent crustal subsidence indicated by a thickening of sedimentary formations towards its center.[36] It has had little effect on present topography and bears no relation to the Flaxville formation.

Two structures which do have topographic expression are the Bull and Sheep Mountain synclines. Fort Union sediments were gently downwarped in the Bull Mountain syncline, causing an especially thick accumulation. Thick layers of sandstone and hardened shale known as clinker have been quite successful

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[34]Map source: Geologic Map of the United States, U.S. Geologic Survey, 1974.

[35]Arthur J. Collier, "Geology of Northwestern Montana," U.S. Geological Survey Professional Paper 120-B (1918): 39.

[36]David Alt and Donald Hyndman, Roadside Geology of Montana (Missoula,MT.: Mountain Press Publishing, 1986): 358.

Geologic Structures

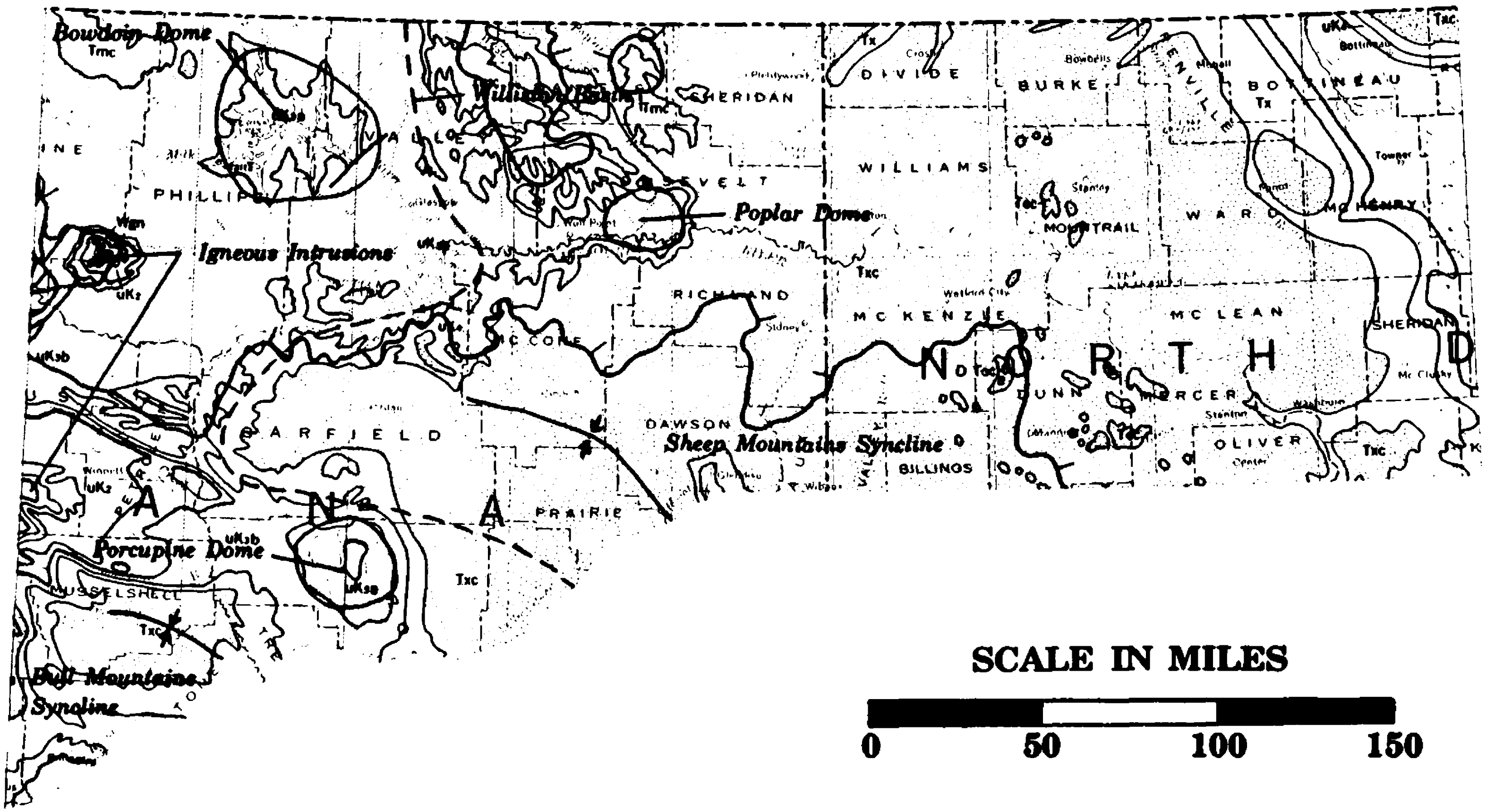

Figure 7

at resisting erosion resulting in a series of broken hills which now stand as much as 1000 feet (308 meters) above the surrounding countryside. A similar scenario is assumed for the Sheep Mountains which now stand as a broad ridge some 1000 feet (308 meters) above its hinterland. It is the highest ground for 100 miles (160 kilometers) in any direction and so has afforded protection to both the Rimroad gravel along its crest, and to Flaxville deposits on both flanks. The igneous intrusions that formed the Little Rocky, Judith, and Little Snowy Mountains along the western study area boundary have already been introduced. Their resistant rocks make them the highest elevations within the study area.

CHAPTER 2

LITERATURE AND RESEARCH REVIEW

Geology of the Flaxville Formation

Collier and Thom describe the Flaxville formation as,

> generally composed of yellowish to ash-gray gravel, clay, and sand, but in places it contains beds of white marl and volcanic ash. The gravel consists of well-rounded pebbles from less than one inch to a foot or more in diameter, of quartzite and argillite derived from the Rocky Mountains. Limestone pebbles from the same source may have been dissolved and the lime redeposited as cementing material and beds of marl. The materials composing the Flaxville gravel are mostly noncoherent...though beds of hard sandstone and conglomerate cemented with calcite from one to several feet thick are encountered... In places the formation is thoroughly cemented with calcite and forms prominently outcropping ledges of sandstone and conglomerate... Many such outcrops present a great deal of cross bedding and are not continuous over large areas.[37]

The pebbles are water-worn and commonly coated with a brown iron oxide.[38]

> The gravels within the Missouri River drainage consist almost entirely of quartzite and chert but include scattered pebbles of quartz. The gravels along the Yellowstone River include numerous pebbles of aphanitic and porphyritic igneous rocks,

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[37]Arthur J. Collier and W.T. Thom, Jr. " The Flaxville Gravel and Its Relation To Other Terrace Gravels of the Northern Great Plains," U.S. Geological Professional Paper 108 (1918): 181.

[38]David Arthur Howard, "Cenozoic History of Northeastern Montana and Northwestern North Dakota With Emphasis On the Pleistocene," U.S. Geologic Survey Professional Paper 326 (1960): 17.

which are largely andesitic.[39]

The age of the Flaxville formation is based on fossils collected from 25 widely distributed locations north of the Missouri River by Collier and Thom; they included the remains of numerous mammals and a fish. One specimen was identified as "apparently Pleistocene", however the paleontologist reports,

> With the exception of the specimen reported as Pleistocene all the material appears to belong to the upper Miocene. It can be stated positively...that with the exception noted, the beds from which these fragments were collected can not be older than Miocene or younger than lower Pliocene.[40]

It is also noted that no fossils have been found in the Flaxville formation along the Yellowstone River.[41]

The three principal tracts of the Flaxville gravel are found in northeast Montana (Figure 6). Lying north of the Milk River and straddling the Canadian border is the Boundary Plateau. Farther east is a group of plateaus separated by stream courses. Collectively these will be referred to as the Missouri Flaxville gravels. The third major occurrence, the Yellowstone Flaxville gravels, is located west of the Yellowstone River between Glendive and Sidney. Each of these

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[39]Ibid.

[40]Arthur J. Collier and W.T. Thom, Jr. " The Flaxville Gravel and Its Relation To Other Terrace Gravels of the Northern Great Plains," U.S. Geological Professional Paper 108 (1918): 181.

[41]David Arthur Howard, "Cenozoic History of Northeastern Montana and Northwestern North Dakota With Emphasis On the Pleistocene," U.S. Geologic Survey Professional Paper 326 (1960): 17.

tracts is large enough to form distinctive flat-topped plateau surfaces that rise from 100 to 300 feet (31 to 92 meters) above the adjacent terrain. They appear on geologic maps because they completely bury the underlying rocks.

Thickness of the Flaxville formation varies from less than 10 feet (3 meters) to 100 feet (31 meters).[42] The Flaxville gravel acts as a caprock on plateau surfaces, preventing the erosion of the material below. The permeable nature of gravel allows for water to infiltrate, thus preventing the formation of gullies and subsequent dissection. The Missouri Flaxville gravels rest atop the gently rolling Missouri Plateau on the eroded surfaces of the Bearpaw, Hell Creek, and Fort Union formations. The Yellowstone Flaxville surfaces appear more terrace-like some 400 feet (123 meters) below the crest of the Sheep Mountains, lying uncomformably on the Fort Union formation.

Elevations of the plateau surfaces generally decrease from west to east. The Boundary Plateau dips east off Cherrypatch Ridge beginning at 3300 feet (1015 meters), but most of the plateau is level at about 3000 feet (923 meters), 700 feet (215 meters) above the floodplain of the Milk River. Missouri Flaxville group elevations vary from 2900 to 3300 feet (892 to 1015 meters) in the west, and from 2550 to 2800

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[42]Arthur J. Collier and W.T. Thom, Jr. " The Flaxville Gravel and Its Relation To Other Terrace Gravels of the Northern Great Plains," U.S. Geological Professional Paper 108 (1918): 181.

feet (785 to 862 meters) in the east. They stand from 600 to 1350 feet (185 to 415 meters) above the level of the Missouri River. The southern portions of many of these plateaus dip gently towards the Missouri River, while in several cases the northern edges dip north. Four locations in this group are reported as driftless.[43] Evidently these plateaus at an average of 2800 feet (862 meters), were sufficiently high to stand above the continental ice sheet.

Elevations in the Yellowstone Flaxville group are more constant and all plateau surfaces dip gently towards the Yellowstone River. Beginning west of Glendive, upslope elevations at 2900 feet dip to 2750 feet (892 to 846 meters). West of Sidney, surfaces dip from 2750 to 2650 feet (846 to 815 meters). These Flaxville plateaus stand about 600 to 900 feet (185 to 277 meters) above the Yellowstone River. Alden suggests that during Flaxville-time the Missouri and Yellowstone Rivers near their junction were flowing at about 2500 feet (769 meters), or about 600 feet (185 meters) above their present channels.[44]

Given its stream-rounded nature, there appears to be little doubt that the Flaxville gravel was transported from some other location to that of the present. Because the rock

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[43]R.B. Colton and A.D. Howard, "Driftless Areas In Northeastern Montana," Geological Society of America Bulletin 62, no.12, pt.2 (1951): 1429.

[44]William C. Alden, "Physiography and Glacial Geology of Eastern Montana and Adjacent Areas." U.S. Geological Survey Professional Paper 174 (1932): 31.

types of individual pebbles are the same as formations in the Rocky Mountains and mountain outliers, they appear to be the source of the Flaxville gravel. The proximity of the Missouri or Yellowstone Rivers to each of the principal Flaxville tracts could indicate a depositional relationship. This idea is supported by the tendency of most of the plateau summits to dip toward the nearby river. It was mentioned that the pebbles in the Boundary Plateau and Missouri Flaxville gravels, differ from those in plateaus along the Yellowstone River. This could further suggest a relationship to the ancestral Missouri and Yellowstone Rivers. Among the three principal Flaxville tracts, summits are also accordant, becoming lower in an easterly direction. This supports the idea of all the Flaxville plateaus being related, once comprising a single, continuous landform.

The Flaxville Gravel As An Alluvial Plain

As stated in the opening remarks, I believe that the Flaxville plateaus and other smaller deposits are the remnants of a formerly continuous surface. Such a surface of aggraded alluvium could be called an alluvial plain. In the case of the Flaxville formation, this is viewed in the context of an arid climate and could accurately be referred to as a desert plain or desert alluvial plain.

The conditions necessary for development of a Flaxville alluvial plain can be inferred from processes active in present arid landscapes. With the onset of aridity, decreased plant cover increases the rate of erosion, loading streams with more, and likely coarser sediment. At the same time, decreasing stream flow diminishes transporting capability, causing deposition in the channels. As valleys fill with sediment, stream beds rise above the surrounding land surface eventually spilling from their original drainage courses. Intermittent and ephemeral streams without banks shift freely across the depositional surface, evenly distributing alluvium. Major interfluves are eventually buried, and the resulting surface becomes a plain. At the further reaches of the growing plain, high-intensity, episodic precipitation, localized in areal extent and duration, extends the surface by direct transport of alluvium. Prevailing winds would redeposit available fines as sand dunes and loess. The formation of a plain the size of the Flaxville would require a long period of aridity, possibly interrupted by wetter intervals of little or no deposition.

The contention that the Flaxville formation represents a former plain surface is not new. In describing Flaxville aggradation Alt and Hyndman state, "As the valleys filled, the gravel deposits buried the hills in between them, and finally spread to make a nearly continuous blanket across the vastness of the High Plains."[45] In describing a specific remnant they state, "Clearly, the flat top of the hill is part of the High Plains surface, a remnant of the desert plain that stretched continuously from the Rocky Mountains to the central Dakotas during late Miocene and Pliocene time..."[46] Howard says of the Flaxville formation, "The plateaus are presumably remnants of a former erosion surface, the Flaxville Plain."[47] Alden suggests that, "The highest of the benches or terraces bordering the mountain fronts are correlatives of the Flaxville Plain of northeastern Montana."[48] Mackin refers to Alden's Flaxville Plain and all correlated benches as, "the Flaxville degradational surface of the Northern Plains..."[49]

Due to its lack of immediate economic importance, the

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[45]David Alt and Donald Hyndman, Roadside Geology of Montana (Missoula,MT.: Mountain Press Publishing, 1986): 24,25.

These authors refer to the remnants of the Flaxville alluvial plain as the High Plains surface. This name is given not because of the present elevation of these remnants, but as a result of their higher position in relation to that of the present land surface. In this sense, the Missouri Plateau is a geologic surface or the present erosional surface, as well as a distinct geographic region.

[46]Ibid., 343.

[47]David Arthur Howard, "Cenozoic History of Northeastern Montana and Northwestern North Dakota With Emphasis On the Pleistocene," U.S. Geologic Survey Professional Paper 326 (1960): 9.

[48]William C. Alden, "Physiography and Glacial Geology of Eastern Montana and Adjacent Areas." U.S. Geological Survey Professional Paper 174 (1932): 31.

[49]J. Hoover Mackin, "Erosional History of the Big Horn Basin, Wyoming," Geological Society of America Bulletin 48, pt.1 (1937): 871.

Flaxville formation has received only marginal attention. The following review of research and speculations about the deposition and subsequent degradation of the Flaxville is limited to those individuals who have examined the formation in the field and given substantial consideration to the implications of the Flaxville remnants. It is interesting to note the diversity of opinions represented, probably the result of evolving geologic perspectives as well as new information.

Collier and Thom recognized only the Flaxville Plateaus north of the Missouri River as representing an erosional level developed in Miocene or Pliocene time of gravels from the Rocky Mountains.[50] They appear to have considered this as a more or less isolated occurrence of conditions favorable for deposition of limited areal extent. Alden defined the Flaxville Plain on the basis of the larger plateau surfaces along the Missouri and Yellowstone Rivers. He correlates this plain with upper level benches and terraces capped with stream-rounded gravel found in scattered locations along the Rocky Mountain front, against the mountain outliers, and along major drainages. He believed the Flaxville Plain was the result of region-wide planation of an older aggradational surface of Oligocene age. The extent of this former surface is

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[50]Arthur J. Collier and W.T. Thom, Jr. " The Flaxville Gravel and Its Relation To Other Terrace Gravels of the Northern Great Plains," U.S. Geological Professional Paper 108 (1918): 181.

indicated by his correlation of remnants from the Cypress Hills in Saskatchewan, Tatman Mountain in the Big Horn Basin of Wyoming, and mountains in North Dakota such as the Killdeers and Sentinel Butte. Thus this material was reworked and let down from a higher level.[51]

Mackin mentions the Flaxville Plain repeatedly in the context of correlating the various surficial deposits in the Big Horn Basin. He believed the Flaxville gravels were widely distributed over the Montana plains and "that they were deposited as thin sheets on stream-cut rock terraces during the current period of degradation..." He also states that,

> The streams of the Northern Plains, like those of the Central Plains area...had high declivities throughout middle and late Tertiary time, because they were heavily loaded, and the load must have been derived from a Rocky Mountain Range that was consistently high.[52]

Howard states that,

> A complete reversal of topography took place during the Flaxville cycle. Uplift of the mountains and a slight increase in the easterly slope of the plains may have caused the master streams to incise themselves into their gravelly floodplains. Tributaries found down-cutting much easier in the unprotected divide areas than in the now-elevated (Rimroad) gravel-capped valley bottoms. In time the divide areas were worn lower than the former valley floors, whose detached remnants now form the highest parts of the Yellowstone-Redwater divide. When the master streams again attained grade, they

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[51]William C. Alden, "Physiography and Glacial Geology of Eastern Montana and Adjacent Areas." U.S. Geological Survey Professional Paper 174 (1932): 13,18,31.

[52]J. Hoover Mackin, "Erosional History of the Big Horn Basin, Wyoming," Geological Society of America Bulletin 48, pt.1 (1937): 888,889.

> opened out broad valleys at the Flaxville level. The Yellowstone River valley at this time was 20 to 30 miles wide and the Missouri River valley was probably wider.[53]

See diagram of Flaxville level (Figure 8[54]). He also believed that the northern-most, flat-lying Flaxville plateaus north of the Missouri River might represent a broad interconfluence area involving additional streams. Collectively, these broad valley bottoms at the Flaxville level are Howard's "Flaxville Plain".[55] Degradation of his Flaxville Plain was caused by another regional rejuvenation and resulting differential erosion.

The Flaxville Plain is an aggraded surface formed as a result of a prolonged desert climate according to Alt and Hyndman.[56] They state,

> Deposition of the Flaxville gravels doubtless began in the old stream valleys that had formed during the wet period of Miocene time. An enormous desert plain developed east of the main mountain front as the shifting desert streams spread a thick blanket of coarse gravel across the region. Now, we find the thickness of the Flaxville gravels ranging from a few to several hundred feet, no doubt because

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[53]David Arthur Howard, "Cenozoic History of Northeastern Montana and Northwestern North Dakota With Emphasis On the Pleistocene," U.S. Geologic Survey Professional Paper 326 (1960): 61.

[54]Diagram source: adapted from Figure 33, David Howard, Cenozoic History of Northeastern Montana and Northwestern North Dakota With Emphasis on the Pleistocene, U.S. Geologic Survey Professional Paper 326 (1960): 59.

[55]Ibid., 9.

[56]David Alt and Donald Hyndman, Roadside Geology of Montana (Missoula,MT.: Mountain Press Publishing, 1986): 23.

Present and Inferred Cross-sections of the Yellowstone and Missouri River Valleys

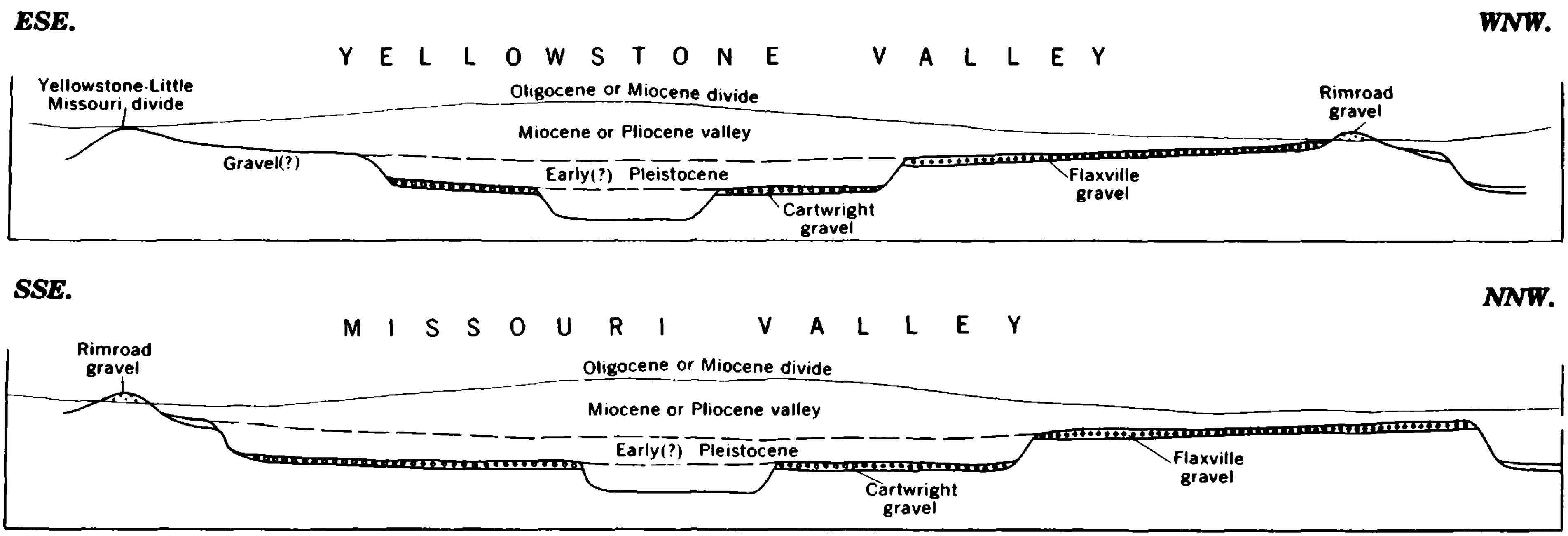

Figure 8

they bury an older landscape.[57]

Subsequent dissection of this desert plain was initiated by a shift to the wetter climate of the Pleistocene. Present remnants are probably the result of, "the ability of the permeable Flaxville gravel to absorb surface water, thus preventing erosion of the surface by surface runoff".[58]

Evidence suggesting the extent of the Flaxville alluvial plain is found beyond the Missouri, Yellowstone and Boundary Flaxville gravel plateaus. The following examples illustrate the extent of the Flaxville gravels within the study area. Two well-preserved, flat-topped interfluves of presumed Flaxville age flanking the Little Rockies are noted by Alden.[59] One northwest of the village of Lodgepole is approximately 6 miles (10 kilometers) long and 2 miles (3 kilometers) wide, while the other is west of the settlement at St. Pauls and is about 7 miles (11 kilometers) by 3 miles (5 kilometers). Speaking of the route between the towns of Roundup and Grassrange Alt and Hyndman observe, "Stream rounded pebbles, the Flaxville gravel, appear scattered in the wheat fields on the high, flat uplands, and roadcuts into that surface (the High Plains)

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[57]Ibid., 23,24,25.

[58]Ibid., 26.

[59]William C. Alden, "Physiography and Glacial Geology of Eastern Montana and Adjacent Areas." U.S. Geological Survey Professional Paper 174 (1932): 19.

expose thick beds of gravel."[60] The Big and Little Snowy Mountains are the probable source highlands in this instance. In McCone County, east of Fort Peck Lake, Flaxville gravel has been identified above Bear Creek, on the divide between Horse Creek and the Redwater River, and at multiple locations above the south bank of the Missouri River.[61] Howard mapped gravels identical in lithology and appearance to the large remnants north of the Missouri River along both sides of the Redwater River and at two locations in Divide County of extreme northwestern North Dakota.[62] During his exploratory survey of the 49th parallel beginning near the east edge of the study area, Dawson noted the occurrence of exotic pebbles of Rocky Mountain quartzite.[63] In addition to these and the principal Flaxville plateau locations, sites of Flaxville equivalents exist all along the Rocky Mountain front, as discrete units in Saskatchewan, and mixed with glacial drift on the plains of Saskatchewan and Manitoba. Hence the evidence suggests that the Flaxville formation originally covered much of eastern

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[60]David Alt and Donald Hyndman, Roadside Geology of Montana (Missoula,MT.: Mountain Press Publishing, 1986): 303.

[61]Eddie Juvan, "Geology of McCone County, Montana," Soil Survey of McCone County, Montana U.S. Department of Agriculture, Soil Conservation Service (1984): 214.

[62]David Arthur Howard, "Cenozoic History of Northeastern Montana and Northwestern North Dakota With Emphasis On the Pleistocene," U.S. Geologic Survey Professional Paper 326 (1960): Plate 4.

[63]George Mercer Dawson, Report on the Geology and Resources of the Region In the Vicinity of the Forty-ninth Parallel, (New York, N.Y.: B. Westermann and Co., 1875): 225.

Montana and parts of North Dakota, Saskatchewan and Manitoba.

Other indicators of a Flaxville alluvial plain include the consistent coarseness of the gravel throughout its extent. Whether of limestone and granite from the mountain outliers, or quartzite and argillite from the Rockies, the formation invariably contains a large fraction of coarse stream-rounded pebbles. This is in keeping with the notion of widespread aggradation characteristic of prolonged aridity. Also, the fossil fauna in the gravels includes ancestors of mammals such as camels and horses that now inhabit semi-arid to arid regions.

Alden, in discussing Flaxville Plain remnants adjacent to the Rocky Mountain front, found that an average slope of 7.4 to 9 feet per mile (1.4 to 1.7 meters per kilometer) would be required to connect them with the next eastern occurrence of Flaxville gravels on the Boundary Plateau some 170 miles (274 kilometers) distant. He states that,

> From 7 to 9 feet per mile is a gradient for streams flowing in narrow valleys or canyons, and such streams readily transport coarse material. These streams however, were flowing in canyons beyond the mountain fronts but were doubtless subdivided into numerous distributaries, which constantly shifted their courses from side to side on the great alluvial fans as the channels became blocked by debris.[64]

While describing the steepened declivities characteristic of an arid climatic regime, he does not appear mindful of this

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[64]William C. Alden, "Physiography and Glacial Geology of Eastern Montana and Adjacent Areas." U.S. Geological Survey Professional Paper 174 (1932): 18.

fact. He has further reported that in projecting the remnant Flaxville surfaces north of the Little Rockies, which dip away from the mountains in all cases, a gradient of about 10 feet per mile (1.9 meters per kilometer) would join them with the level of the Flaxville Plain over the present Milk River Valley.[65]

The processes responsible for the hypothesized Flaxville plain have been described, and evidence of such a plain has been suggested by a number of field researchers. The most compelling evidence appears to be that similar deposits, all of which contain a significant percentage of coarse gravel derived from the Rocky Mountains, are found throughout the region. These deposits are presently observed as flat-topped plateaus whose summits are accordant, and dip to the east across the entire study area. Evidence has also indicated an arid climate prevailed during late Miocene and Pliocene time. Thus many of the elements suggesting the development of a Flaxville alluvial plain by the processes outlined appear to be present.

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[65]Ibid., 19.

CHAPTER 3

DATA COLLECTION AND RESEARCH METHODS

Slope Profile Analogues

The areal extent of the presumed Flaxville plain has been cited, and the processes responsible for its creation have been discussed. It remains to demonstrate that the topographic surface of the study area, at the Flaxville level, will have the configuration associated with an alluvial plain when recreated in map form. To test this supposition, it is necessary to develop a quantifiable longitudinal profile as well as a qualitative description of the proposed landform. These are useful for comparison with, and evaluation of the project results.

The literature is rife with qualitative descriptions of arid-climate landforms, and some authors have risked occasional numeric estimates of slope profiles. These however, center on landforms that encompass areas measuring thousands of square feet up to perhaps hundreds of square miles. The landform proposed in this project would measure many thousands of square miles, clearly a different order of magnitude. While contemporary arid-climate landforms will be considered in a following section, attention will now be directed to what I believe is the closest analogue to the Flaxville plain that remains largely intact. This is the Ogallala formation which projects east along the Rocky Mountain front from Wyoming through New Mexico and laps onto the plains of Nebraska, Kansas, Oklahoma and Texas.

Some authors believe that the Flaxville and Ogallala formations are simply geographic extensions of one another. Alt and Hyndman state directly, "South of Montana, the same gravel (Flaxville) is called the Ogallala formation."[66] Mackin describes the Ogallala with, "Aggradation of the Central Plains area culminated in late-Tertiary time in the production of a vast, eastward-sloping alluvial surface..."[67] Speaking of a possible difference in the onset of the most recent stage of degradation, he states,

> Such a difference is suggested independently by the widespread preservation of the old constructional surface in the High (Central) Plains surface and its complete, or almost complete, removal in the Northern Plains. The difference in the date of inception of degradation in the Central and in the Northern Plains might have been due to a difference in the date of uplift of the two regions or, . . .to a difference in climatic conditions in the two latitudes. . . .it is possible that the apparently conflicting testimony from the northern and southern areas may not actually conflict at all, but that active degradation in Montana in the Pliocene may have been contemporaneous with continued upbuilding...in southern Wyoming and Colorado.[68]

Swinehart describes Ogallala deposition in western Nebraska as

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[66]Ibid., 24.

[67]J. Hoover Mackin, "Erosional History of the Big Horn Basin, Wyoming," <u>Geological Society of America Bulletin</u> 48, pt.1 (1937): 821.

[68]Ibid., 872.

a heterogeneous mixture of alluvially deposited sands and gravels resulting from tectonic uplift of the Rocky Mountain sources during the mid and late Miocene.[69] This closely parallels the deposition of the Flaxville formation.

Slope profile measurements of the Ogallala formation were made using U.S.G.S. 1:250,000 scale topographic maps, commencing on the "Gangplank"[70] and extending eastward. It was found to be a broadly concave surface with a slope of approximately 85 feet per mile (16.3 meters per kilometer) along Duck Creek where the west end of the Gangplank laps onto Precambrian bedrock in southeastern Wyoming. Slopes are about 8.4 feet per mile (1.6 meters per kilometer) midplain (south of the town of Ogallala in western Nebraska), and about 8.7 feet per mile (1.7 meters per kilometer) near the toe of the alluvial plain (on the interfluve surface between the Middle and North Loup Rivers in central Nebraska). It is interesting to note that these figures correspond fairly well with Alden's projections of "an initial slope near the mountains (Rocky Mountain front of northern Montana) of 100 to 200 feet to the

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[69]James B. Swinehart et al., "Cenozoic Paleogeography of Western Nebraska," In Cenozoic Paleogeography of West-Central U.S., ed. R.M. Flores and S.S. Kaplan (Denver: Rocky Mountain Section - S.E.P.M., 1985): 209,223,227.

[70]Russell G. Shepherd and Willard G. Owens, "Hydrogeographic Significance of Ogallala Fluvial Environments, The Gangplank," S.E.P.M. Special Publication 31 (1981): 89.

mile"[71] (19 to 38 meters per kilometer), and 7.4 to 9 feet and 10 feet to the mile (1.4 to 1.7 and 1.9 meters per kilometer) at the west end of the study area (roughly midplain). It is also important to recognize that due to whatever hydrologic regime existed, stream declivities similar to those projected for the Flaxville Plain were sufficient for the deposition of up to 700 feet (215 meters) of relatively coarse Ogallala sediments. There is little to suggest post-Ogallala downwarping; to the contrary, some evidence suggests that late Tertiary doming of the Central Rockies and adjacent plains may have continued. Thus it is fairly certain that the observed slope profile of the Ogallala surface is a reliable maximum.

Other features in North American arid landscapes that might serve as analogues to the Flaxville Plain include bajadas and the alluvial floodplains of desert rivers. This synthesis is based on the field work of numerous authors, conducted primarily in the Basin and Range Province of the southwestern United States. Bajadas are aggradational features that form as a number of alluvial fans coalesce along a mountain front. Where fully developed, such a detrital apron becomes gently undulatory. Each fan surface is underlain entirely by variable accumulations of coarse alluvium and its longitudinal profile is concave. Bajadas tend to form along mountain fronts bounded by active, high angle faults where

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[71]William C. Alden, "Physiography and Glacial Geology of Eastern Montana and Adjacent Areas." U.S. Geological Survey Professional Paper 174 (1932): 17.

alluvium builds up on the edge of the down-dropped block. These features are the result of intermittent or ephemeral streams that are not at grade. In more structurally stable locations, bajadas represent an early stage in the process of erosion. Profile declivities are quite variable, but the fans of large canyons commonly slope 50 to 350 feet per mile (10 to 67 meters per kilometer).[72] Other researchers suggest slopes of 500 to 1000 feet per mile (96 to 191 meters per kilometer) where fans abut the uplands and less than 115 feet per mile (22 meters per kilometer) at the toe.[73] The figures suggested by Blackwelder for the fans of large canyons roughly agree with those suggested by Alden for the initial slope off the Rocky Mountain front, and with my own measurements of the upper Ogallala formation.

The floodplains of desert rivers characteristically lie on thick sequences of alluvial valley fill. Marked by numerous distributary channels, these streams do not possess sufficient grade or volume of water to maintain a single channel through the coarse material in their floodplains. This situation would be analogous to streams flowing across the surface of an alluvial plain. Examples of this type of river include the Gila River in western Arizona and the Humboldt River in northern Nevada. These streams have an average grade of 5 to

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[72]Eliot Blackwelder, "Desert Plains," Journal of Geology 39 (1931): 137.

[73]J.A. Mabbutt, Desert Landforms, (Cambridge, MA.: M.I.T. Press, 1977): 100.

10 feet per mile (1 to 1.9 meters per kilometer). Blackwelder suggests longitudinal profiles of 6 to 30 feet per mile (1.1 to 5.7 meters per kilometer) for desert streams in the Sonoran Desert.[74] These figures agree closely with Alden's slope estimates for the western portion of the Flaxville study area (7.4 to 9 feet per mile (1.4 to 1.7 meters per kilometer)), and my own measurements of the middle and lower Ogallala formation (8.4 to 8.7 feet per mile (1.6 to 1.7 meters per kilometer)).

In an attempt to locate other large alluvial deposits analogous to the Flaxville formation, arid climate landforms on other continents were examined. Examples from Australia and Saudi Arabia are discussed.

The expansive landscape of interior Australia with its numerous desert basins and dry plateaus is the result of long tectonic stability in an arid climate. Within this broad context, repeated climatic shifts have affected isolated interior highlands, and thus indirectly the adjacent depositional basins. As a result, recent landforms stand alongside relic features of varying ages.

The Flinders Ranges in South Australia are a good example. These semi-arid to arid highlands are bounded on three sides by arid plains. Drainage is primarily to saline dry lake beds on the adjacent plains. "In this typical desert

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[74]Eliot Blackwelder, "Desert Plains," Journal of Geology 39 (1931): 134.

upland, rivers are ephemeral. Nevertheless, during floods they transport large volumes of debris, including incredibly large blocks, and achieve much erosion and deposition."[75] Runoff in this region is made particularly effective by sparse vegetative cover and attendant slope instability, and raindrop splash erosion.

The present plains are of depositional origin and are mantled with a considerable thickness of coarse subangular to rounded debris in a matrix of finer material. The plains are punctuated with smooth erosional surfaces on which drainage is generally disarticulated and distinct channels are lacking. These are thinly mantled by fine textured material which is in transit via periodic rills and sheet washes. Longitudinal profiles throughout the modern plains are commonly from 235 to 350 feet per mile (45 to 67 meters per kilometer).[76]

In many portions of the Flinders Ranges, remnants of former valley floors and depositional plains remain as dissected plateaus and mesas. Former valley floors are mantled with coarse detritus which has protected them from erosion, similar to the Flaxville deposits in Eastern Montana, and have thus allowed an inversion of topography. These older surfaces have slopes of from 120 to 470 feet per mile (23 to 90 meters

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[75]C.R. Twidale, "Hillslopes and Pediments In the Flinders Ranges, South Australia," In Landform Studies From Australia and New Guinea, ed. J.N. Jennings and J.A. Mabbutt (Cambridge, MA.: M.I.T. Press, 1977): 96,97.

[76]Ibid., 103.

per kilometer).[77] Thus the depositional surfaces of the Flinders Ranges, while possessing some characteristics common to the Flaxville gravels, do not appear to closely resemble them.

Farther east in New South Wales and Victoria is the Riverine Plain, a large depositional plain across which the Lachlan, Murrumbidgee, Billabong, and Murray Rivers flow. These rivers drain the Great Dividing Range to the south and east, and hence traverse a substantial climatic gradient. Average annual precipitation decreases from 50 inches (120 centimeters) in the source highlands to about 12 inches (30.5 centimeters) where all four rivers join 300 miles (483 kilometers) west.[78] In this regard the Riverine Plain is analogous to the Missouri Plateau of eastern Montana.

During late Tertiary time the Riverine Plain was near sea level and subject to alternating marine and lacustrine deposition as evidenced in approximately 400 feet (123 meters) of Tertiary sediments.[79] This is overlain by 150 feet (46 meters) of Quaternary alluvium which is interbedded with thin eolian and lacustrine deposits and is dominated by sand and

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[77]Ibid., 106.

[78]F.R. Kalf and D.R. Woolley, "Application of Mathematical Modelling Techniques To the Alluvial Aquifer System Near Wagga Wagga, New South Wales," <u>Journal of the Geological Society of Australia</u> 24, pt.4 (June 1977): 179.

[79]Stanley A. Schumm, "River Adjustment To Altered Hydrologic Regime - Murrumbidgee River and Paleochannels, Australia," <u>U.S. Geological Survey Professional Paper</u> 598 (1968): 7.

clay-sized particles. Two former channels of the Murrumbidgee River, believed to be of Pleistocene age, have been studied in detail by Schumm and have yielded some fine gravel-sized material mixed with sand.[80] Holocene sediments are restricted to fluvial sand and clay, while present rivers carry primarily suspended sediment.

The Eastern Highlands of the Great Dividing Range have not experienced any tectonic modification since before Tertiary time, hence shifts in sediment and runoff on the Riverine Plain are assummed to be the result of changes in climate. Thus the coarser paleochannel deposits are believed to represent drier, perhaps interglacial climatic periods.[81] Farther upstream where the Murrumbidgee River is confined to a valley channel, a thick section of gravel is believed to be the time-equivalent of these same paleochannel deposits.[82] Pebbles in this layer are subangular to rounded and range from fine to coarse. This increase in particle size with decreasing distance from the sediment source is in keeping with accepted depositional principles.

The Riverine Plain is very flat, having a surface gradient of about 1.5 feet per mile (0.3 meters per

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[80]Ibid., 57.

[81]Ibid.

[82]F.R. Kalf and D.R. Woolley, "Application of Mathematical Modelling Techniques To the Alluvial Aquifer System Near Wagga Wagga, New South Wales," Journal of the Geological Society of Australia 24, pt.4 (June 1977): 181.

kilometer). Data suggest that the paleochannels of the Murrumbidgee River had similar average gradients.[83] In light of this, the amount of sand alluvially transported and deposited some 200 to 300 miles (322 to 483 kilometers) from source highlands is rather remarkable.

Many similarities exist between the Riverine Plain and the presumed Flaxville Plain. Widespread alluvial deposition across similar distances appears to be the result of arid climatic periods. The difference in particle size between Riverine sands and Flaxville gravels is probably a function of gradient. Thus the gradient across the Flaxville surface during the time of deposition must have exceeded 1.5 feet per mile (0.3 meters per kilometer). Differences in degree and length of aridity, as well as source rock types may also have contributed to differences in alluvial particle size.

Large alluvial deposits also exist in Saudi Arabia. Despite the present extremely arid climate, many former watercourses, or wadis are known. They characteristically begin in highlands and extend to adjacent lowlands as shallowly incised, gravel-floored channels that are buried by dune tracts. Two such wadis, although now bisected by the dunes of the Dahna desert in central Saudi Arabia, are believed to have been one channel during Pleistocene pluvial

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[83]Stanley A. Schumm, "River Adjustment To Altered Hydrologic Regime - Murrumbidgee River and Paleochannels, Australia," U.S. Geological Survey Professional Paper 598 (1968): 37.

periods. The Wadi ar-Rimah transported gravel from crystalline uplands in the western portion of the country during intermittent floods, some 600 miles (965 kilometers) east through the lower Wadi al-Batin to the Tigris-Euphrates Valley in southern Iraq. The overall gradient of this surface is a mere 5 to 6 feet per mile (1 to 1.1 meters per kilometer). The area of deposition is a delta-shaped gravel plain called the ad-Dibdibba and is presently traversed by the Wadi al-Batin. Numerous divergent gravel trains cover the surface of the plain, which has a gradient of 2.4 feet per mile (0.5 meters per kilometer).[84] Cobbles and pebbles decrease in size from its apex toward the outer edge.

Farther south, the Nisah-Sahbah wadi system also formed a similar gravel plain. Beginning in the central plateau region, gravels were transported east to the Qatar Peninsula across a surface gradient of about 10 feet per mile (1.9 meters per kilometer). Gradients across the gravel plain at the system terminus vary from 1.8 to 2 feet per mile (0.3 to 0.4 meters per kilometer).[85]

The depositional features described above are considered deltaic, having been graded to Pleistocene sea levels. In this respect they are quite different from the gravel plain of the Flaxville formation. However, the Arabian wadis suggest that

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[84]Donald August Holm, "Desert Geomorphology In the Arabian Peninsula," Science 132, no. 3437 (1960): 1374.

[85]Ibid., 1375.

gradients equivalent to the Flaxville Plain allow transportation of coarse material for great distances. The terminal gravel plains may indicate a gradient threshold beyond which widespread deposition occurs, or perhaps higher sea levels.

In conclusion, I believe that its contemporaneous nature makes the plain of the Ogallala formation the best available analogue to the Flaxville Plain. At its maximum extent, the Flaxville Plain may have closely resembled that of the Ogallala. It probably began as an immense bajada along the Rocky Mountain front and extended into the study area as a gently rolling plain. In longitudinal profile it was broadly concave. Intermittent and ephemeral streams with many distributaries resembling modern desert rivers, shifted across the surface in wide, shallow channels. The mountain outliers probably appeared as islands partially buried in their own debris.

Based on the Ogallala formation and estimates made by Alden, surface gradients of the Flaxville Plain probably ranged from 7 to 12 feet per mile (1.3 to 2.3 meters per kilometer) along its mid section in the western portion of the study area. Near its distal end in North Dakota, a gradient from 5 to 10 feet per mile (1.0 to 1.9 meters per kilometer) is likely. These figures exceed the apparent lower limit of gravel transport suggested by the gradients of the Riverine Plain and the alluvial gravel plains in the Saudi Arabian example. Near the mountain outliers, the estimated gradient steepened to as much as 100 feet per mile (19 meters per kilometer) as these uplands contributed detritus directly to the plain in their vicinities.

Techniques

Cartographic reconstruction of the Flaxville Plain surface was accomplished using the Surfer computer program by Golden Software Inc. The program, which runs on desktop computers, is designed to create two or three dimensional plots from randomly distributed X,Y,Z coordinate data. Topographic maps of the study area were produced using the Topo subprogram which allows comparison with maps of the present surface. The Surf subprogram was used to create three-dimensional representations that illustrate the former surface and make it easier to visualize.

Trend surface analysis was also used in evaluating the reconstructed surface. This procedure allows a smoothing of the spatial surface thus removing local "noise", or departures from the trend. It was accomplished using the SYMAP, or Synergraphic Mapping program written at Harvard University, to rasterize the trend surface data of the study area. This information could then be viewed from variable oblique perspectives and plotted using ASPEX, or Automated Surface Perspectives, also of Harvard University. Maps of trend surface and residuals were used in evaluating how closely the reconstructed surface resembled the proposed model, and where deviations occurred. All work with these two programs was done on a VAX mainframe computer.

The necessary X and Y control points and elevations were taken from 14 U.S.G.S. 1:250,000 scale topographic maps that cover the study area. Control points were digitized using a grid system described below, while elevations were determined visually and entered into the data base manually. The same data sets were used in all computer applications.

Coordinates taken from a computer-generated topographic map, were used in creating a slope profile. This profile allowed direct calculations of surface declivities and thus quantitative comparison to the Ogallala formation.

Sampling Design

Sample size was based on a pilot study of 26 slope measurements of the upland surfaces within the study area. Thus the variability in slope was determined to have a standard deviation of $(1.63)^{-5}$ feet per mile. The formula N = (standard deviation)^2 x $(Z)^2$ / $(T)^2$ was used to determine the minimum sample size required. In this formula N = sample size and Z = the confidence interval which was set at .99, for which a corresponding Z value of 2.57 was used. T = the acceptable amount of error and was set at $(5)^{-4}$, which is below the limit of slope accurately detectable due to the contour interval of the maps used. By this procedure a minimum required sample size of 431 points was established.

A grid network roughly corresponding to latitude and longitude was placed over the study area. The operational taxonomic unit or grid cell size, was set at two inches overlaying maps of scale 1:250,000. Over the extent of the study area, this produced a total of 1093 grid cells. It was felt that this cell size was justified, given that it greatly exceeds the necessary minimum sample size and was convenient to work with. Control points, or X and Y locations, were located within the center of each grid cell. The elevation or Z value to be posted at each control point was the highest elevation that occurred within each grid cell (Appendix A).

The ultimate objective of the sampling procedure was to capture the former land surface with as much accuracy and validity as the data would allow. This is the reason it was decided to purposely select the highest point from each cell, as any random system of selection would have risked the possibility of many points within modern drainage courses being chosen. The system used did insure sample points selected only on upland interfluves, but on occasions the highest elevation in a cell occurred on an isolated butte or ridge which was not generally representative of the flattish High Plains surface. There appeared to be no way out of this dilemma and yet retain the necessary uniformity of procedure, thus the decision was made. It was also thought that departures from the genuine High Plains surface as those noted would be recognizable as such on output maps.

The placement of the control point at the center of each grid cell facilitated the operational aspect of the data gathering process. Moreover, by locating these points uniformly, a smoother more generalized surface would result which does not so directly reflect present topographic features. This also avoided some of the practical difficulties of digitizing and doing detailed work with a 12 foot (3.7 meter) map on a 3 foot (0.9 meter) digitizing board.

CHAPTER 4

DATA ANALYSIS

Map Presentation and Analysis

The reconstructed topographic surface that existed in Flaxville-time is represented in a variety of ways for comparison to the hypothetical model. Each type of representation has inherent advantages and disadvantages, making it difficult to draw conclusions from any single one. The comparison begins with the topographic map, the type of surface representation with which most people are familiar.

Three topographic maps of the study area were produced with differing contour intervals. These provide a perspective of the topographic surface that existed during Flaxville-time with varying degrees of generalization. The first two maps (Figures 9 and 10), are at contour intervals of 500 feet (154 meters) and 200 feet (61.5 meters) respectively. A much larger, more detailed map (Figure 11) with a contour interval of 100 feet (31 meters) is in a pocket on the back cover.

Distances and elevations on all three maps are given in British units. The United States Geologic Survey is currently in the process of converting topographic maps to metric units, but those covering the study area are not yet available. The blank spaces within the map border are the result of the irregular shape of the study area. Contour lines were not

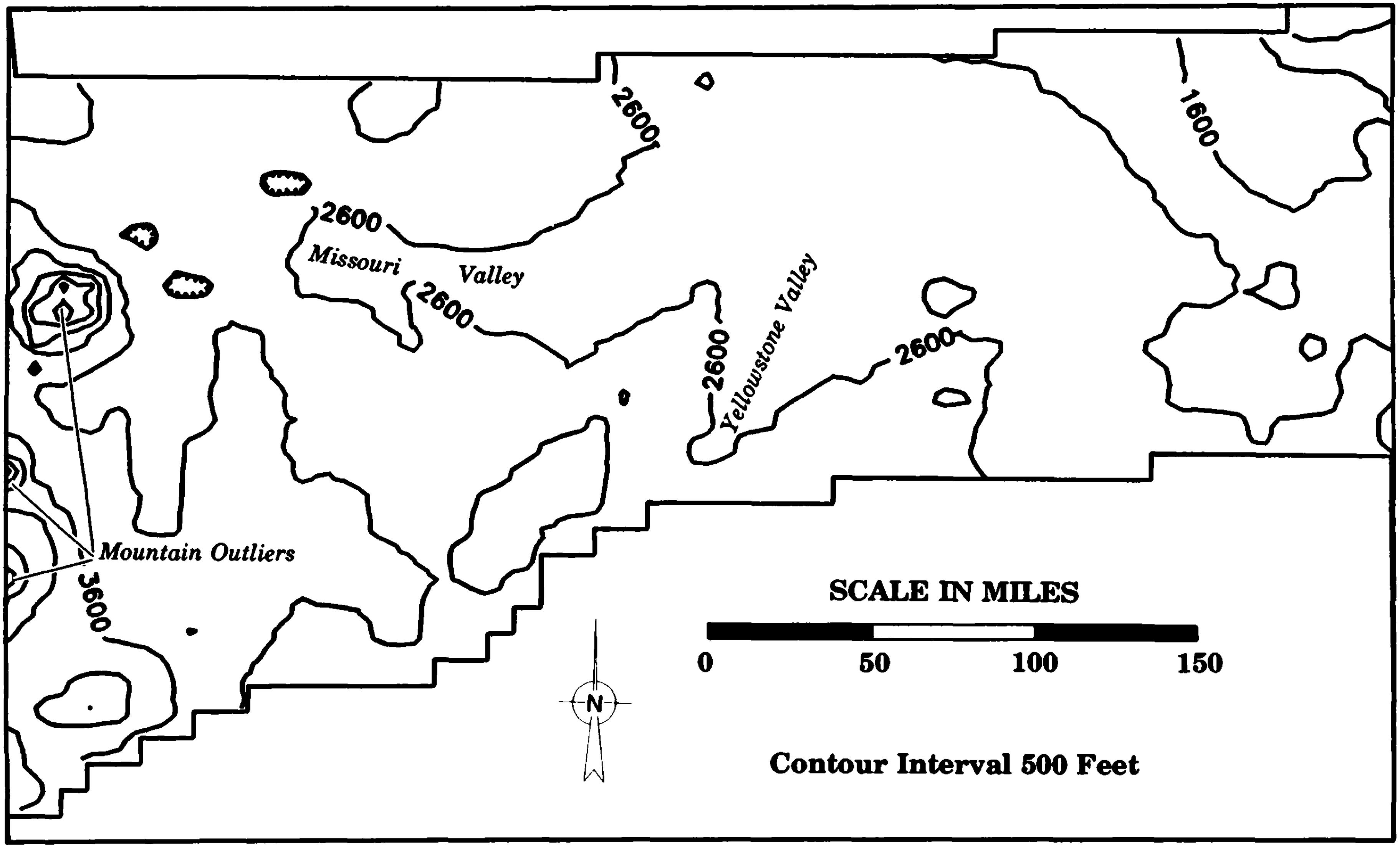
2600
1600
2600
Missouri
Valley
2600
2600
Yellowstone Valley
2600
Mountain Outliers
3600
SCALE IN MILES
0
50
100
150
N
Contour Interval 500 Feet

Figure 9

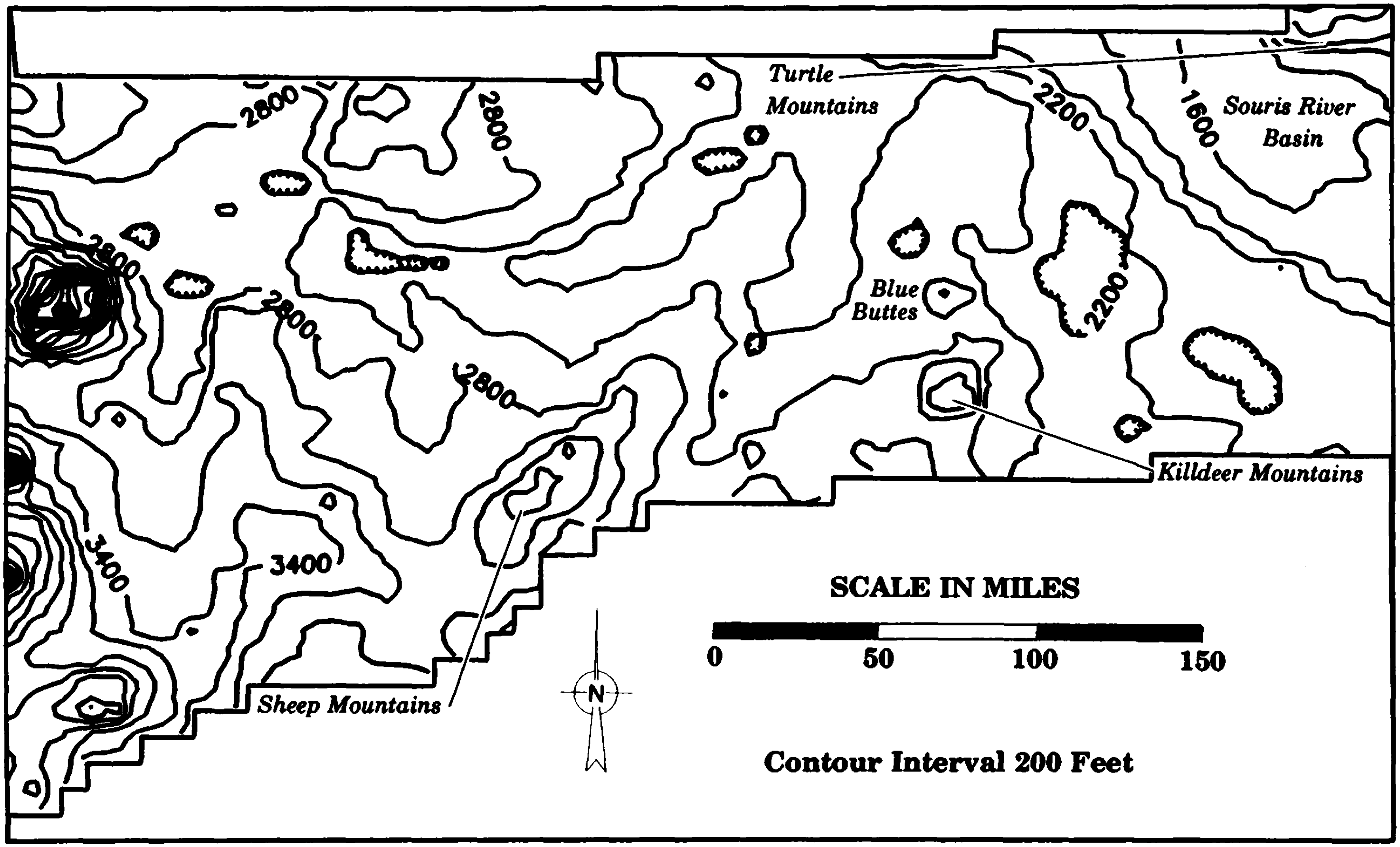
Turtle Mountains
Souris River Basin
Blue Buttes
Killdeer Mountains
Sheep Mountains
2800
2200
1600
3400
SCALE IN MILES
0
50
100
150
N
Contour Interval 200 Feet

Figure 10

extended into these spaces because data were not included for them.

Figure 9 shows the greatest degree of generalization. The regional surface appears flattish, but slopes to the northeast in keeping with the hypothesized Flaxville Plain. Along the left-hand margin closely spaced concentric contour lines represent areas of great relief, the mountain outliers. Since contour lines that cross watercourses always point upstream, the finger-like projections in the line at the center of the map denote the river valleys of the Missouri and Yellowstone.

In Figure 10, much more detail is apparent. It shows features of moderate relief, such as the Sheep and Killdeer Mountains and the Blue Buttes. The Missouri Escarpment is represented by several parallel lines in the northeast corner of the map. These border the Souris River Basin and the Turtle Mountains which belong to the present Central Lowlands province. Taken as a whole, this map indicates a fairly complex landscape existed during Flaxville-time.

The most striking aspect of Figure 11 is its resemblance to the modern landscape. All highlands and plateaus as well as most major stream channels are visible. There are, however, some differences from the modern land surface. Most of these are associated with the absence of the modern Missouri River Channel. The trough of the Musselshell River emerges between the Bull and Little Snowy Mountains, and extends north to the former Missouri River channel, now occupied by the Milk River.

The present Missouri River incised the northern projection of highland east of the Little Rockies while flowing along the front of the continental ice sheet. Beginning in the vicinity of 106 degrees west longitude, the Missouri River trough widens and veers north of the present river valley. This course probably represents the pre-ice age channel. Thus the present confluence of the Missouri and Yellowstone Rivers near the intersection of 48 degrees north latitude and 104 degrees west longitude, may be 60 or 70 miles (97 to 113 kilometers) southwest of a confluence suggested by the map. Figure 11 indicates a landscape traversed by streams. Because the important ice age modifications to the regional drainage system are confined to those mentioned above, it seems reasonable to assume that the stream channels suggested by the map were present before the end of Flaxville gravel deposition. Thus the topographic maps do not support the notion of the Flaxville formation as a continuous, rolling, largely streamless, desert plain.

The block diagram is a pictorial representation of a topographic surface. It is drawn from an oblique perspective which produces the impression of three dimensions, thus making the surface easier to comprehend. The block diagrams produced with the Surf subprogram simply portray the surface as it existed in Flaxville-time. To make surface irregularities more apparent, the vertical scale is approximately 120 times that of the horizontal scale (Figure 12). The "walls" surrounding

Block Diagram View Northeast

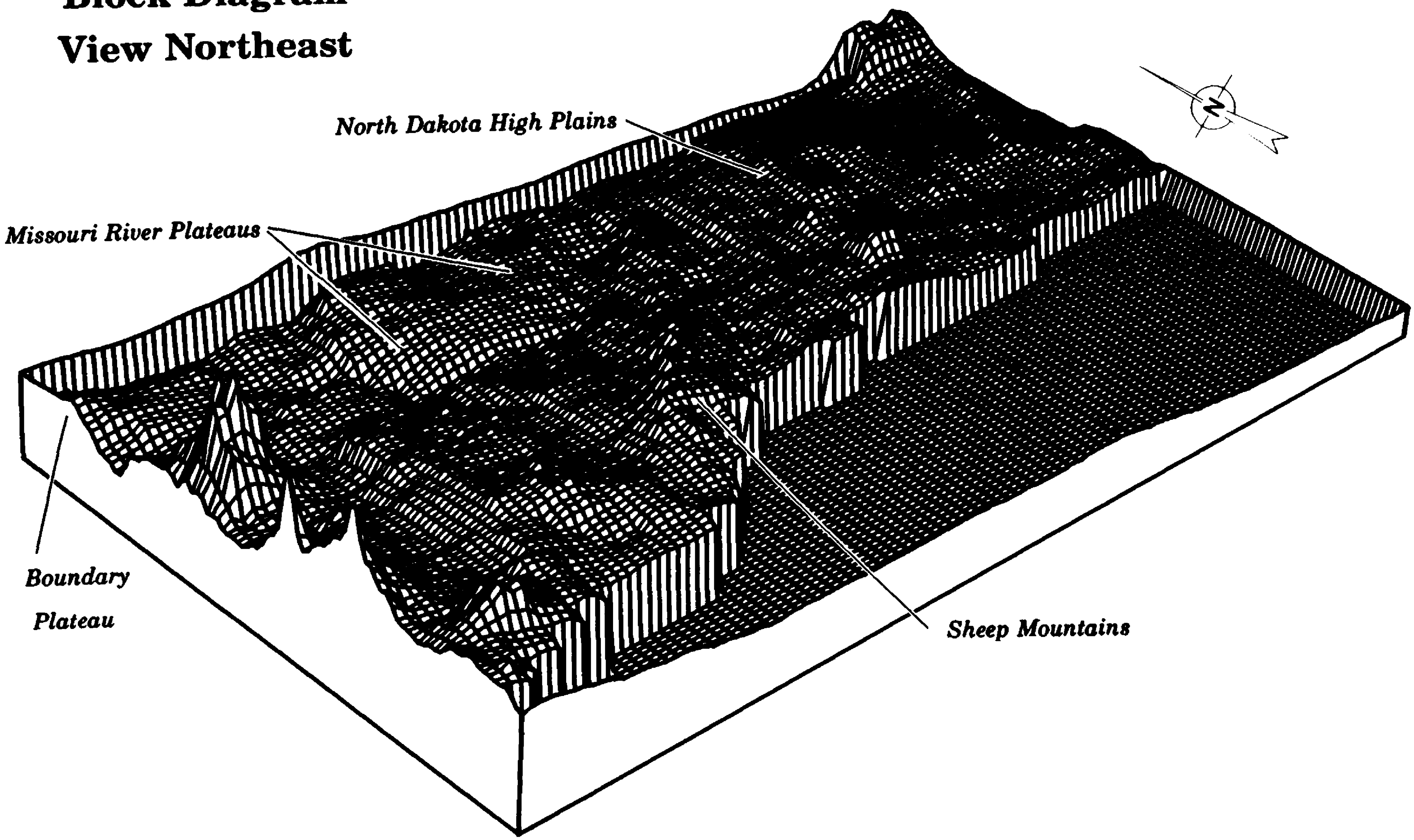

Figure 12

the diagram are an artifact of the program. The flat areas correspond to the blank sections of the topographic maps for which there were no data, giving the overall impression of a relief model lying in a rectangular bathtub. In Figure 12 the view is to the northeast from 35 degrees above the horizontal. As on the detailed topographic map, the mountain outliers are immediately apparent, as are the lesser highlands of the Bull, Sheep, Killdeer and Turtle Mountains. The flat-topped interfluves that bear Flaxville gravel are made more obvious by the vertical exaggeration. These include the Boundary and Missouri River Plateaus, the large expanse of upland east of the mountain outliers and that flanking the Sheep Mountains. The tract that lies north of the Missouri River in northwest North Dakota appears similar, although Flaxville gravel has not been reported there.

Figure 13 provides another perspective, looking to the northwest from 35 degrees above the horizontal. In this diagram the dark-appearing troughs are more easily recognised as drainage courses. The most prominent of these are; the Musselshell River just east of the mountain outliers, the pre-ice age Missouri River, and the lower Yellowstone River. The plateau-like interfluves of the High Plains surface are also visible from this perspective. These remnants stand above adjacent drainage courses and lower-lying basins. Acknowledging the vertical exaggeration present, the impression conveyed by the block diagrams is that the overall

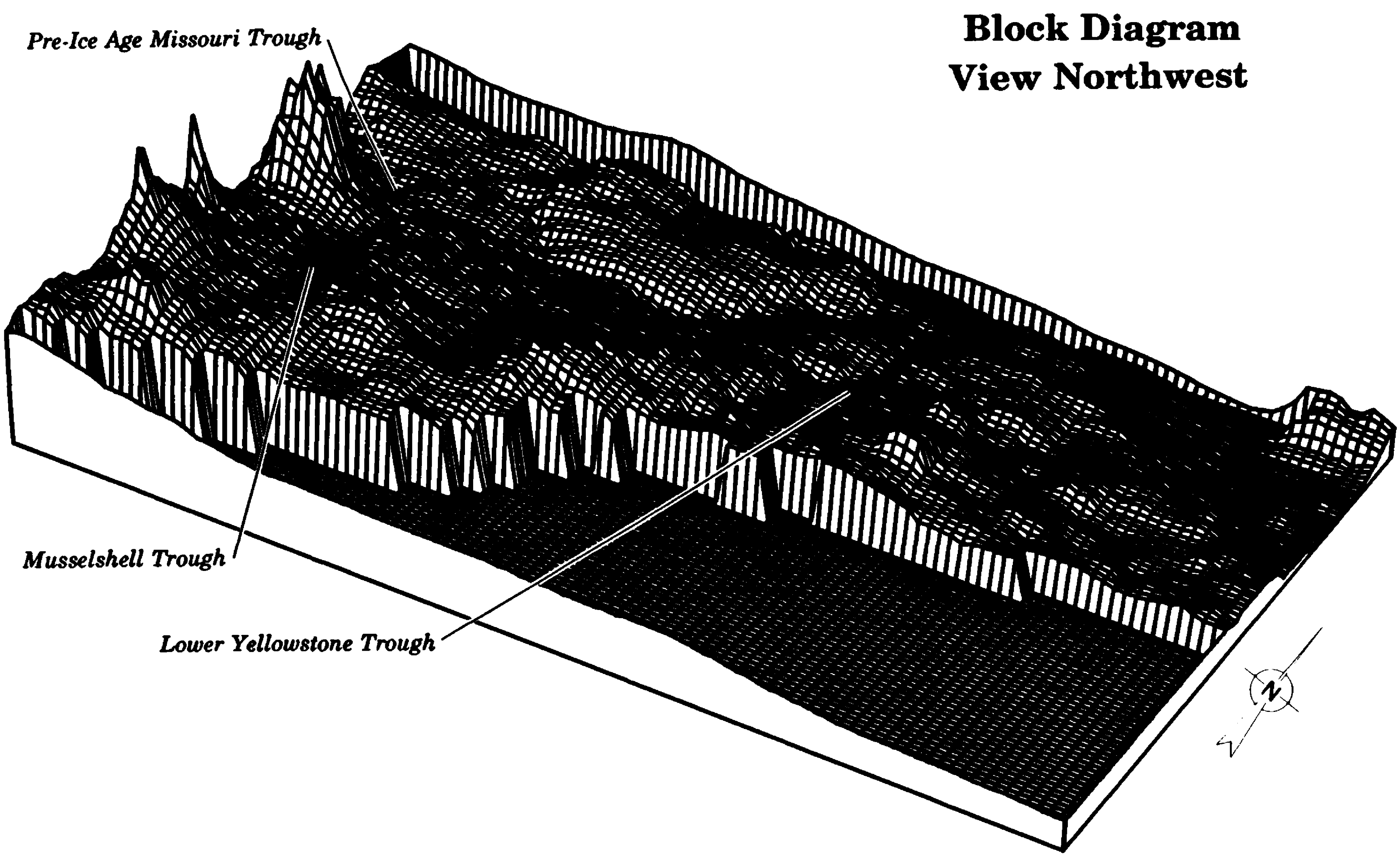
Block Diagram
View Northwest
Pre-Ice Age Missouri Trough
Musselshell Trough
Lower Yellowstone Trough
N

Figure 13

surface is relatively flat and plain-like. This offers some contrast to the topographic maps which focus attention on surface irregularities. On the basis of these diagrams, widespread, if not continuous Flaxville deposition appears somewhat more plausible.

The next set of maps was produced for trend surface analysis. This process is similar to regression analysis where a "best fit" line is determined for a scattering of points on an X, Y grid. Trend surface analysis however, includes a third dimensional "Z" term, hence the resulting surface is a best fit plane. The purpose of the analysis is to produce a smoothed spatial surface which allows the detection and separation of trends masked by the complexity of the actual topography. In the present case the trend surface should demonstrate the formerly continuous level of the High Plains extending smoothly and predictably over most of the study area. This technique of large-scale generalizing is especially valuable, given the unexpected complexity of the derived topographic maps.

The basic trend surface equation can be stated as: elevation (Z), as related to trend (the location in the X and Y directions), plus residuals (local departures from this relationship). Specifically the residual is the difference between the observed Z value and the derived value from the fitted surface at the same X, Y location. The trend surface is calculated as an equation according to the least-squares criterion so that the sum of the squared residuals is minimum.[86] The simplest trend surface equation is linear, resulting in a plane. A more complex equation, the quadratic, includes a squared term to allow a bend in the trend surface. A cubic equation utilizes a cubic term in addition to the squared and linear terms, to describe a surface with two bends. As the best fit calculations are made more complex and flexible, the trend surface increasingly resembles the actual surface.

The mapped trend surface may be compared with maps of the actual surface to detect any degree of similarity which may be interpreted as a trend. The coefficient of determination (Appendix B), which is a measure of how closely the trend surface fits the original, provides an index of the strength of the trend.[87] This is stated numerically on a scale from zero to one where zero indicates no fit or trend, while one represents a perfect fit. Finally an F-ratio is calculated to insure that the coefficient has statistical significance. Once verified, the specific processes responsible for the trend may be suggested, based on geographic laws, theories and hypotheses. Analysis of mapped residuals may also be

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[86]For examples and more information consult:
David Unwin, Introductory Spatial Analysis (New York, N.Y.: Methuen and Co. Ltd., 1981): 175-181.
or
R.J. Chorley and P. Hagget, "Trend surface mapping in geographical research," Transactions, Inst. Brit. Geogr. 37(1965): 47-67.

[87]Ibid.

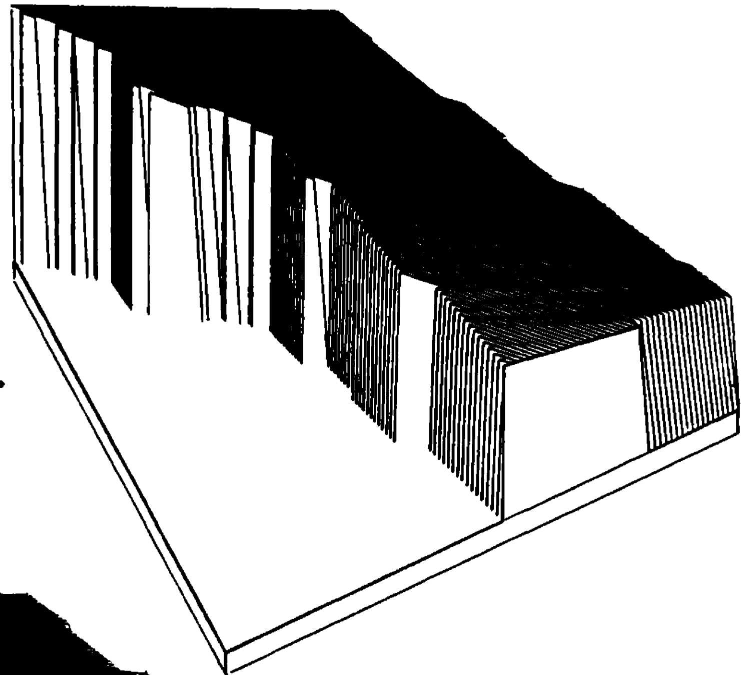
instructive since they might represent other systematic trends, and hence processes, not captured by the trend surface. They may however, also represent isolated departures from the trend or outright errors in the data base.

The series of diagrams in Figure 14 are trend surfaces of the study area at the first, third and sixth orders (Appendix B). The view in all three cases is toward the northwest. Initial inspection of the diagrams confirms the supposition of the regional surface sloping to the northeast.

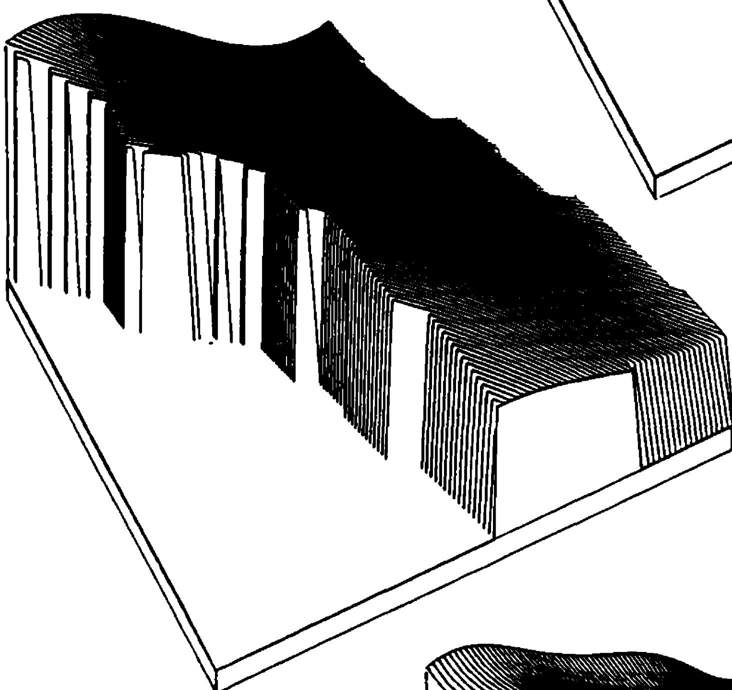
Diagram A. is a first order trend surface or simple inclined plane. All irregularities of the study area topography have been removed, leaving a uniformly sloping surface that is the closest possible fit to all of the elevations taken in the aggregate. The surface has a slope of approximately 6.5 feet per mile (1.2 meters per kilometer) and trends 46 degrees east of north. The coefficient of determination is 0.743 which indicates the amount of agreement between the actual and the trend surfaces. This figure is statistically significant at the .025 level. The primary utility of this highly generalized diagram is in the provision of an easily-grasped conception of the trend for comparison to more complex trend surfaces.

Diagram B. is a cubic or third order trend surface. The greater flexibility of this surface results in a generalized trough across much of the study. It appears to be created as the surface is curved upwards to conform to both the Boundary

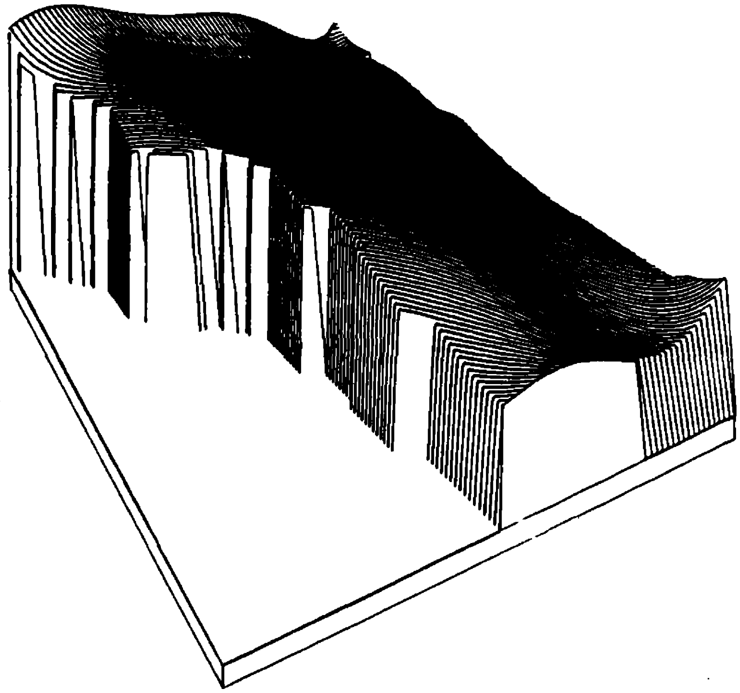
Trend Surface Plots



A.



B.



C.

Figure 14

and Missouri River plateaus along the northern boundary of the study area, and the mountain outliers and Bull Mountains near the western boundary. Hence this trough roughly represents the channels of the Milk and Missouri Rivers. The third bend in this surface is seen as a downturn towards the southwest edge of the study area along which the Yellowstone River flows. The flexibility in this surface produces a higher coefficient of determination of 0.787. Its F-ratio is also significant at the .025 level.

Diagram C. is a trend surface at the sixth order. The complexity of this surface reveals the general outlines of a number of features. The broad trough in the previous diagram representing the former Missouri River channel, presently occupied by the Milk River, is now much narrower and farther north. It is confined between upturns representing the Boundary Plateau to the north and the Little Rockies to the south. A slight dip between the Little Rockies and the next upturn to the south probably represents the sag through which the modern Missouri River has cut its gorge. The final downturn along the southern boundary represents the Little Snowy and Bull Mountains sloping down to the Yellowstone River. At the east end of the diagram a trough indicates the Souris River Basin and adjacent Turtle Mountains. The flexibility in approximating the actual surface which was achieved by six bends in the trend surface, yielded a coefficient of determination of 0.826. This figure is significant at the .025 level.

All three trend surface plots portray a subdued landscape which probably reflect both the flat-lying rock layers which underlie most of the study area as well as possible widespread Flaxville gravel deposition. The surface is modified however, by various peaks and troughs, which on the basis of their locations, correspond to mountains, plateaus and river valleys. Because the plots are based on the land surface that presumably existed during Flaxville-time, they suggest that sizable variations in the High Plains surface also existed at the time. The graphic peaks of the mountain outliers are to be expected since they are known to pre-date Flaxville deposition. The position of the troughs however, point to alluvial erosion and transport as the process most likely responsible for the remaining departures. The trend surface plots presented, represent a spatial surface free of local irregularities. But because Figures 14 B. and C. still contain significant departures from a more or less smooth surface, they do not appear to support the notion of a simple, continuous Flaxville plain resulting from a single geologic process. As expected, the higher the order of the trend surface, the closer the fitted surface approximates the actual. That greater flexibility is reflected in the increasing coefficient of determination scores. However, given the relatively subdued landscape over much of the study area, a coefficient higher than 0.826 for the sixth order trend surface might be expected. To pursue this further and to investigate other possible trends within the study area, the residuals from the first, third and sixth order trend surfaces have been plotted (Figure 15).

The view in each of the residual plots of Figure 15 is to the northeast. The features most prominent in these plots are those that deviate most from the corresponding fitted trend surface. They are the features in the actual landscape with the greatest relief. Hence it is not surprising that all three of the plots resemble the block diagram of the study area in Figure 12.

There is little difference between the upper and middle residual plots. The abrupt graphic peaks of the Little Rockies, Judith and Little Snowy Mountains are visible, as are the Bull, Sheep, Killdeer and Turtle Mountains and Blue Buttes. Also apparent are troughs representing the Milk, Musselshell, Yellowstone and lower Missouri Rivers. Although the same features are visible in the lower plot, it is somewhat more subdued as a result of the flexibility in the sixth order trend surface. Where the fitted trend surface was bent to accomodate large topographic features, the corresponding residual features have been reduced. This is seen in the Boundary and Missouri River Flaxville plateaus, in the Turtle Mountains and to some extent in the mountain outliers.

What is most striking about these residual surfaces is

Residual Plots

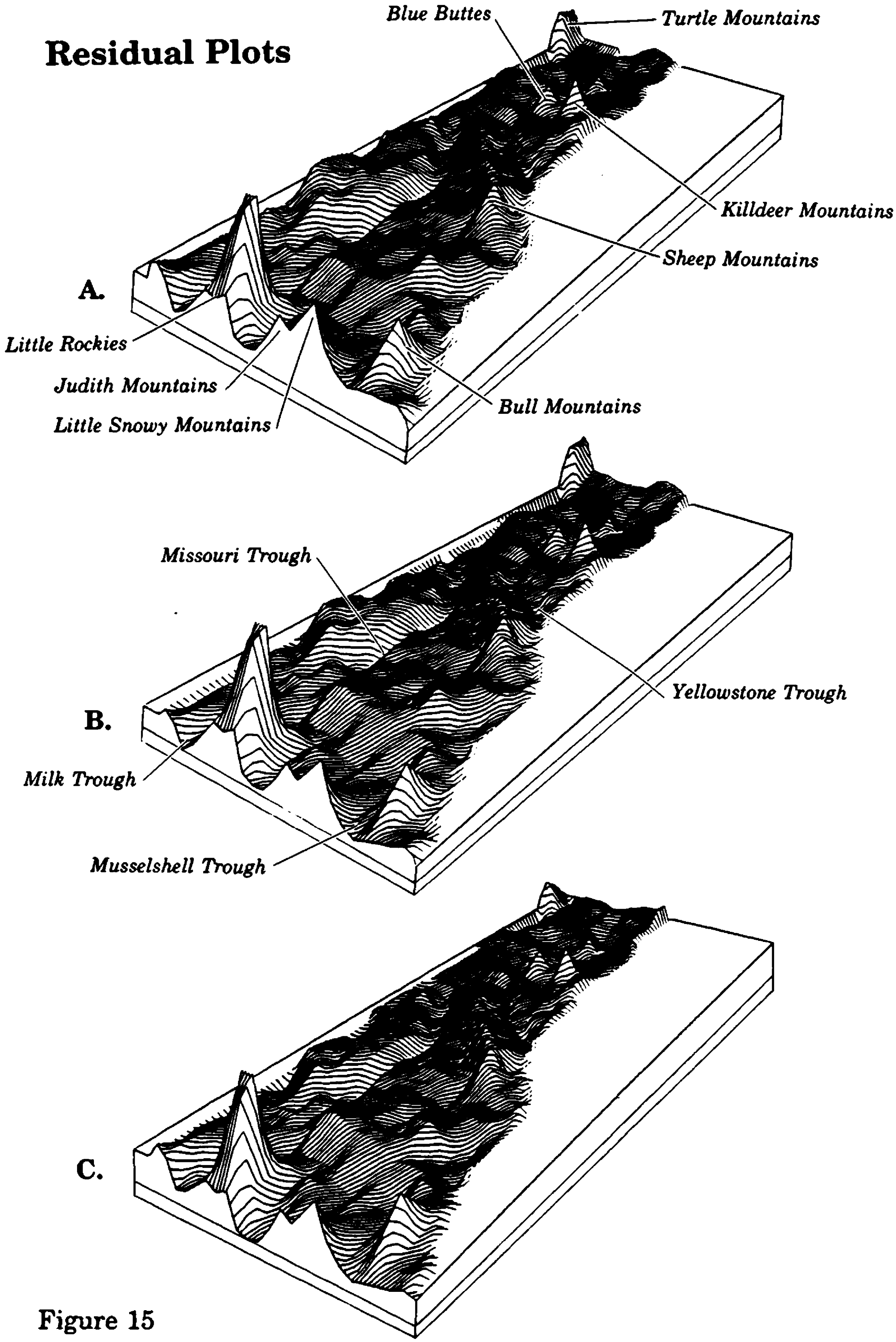


Figure 15

their similarity. Because residual areas are recognisable as prominent,individual topographic features in all three plots, it can be seen that the deviations from the trend surface are both localized and abrupt. This suggests that they are not part of the general trend, and that processes other than Flaxville deposition are responsible for their creation. Such processes would include igneous intrusions of Paleocene age for the mountain outliers, and differential erosion of primarily Fort Union formation sediments, also of Paleocene age. Thus the mountain-like features long pre-date Flaxville deposition. The appearance of troughs which correspond to rivers suggest that these channels were cut before Flaxville deposition and were only partly filled, or that they were in some way connected to Flaxville deposition. It is the presence of these troughs that make the idea of a continuous Flaxville plain uncertain.

The residuals do provide a partial explanation for the trend surface coefficient of determination scores. While a statistically valid trend across the study area does exist, departures from the trend are localized and abrupt. Thus it would require a trend surface of much higher order to conform closely enough to these departures to obtain a significantly higher coefficient of determination.

The final data to be presented are slope measurements of the Flaxville surface. These are compared with the estimates based on a review of other desert landforms.

The first estimate of slope was taken from the first order trend surface or best fit plane. By using the formula: $G = [X^2 + Y^2]^{0.5}$, where gradient = $[(X\ slope)^2 + (Y\ slope)^2]^{0.5}$, the slopes in both the X and Y direction are taken into account. Finding the cotangent of this angle yielded a slope of 6.5 feet per mile (1.2 meters per kilometer). This figure provides only a very general idea of the study area slope because it averages the steep slopes of the mountain outliers with the rest of the surface.

The remaining slope measurements are based on a plot (Figure 16) of actual occurences of Flaxville gravel throughout the study area. Locations of the formation reported in the literature and on maps were plotted on a copy of the computer-generated topographic map of the study area (Figure 11) on the basis of latitude and longitude. Fifty two points were then plotted from this map on an X, Y grid where the X-axis represented distance from the western boundary of the study area, and the Y-axis represented elevation (Appendix C). This plotting was done perpendicular to the trend or fall line across the study area to allow the use of all points, and to maintain the appropriate distance between points on the X-axis. Of the 52 points used, 5 points represent the mountain outliers, 4 points were taken from the Boundary Plateau, 41 points from the Missouri and Yellowstone River Flaxville plateaus and 2 points repesented the only reported occurences from North Dakota.

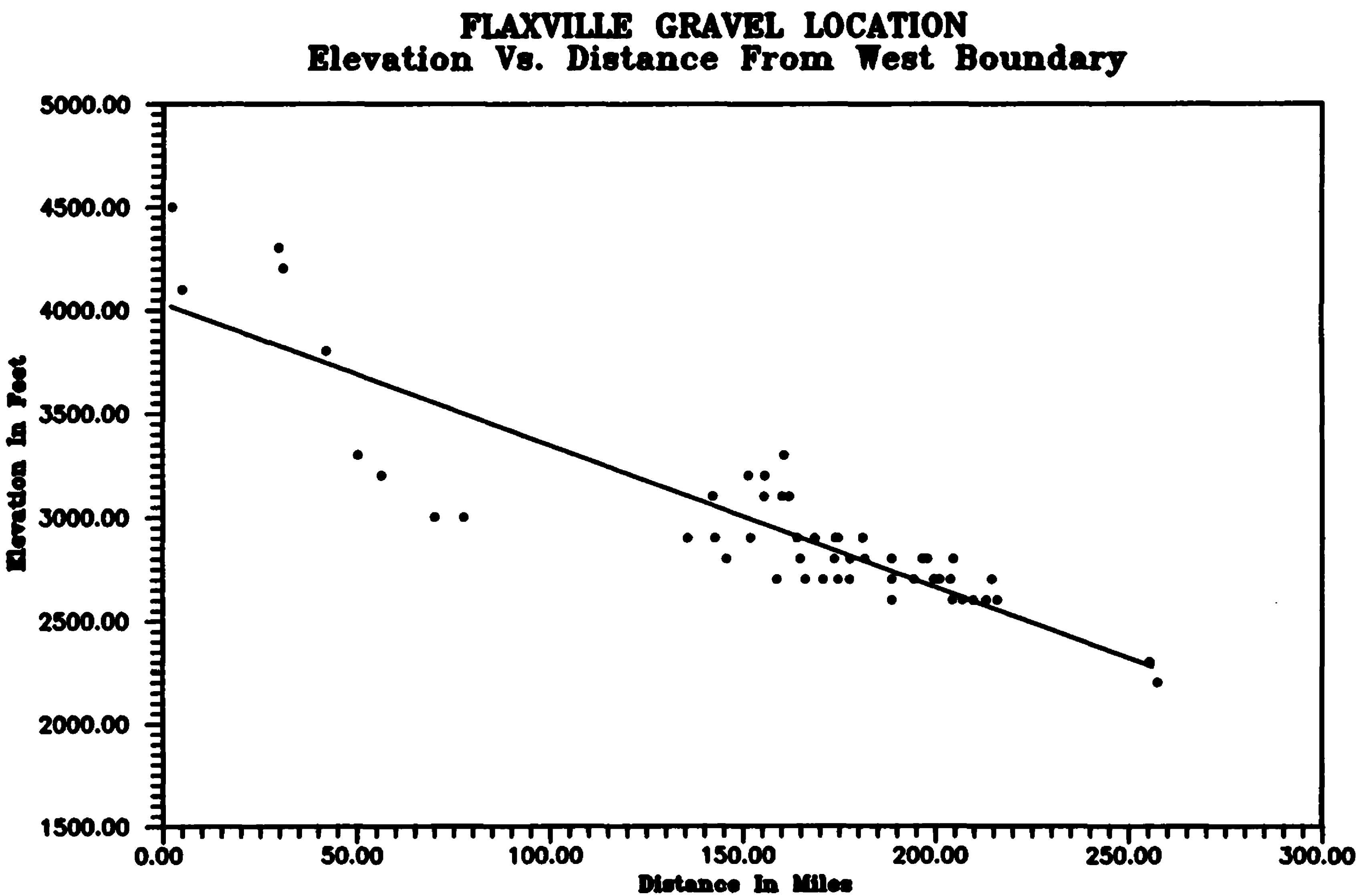

FLAXVILLE GRAVEL LOCATION
Elevation Vs. Distance From West Boundary
5000.00
4500.00
4000.00
3500.00
3000.00
2500.00
2000.00
1500.00
Elevation In Feet
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Distance In Miles

Figure 16

Slope measurements were calculated as part of a regression equation with Minitab, a Vax mainframe computer program (Appendix C). A slope figure was calculated for all 52 points as well as for selected subsets representing different portions of the Flaxville surface. Each was tested using an F-ratio and with the exception of the mountain outlier subset, all were statistically significant. The slope for the Flaxville surface as a whole was 5.4 feet per mile (1.0 meter per kilometer). The slope for all points not taken from the mountain outliers (ie. the plateau surfaces) was 3.4 feet per mile (0.64 meter per kilometer). A slope of only 3.2 feet per mile (0.6 meter per kilometer) was determined for the Boundary Plateau, Missouri River and Yellowstone River Flaxville plateaus. When the points from North Dakota were substituted for the Boundary Plateau, a slope of 4.9 feet per mile (0.9 meter per kilometer) was obtained. Finally the slope of the mountain outliers alone was determined to be 7.4 feet per mile (1.4 meters per kilometer). The variability that makes this last figure questionable is probably the result of figuring a regression line on only 5 points.

Without exception these slope gradients are less than those predicted. A slope of 3.4 feet per mile (0.64 meter per kilometer) is less than half the 7 to 12 feet per mile (1.3 to 2.3 meters per kilometer) anticipated for the mid section of the proposed plain. Even 5.4 feet per mile (1.0 meter per kilometer) for the whole Flaxville surface including the mountain outliers is less than this estimate. A toe slope of 4.9 feet per mile (0.9 meter per kilometer) is also less than the 5 to 10 feet per mile (1.0 to 1.9 meters per kilometer) predicted. The greatest discrepency however is between the calculated 7.4 feet per mile (1.4 meters per kilometer) and the estimate of up to 100 feet per mile (19 meters per kilometer) for the slopes that encircle the mountain outliers.

Clearly the Flaxville surface is almost flat. Gradients similar to these characterize alluvial plains on other continents. This confirmation lends support to the hypothesis of the surface as an alluvial plain. The slope measurements provide little clue though, to the original extent of the plain.

Evaluation of Hypothesis

The goal of this research project is to test the hypothesis that the presently disjunct upland surfaces which bear the Flaxville formation, were once part of a continuous alluvial plain which extended across the study area into the high plains of North Dakota. This has been accomplished by development and comparison of evidence of several kinds. The former extent of the Flaxville formation has been outlined on the basis of location of present remnants and topography similar to present remnants, and comparison with the Ogallala alluvial plain. The geologic processes of shifting desert streams and sheetwash, responsible for the Flaxville surface have been discussed. Analysis of topographic maps, block diagrams, trend surfaces and slope measurements, has tested the degree to which cartographic representations of the former Flaxville surface possess the configuration of an alluvial plain.

In conclusion, the portion of the hypothesis suggesting that the Flaxville formation represents the remnants of an alluvial plain, is accepted. Beyond the stream-rounded nature of the gravels, and the accordant summits of the plateaus capped with it, the slope gradients determined for the formation leave little other explanation. Slopes of 4 or 5 feet per mile (0.76 to 0.95 meter per kilometer) are most similar to plains of alluvial material deposited in a desert climate in other parts of the world.

However, evidence was not found to support the remainder of the hypothesis because the Flaxville plain was not continuous and did not extend widely into North Dakota. Such a limitation is based largely on the detailed topographic map of the study area at the Flaxville level (Figure 11) which portrays a landscape similar to the present. The surface is much more complex than the continuous, streamless, rolling alluvial plain proposed. The trend surface analysis yielded a similar result with broad troughs corresponding to rivers crossing the highly generalized third and sixth order trend surfaces. Residual plots indicate that these troughs were relatively deep and narrow, hence they must pre-date the Flaxville surface and have been partially filled, or be in some way connected with Flaxville deposition. There is an apparent spatial association between these ancestral river channels and the stream-rounded Flaxville gravels. Because the channels converge in the extreme northwestern corner of North Dakota and appear to continue north, and because no Flaxville gravel has yet been found outside of Divide County, it is reasonable to conclude that the Flaxville formation did not extend across the high plains of North Dakota.

CHAPTER 5

CONCLUSIONS

Implications and Discussion of Results

The challenge presented by the Flaxville gravel is its proper interpretation, based on the scarce present remnants of the formation. However, from some facts about the formation, reasonable, if not irrefutable, conclusions can be drawn.

The Flaxville formation buries a former landscape, lying unconformably on the eroded sufaces of older geologic formations. Weakly consolidated gravel such as that in the Flaxville formation, tends to resist erosion by allowing water to infiltrate rather than run off. A thick deposit of gravel is more likely to resist erosion than a thin one. In the case of Flaxville deposition, a thicker accumulation of gravel is likely to have occurred in the basins or river valleys of the time. Thus it seems probable that the present remnants which have successfully resisted erosion, may represent the basins of the pre-Flaxville landscape or the river valleys of that time.

The pre-ice age Missouri River and the present Yellowstone River, are adjacent to the overwhelming volume of remnant Flaxville gravels. On the basis of the computer-generated topographic map of the Flaxville surface, it can be seen that the Missouri and Yellowstone Rivers were present during Flaxville-time. Fossil evidence indicates that an arid climate prevailed during much of the late Miocene and Pliocene periods. Based on the slope measurements of the Flaxville surface, the gradient was found to be very gentle. In order to transport the volume of material represented by the Flaxville formation, hundreds of miles from its source over very low gradients, the concentrated transporting power of an intermittent desert river would probably be required. In the Saudi Arabian alluvial plains cited earlier this is the case, where gravel transport over similar distances and gradients is confined to wadis rather than being distributed by overland sheetwash. For these reasons, the ancestral Missouri and Yellowstone Rivers are the most probable source for the present remnants, which may represent the thickest accumulations of the Flaxville formation.

It follows that the mountain outliers being the source of much smaller streams, contributed an accordingly smaller volume of material to the Flaxville surface. As the bajadas encircling the outliers were extended by sheetwash, they probably merged with the river-transported alluvium accumulating in the lowlands, but became lenslike or discontinuous where uplands were encountered. These thinning deposits may account for much of the apparent absence of Flaxville gravel in portions of the interfluve between the Missouri and Yellowstone Rivers.

On the basis of my research and a review of the work of previous authors on the Flaxville formation, I conclude that the following scenario of Flaxville deposition and subsequent erosion best fits the facts as I have outlined them. During the course of Flaxville deposition, Rocky Mountain detritus was carried several hundred miles north and east by the Flaxville-age Missouri and Yellowstone Rivers. Their floodplains were probably very shallow; in the case of the Missouri up to 100 miles (161 kilometers) wide, while the Yellowstone may have been closer to 30 miles (48 kilometers) wide. Being overloaded with alluvium, the rivers probably broke into distributary channels which shifted back and forth within their wide floodplains. At the same time a more limited desert plain grew from around the mountain outliers as a series of coalescing bajadas. This plain probably merged with those of the Missouri and Yellowstone Rivers where topography was favorable, and thinned with increasing distance to the east, or where the older surface sloped up. In the extreme northwest corner of North Dakota, the two major alluvial plains merged and appear to have continued north into Saskatchewan. Thus only the corner of North Dakota ever received any accumulation of Flaxville gravel.

The subsequent climate changes which triggered the ice ages, favored erosion and allowed the rapid cutting of the narrower present river valleys into these alluvial plains. This left the Flaxville surface as a series of plateaus and terraces adjacent to the two rivers. Pleistocene erosion was also sufficient to remove most of the Flaxville gravel from the interfluve between the Missouri and Yellowstone Rivers, except in the vicinity of the mountain outliers where it was originally the thickest.

Before completion of the cartographic analysis in Chapter 4, I believed the Ogallala alluvial plain to be a good analogue for the poorly preserved Flaxville formation. The slopes of the Ogallala plain have however, been shown to be approximately twice as steep as those of the Flaxville surface. That probably resulted in much thicker accumulations of Ogallala alluvium and hence the much more complete preservation of the formation. The Flaxville alluvial plain is quite different from the Ogallala. Because of the much lower gradients, the thickest accumulation of alluvium was along the two master streams. Thus the Flaxville plain was probably never as thick or as continuous as the Ogallala plain, a notion supported by the greater irregularity on the topographic map of the Flaxville surface. This predisposed the more poorly developed Flaxville alluvial plain to greater erosion than the Ogallala. The proximity of the Flaxville to the repeated advances and retreats of the continental ice sheet may also have predisposed it to greater erosion than the more southerly Ogallala formation.

Sources of Error

It is critical that the method used to graphically capture the Flaxville surface be appropriate. Data gathered in accordance with this method led to production of maps and diagrams of the surface on which many of the conclusions of the thesis rest. As previously noted, the reconstructed Flaxville surface does bear a great resemblance to the modern landscape. It is possible that this resemblance indicates some degree of failure of the method used to achieve the desired result. If this is so, then the conclusions based on this information could be in error.

For the purposes of this project, it has been assumed that the study area has not undergone any significant tectonic deformation since the deposition of the Flaxville formation. Any post-Flaxville change in angle or trend of slope, might prompt inaccurate conclusions about the processes controlling the deposition and subsequent erosion of the formation. No direct evidence however, such as systematic drainage changes between Flaxville-age and modern streams, was observed. Also no reference to such a change was encountered in the literature reviewed.

Recommendations For Further Study

The first priority for further study, should be more detailed fieldwork and mapping. The area around the mountain outliers and the interfluve between the Missouri and Yellowstone Rivers is most in need of systematic Flaxville gravel identification. In addition to location, this identification should include deposit depths and apparent source, with special attention given to the discovery of fossils. Because so much of the original Flaxville plain has been removed, only detailed mapping on a region-wide basis will provide a more accurate picture of its former extent.

It might be instructive to map precisely-dated fossil remains from the Flaxville formation. By plotting all fossils according to their depth within the formation in addition to their location, a pattern of deposition might be detected. Extended over the entire region, this would shed light on the sequence of development of the alluvial plain.

Detailed mapping of areas where large thicknesses of the Flaxville formation persist would allow accurate reconstruction of the former surface. From these it would be possible to test for post-Flaxville deformation as suggested in the previous section. By superimposing the modern drainage system over the former surface, any systematic departures of the modern drainage would indicate the trend and possibly the degree of deformation. If this was duplicated across the region, even modest changes in orientation of the surface might be detected.

APPENDIX A Study Area Data Set

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28.76	16.7	2800

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28.76 14.71 2900	31.91 30.67 2700	33.78 19.67 2700	36.8 24.63 2400	39.83 25.61 2400	42.86 25.59 2300	45.85 24.56 2400	48.82 21.54 2600
28.76 13.71 3000	31.86 29.67 2700	33.77 18.66 2900	36.8 23.65 2500	39.81 24.6 2600	42.85 24.59 2200	45.84 23.56 2400	48.81 20.54 3100
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28.7 8.73 2900	31.82 24.68 2300	33.74 13.68 2800	36.79 18.64 2900	39.78 19.63 2300	42.8 19.6 2600	45.79 18.57 2700	49.91 33.51 1900
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29.88 29.68 2900	31.79 21.68 2700	34.92 30.66 2800	36.76 15.66 2700	39.76 16.64 2700	42.77 16.6 2800	46.9 32.54 2100	49.9 30.51 2500
29.86 28.7 3000	31.84 20.69 2800	34.87 29.65 2800	36.76 14.64 2600	39.76 15.64 2800	42.76 15.6 2800	46.9 31.54 2400	49.9 29.51 2500
29.86 27.69 2900	31.79 19.68 2800	34.86 28.66 2700	37.9 32.61 2500	40.89 32.6 2200	43.9 32.57 2300	46.9 30.54 2400	49.89 28.51 2600
29.82 26.68 2800	31.78 18.68 2800	34.86 27.66 2700	37.91 31.61 2500	40.9 31.59 2200	43.9 31.57 2300	46.9 29.54 2500	49.88 27.52 2500
29.84 25.7 2800	31.76 17.68 2900	34.81 26.65 2500	37.89 30.61 2600	40.9 30.6 2200	43.9 30.57 2300	46.89 28.54 2500	49.87 26.52 2500
29.81 24.7 2400	31.76 16.69 3100	34.83 25.65 2300	37.88 29.61 2500	40.9 29.59 2100	43.9 29.57 2200	46.88 27.55 2400	49.86 25.52 2500
29.82 23.7 2500	31.75 15.7 3600	34.82 24.65 2200	37.85 28.62 2300	40.85 28.6 2200	43.89 28.57 2200	46.87 26.55 2400	49.85 24.52 2200
29.8 22.69 2600	31.73 14.69 3400	34.8 23.66 2500	37.86 27.61 2300	40.85 27.58 2500	43.88 27.58 2200	46.86 25.55 2300	49.84 23.52 2300
29.79 21.69 2700	31.74 13.7 3400	34.81 22.66 2600	37.83 26.62 2300	40.82 26.6 2600	43.87 26.58 2200	46.85 24.55 2400	49.83 22.52 2400
29.83 20.7 2900	31.74 12.69 3000	34.79 21.66 2600	37.85 25.62 2300	40.82 25.61 2600	43.86 25.58 2200	46.84 23.55 2500	49.82 21.53 2700
29.79 19.7 2800	31.73 11.7 2900	34.84 20.67 2600	37.8 24.62 2400	40.82 24.59 2500	43.85 24.58 2300	46.83 22.55 2500	49.81 20.53 2500
29.77 18.7 2900	31.71 10.72 2600	34.79 19.67 2600	37.82 23.63 2400	40.8 23.6 2300	43.84 23.58 2300	46.82 21.56 2500	49.8 19.53 2400
29.78 17.69 2900	32.91 31.67 2700	34.78 18.66 3200	37.82 22.63 2700	40.81 22.61 2400	43.83 22.58 2400	46.81 20.56 2700	49.79 18.53 2500
29.77 16.69 2800	32.9 30.69 2700	34.77 17.66 3300	37.79 21.63 2700	40.77 21.61 2300	43.82 21.59 2600	46.8 19.56 2700	49.78 17.53 2400
29.76 15.7 3000	32.88 29.67 2700	34.77 16.65 3200	37.86 20.63 2800	40.77 20.61 2400	43.81 20.59 2600	46.79 18.56 2700	49.77 16.53 2600
29.76 14.7 3000	32.86 28.68 2800	34.76 15.67 3200	37.79 19.64 2900	40.77 19.61 2600	43.8 19.59 2700	46.78 17.56 2900	50.91 33.5 1900
29.75 13.7 3200	32.86 27.68 2800	34.74 14.67 3000	37.78 18.63 2800	40.75 18.62 2500	43.79 18.59 2700	46.77 16.56 2900	50.9 32.5 2000
29.75 12.7 3100	32.83 26.67 2700	34.76 13.67 2700	37.77 17.64 2800	40.75 17.62 3000	43.78 17.59 2600	47.9 32.53 2000	50.9 31.5 2300
29.74 11.71 3000	32.83 25.68 2600	35.89 32.63 2500	37.77 16.63 2600	40.73 16.63 2800	43.77 16.59 2700	47.9 31.53 2500	50.9 30.5 2500
29.71 10.71 2900	32.81 24.67 2200	35.9 31.61 2400	37.76 15.63 2600	40.73 15.63 3000	43.76 15.59 2900	47.9 30.53 2500	50.9 29.5 2400
29.71 9.71 3000	32.82 23.68 2500	35.94 30.64 2700	38.9 32.61 2400	41.9 32.59 2300	44.9 32.56 2200	47.9 29.53 2500	50.89 28.5 2400
30.91 31.7 2700	32.8 22.67 2500	35.87 29.65 2700	38.91 31.61 2700	41.9 31.59 2300	44.9 31.56 2200	47.89 28.53 2500	50.88 27.51 2400
30.9 30.69 2800	32.79 21.68 2600	35.85 28.66 2600	38.9 30.61 2500	41.9 30.59 2400	44.9 30.56 2300	47.88 27.54 2500	50.87 26.51 2400
30.88 29.7 2800	32.83 20.69 2700	35.86 27.64 2600	38.9 29.61 2300	41.9 29.59 2300	44.9 29.58 2400	47.87 26.54 2400	50.86 25.51 2500
30.86 28.7 2900	32.79 19.68 2700	35.83 26.65 2500	38.86 28.61 2100	41.89 28.59 2500	44.89 28.56 2400	47.86 25.54 2500	50.85 24.51 2300
30.88 27.7 2900	32.78 18.68 2800	35.83 25.65 2200	38.86 27.61 2200	41.88 27.6 2500	44.88 27.57 2400	47.85 24.54 2500	50.84 23.51 2200
30.84 26.69 2800	32.77 17.67 3100	35.81 24.64 2400	38.82 26.62 2300	41.87 26.6 2500	44.87 26.57 2500	47.84 23.54 2900	50.83 22.51 2300
30.83 25.68 2700	32.76 16.67 3500	35.8 23.65 2600	38.85 25.62 2500	41.86 25.6 2400	44.86 25.57 2500	47.83 22.54 2600	50.82 21.52 2400
30.82 24.7 2500	32.74 15.68 3500	35.8 22.64 2500	38.82 24.6 2500	41.85 24.6 2500	44.85 24.57 2400	47.82 21.55 2500	50.81 20.52 2500
30.81 23.69 2500	32.74 14.69 3100	35.78 21.66 2600	38.82 23.62 2700	41.84 23.6 2200	44.84 23.57 2500	47.81 20.55 3000	50.8 19.52 2400
30.79 22.68 2500	32.74 13.69 3000	35.83 20.67 2800	38.81 22.62 2600	41.83 22.6 2300	44.83 22.57 2500	47.8 19.55 3300	50.79 18.52 2500
30.8 21.69 2600	32.73 12.7 3000	35.79 19.66 3200	38.79 21.63 2700	41.82 21.61 2500	44.82 21.58 2500	47.79 18.55 2700	50.78 17.52 2400
30.82 20.7 2800	32.73 11.68 3000	35.77 18.65 3100	38.86 20.63 2700	41.81 20.61 2500	44.81 20.58 2500	47.78 17.55 2800	50.77 16.52 2300
30.79 19.69 2800	33.92 31.66 2800	35.76 17.66 2900	38.79 19.62 2700	41.8 19.61 2600	44.8 19.58 2700	47.77 16.55 2800	51.91 33.49 1900
30.79 18.69 2900	33.93 30.65 2800	35.76 16.66 3000	38.77 18.63 2700	41.79 18.61 2600	44.79 18.58 2700	48.9 32.52 2000	51.9 32.49 1900
30.77 17.68 2900	33.9 29.66 2800	35.75 15.66 2900	38.77 17.63 2400	41.78 17.61 2600	44.78 17.58 2900	48.9 31.52 2500	51.9 31.49 2000
30.77 16.69 2900	33.86 28.68 2700	35.75 14.67 2900	38.77 16.63 2700	41.77 16.61 2800	44.77 16.58 2700	48.9 30.52 2500	51.9 30.49 2300
30.75 15.69 3200	33.84 27.67 2700	36.9 32.64 2600	38.75 15.63 2700	41.76 15.61 2800	45.9 32.55 2100	48.9 29.52 2400	51.9 29.49 2300
30.75 14.69 3400	33.81 26.66 2700	36.9 31.64 2400	39.9 32.61 2200	42.9 32.58 2300	45.9 31.55 2300	48.89 28.52 2500	51.89 28.49 2400
30.75 13.69 3200	33.83 25.67 2500	36.93 30.64 2600	39.91 31.59 2500	42.9 31.58 2300	45.9 30.55 2300	48.88 27.53 2400	51.88 27.5 2300
30.73 12.7 3200	33.81 24.67 2200	36.88 29.64 2700	39.9 30.6 2500	42.9 30.58 2300	45.9 29.55 2400	48.87 26.53 2400	51.87 26.5 2300
30.73 11.71 3100	33.81 23.68 2400	36.85 28.66 2600	39.89 29.61 2300	42.9 29.58 2300	45.89 28.55 2400	48.86 25.53 2300	51.86 25.5 2300
30.71 10.7 2900	33.8 22.67 2500	36.86 27.64 2300	39.85 28.6 2100	42.89 28.58 2300	45.88 27.56 2500	48.85 24.53 2400	51.85 24.5 2100
30.71 9.7 2800	33.79 21.67 2500	36.81 26.65 2200	39.87 27.6 2300	42.88 27.59 2400	45.87 26.56 2500	48.84 23.53 2700	51.84 23.5 2200

51.83	22.5	2300
51.82	21.51	2400
51.81	20.51	2400
51.8	19.51	2300
51.79	18.51	2400
51.78	17.51	2400
51.77	16.51	2300
52.91	33.48	1900
52.9	32.48	1900
52.9	31.48	1900
52.9	30.48	2100
52.9	29.48	2300
52.89	28.48	2400
52.88	27.49	2200
52.87	26.49	2100
52.86	25.49	2100
52.85	24.49	2100
52.84	23.49	2200
52.83	22.49	2100
52.82	21.5	2200
52.81	20.5	2300
52.8	19.5	2300
52.79	18.5	2300
52.78	17.5	2400
52.77	16.5	2200
53.91	33.47	1800
53.9	32.47	1800
53.9	31.47	1900
53.9	30.47	2000
53.9	29.47	2200
53.89	28.47	2300
53.88	27.48	2300
53.87	26.48	2200
53.86	25.48	2200
53.85	24.48	2200
53.84	23.48	2200
53.83	22.48	2200
53.82	21.49	2200
53.81	20.49	2300
53.8	19.49	2400
53.79	18.49	2300
53.78	17.49	2300
53.77	16.49	2300
54.91	33.46	1700
54.9	32.46	1800
54.9	31.46	1800
54.9	30.46	1800
54.9	29.46	1900
54.89	28.46	2100
54.88	27.46	2300
54.87	26.47	2200
54.86	25.47	2200
54.85	24.47	2200
54.84	23.47	2200
54.83	22.47	2400
54.82	21.48	2200
54.81	20.48	2200
54.8	19.48	2300
54.79	18.48	2100
54.78	17.48	2200
54.77	16.48	2300
55.91	33.45	1600
55.9	32.45	1700
55.9	31.45	1700
55.9	30.45	1700
55.9	29.45	1800
55.89	28.45	1900
55.88	27.46	2100
55.87	26.46	2200
55.86	25.46	2200
55.85	24.46	2200
55.84	23.46	2300
55.83	22.46	2300
55.82	21.47	2000
55.81	20.47	2200
55.8	19.47	2200
55.79	18.47	2200
55.78	17.47	2300
55.77	16.47	2400
56.91	33.44	1600
56.9	32.44	1600
56.9	31.44	1600
56.9	30.44	1600
56.9	29.44	1700
56.89	28.44	1800
56.88	27.45	1800
56.87	26.45	2100
56.86	25.45	2100
56.85	24.45	2200
56.84	23.45	2100
56.83	22.45	2000
56.82	21.46	2000
56.81	20.46	2100
56.8	19.46	2000
56.79	18.46	2300
56.78	17.46	2300
57.91	33.43	1500
57.9	32.43	1500
57.9	31.43	1600
57.9	30.43	1600
57.9	29.43	1600
57.89	28.43	1600
57.88	27.44	1700
57.87	26.44	1900
57.86	25.44	2200
57.85	24.44	2200
57.84	23.44	2200
57.83	22.44	2000
57.82	21.45	1900
57.81	20.45	2000
57.8	19.45	2000
57.79	18.45	2300
57.78	17.45	2300
58.91	33.42	1500
58.9	32.42	1500
58.9	31.42	1500
58.9	30.42	1500
58.9	29.42	1500
58.89	28.42	1600
58.88	27.43	1600
58.87	26.43	1700
58.86	25.43	2000
58.85	24.43	2100
58.84	23.43	2100
58.83	22.43	2000
58.82	21.44	2000
58.81	20.44	2000
58.8	19.44	2000
58.79	18.44	2300
58.78	17.44	2200
59.91	33.41	1500
59.9	32.41	1500
59.9	31.41	1500
59.9	30.41	1500
59.9	29.41	1500
59.89	28.41	1500
59.88	27.42	1600
59.87	26.42	1600
59.86	25.42	1800
59.85	24.42	2100
59.84	23.42	2100
59.83	22.42	2000
59.82	21.43	2000
59.81	20.43	2000
59.8	19.43	1900
59.79	18.43	2000
59.78	17.43	2100
60.91	34.4	2500
60.91	33.4	2200
60.9	32.4	1600
60.9	31.4	1500
60.9	30.4	1500
60.9	29.4	1500
60.89	28.4	1500
60.88	27.41	1600
60.87	26.41	1600
60.86	25.41	1600
60.85	24.41	2300
60.84	23.41	2200
60.83	22.41	2000
60.82	21.42	2000
60.81	20.42	2000
60.8	19.42	2000
60.79	18.42	2200
60.78	17.42	2100
61.91	34.39	2500
61.91	33.39	2300
61.9	32.39	1600
61.9	31.39	1500
61.9	30.39	1500
61.9	29.39	1500
61.89	28.39	1500
61.88	27.4	1600
61.87	26.4	1600
61.86	25.4	1600
61.85	24.4	1900
61.84	23.4	2000
61.83	22.4	2100
61.82	21.41	2200
61.81	20.41	2000
61.8	19.41	2000
61.79	18.41	2200
61.78	17.41	2200
62.91	34.38	2200
62.91	33.38	2200
62.9	32.38	1600
62.9	31.38	1500
62.9	30.38	1500
62.9	29.38	1500
62.89	28.38	1500
62.88	27.39	1700
62.87	26.39	1600
62.86	25.39	1700
62.85	24.39	1700
62.84	23.39	2000
62.83	22.39	2100
62.82	21.4	2000
62.81	20.4	2100
62.8	19.4	2100
62.79	18.4	2100
62.78	17.4	2300
63.91	34.37	2400
63.91	33.37	2100
63.9	32.37	1600
63.9	31.37	1600
63.9	30.37	1600
63.9	29.37	1700
63.89	28.37	1600
63.88	27.38	1600
63.87	26.38	1600
63.86	25.38	1600
63.85	24.38	1800
63.84	23.38	1800
63.83	22.38	2100
63.82	21.39	2200
63.81	20.39	2200
63.8	19.39	2100
63.79	18.39	2200
63.78	17.39	2100
64.87	26.36	1600
64.86	25.36	1700
64.85	24.36	1700
64.84	23.37	1700
64.83	22.37	2000
64.82	21.37	2100
64.81	20.38	2100
64.8	19.38	2100
64.79	18.38	2000
64.78	17.38	2100

APPENDIX B

Trend Surface Equations and Coefficients

COEFFICIENTS OF THE TREND SURFACE (ORDER 1), SYMAP AXIS SYSTEM

THE VALUE OF THE FUNCTION AT COORDINATES X AND Y IS

Z = + 0.42930697911D+04 - 0.27793087739D+02 X - 0.27426405893D+02 Y

ERROR MEASURES

STANDARD DEVIATION	310.68
VARIATION EXPLAINED BY SURFACE	0.30436256E+09
VARIATION NOT EXPLAINED BY SURFACE	0.10550113E+09
TOTAL VARIATION	0.40986368E+09
COEFFICIENT OF DETERMINATION	0.74259463
COEFFICIENT OF CORRELATION	0.86173928

COEFFICIENTS OF THE TREND SURFACE (ORDER 3), SYMAP AXIS SYSTEM

THE VALUE OF THE FUNCTION AT COORDINATES X AND Y IS

Z = + 0.59364541643D+04 + 0.10637289337D+03 X - 0.24080901763D+03 Y - 0.16125306380D+02 X2 + 0.79167815308D+01 XY
+ 0.36153130522D+01 Y2 + 0.30103284467D+03 X3 - 0.13859608233D+00 X2Y - 0.19230223317D-01 XY2 - 0.27844206274D-01 Y3

ERROR MEASURES

STANDARD DEVIATION	282.55
VARIATION EXPLAINED BY SURFACE	0.32260634E+09
VARIATION NOT EXPLAINED BY SURFACE	0.87257344E+08
TOTAL VARIATION	0.40986368E+09
COEFFICIENT OF DETERMINATION	0.78710645
COEFFICIENT OF CORRELATION	0.88719022

COEFFICIENTS OF THE TREND SURFACE (ORDER 6), SYMAP AXIS SYSTEM

THE VALUE OF THE FUNCTION AT COORDINATES X AND Y IS

Z = + 0.24366094941D+05 - 0.12953657738D+04 X - 0.32162356287D+04 Y + 0.49867241905D+02 X2 + 0.18051702760D+03 XY
+ [illegible] Y2 + [illegible] X3 - [illegible] X2Y - [illegible] XY2 + [illegible] Y3
- 0.37172785933D-01 X4 - 0.12020528702D+03 X3Y + [illegible] X2Y2 - [illegible] XY3 + [illegible] Y4
- [illegible] X5 + [illegible] X4Y - [illegible] X3Y2 + [illegible] X2Y3 + [illegible] XY4
- [illegible] Y5 + [illegible] X6 - [illegible] X5Y + [illegible] X4Y2 - [illegible] X3Y3
- 0.11383374487D-04 X2Y4 + 0.86358236603D-06 XY5 + 0.71398629234D-05 Y6

ERROR MEASURES

STANDARD DEVIATION	255.76
VARIATION EXPLAINED BY SURFACE	0.33837786E+09
VARIATION NOT EXPLAINED BY SURFACE	0.71485832E+08
TOTAL VARIATION	0.40986368E+09
COEFFICIENT OF DETERMINATION	0.82558632
COEFFICIENT OF CORRELATION	0.90861779

APPENDIX C

Slope Profile Data Set and Statistics

Entire surface:

```
MTB > REGRESS 'ELE' 1 'DIST'

The regression equation is
ele = 0.764 - 0.00130 dist

Predictor        Coef        Stdev     t-ratio      p
Constant      0.76433     0.01574       48.53   0.000
dist     -0.00129874  0.00009559      -13.86   0.000

s = 0.04031     R-sq = 79.6%     R-sq(adj) = 79.0%

Analysis of Variance

SOURCE       DF        SS         MS        F       p
Regression    1   0.31290    0.31290   192.56   0.000
Error        50   0.08125    0.00162
Total        51   0.39415

Unusual Observations
Obs.   dist      ele       Fit  Stdev.Fit  Residual  St.Resid
  1       2  0.85227   0.76091    0.01553   0.09136    2.46RX
  2       5  0.77652   0.75754    0.01531   0.01897    0.51 X
  3      30  0.81439   0.72511    0.01316   0.08929    2.34R
```

Entire surface less mountain outliers:

```
MTB > REGRESS 'ELE' 1 'DIST'

The regression equation is
ele = 0.670 -0.000786 dist

Predictor        Coef        Stdev     t-ratio      p
Constant      0.67301     0.01725       38.86   0.000
dist     -0.00078587  0.00009762       -8.05   0.000

s = 0.02817     R-sq = 59.0%     R-sq(adj) = 58.1%

Analysis of Variance

SOURCE       DF         SS          MS        F       p
Regression    1   0.051431    0.051431    64.81   0.000
Error        45   0.035710    0.000794
Total        46   0.087141

Unusual Observations
Obs.   dist      ele       Fit  Stdev.Fit  Residual  St.Resid
  1      53  0.62500   0.63047    0.01233  -0.00547    -0.22 X
  2      54  0.60606   0.62567    0.01197  -0.01961    -0.77 X
  3      70  0.56818   0.61491    0.01073  -0.04673    -1.79 X
```

Boundary, Missouri River and Yellowstone River plateaus:

```
MTB > REGRESS 'ELE' 1 'DIST'

The regression equation is
ele = 0.653 -0.000676 dist

Predictor        Coef        Stdev     t-ratio      p
Constant      0.65360     0.01770       36.91   0.000
dist     -0.0006756   0.0001027       -6.58   0.000

s = 0.02686     R-sq = 50.1%     R-sq(adj) = 49.0%

Analysis of Variance

SOURCE       DF         SS          MS        F       p
Regression    1   0.031160    0.031160    43.25   0.000
Error        43   0.030982    0.000721
Total        44   0.062143

Unusual Observations
Obs.   dist      ele       Fit  Stdev.Fit  Residual  St.Resid
  1      50  0.62500   0.61940    0.01272  -0.00560    -0.24 X
  2      54  0.60606   0.61237    0.01217  -0.00631    -0.38 X
  3      70  0.56818   0.60602    0.01081  -0.03784    -1.52 X
```

ROW	dist	ele
1	2.405	4500
2	[illegible]	4100
3	29.970	[illegible]
4	31.080	4200
5	42.140	[illegible]
6	50.320	3300
7	[illegible]	3200
8	70.115	[illegible]
9	77.700	3000
10	133.605	2900
11	[illegible]	[illegible]
12	[illegible]	2900
13	[illegible]	[illegible]
14	[illegible]	[illegible]
15	[illegible]	2900
16	155.600	3100
17	155.585	3200
18	[illegible]	[illegible]
19	160.025	[illegible]
20	160.580	[illegible]
21	161.875	[illegible]
22	[illegible]	[illegible]
23	[illegible]	[illegible]
24	[illegible]	[illegible]
25	[illegible]	[illegible]
26	[illegible]	[illegible]
27	[illegible]	2700
28	[illegible]	[illegible]
29	[illegible]	2900
30	[illegible]	2700
31	177.600	[illegible]
32	177.600	2700
33	[illegible]	[illegible]
34	[illegible]	2800
35	[illegible]	2800
36	188.700	[illegible]
37	188.700	[illegible]
38	[illegible]	2700
39	[illegible]	2600
40	197.950	2800
41	199.615	2700
42	201.095	2700
43	[illegible]	2700
44	[illegible]	2600
45	[illegible]	[illegible]
46	[illegible]	[illegible]
47	[illegible]	[illegible]
48	213.120	2400
49	[illegible]	[illegible]
50	[illegible]	[illegible]
51	[illegible]	[illegible]
52	257.520	2200

Missouri and Yellowstone River plateaus and North Dakota locations:

```
MTB > REGRESS 'ELE' 1 'DIST'

The regression equation is
ele = 0.745 - 0.00118 dist

Predictor        Coef        Stdev     t-ratio      p
Constant      0.74570     0.02600       28.68   0.000
dist     -0.0011826   0.0001416       -8.35   0.000

s = 0.02525     R-sq = 63.0%     R-sq(adj) = 62.1%

Analysis of Variance

SOURCE       DF         SS          MS        F       p
Regression    1   0.044510    0.044510    69.80   0.000
Error        41   0.026146    0.000638
Total        42   0.070656

Unusual Observations
Obs.   dist      ele       Fit  Stdev.Fit  Residual  St.Resid
 11     161  0.62500   0.55480    0.00447   0.07020    2.81R
 41     232  0.43561   0.44279    0.01111  -0.00718    -0.32 X
 43     238  0.41667   0.44016    0.01141  -0.02350    -1.04 X
R denotes an obs. with a large st. resid.
X denotes an obs. whose X value gives it large influence.
```

Mountain outliers:

```
MTB > REGRESS 'ELE' 1 'DIST'

The regression equation is
ele = 0.851 - 0.00177 dist

Predictor        Coef        Stdev     t-ratio      p
Constant      0.85076     0.03399       25.03   0.000
dist     -0.001767    0.001254       -1.41   0.254

s = 0.04391     R-sq = 39.8%     R-sq(adj) = 19.8%

Analysis of Variance

SOURCE       DF         SS          MS        F       p
Regression    1   0.003828    0.003827     1.99   0.254
Error         3   0.005785    0.001928
Total         4   0.009613
```

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