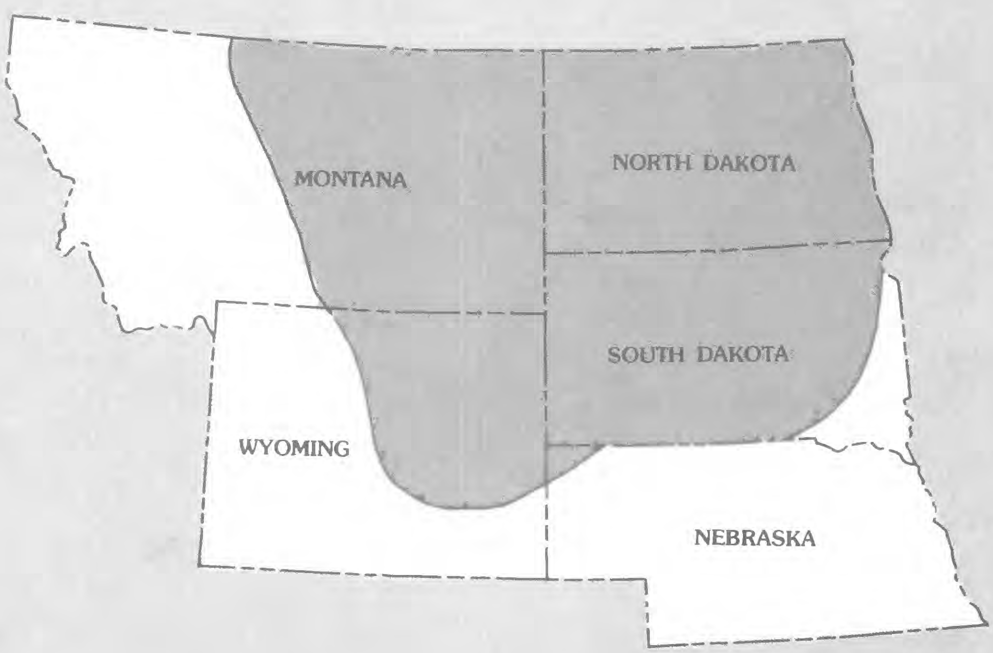
GEOLOGIC FRAMEWORK OF THE GROUND-WATER SYSTEM IN JURASSIC AND CRETACEOUS ROCKS IN THE NORTHERN GREAT PLAINS, IN PARTS OF MONTANA, NORTH DAKOTA, SOUTH DAKOTA, AND WYOMING

REGIONAL AQUIFER-SYSTEM ANALYSIS



U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1402–B

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By LAWRENCE O. ANNA

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FOREWORD

The Regional Aquifer-System Analysis (RASA) program was started in 1978 after a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA program represents a systematic effort to study a number of the Nation's most important aquifer systems which, in aggregate, underlie much of the country and which represent important components of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system, and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system, and of any changes brought about by human activities, as well as to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA program is assigned a single Professional Paper number, and, where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretative reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretative products of subsequent studies become available.

Dallas L. Peck
Director

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[Plates are in pocket]

GEOLOGIC FRAMEWORK OF THE GROUND-WATER SYSTEM IN JURASSIC AND CRETACEOUS ROCKS IN THE NORTHERN GREAT PLAINS, IN PARTS OF MONTANA, NORTH DAKOTA, SOUTH DAKOTA, AND WYOMING

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ABSTRACT

Energy development in the Northern Great Plains will place new and increased demands on ground-water development. Water from Jurassic and Cretaceous rocks might supply part of the needed water.

Geologic framework of the ground-water flow system in the Northern Great Plains is divided into two parts: structural and stratigraphic. Jurassic and Cretaceous rocks are divided into six chronostratigraphic intervals. Thickness and sedimentological variations of each interval show distinct patterns or lineaments. These lineaments may reflect paleogeographic and paleostructural trends. The tectonic and sedimentation model most appropriate for the lineaments and the orientations of these lineaments can be explained best by a horizontal stress system. This system created the structural configuration of grabens, half-grabens, and horsts, initiated in Precambrian time, that influenced the position of depositional environments, subsequently influenced the lateral and vertical distribution of sediments, and was enhanced by eustatic changes in sea level.

Orientation of tensional and compressional structural features and lineaments is predictable under this stress system. Tensional features, oriented east-west and northeast-southwest, enhance secondary porosity or permeability; thus, they become partial conduits for ground-water flow. Compressional features, oriented generally north-south and northwest-southeast, decrease porosity or permeability and become barriers or partial barriers to ground-water flow.

INTRODUCTION

Energy development in the Northern Great Plains (fig. 1) will place new and increased demands on ground-water development because all usable surface water has been appropriated. Development of coal mining, coal gasification, solution mining, and secondary recovery of oil and gas will require the use of ground water and a knowledge of the ground-water system. Rocks of Mesozoic and Cenozoic age underlying the Northern Great Plains have been suggested as possible sources of this needed water.

In 1975, the Madison Limestone Project was initiated to study the ground-water flow system of the Madison Limestone and associated Paleozoic rocks. However, the system could not be fully evaluated unless the overlying Mesozoic and Cenozoic units were also evaluated. Therefore, the Northern Great Plains study was initiated in 1978 to describe and interpret the regional ground-water flow system of post-Paleozoic rocks.

This report defines the geologic framework within which the flow system operates. The report is in two parts: (1) a description and interpretation of the regional stratigraphy and sedimentation of the Northern Great Plains; and (2) a description and interpretation of structural influences on sedimentation of the Northern Great Plains. Weimer and others (1982) described in detail the structural influences on sedimentation along the western and southern flanks of the Black Hills uplift as part of the Northern Great Plains geologic study. The reader is encouraged to review that paper for proper perspective of regional and detail descriptions.

OBJECTIVES

The purpose of this report is to describe and interpret geology of the porous medium (rocks) that determines distribution and movement of ground water. Specific objectives are: (1) To identify regional lithostratigraphic and chronostratigraphic units in the subsurface and to establish a correlation framework and data base; (2) to delineate areas of similar depositional environments and relate those areas to patterns of sedimentation and tectonics; (3) to identify areas of primary and secondary porosity and permeability for specific geologic units, based on facies and fracture patterns; and (4) to define the effects of regional tectonism on sedimentation, porosity, and permeability. These objectives will give a definitive framework from which to describe and understand the geochemistry and hydrology of the ground-water system.

LOCATION

The Northern Great Plains study area covers about 250,000 square miles, including parts of Montana, North Dakota, South Dakota, and Wyoming (fig. 1). The study area includes the Powder River and Williston structural basins; the area is bordered by the central Rocky Mountains on the west, the Canadian Shield on the east, and the central High Plains on the south. The topography is gently rolling, interrupted principally by the Black Hills, the Central Montana uplift, and occasionally by several hundred feet of topographic relief where streams have dissected relatively soft sands and clays. The climate typically is continental, with an average rainfall of approximately 16 inches per year.

ACKNOWLEDGMENTS

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PREVIOUS WORK

There are many geologic reports on the abundant natural resources of the study area. Petroleum, natural gas, uranium, coal, and water provide economic incentives to describe, interpret, and understand the geologic framework that harbors these abundant resources. Some of the more noteworthy publications on the regional structure and stratigraphy of Mesozoic and Cenozoic rocks in the project area and adjacent regions (listed chronologically) include: Darton (1901), Thom (1923), Chamberlin (1945), Crowley (1951), Gries (1954, 1962), Sonnenberg (1956), Peterson (1957, 1966, 1972), Brown (1958), Waage (1959), Love (1960), Weimer (1960), Haun and Weimer (1960), Haun and Barlow (1962), Wulf (1962), Haun and Kent (1965), Hoppin and Palmquist (1965), Sales (1968), Frye (1969), Stone (1969, 1970, 1971, 1974), Blackstone (1971), Stearns (1971), Rocky Mountain Association of Geologists (1972), Gill and Cobban (1973), Matthews (1978), Warner (1978), Weimer (1978), and Rice and Shurr (1980).

Regional studies of the ground-water resources of Mesozoic and Cenozoic rocks are limited. Some of the more noteworthy are Darton (1901, 1909), Kelly (1968), Swenson (1968), and Schoon (1971).

The Northern Great Plains physiographic province is thought by many authors to be part of an inactive cratonic shelf during most of Mesozoic and Cenozoic time, except during the Laramide orogeny. Some authors, however, believe that during anorogenic periods, the Craton was tectonically active and not passive (Thom, 1923; Sonnenberg, 1956; Smith, 1965; Sales, 1968; Stone, 1969; Thomas, 1974, 1976; Shurr, 1976; Brown, 1978; and Weimer, 1978, 1980).

Tectonic effects on sedimentation have long been recognized (Dickinson, 1974); however, the exact nature of the controls on depositional environments of sediments in the Northern Great Plains and adjacent areas has not been clearly defined, except as described by Smith (1965), Thomas (1974), Shurr (1976), Brown (1978), and Weimer (1978).

GENERAL PALEOGEOGRAPHY

PRE-LARAMIDE

During Jurassic and most of Cretaceous time, the western interior of North America was dominated by a marine environment, with numerous sea-level rises and drops. Exact relationships between the Jurassic seaway of the western interior and the western coast are difficult to establish because of extensive Tertiary volcanic cover and postdepositional erosion; it is suspected that the Jurassic sea was separate from the marine environment of the Gulf Coast (Peterson, 1972, p. 177). Major rock types during Jurassic time were mostly marine shale,

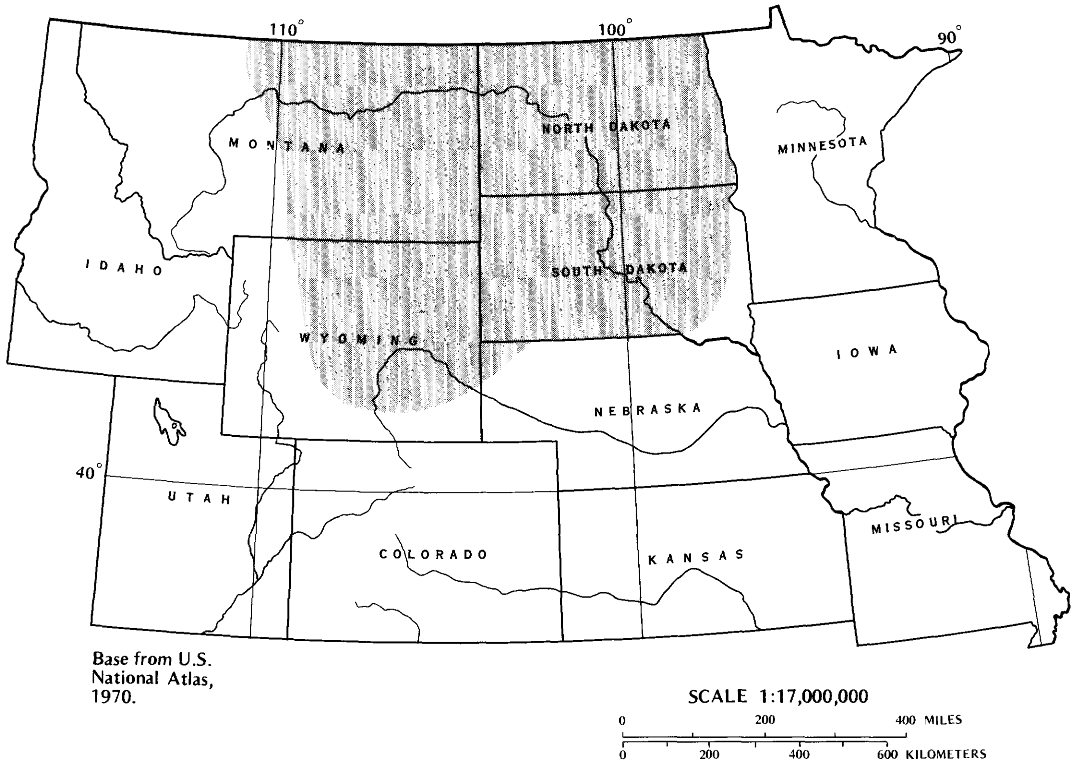


FIGURE 1.—Northern Great Plains study area.

sandstone, siltstone, and carbonate. Sediment sources were derived from the Sevier organic belt to the west, from the Canadian Shield to the north, and from the Transcontinental arch to the east. Continental redbeds and varicolored shale were deposited during final regression of the Jurassic sea.

The initial advance of the Early Cretaceous sea was during early to middle Albian time. The sea extended from the Arctic to the Gulf of Mexico and was about 1,000 miles wide (Gill and Cobban, 1973). It was bounded on the west by a narrow, unstable, and repeatedly rising north-trending Cordilleran highland. This highland was the source of the clastics that ultimately filled the epicontinental seas (Gill and Cobban, 1973).

During Late Cretaceous time, the sea was at its widest extent, but marine deposition was interrupted by frequent east-west regressions; these regressions were controlled in part by worldwide eustatic changes in sea level and in part by regional tectonism. Thus, nonmarine sediments intertongue with thick sequences of marine shale (Weimer, 1960, p. 3).

The eastern margin of the western interior basin was formed by the central part of the North American craton, the Canadian Shield, and the southwestern extension of the Transcontinental arch. The western margin was formed by the Cordilleran highland (miogeosyncline) (fig. 2). Within the basin, sedimentary processes were influenced in varying degrees by the quantity and quality of sediment, sea-level changes, regional tectonism, and elevation and depression of several paleostructural elements associated with structural development and growth of the western interior. This concept will be discussed in more detail later.

The major Jurassic and Cretaceous paleostructural elements in the Northern Great Plains were the Williston basin and, to lesser degree, the Powder River basin, the Central Montana trough and uplift, the Cedar Creek anticline, and the Alberta shelf. Other important structural elements included the Lake Basin and Cat Creek fault zones, Black Hills, Sweetgrass arch, Miles City arch, Chadron arch, Sioux arch, Bighorn Mountains, Laramie Mountains, and Hartville uplift (figs. 2 and 3).

The Williston basin is a structural-sedimentary, intracratonic basin of more than 50,000 mi^2 (square miles) which covers parts of North Dakota, South Dakota, southern Saskatchewan, southwestern Manitoba, and eastern Montana. A relatively complete sedimentary rock section of Late Cambrian through Tertiary age ranges from more than 15,000 ft (feet) thick in the deepest part of the structural basin (western North Dakota) to a less complete sedimentary section of less than 10,000 ft on the western border of the basin (eastern Montana). The basin began to take shape as a distinctive area of increased subsidence during Middle Ordovician time (Carlson and Anderson, 1965), although there is also evidence, based on limited control, of Cambrian subsidence in the basin center (Brown, 1978). Carbonate sedimentation prevailed within the basin and surrounding area during much of early to middle Paleozoic time, changing to a dominance of clastics in late Paleozoic, Mesozoic, and Cenozoic times (J. A. Peterson, U.S. Geological Survey, written commun., 1980).

The Central Montana trough was an elongate east-west basin, bounded on at least the north side by Precambrian faults, connecting the Williston basin and the Cordilleran miogeosyncline (fig. 2). The area has been actively subsiding since Precambrian time (Belt embayment) through Early Cretaceous time. It appears that after Early Cretaceous time, the Central Montana trough was active as an uplift. The Cat Creek fault zone appears to have had the greatest influence on sedimentation.

The Alberta shelf extended northward from the Central Montana trough into Canada (fig. 2) and had its greatest influence on sedimentation during Early Cretaceous time.

The Cedar Creek anticline was a dominant structural feature throughout the history of the Williston basin, especially during four main growth periods (Clement, 1976, fig. 2). On the basis mainly of apparent sedimentary textural changes near the anticline, it appears that the anticline divided the Williston basin into two subbasins. Stratigraphic intervals thin across the anticline, and sedimentation patterns are influenced by movement along and adjacent to the axis.

The Powder River basin area was relatively positive during Middle Jurassic time because of little or no deposition. During Late Jurassic time, the area was only slightly positive compared with the Williston basin, based on relative sedimentary rock thicknesses, and assuming equal sediment supplies and equal subsidence rates. The basin continued to subside and receive sediments during Cretaceous time. During the Laramide

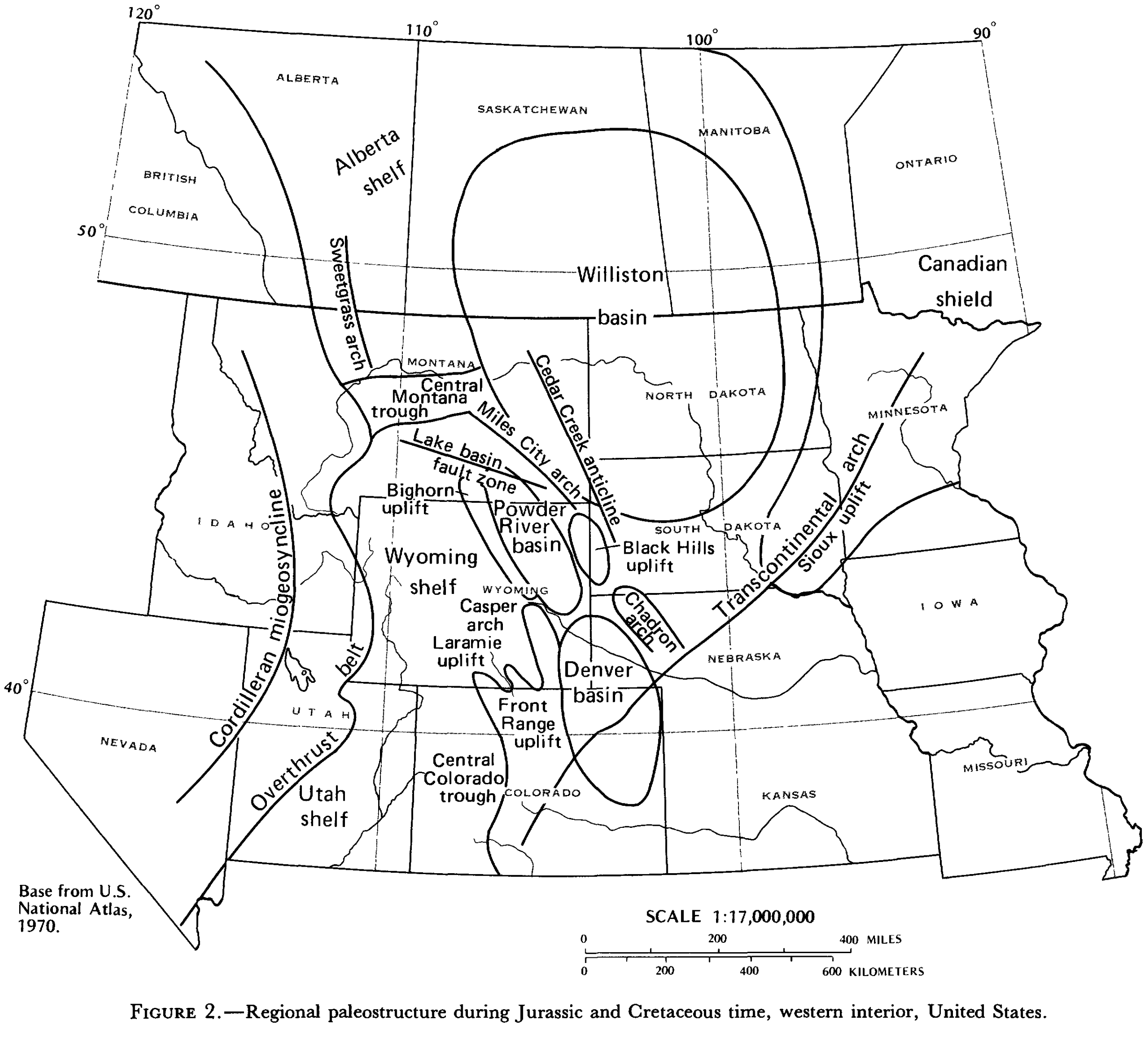


FIGURE 2.—Regional paleostructure during Jurassic and Cretaceous time, western interior, United States.

orogeny, the basin was downwarped into essentially its present configuration.

The Black Hills area, including the Chadron arch, showed varying periods of growth and subsidence (Crowley, 1951; and Tenney, 1966) during parts of late Paleozoic, Jurassic, and Cretaceous time.

LARAMIDE

Laramide tectonics in the Northern Great Plains and in the bordering uplifted areas have been described in great detail by numerous authors (Matthews, 1978; and Renfro, 1971). The Laramide orogeny was characterized by large-scale warping, deep erosion of uplifts, and deposition of orogenic sediments into basins (Tweto, 1975, p.3).

In this paper, the term Laramide is applied to an orogenic event that occurred between early Maestrichtian (Cretaceous) and late Eocene (Tertiary) time in the Northern Great Plains. Most, if not all, pre-Laramide structural features were reactivated and became more prominent during the Laramide orogeny (fig. 3, and pl. 1). Movement along preexisting basement faults formed the Bighorn and Laramie Mountains, Black Hills, and Central Montana uplift, and intensified thrusting in the Sevier orogenic belt (overthrust belt) to the west. The Williston and, especially, the Powder River basins were downwarped into essentially their present configuration. The adjacent uplifted areas became not only sources of sediment supplied to the Williston and Powder River basins, but also areas for major ground-water recharge into the basins. During the Laramide orogeny, the Williston basin subsequently received more than 3,000 ft of sediment; the Powder River basin received 9,000 ft of sediment.

Regression of the sea during Fox Hills time marked the final retreat of the Cretaceous sea and the beginning of the main Laramide orogenic event. Subsequent deposition of fluvial sediments from the highlands characterizes the stratigraphic history of the area to date.

POST-LARAMIDE

In the post-Laramide period, magmatism, rifting, block-faulting, and rejuvenation of basins occurred because of movement of fault-bounded basement blocks. This movement produced modern-day topographic features of the Northern Great Plains, characterized by gently rolling flatlands dissected by occasional gentle-to-steep valleys, uplifts with exposed Precambrian core on the west, and Precambrian rocks subcropping beneath glacial till on the east. The Black Hills uplift, although it appears isolated near the south-central part of the Northern Great Plains, is oriented along the strike of other Laramide flexures (fig. 3).

No precise data can be assigned to the end of the Laramide orogeny, but it appears to have been during late Eocene time. There was little deposition until middle Miocene to Pliocene time, when a resurgent tectonic pulse again activated preexisting Precambrian structures and uplifted major mountainous areas,supplying a modest amount of sediment to the basins.

STRATIGRAPHY AND SEDIMENTARY FACIES

JURASSIC

Rocks of Jurassic age in the Northern Great Plains overlie Triassic and Paleozoic formations with a pronounced disconformity. The Nesson, Piper, and Rierdon Formations and their equivalents (pl. 2) are predominantly carbonate, shale, and calcareous shale. The Nesson Formation is divided into three members: (1) The lower Poe Evaporite Member, an anhydrite, which also includes the Dunham salt (informal subsurface usage), occurring in restricted parts of the Williston basin; (2) the middle Picard Shale Member; and (3) the upper Kline Member, a carbonate. The Piper Formation is also divided into three members (Nordquist, 1955): (1) the oldest, the Tampico Shale Member with local sandstone in central Montana; (2) the middle, the Firemoon Limestone Member; and (3) the youngest, the Bowes Member, a red to varicolored shale and siltstone. In north-central Montana, the Piper Formation thins appreciably and consists chiefly of sandstone. The Rierdon Formation consists mainly of shale, siltstone, and calcareous shale, with local sandstone along the eastern fringes of the Williston basin. The well control points are shown on plate 3, and the lines of stratigraphic sections are shown on plates 4 through 7.

Combined thicknesses of the three formations range from less than 100 ft along the periphery of the Williston and Powder River basins to more than 600 ft north of the deepest part of the Williston basin (fig. *A*, pl. 8).

The Swift Formation of Late Jurassic age (Interval 2) was deposited in a marine environment; in the western part, the formation consists of medium-to-thick bedded, glauconitic, ripple-marked sandstone. In the eastern part, the formation consists mostly of silty shale. From geophysical log interpretations, a subtle coarsening upward occurs in about the upper one-third of the Swift Formation; it is usually capped by a thin regressive sandstone or siltstone. The formation is about 600 ft thick along the northern axis of the Williston basin and goes to a zero edge in western Montana and eastern North Dakota and South Dakota. From geophysical log interpretation, the upper part of the Swift is less porous than sands in the lower part, which locally contains more than 50 ft of sand with greater than 20 percent porosity (fig *C*, pl. 9).

Continental beds of the Morrison Formation were deposited as a region-wide blanket of sand, silt, and clay, on a plain that emerged after the regression of the Swift sea (Peterson, 1972, p. 177). The Morrison is about 250 ft thick in south-central Montana and thins eastward to a zero edge in western North Dakota and South Dakota. In central North Dakota, the formation is thin along narrow linear patterns. Sandstone developed mostly in areas where the formation is relatively thick. The Morrison shows some evidence of a regional unconformity where the base of the Lower Cretaceous truncates the Morrison and, occasionally, the upper part of the Swift Formation.

LOWER CRETACEOUS

Lower Cretaceous rocks in the study area consist of sequences of both marine and nonmarine clastic strata. Thicknesses in the project area range from zero in eastern North Dakota and South Dakota to more than 1,400 ft in west-central Montana (fig. *B*, pl. 10).

The Lower Cretaceous Lakota and Fuson Formations and their equivalents are fluvial sandstone, siltstone, and shale. The Lakota consists mostly of sandstone and occasional conglomerate. Locally, the Lakota has scoured into the Morrison and, where the Morrison is thin or absent, into or through the Swift. The Lakota ranges in thickness from zero to 100 ft, except on the south flank of the Black Hills uplift, where the formation is several hundred feet thick. Generally, the Lakota is a channel and valley-fill deposit, although in the subsurface it is often difficult to distinguish from the valley fill of the overlying Fuson Formation.

Determined from geophysical log characteristics, the Fuson Formation consists mostly of valley fill and

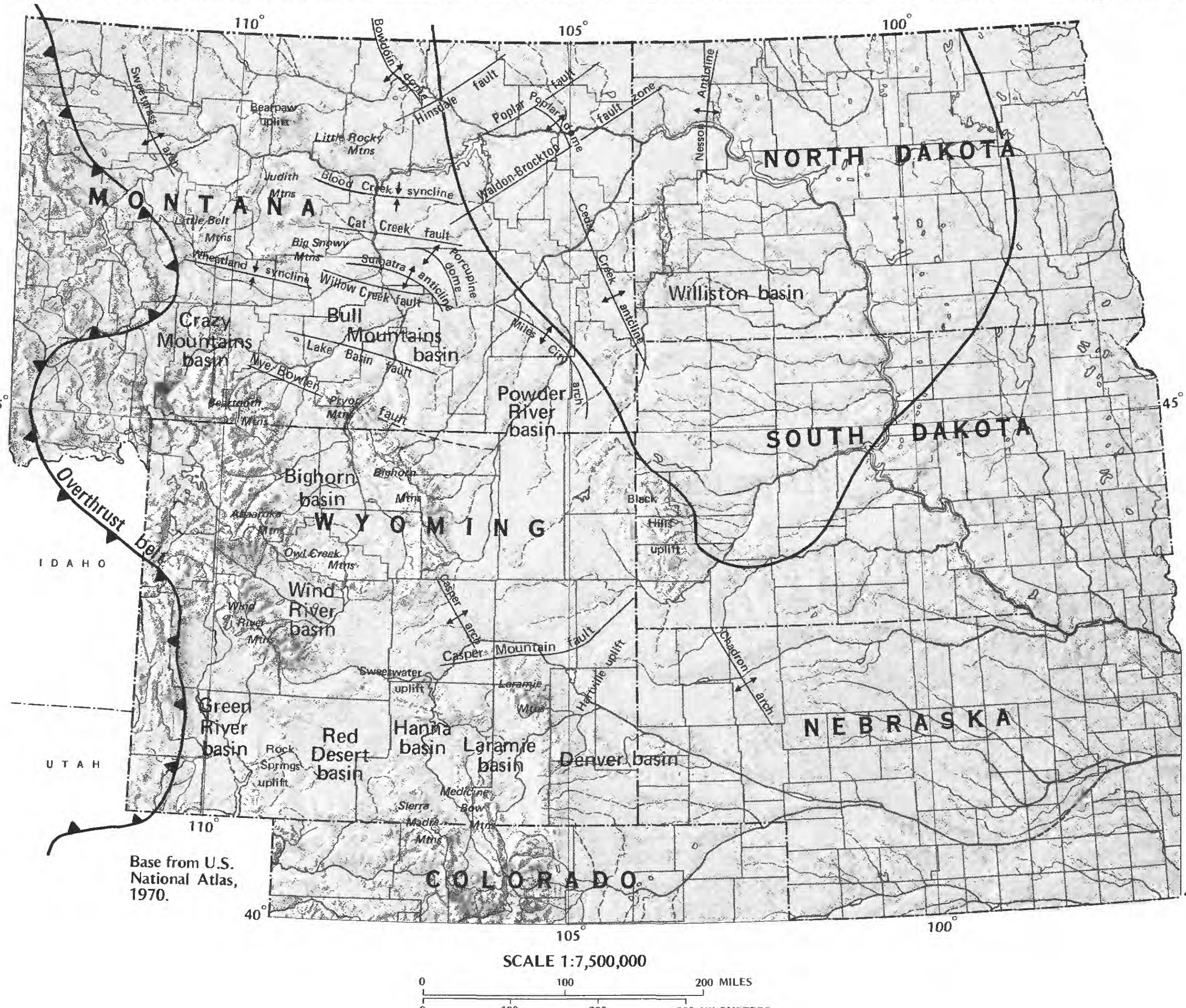


FIGURE 3.—Present-day structural features, western interior, United States.

channel-margin silty shale that has occasional well-developed, thick channel-fill sandstone. The Fuson and its equivalent range in thickness from approximately 400 ft in central Montana to less than a few feet in eastern North Dakota and South Dakota and, finally, to a zero edge in eastern South Dakota.

The Fall River Sandstone represents the initial advance of the Early Cretaceous sea, which rapidly deposited fine sands, silts, and clays under marginal marine, tidal-flat, coastal-swamp, and deltaic conditions (Waage, 1959, p. 63). Waage (1959) and Mettler (1966) have noted nonmarine point-bar and channel deposits in northeastern Wyoming. Silt and shale deposits in central Montana and Wyoming suggest a deeper water-shelf environment.

Porosity trends of the Lakota, Fuson, and Fall River in the Inyan Kara Group of the Black Hills, South Dakota, mapped from sonic logs (Interval 3) show that the areas of higher porosity are in the central and eastern parts of the study area, although the total footage of higher porosity decreases eastward as the overall thickness of the group decreases (fig. *C*, pl. 11). In the Powder River basin, all the formations generally have less than 20 percent porosity, because of the increase in depth to the formations.

The Lakota and Fuson Formations and the Fall River Sandstone thin eastward and are truncated by pre-Skull Creek erosion. Total thickness of the three formations ranges from about 700 ft in central Montana to a zero edge in eastern North Dakota and South Dakota.

The Skull Creek Shale consists of two informal facies: (1) A lower, slightly glauconitic siltstone, informally termed "basal silt", and (2) an upper shale. The silt facies is of regional extent and contains minor amounts of sand that increase in central and south-central Montana. A regional marker bed consisting of siltstone (identified from geophysical log characteristics) is present in the upper part. The shale facies was deposited under strong reducing conditions (Wulf, 1962) and consists mainly of black shale that contains associated pyrite and considerable organic matter. The Skull Creek Shale ranges in thickness from zero feet in eastern South Dakota to more than 250 ft in parts of Montana, Wyoming, and the western parts of South Dakota and North Dakota.

Withdrawal of the Skull Creek sea created an unconformity at the base of the Newcastle Sandstone in eastern Wyoming and southeastern Montana. Incisement into the Skull Creek Shale during the hiatus was subsequently filled with channel and valley fill of the Newcastle/Muddy Sandstone (Interval 4) (Baker, 1962; Stone, 1971; Waring, 1975; Weimer and others, 1982). As sea level rose, marginal marine deposits formed over a broader area than did the valley-fill deposits. Later, the sea transgressed from west to east, developing extensive delta systems in eastern Montana and northeastern Wyoming, and, even later, in southeastern South Dakota. Sediment supply to the deltas originated in eastern and south-central South Dakota, and the deltas supplied sediment to the shelf areas in central Montana and in Wyoming. A delta system originating in northwest Montana was also supplying sediment to the shelf areas in central Montana.

Thickness of the Newcastle/Muddy Sandstone is variable, ranging from zero feet in large areas of North Dakota to tens of feet in central Montana and in Wyoming and increasing abruptly to several hundred feet in southeastern North Dakota and eastern and south-central South Dakota. Where the formation is several hundred feet thick, the Newcastle/Muddy is often referred to as the Dakota Sandstone (pl. 2).

Porosity trends in the Newcastle/Muddy generally parallel thickness trends. Thickness of sands greater than 20 percent porosity range from zero feet to over 400 ft in eastern South Dakota but not in southern South Dakota (fig. *C*, pl. 12).

As the Skull Creek sea encroached farther eastward during late Newcastle/Muddy time, the Mowry Shale was deposited over the central and western parts of the Northern Great Plains. The Mowry consists of dark-to light-gray, siliceous shale containing disarticulated fish scale and bone. Davis (1970) and Cluff (1976) reported the source of the silica to be biogenic. In the Northern Great Plains, the Clay Spur Bentonite Bed marks the top of the Mowry and also divides the Lower from the Upper Cretaceous; this bentonite is used as a regional time marker. Thickness of the Mowry ranges from a zero edge in eastern and southeastern South Dakota and in eastern North Dakota to more than 700 ft in south-central Montana.

UPPER CRETACEOUS

The sedimentary pattern for the Upper Cretaceous in the Northern Great Plains can be described as four main transgressions and four main regressions (Weimer, 1960, p. 3) (fig. 4).

TRANSGRESSION (1)

The Belle Fourche Shale and Greenhorn Formation were deposited as continuations of the Mowry Shale transgression, and they extend over most of the Northern Great Plains region. The Belle Fourche Shale is about 500 ft thick (although its thickness varies greatly) and consists of gray to black shale that has numerous bentonite beds. The Greenhorn Formation is about 200 ft thick and consists of a thin, upper limestone, thin, tight sandstone, and a lower shale and chalky shale. Rice and Shurr (1980, p. 979) divide the two formations into three main facies from east to west: (1) shaly chalk, (2) shelf sandstone, and (3) shale.

The Carlile Shale is about 300 ft thick and consists of gray marine shale with thin, tight sandstone (in informal usage called Bowdoin sandstone in Montana, and called Turner Sandy Member in eastern Powder River basin, Wyoming). Rice and Shurr (1980, p. 979) divide the Carlile into three facies from east to west: shaly chalk, shelf sandstone, and shale.

REGRESSION (1)

The Frontier Formation is the southwestward equivalent of the Belle Fourche Shale and Greenhorn Formation. The Frontier is areally restricted to the central and north-central parts of Wyoming. The formation is 500 ft to 2,000 ft thick and consists of alternating beds of deltaic sandstone and shale (Barlow and Haun, 1966).

TRANSGRESSION (2)

The Niobara Formation is about 350 ft thick, consists of gray shale with chalky beds, and is characterized by small white calcareous lenses or by white specks. Lithologic variations range from dominantly chalk in the east to mostly shale in the west.

REGRESSON (2)

The Telegraph Creek Formation is about 300 ft thick and consists mainly of sandy shale that has thin beds of concretionary sandstone in the middle and upper parts, which often cap escarpments.

The Eagle Sandstone (including the Virgelle Sandstone) is about 600 ft thick and consists of light-colored, massive, nonmarine and marine sandstone. The marine-sandstone facies (off-shore bar) is the Shannon, Sussex Sandstone Members of the Steele Shale, or Cody Shale where it extends into the Powder River basin.

TRANSGRESSION (3)

The Claggett Shale in Montana is about 300 ft thick and thins eastward. The formation generally consists of dark marine shale and siltstone. Numerous thick and persistent bentonite beds occur in the lower part.

REGRESSION (3)

The Judith River Formation in Montana is about 400 ft thick and thins eastward. The formation consists of nonmarine, light-colored sandstone with abundant coarse volcanic detritus to the west. Finer-grained marine equivalents lie to the east. The Judith River is stratigraphically equivalent to the Parkman Sandstone Member of the Mesaverde Formation and an unnamed shale member of the Steele Shale in the western Powder River basin, Wyoming.

The Mesaverde Formation in the Powder River basin consists of the lower Parkman Sandstone Member, an unnamed shale member, and the upper Teapot Sandstone Member. A major unconformity exists at the base of the Teapot Sandstone Member.

TRANSGRESSION (4)

The Bearpaw Shale in Montana consists of about 800 ft of dark marine shale with numerous bentonite beds and is equivalent to the Lewis Shale in the western Powder River basin and to the upper part of the Pierre Shale of the eastern Powder River basin in North Dakota and South Dakota. The Pierre Shale consists of over 2,000 ft of dark marine shale. The Pierre is the eastern equivalent of the Eagle Sandstone, Claggett Shale, Judith River Formation and Bearpaw Shale in central Montana, and of the Mesaverde Formation, and Lewis Shale in the western Powder River basin.

REGRESSION (4)

The final regression of the Late Cretaceous sea deposited the Fox Hills Sandstone (and equivalent rocks). The overlying Hell Creek Formation was being deposited as the continental part of the regressive system (Frye, 1969). Both formations and their equivalents are areally extensive in the subsurface and crop out over sizeable areas in southern and central North Dakota.

The Fox Hills and equivalent units consist of about 300 ft of deltaic, interdeltaic, and shoreline sandstone, siltstone, and shale over the entire study area. In the subsurface, electric-log characteristics display a typical coarsing upward, typical of a regressive or prograding sequence.

The Hell Creek Formation, or Lance Formation, ranges from about 350 ft to 1,500 ft thick and consists of fluvial sandstone, siltstone, and carbonaceous claystone, with occasional thin lenticular coal beds.

TERTIARY

Tertiary units of the Northern Great Plains presently contain the most important ground-water systems for development of domestic and agricultural water supplies because their ground water systems have rélatively shallow drilling depth and better water quality than do deeper aquifers. These units were deposited in a continental environment and were largely alluvial, lacustrine, and paludal in origin. The exceptions are the Cannonball Member of the Fort Union Formation in western North Dakota, which was deposited in a marine environment, and the underlying Ludlow Member of the Fort Union, deposited in parts of western North Dakota in a marginal marine environment (Moore, 1976, p. 23). The Tertiary units are areally extensive, cropping out in over half of the study area.

Most of the sediment making up the Tertiary deposits was derived from highlands to the west and northwest

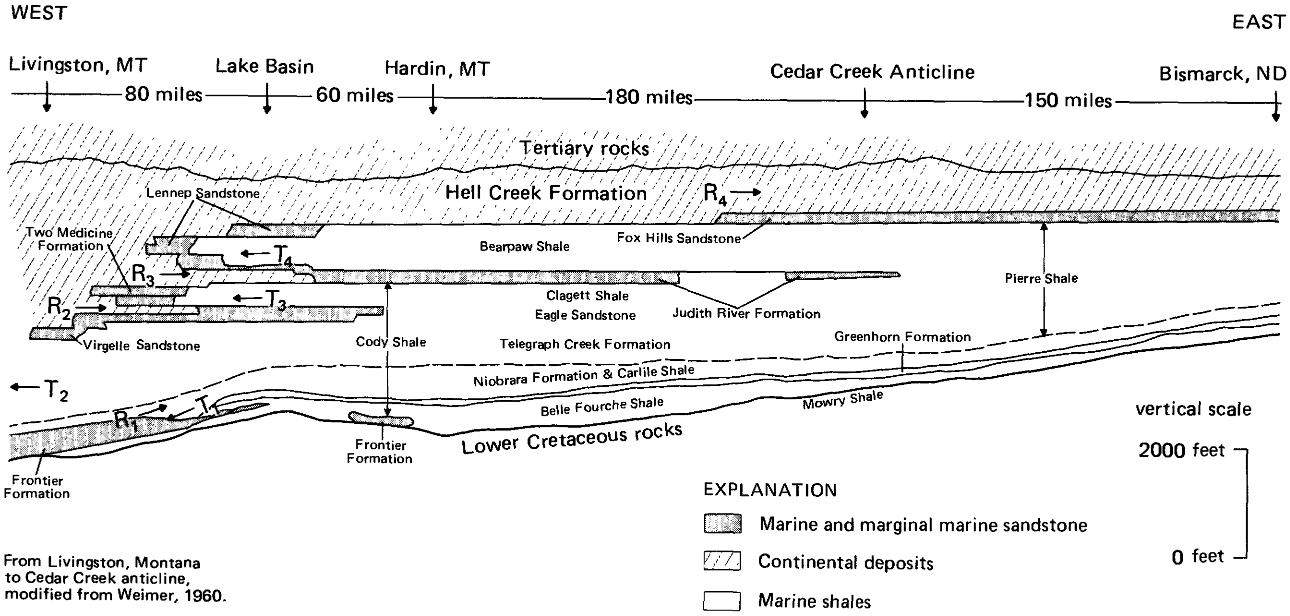


FIGURE 4.—Diagramtic restored cross section of Upper Cretaceous rocks from southwestern Montana to central North Dakota. T_{1-4} and R_{1-4} indicate major transgressions and regresssions during Late Cretaceous time; arrows show direction of sea movement.

during and after the Laramide orogeny (McGrew, 1971; Seeland, 1976). Streams carrying sediment flowed generally north or northeast, although Law and others (1975, p. 1163) postulate a southeasterly direction in the western Powder River basin during Paleocene time.

PALEOCENE

The Fort Union Formation consists of three members: (1) the lower Ludlow or Tullock, (2) the middle Lebo Shale and (or) Cannonball, and (3) the upper Tongue River. All consist of alternating gray to buff sandstone, siltstone, and claystone with thin to thick lignite and subbituminous coal beds. Individual channel systems can be traced in the subsurface for considerable distances, especially in the Powder River basin, even though the vertical and lateral texture distribution may have considerable variability.

The contact with the underlying Cretaceous Hell Creek, or Lance Formation is placed at the base of the lowest persistent coalbed (Brown, 1958). Local unconformities at the base of the Ludlow, or Tullock, occur from basal channel scour of the Ludlow, or Tullock, into the Hell Creek, or Lance.

Thickness of the Fort Union Formation ranges from more than 3,000 ft in the Powder River basin to less than 300 ft in the Williston basin and in central North Dakota and northeast Montana, although the formation is slightly thicker in the central part of the Williston basin. Sandstone textures in the Powder River basin generally are coarser grained and better sorted than in eastern Montana and in North Dakota and South Dakota. In general, sandstone in the Powder River basin has higher permeabilities, although the bottom part of the formation of a thick sequence may have reduced permeabilities owing to loading effects.

The uppermost Sentinel Butte Member of the Fort Union Formation in the Williston basin is equivalent in time to the uppermost Tongue River Member of the Fort Union Formation in the Powder River basin (R. H. Tschudy, U.S. Geological Survey, written commun., 1976). The Fort Union formation consists mostly of somber-colored siltstone and of claystone and has lenticular sandstone near the base.

EOCENE

The Wasatch Formation, present only in the Powder River basin, consists of as much as 1,000 ft of alternating beds of valley-fill and channel-fill sandstone, siltstone, and claystone, similar to the makeup of the Tongue River Member of the Fort Union, although mineralogical differences have been noted (Denson and Chisholm, 1971). The contact between the Wasatch and underlying Tongue River Member is unconformable and is placed at the top of the Roland-Anderson coal bed of the Tongue River. This bed is about 50 ft to 100 ft thick and is areally extensive over most of the southern Powder River basin. At the southernmost end of the basin, the Roland-Anderson coal splits into numerous thinner beds, some of which have been miscorrelated as the top of the Roland-Anderson. As a result, the Wasatch-Tongue River contact often is mislocated.

The Golden Valley Formation of Paleocene and Eocene times consists of about 150 ft of kaolinitic claystone, mudstone, lignite, and micaceous sandstone (Hickey, 1972). The formation is present only in western North Dakota, usually as small remnants underlying younger cap rocks. Hickey (1972) divides the formation into upper and lower units, the lowermost of Paleocene age and the uppermost of Eocene time. Both Hickey (1972) and Denson and Gill (1965a) give excellent descriptions of the formation.

OLIGOCENE

The White River Formation (or, where divided called Group) unconformably overlies Eocene units and is about 250 ft thick. In several localities in the Williston basin, the formation is exposed only as remnants capping buttes; in south-central South Dakota, the formation is exposed as areally extensive deposits that form the Badlands. The White River Group is divided into the lower Chadron Formation and the upper Brule Formation. The Chadron consists of a basal conglomerate and arkose, and of overlying tuffaceous sandstone, siltstone, and shale; the upper Brule consists mostly of claystone, siltstone, and thin, lenticular sandstone (Denson and Gill, 1965a). It is believed that, before widespread erosion of the White River Group, the tuffaceous sandstone of the Chadron Formation was a source of uranium found in numerous localities in underlying beds.

MIOCENE, PLIOCENE, AND QUATERNARY

The Arikaree Formation of Miocene time in the Northern Great Plains is present as remnants capping higher buttes, which resulted from widespread Pliocene and Pleistocene erosion in North Dakota and in South Dakota.

The Arikaree rests unconformably on the White River Formation and is about 250 ft thick. It consists of massive tuffaceous sandstone, siltstone, and a few thin beds of quartzite, dolomite, and volcanic ash (Denson and Gill, 1965a, p. 7).

The Ogallala Formation of Miocene time is present only in southwestern South Dakota, but it is present as an extensive veneer of interbedded sandstone, siltstone, and claystone over most of the central Great Plains region.

The Flaxville Formation, of Miocene or Pliocene age, is a thin widespread pediment capping numerous plateaus and consists of poorly cemented sandstone and conglomerate. The formation is recognized only in northeast Montana but may be correlative to local pediments along flanks of major buttes (Denson and Gill, 1965a, p. 7).

Quaternary deposits in the Northern Great Plains consist of alluvium and glacial till and outwash. Alluvial deposits, varying in thickness, fill major drainages of the Northern Great Plains; whereas glacial till and outwash deposits are located only in eastern North Dakota, northeast South Dakota, and northernmost Montana. The outwash deposits range in thickness from a few feet to several hundred feet and consist of sand and gravel. Widths generally range from less than 1 mile to several miles; they commonly are tens of miles in length.

STRUCTURAL INFLUENCE ON STRATIGRAPHY

INTRODUCTION

The degree of structural influence on stratigraphy depends, in part, on the scale of viewing. Large-scale patterns of sedimentation are influenced by the rate and extent of orogenesis and basin development. Smaller scale patterns can be influenced by syndepositional structural adjustments. In turn, lithologic facies, texture, porosity, permeability, and diagenetic history are controlled by both large- and small-scale tectonism (such as quality and quantity of source material and subsidence rates) and by structure.

It is inadequate to describe only the external geometry of an aquifer system. The vertical distribution, the depositional environment, and the degree of, and potential for, secondary enhancement of porosity and permeability in aquifers must also be described. This section emphasizes the physical framework controlling the ground-water flow system. Similar discussion of confining units is also necessary to evaluate the concept of leakage or vertical communication between aquifer systems because leakage is from primary or secondary permeability.

The physical framework in areas of little or no data can be more clearly defined if certain structural adjustments produce specific or predictable sedimentation patterns. If only part of an aquifer system can be described, other parts of the system may be predicted when (1) the paleostructural history of the entire area is known and (2) a depositional model is established that takes structural adjustments into account.

Recurrent movement of Precambrian basement blocks in the Northern Great Plains (although subtle compared with orogenic events) has affected lithofacies and the distribution of porosity and permeability. Fault-block movement controls topography or bathymetry; these, in turn, control facies and the physical character of the sediment, depending on the quality and quantity of available sediment. The following section describes the lineations expressed by sedimentary geometries and textures that are believed to be the result of recurrent movement of Precambrian basement faults.

Most of the units described here are chronostratigraphic intervals; a chronostratigraphic interval everywhere represents the same horizon in geologic time. Boundaries of the intervals generally are based on lithostratigraphic intervals mapped from geophysical well logs that provide approximate time surfaces. This approach affects not only the accuracy of the maps but also an understanding of stratigraphic relations and the reconstructions of geologic events inferred from these relations (Oriel, 1959).

Thickness patterns, sand accumulations, and sand textures are described for each of the six chronostratigraphic intervals listed in figure 5; these parameters are then related to possible structural controls on their distribution. Sand thickness was determined from geophysical well logs using only intervals of 20 or more continuous feet of sand. Sand textures and trend-surface residual maps were provided by American Stratigraphic Company.[1]

Changes in sediment thickness are controlled by several factors: (1) differing rates of sedimentation, such as (from) on-lap and off-lap; (2) differing rates of uplift or subsidence; (3) erosion or fill; (4) differential compaction; and (5) faulting. By mapping chronostratigraphic intervals, effects of erosion and fill can be eliminated. At the scale and contour intervals used in preparing maps for this paper it is believed that thickness changes from differential compaction are also thought to be eliminated. Care was used to isolate thickness changes that were thought to result from local faulting.

Lineaments, as used in this report, are based on interpretations of both subsurface and surface data. Lineaments interpreted from subsurface data are derived from linear trends of thickness and from sedimentation patterns. Lineaments interpreted from surface data are derived from alinement of faults, folds, shears, or tonal changes on Landsat imagery. The paleostructural elements shown on plate 13 are classified as lineaments, even though their present-day structural configurations may be well documented. For example, the Cedar Creek is now an anticline, but in the geologic past it may have operated as a fault, a hinge line, or a negative area, or it may have remained quiescent.

	FORMATIONS (equivalent rocks shown on Plate 2)	CHRONOSTRATIGRAPHIC INTERVAL
	Ardmore Bentonite Bed	
UPPER CRETACEOUS	Pierre Shale (part) Niobrara Formation Carlile Shale	6
UPPER CRETACEOUS	Greenhorn Formation Belle Fourche Shale	5
LOWER CRETACEOUS	Mowry Shale Newcastle Sandstone Skull Creek Shale, upperpart including silt-marker bed	4
LOWER CRETACEOUS	Basal silt of Skull Creek Shale Inyan Kara Group	3
JURASSIC	Morrison Formation Swift Formation	2
JURASSIC	Rierdon Formation Piper Formation Nesson Formation	1

FIGURE 5.—Diagrammatic correlation chart of chronostratigraphic Intervals 1-6.

SUBSURFACE LINEAR PATTERNS

INTERVAL 1

Boundaries for Interval 1, which comprises the Nesson, Piper, and Rierdon Formations and equivalent rocks, were placed at formation contacts; therefore, the lithologic boundary possibly is not the same age throughout the region. This boundary is thought to represent a "practical time-boundary" as described by Rogers (1954, p. 659). Rogers states that practical time-stratigraphic units are defined as "***material rock units defined in their type areas by agreement among stratigraphers, elsewhere by criteria of (time-) correlation found in the contained rocks; that is, by physical properties, fossil content, or radioactive age determinations believed by practicing stratigraphers to indicate time-equivalence with the type *** unit." Therefore, boundaries for Interval 1 are thought to be practical time-boundaries and not ideal time-boundaries. Overall thickness change using practical time-boundaries rather than ideal time-boundaries is small and is an amount that could be used to determine regional thickness patterns.

Combined thickness of the Nesson, Piper, and Rierdon Formations ranges from zero along the periphery of the study area to more than 600 ft in northeastern Montana and northwestern North Dakota (pl. 8). The depocenter for the three formations was north of the pre-

[1]Any use of trade names is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

sent center of the Williston basin. The Powder River basin area seems to have been structurally positive and had little influence on sedimentation of Interval 1.

Thickness patterns in central Montana indicate that the east-west trending Central Montana trough (presently the Central Montana uplift) also was structurally depressed during deposition of this interval, although the boundaries of the trough were not as sharp in Interval 1 time as during the deposition of the Big Snowy Group in Late Mississippian time (Peterson, 1981). When referring to Paleozoic time, the area has been termed the Big Snowy trough (Norwood, 1965). The area just north of the trough was structurally positive, indicated by the east-west linear belt of thin sediment. These thickening and thinning trends reflect a horst and graben system that was dominant during Interval 1 time but did not recur in Interval 2 time (compare pls. 8 and 9).

Other linear thickness patterns shown on plate 7 occur in northeast and southwest North Dakota and in central Montana. A rose diagram of lineament directions for Interval 1 (pl. 8) shows that northeast and northwest directions are dominant, but most other directions are also represented. An isopach map of the Dunham salt in the Poe Member of the Nesson Formation of Jurassic age (fig. 6) shows that deposition was confined to an area bounded by the northwesterly trending lineament paralleling the Cedar Creek anticline to the southwest, and by a northeasterly trending lineament to the southeast. These structural boundaries probably enhanced conditions for an isolated basin, subsequently leading to salt deposition. A thickness map of evaporites in the Poe Member of the Nesson Formation (fig. 7) shows that the thickest evaporite deposits are in the same general area as the Dunham salt deposit (fig. 6). Even though the thickest part of the Nesson evaporites extends farther to the north and east than the Dunham salt, it is believed that the same structural features that controlled the Dunham salt accumulation also controlled Nesson evaporite accumulation.

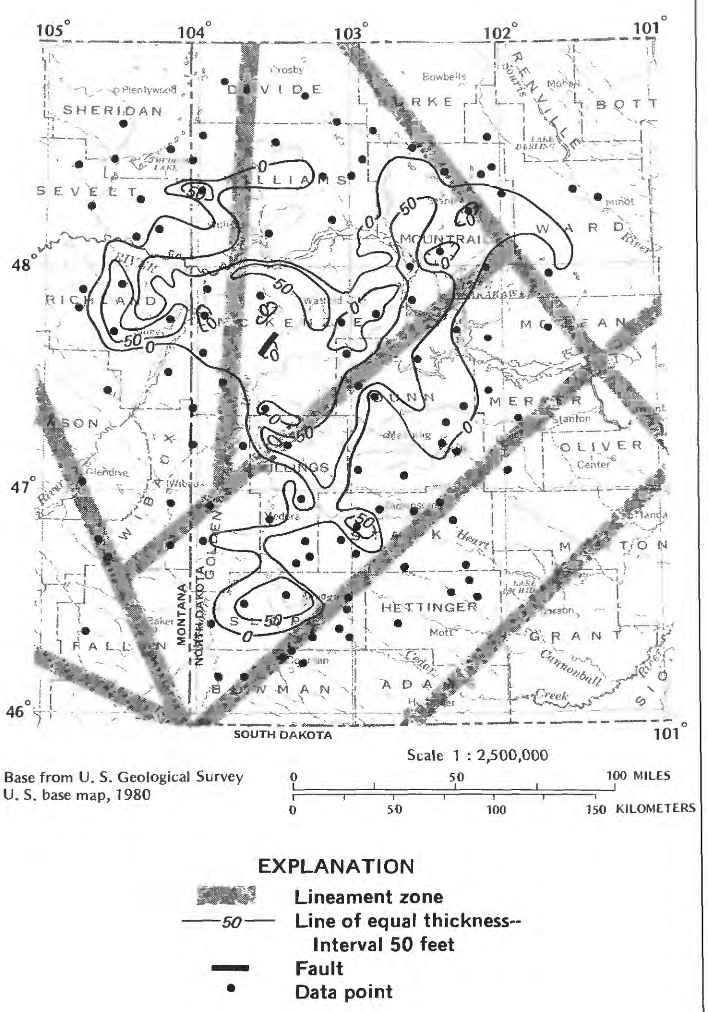


FIGURE 6.—Isopach map of Dunham salt in the Poe Member of the Nesson Formation, Montana and North Dakota. Zero contour modified from American Stratigraphic Company. Lineament zones, taken from plate 12, show possible structural control on salt thickness.

INTERVAL 2

As in Interval 1, time interval boundaries of Interval 2, which comprises the Swift and Morrison Formations and equivalent rocks, were placed at formation contacts; therefore, the lithologic boundary is not necessarily the same age everywhere in the region. However, it is believed that Interval 2 represents an approximate time interval, because there is a regional unconformity at the top of the Morrison. Well locations that had an anomalously thin Morrison Formation were not used in thickness calculation, because it was felt that the Morrison had been significantly eroded.

Thickness of Interval 2 ranges from more than 700 ft in Dawson and Carter Counties, Montana, and Harding County, South Dakota, to zero along the eastern flank of the Williston basin (pl. 14). The interval generally thickens east of the Cedar Creek anticline, north and south of the Black Hills uplift, and along the southwest flank of the Powder River basin. Thickening in these areas results from an increase in sedimentation in structurally depressed areas. The interval thins along the east flank of the Williston basin, southward into Nebraska, and in the Alberta shelf area in north-central Montana. These areas result from a decrease in sedimentation in structurally positive areas.

Net sand-thickness patterns of the Swift Formation show a northeasterly linear thickening trend across northeast Wyoming, northwest South Dakota, and southwest North Dakota (fig. *A*, pl. 9). Increased sand

FIGURE 7.—Net thickness of evaporites in the Poe Member of the Nesson Formation (excluding Dunham salt), Northern Great Plains; lineament zones, from plate 12, show possible structural control on salt thickness.

thickness results from an increase in sedimentation from a shoaling, shallow marine environment, where fault-blocked movement (horst) controlled the relief of the depositional surface. Other major sand accumulations, in areas such as the southern flank of the Black Hills uplift, can be attributed to similar shoaling mechanisms. In the marine environment, areas of thin or no sand accumulation are found in depressed fault-blocks (such as the area of the Big Snowy trough). A rose diagram of net sand and thick and thin linear patterns shows preferred trends of N. 45° E. and N. 60° W. (pl. 9).

A grain-size distribution map of sand in the Swift Formation shows larger grain sizes along the periphery of the basins and uplifts and smaller grain sizes in the centers of the basins (fig. *B*, pl. 9). Structural adjustments along the Cedar Creek anticline may have controlled distribution of sediment over, and adjacent to, the anticline. A correlation occurs between trends of net sand distribution and trends of sand grain-size distribution. A rose diagram of grain-size trends (pl. 9) shows three distinct preferred linear directions: N. 40° E., N. 35° W., and N. 65° W. A trend-surface, residual map of grain size, not presented here, also shows northeast, north-south, and northwest linear trends.

Where linear thick and thin isopach patterns of the Swift and Morrison Formations are overlain by thick and thin linear patterns of the next youngest time interval (Interval 3), distinct northeast and northwest patterns emerge. In many places, the overlying interval (Interval 3) thickens in an area where the underlying interval (Interval 2) is thin (compare pls. 14 and 15). This indicates that there was a reversal of some of the structural features between Interval 2 and Interval 3. Some areas that were structurally depressed (graben) during Interval 2 time were structurally positive (horst or arch) during Interval 3 time, and vice versa.

INTERVAL 3

The regional unconformity at the base of Interval 3 marks the base of the Lower Cretaceous. Included in Interval 3 are (1) the Lakota and Fuson Formations and the Fall River Sandstone of the Inyan Kara Group, and (2) the basal silt in the lower part of the Skull Creek Shale and equivalent rocks. The top of the interval is a regional silt marker bed, identified on geophysical logs, near the top of the marine basal silt of the Skull Creek Shale.

Interval 3 is more than 600 ft thick in central Montana and has a conspicuous east-west trending tongue of thick sediment extending into eastern Montana. The interval is also thick on the south flank of the Black Hills uplift and thins to 200 ft or less along the eastern flank of the Williston basin and in the central part of the Powder River basin (pl. 15). A rose diagram of linear thick and thin trends shows a strong preferred northeast direction and a less prominent northwest direction (pl. 15).

Net-sand thicknesses were combined for the Lakota and Fuson Formations and the Fall River Sandstone (pl. 11*A*). Although the net sand thicknesses are not as well defined for Interval 3 as they are for other intervals, a northwesterly trend, or grain, is evident on plate 11*A*, whereas the isopach interval thickness has a more dominant northeasterly grain (pl. 15). The thickness trends shown on plate 15 can be attributed to large-scale horst and graben systems. In contrast with Intervals 1 and 2, which are mostly marine rock, the predominately fluvial deposits of Interval 3 show thick, linear-trending sand accumulations in topographic or structural lows and thin, finer grained channel margin deposits accumulating on topographic or structural highs.

In eastern and north-central South Dakota, Interval 3 thins greatly over a large, northeast-trending elevated structural block that includes the Sioux uplift. In approximately the same area, Mereweather and Cobban (1981) show a northeast-trending paleostructure developed during Carlile time, although the structure was depressed then, in contrast to its elevated position in Interval 3 time. The Powder River basin was relatively positive during deposition of Interval 3, receiving little sand except for a few linear belts adjacent to the Black Hills uplift. It is not known whether in eastern South Dakota there was little original deposition or substantial deposition of Inyan Kara equivalent sediments (and subsequent uplift and erosion) or little original deposition, or both.

Coarsest sands of Inyan Kara age are in the eastern part of North Dakota and in northwestern Nebraska, adjacent to major sediment-source areas (fig. *B*, pl. 11). Grain size diminishes to the northwest and north toward the center of the Williston and Powder River basins. A rose diagram of linear trends of grain-size of Inyan Kara equivalent sediments shows a dominant northwest direction (pl. 11). An unpublished, trend-surface residual map of grain size shows a general decrease of the average grain size over and east of the Cedar Creek anticline. In northern Montana, west of the Cedar Creek anticline, grain sizes are larger than average; in the southern half of Montana and most of the Powder River basin, grain sizes are less than average.

Comparison of thick and thin isopach patterns of Interval 3 with thick and thin patterns of underlying and overlying time intervals shows that, in several localities where Interval 3 is thick, the underlying Swift-Morrison interval is thin, and vice versa (compare pls. 14 and 15). Thinning of the underlying unit generally is the result of incisement into the lower unit. Furthermore, the axes of thin, linear trends of Interval 4 generally overlie the axes of thick, linear trends of Interval 3 (compare pls. 15 and 16). This occurrence corresponds with the fact that with the thicker sediments accumulated in grabens and thinner sediments accumulated over horsts.

INTERVAL 4

Interval 4 consists of the silt-marker bed and upper part of the Skull Creek Shale, the Newcastle/Muddy Sandstone, Mowry Shale, and equivalent rocks (pl. 16). The top of the Mowry is picked at the Clay Spur Bentonite Bed, a regional marker at the top of the Lower Cretaceous.

An isopach map of Interval 4 (pl. 16) shows an overall thickening in west-central and south-central Montana. Most of the thickening in these areas is attributed to the Mowry Shale. The map also shows substantial thickening in southeastern South Dakota and northern Nebraska, although this thickening is attributed mostly to the Newcastle/Muddy Sandstone. Thin areas in northeastern North Dakota are attributed to thinning of all the formations in Interval 4.

A net sand-thickness map of the Newcastle/Muddy Sandstone (fig. *A*, pl. 12) within Interval 4 shows a broad, northeasterly trending band of thick sand that was deposited in a deltaic environment in southeastern and south-central South Dakota and in northern Nebraska. In other areas of the Northern Great Plains, the internal and external geometries of the sandstone indicate a variety of depositional environments, ranging from upper meander belt (fluvial), to deltaic, to marginal marine (Baker, 1962; Wulf, 1962; Waring, 1975; Weimer and others, 1982). Most of the sediment deposited in northeastern Wyoming and eastern Montana and in North Dakota and South Dakota originated east and southeast of these areas; in north-central and northwest Montana, sediment originated in southwestern Saskatchewan, in southeastern Alberta, Canada, and in northwestern Montana. The overall thickness pattern has a conspicuous northeasterly trend or grain, especially east of the Cedar Creek anticline in northeastern Montana and western North Dakota. The northeasterly trend is also present west of the Black Hills uplift, except for a strong northwesterly trend in western South Dakota paralleling the Cedar Creek anticline. The northeasterly grain of Newcastle sedimentation contrasts with the northwesterly grain of Inyan Kara sedimentation.

A map of the average grain-size distribution of the Newcastle/Muddy Sandstone shows good correlation between the areas of larger grain size and thicker sand accumulations (fig. *B*, pl. 12). Where there is a northeasterly trending belt of little or no Newcastle/Muddy sand equivalent in eastern Montana, there is also a similar northeasterly trend of very fine grained sand. The northeasterly trending belt of thicker sand accumulation in southeastern Montana and western North Dakota has an average grain size of fine to medium. Near the source area and main deltaic province in eastern and south-central South Dakota, the grain-size average is medium. An unpublished trend-surface residual map of average Newcastle/Muddy grain size shows similar trends; this map also shows anomalous patterns near to, and east of, the Cedar Creek anticline. A rose diagram of linear trends of Newcastle/Muddy grain- size distribution indicates a dominant northeasterly direction and a subordinate northwesterly direction (pl. 12).

Thick and thin linear trends of Interval 4 show a correlation with linear trends of Newcastle/Muddy sand accumulations (compare fig. *A*, pl. 16, and pl. 12). Except for a few trends, there is little correlation between thickening and thinning trends of Interval 4 and the overlying Interval 5.

The top of Interval 4 marks the top of the Early Cretaceous. Both Vail and others (1977, p. 85) and Hancock (1974) show a substantial worldwide increase in sea level starting in Late Cretaceous time. That rise may, in part, have been tectonically controlled (Vail and others, 1977, p. 93). Thick and thin patterns coincide for both Intervals 4 and 5 near the periphery of the Williston basin or near present uplifts, especially to the west. Rose diagrams illustrating directions of thick and thin trends show the northeasterly direction very dominant in Interval 4 time (Early Cretaceous, pl. 16) and the northwesterly direction dominant in Interval 5 time (Late Cretaceous, pl. 17).

INTERVAL 5

Interval 5 consists of the Belle Fourche Shale, Greenhorn Formation, and equivalents rocks (pl. 17). This interval was deposited in, essentially, a marine environment, consists of shale, calcareous shale, and limestone, and has occasional thin, low-permeability sandstone or siltstone.

Depocenters for Interval 5 are the Powder River basin and the northern Black Hills. There was significant downwarping in the Powder River basin, possibly related to incipient movement of the Laramide orogeny, even though the main orogenic event started after Interval 6. Interval 5 is thin in central and northern Montana due to major unconformities and in eastern North Dakota and South Dakota, and moderately thick in the Williston basin. Northeast of the central Montana uplift, the interval thickens abruptly across a feature that may have been a hingeline between the Alberta shelf and the Wyoming shelf. A rose diagram of thick and thin linear trends of Interval 5 indicates that northwesterly and northeasterly directions dominate (pl. 17).

INTERVAL 6

Interval 6 consists of the Carlile Shale, Niobrara Formation, and Pierre Shale to the top of the regionally extensive Ardmore Bentonite Bed (base of the Claggett Shale in Montana). The Ardmore is approximately equivalent to the top of the Eagle Sandstone in Montana. Interval 6 consists mostly of marine shale, but, in the western part, thick sandstone units of the Eagle Sandstone and equivalent rocks form significant sand intervals. Within Interval 6, the Niobrara Formation consists of chalk in North Dakota and South Dakota (Rice and Shurr, 1980) and of thin, low-permeability, marine sandstone, siltstone, and shale in Montana, Wyoming, and North Dakota.

Thickness patterns of Interval 6 (pl. 18) generally are comparable to those of Interval 5. The Powder River basin is significantly downwarped; however, the area north of the Black Hills was a less structural and topographic low. Downwarping seems to increase progressively north and west toward the disturbed belt in west-central Montana. Thinning of Interval 6 started between the Powder River basin and a small depression in Custer, Fallon, and Carter Counties, Montana; this may reflect initial stages of the final separation of the Williston basin from the Powder River basin. The area of thickening in Custer and Carter Counties, Montana, was slightly downwarped, possibly owing to a pulling apart of these basins. During the Laramide orogeny, this area was upwarped into its present configuration, the Miles City arch. The area near the Cedar Creek anticline was structurally low during Interval 6 time, as indicated by the linear thickening trend paralleling its axis. The Hartville fault, southeast of the Black Hills, was very active during this interval; within about 10 miles along the trace of the present-day Hartville fault, there is an increase of about 800 ft in the thickness of Interval 6. A rose diagram of Interval 6 shows a dominant northeast trend for thick and thin linear features (pl. 18).

Rose diagrams of thick and thin linear trends for Intervals 1-6 are shown in figure 8. All diagrams show distinct northeast and northwest preferred trends, with the northeast direction often dominant.

YOUNGER INTERVALS

Individual time intervals younger than the Ardmore Bentonite Bed of the Pierre Shale were not defined for this study, because there are no post- Ardmore time markers of regional extent from which to interpret regional tectonic events. Therefore, decriptions of major sand units above the Ardmore Bentonite Bed and structural effects on their deposition are not included in this paper.

SURFACE-LINEAR PATTERNS

As part of this study, surface-lineament mapping using Landsat imagery by Cooley (1982) shows two distinct lineament patterns (fig. 9): (1) in North Dakota and in South Dakota, the dominant direction of lineaments is northeast and northwest; and (2) in Montana and in Wyoming, the dominant northeast and northwest directions are supplemented by strong east-northeast and north-south components (fig. 9). West-northwest lineaments, although absent from figure 9, have been mapped by several authors (Smith, 1965; Stone, 1969; Thomas, 1974, 1976). These west-northwest lineaments parallel the Lewis and Clark lineament, the Lake basin fault zone, the Cat Creek fault zone, the Willow Creek fault, and the Nye-Bowler lineament (fig. 3).

Surface features such as faults and folds have been mapped and described in hundreds of published and unpublished papers. In figure 10, rose diagrams summarize orientations of major faults and fold axes in the Northern Great Plains, as mapped by Stone (1971), and compare them with subsurface linear trends composited from Intervals 1-6. The subsurface trends show a dominant northeast-northwest pattern. Major folds mapped at the surface trend north-south and northwest-southeast, whereas most major faults mapped at the surface trend east-west and northeast-southwest (fig. 10).

PRECAMBRIAN STRUCTURE

Cloos (1948) stated that the major tectonic features of our continents (from his observations in Europe) have been active during practically all the tectogenetic periods of the Earth's history. Thomas (1976) defined the initial northeast-northwest, orthogonal linear trends for the North American continent that developed during primordial Precambrian time and the east-west, north-northwest, and north-northeast trends of secondary features that developed during Archean and Proterozoic (Precambrian) time. On the basis of these definitions, it is believed that Precambrian tectonic events and their recurrent movement along preexisting zones of weakness played a major role in the development of most of the major fault and shear systems in the Northern Great Plains.

Redden (1968, p. 392) describes three major periods of deformation in Precambrian time for the Black Hills area: (1) major north-northwest-trending folds and subparallel faults were developed, followed by metamorphism; (2) in metamorphosed rocks, shear deformation, localized along northeast trends, formed near vertical foliation; and (3) granite intrusion.

Gott and others (1974, p. 30) described deformation of Mesozoic rocks in the southern Black Hills area that paralleled the northeast-trending structures of Precambrian age. In a detailed surface and subsurface study, part of the Northern Great Plains project, Weimer and others (1982) postulate that the vertical and lateral distribution of the Newcastle/Muddy Sandstone, on the east flank of the Powder River basin, was controlled in part by the recurrent movement of Precambrian basement blocks, most of which are orientated in a northeast-southwest direction.

The most prominent Precambrian structure is the Colorado lineament defined by Warner (1978, 1980) (fig. 11). This major structure is approximately 1,600 miles long and 100 miles wide and extends from Arizona to Minnesota. In southeast Wyoming, the northern margin is the Mullen Creek-Nash Fork shear zone—the shear zone that separates basement in central Wyoming (≥ 2,400 million years old) from younger rocks to the south and east (≤ 1,750 million years old). Gravity and aeromagnetic data and radiometric-age data from well cores indicate an extension of the boundary beneath part of the Northern Great Plains and into the midcontinent region. Warner (1978) states that the system formed in connection with the Penokean orogeny 2,000 to 1,700

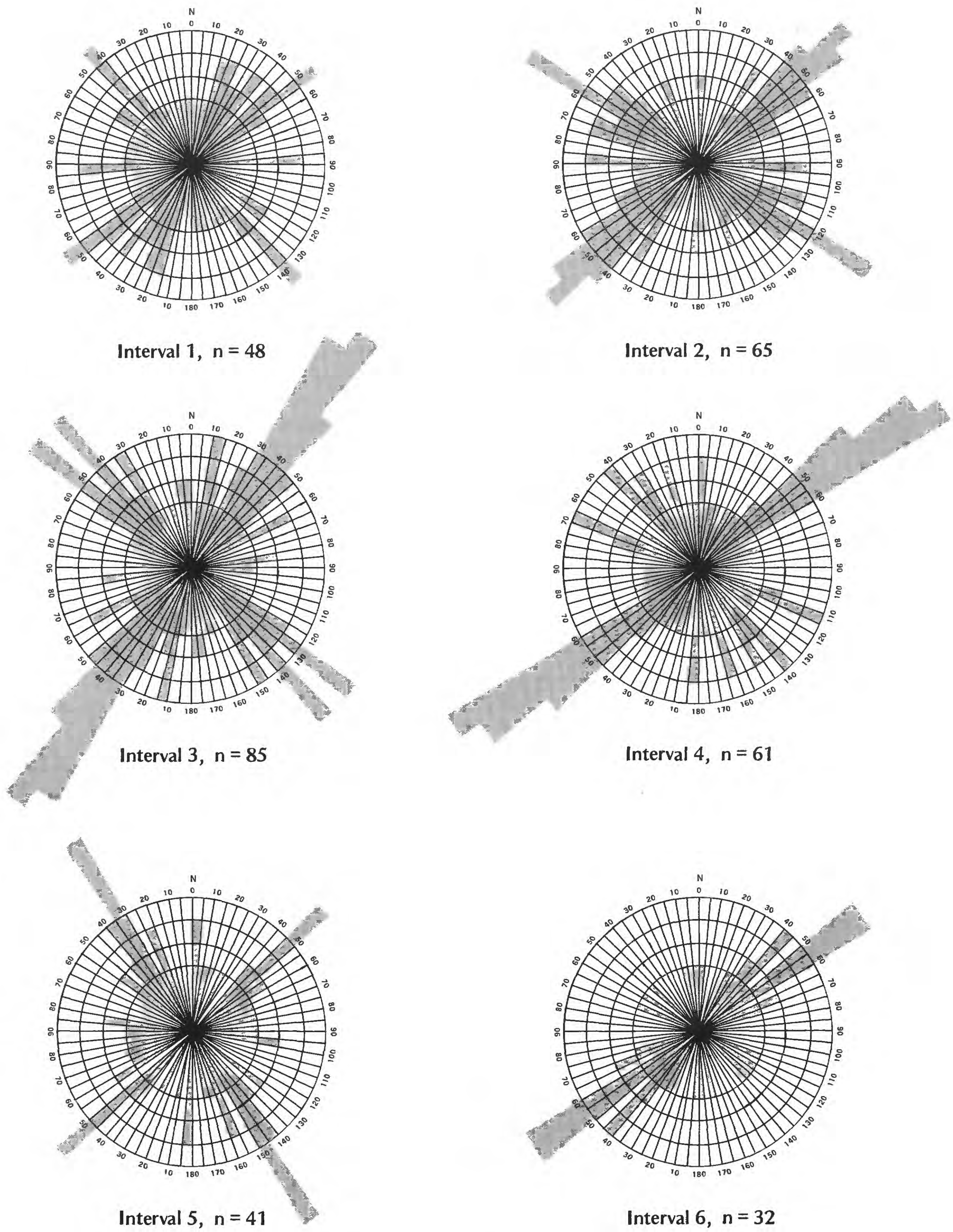


FIGURE 8.—Rose diagrams for isopach Intervals 1-6 showing direction of thick and thin lineament trends; n, number of lineaments in each diagram.

million years before present. Warner (1978) also states, "It appears to be a Precambrian counterpart of Phanerozoic wrench fault systems that have formed commonly along continental margins during episodes of mountain building."

In the Bighorn Mountains of Wyoming, Houston (1971, p. 20) reports that the gneiss that makes up part of the Precambrian core has a northeast-trending fabric. Hoppin and Jennings (1971, p. 44-45) describe east-west-trending lineaments in the Precambrian rocks of the Bighorn Mountains, Wyoming. The authors speculate that the lineaments may be the expression of transcurrent faulting originating within the lower part of the lithosphere during Cenozoic time, but doubt that the faults are recurrent from faults developed during Precambrian time, because of the lack of direct evidence.

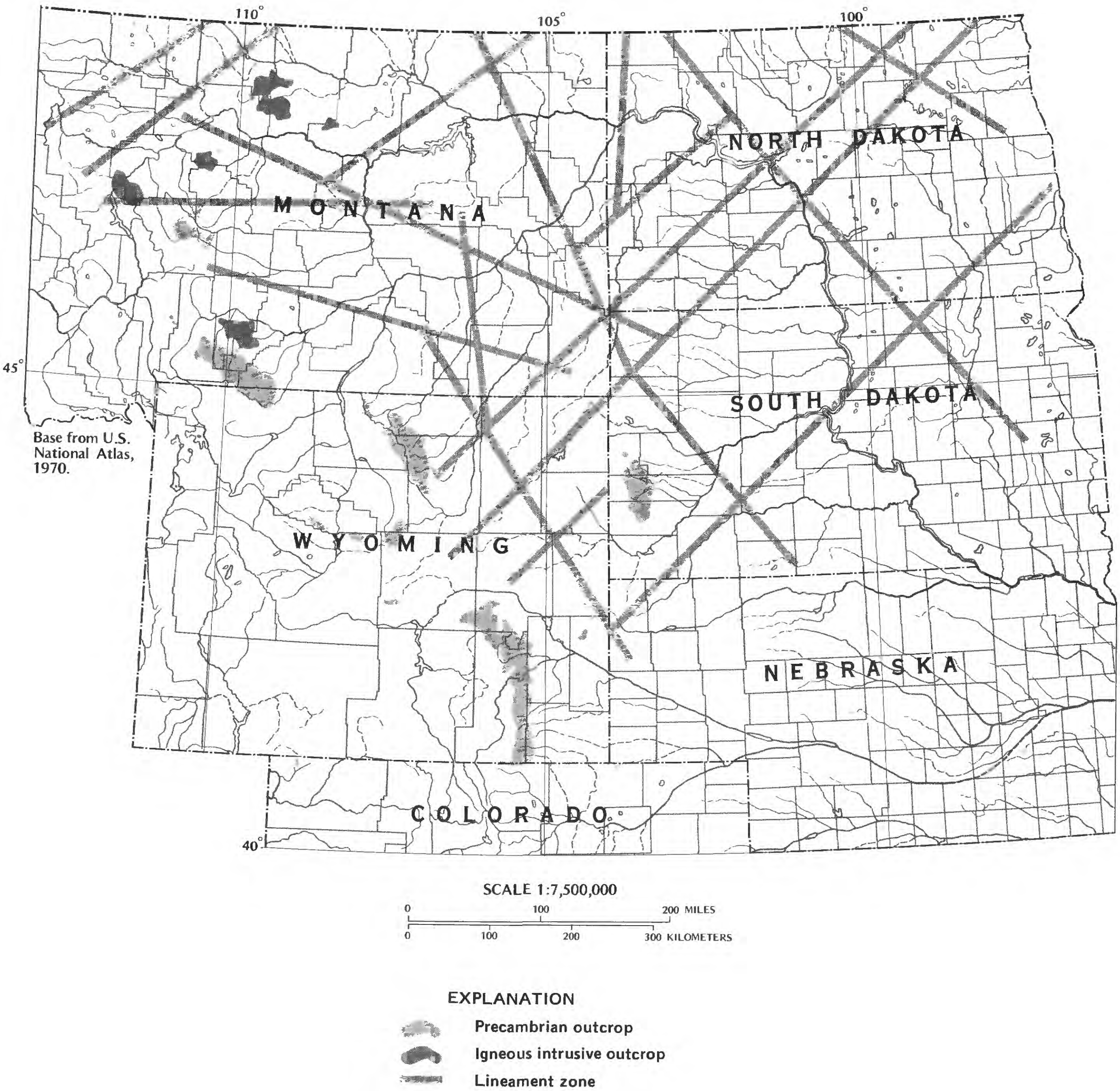


FIGURE 9.—Lineament trends in the Northern Great Plains.

Gorham and others (1979) described fractures in Cretaceous rocks in the San Juan basin and made the following observations: (1) Precambrian foliation is predominately northeastward; (2) northeasterly trending fault zones with major displacement of Precambrian age have influenced later Phanerozoic fracture trends (according to Shoemaker and others, 1974); and (3) Laramide compression resulting in simple- and pure-shear stress on the Colorado Plateau area probably generated both northeast and northwest conjugate joint sets and northeasterly trending extensional fractures.

STRUCTURE-STRATIGRAPHIC MODEL

The influence of paleostructure on sedimentation in the Northern Great Plains is reflected by lithofacies distribution and thickness patterns resulting from the presence of grabens, half-grabens, and horsts. Recurrent

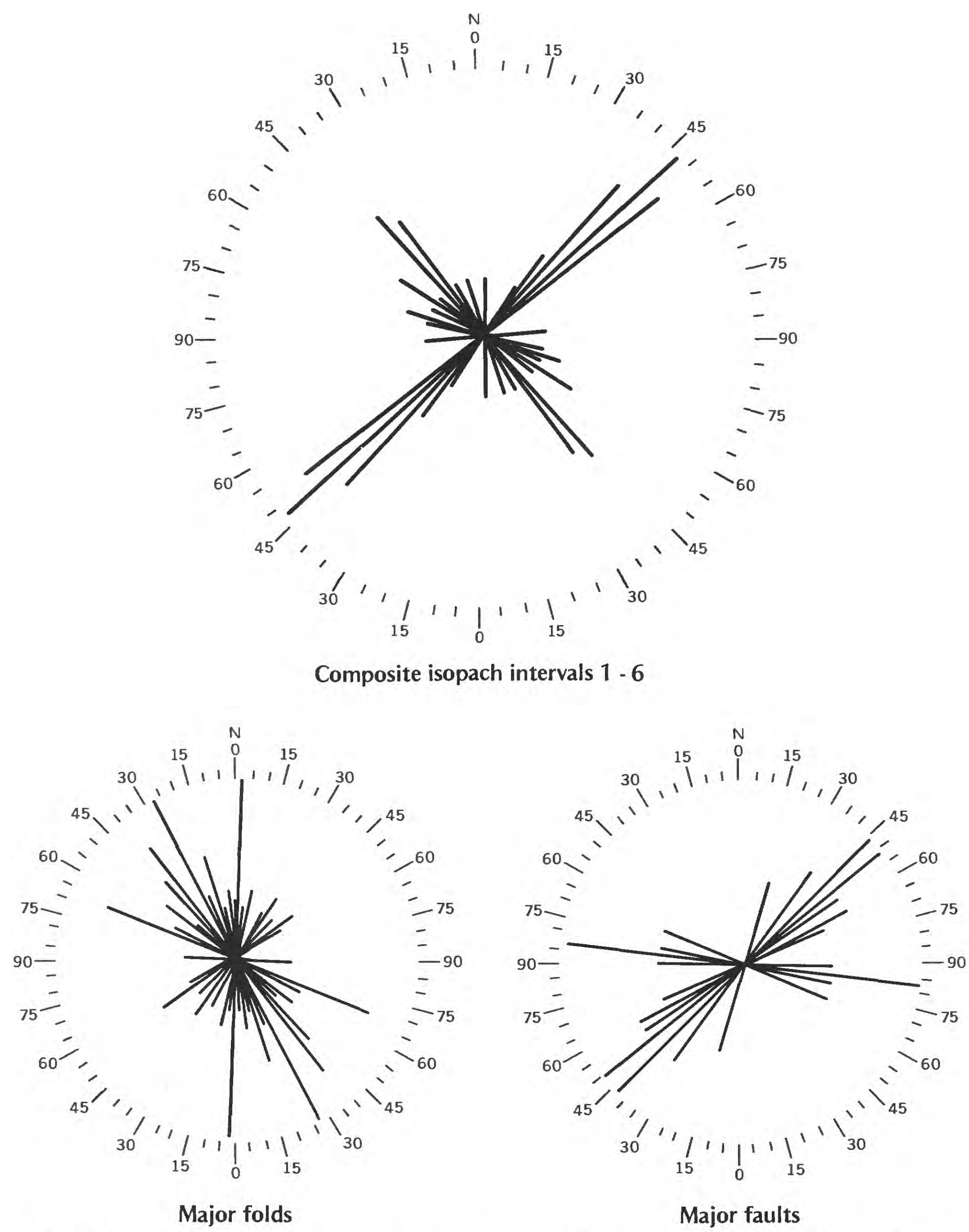


FIGURE 10.—Rose diagrams for composite isopach Intervals 1-6 with directions of major folds and faults, Northern Great Plains. Most fault and fold directions taken from Stone, 1971.

movement of basement blocks in the study area occurred periodically, with blocks being elevated at one time and depressed at another time.

Reactivated faults in Precambrian rocks are propagated upward, deforming overlying sediments by faulting or through drape folding. These faults are manifested either as linear features on a paleo-surface of deposition or on the present-day surface (fig. 12).

Response of the rock column to stress is regionally repetitive and is expressed by structural patterns of faults, fractures, and folds that are also repetitive. Wrench or strike-slip faults exist as simple shears and are commonly associated with folds and with thrust-and-reverse faults (fig. 13). Scissor-type faults are also common and are characterized by reversal of apparent dip-slip displacement along strike. Folds, thrusts, and reverse faults are commonly recognized as Laramide features, but are not usually directly observed as pre-Laramide (paleostructure) features. Drape-type folds responding to basement faulting (fig. 14) are probably the most common type of paleostructure (see Stearns, 1971, for a review of drape folds). The change of topographic relief from one fault block to another is probably in the form of a drape fold, that is, it is not necessarily in the form of a fault plane. Figure 14 indicates that basement faults have less effect on sedimentation distribution at the surface as the rock section thickens. Yet, the degree of drape is primarily controlled by how high the faults propagate upward.

The observed distribution and thickness of sediments in a detrital-depositional system stem from recurrent movement of Precambrian blocks as horsts, grabens, or half-grabens, from eustatic changes in sea level, and from the quantity and quality of available sediments. From detailed work, Weimer and others (1982) developed a series of diagrams (models) summarizing possible depositional environments that existed pre-, during, and post-Muddy Sandstone time, along the south and southwest flanks of the Black Hills uplift (fig. 15). The same model can be applied regionally to similar units. Initial conditions, prior to change in sea level with a horst-graben sequence in the marine environment, are shown in figure 15 part *A*. Off-shore bars develop over the horst because of the slightly shallower water. After a drop in sea level, incisement occurs on the graben block, because streams are channeled into topographic or structural lows (fig. 15, part *B*). As sea level rises, (fig. 15 part *C*) valley- and channel-fill deposition occurs in the incised channel. Continued rise in sea level results in deposition over the entire graben, not only in the in-

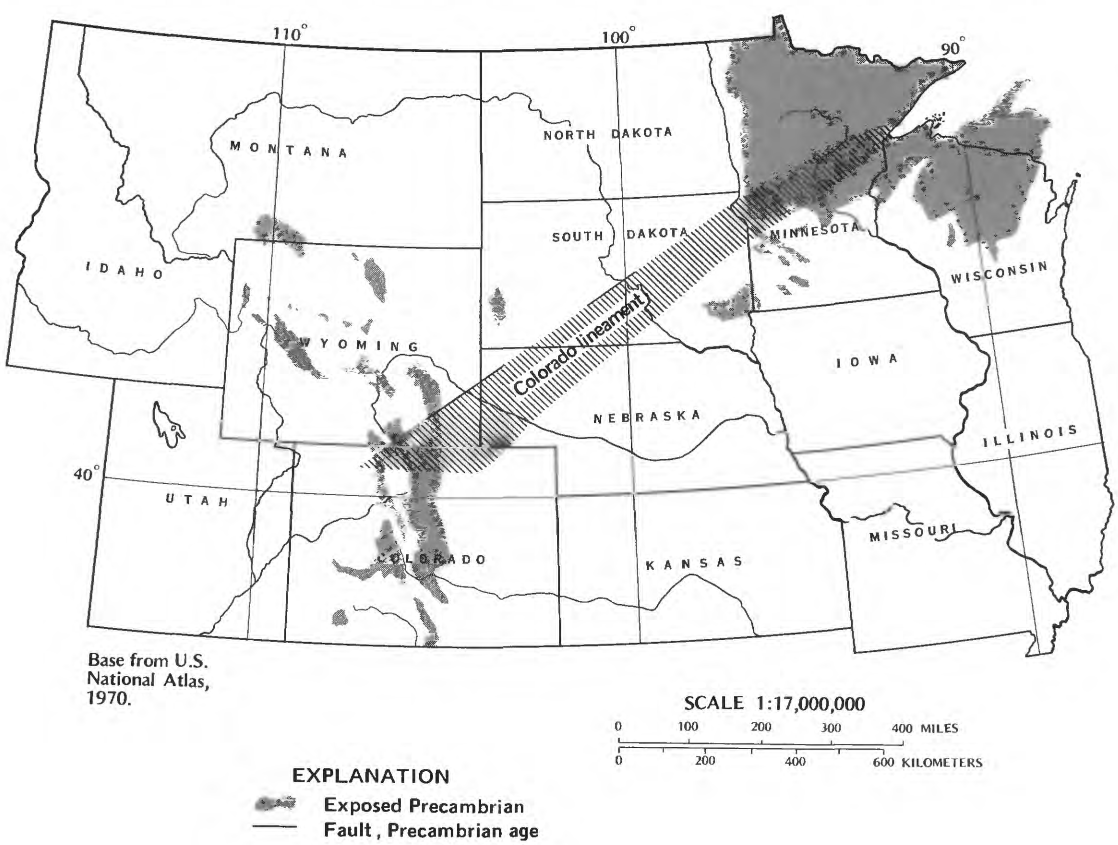


FIGURE 11.—Map showing the Colorado lineament. Modified from Warner (1978, figures 2 and 5).

cised channel (fig. 15, part *D*). With continued rise in sea level, thick near-shore, shoreface, and well-drained swamp deposits are deposited over horst or upthrown blocks (fig. 15, part *E*); estuarine, tidal flats, and poorly drained swamp deposits form over graben or downthrown blocks. The final step in the process is a complete transgression, resulting in marine deposits at the base of the next cycle. Therefore, in a nonmarine environment, rivers channel into topographically or structurally low areas, resulting in thicker, coarser-grained deposits. In contrast, interchannel areas develop in topographically or structurally high areas, resulting in finer-grained deposits. In a marine environment, sand deposits generally develop over structurally high areas (due to shoaling effects), and shale deposits accumulate in structurally low areas. The same principles apply to areas of half-grabens; however, the geometry of the deposit is modified because the configuration of the structural block is modified.

Structural adjustments or recurrent movement of basement blocks may result from changes in magnitude of the local stress field or, less frequently, of the regional stress field. Basement blocks might also have experienced structural adjustment or recurrent movement when the resistance to movement in one direction was greater than another; therefore, the new direction of movement along a fault plane would be in the direction of least resistance. Thus, a particular block may be elevated at one time and depressed at another, depending on the change of direction of the stress and the amount of change in the resistance.

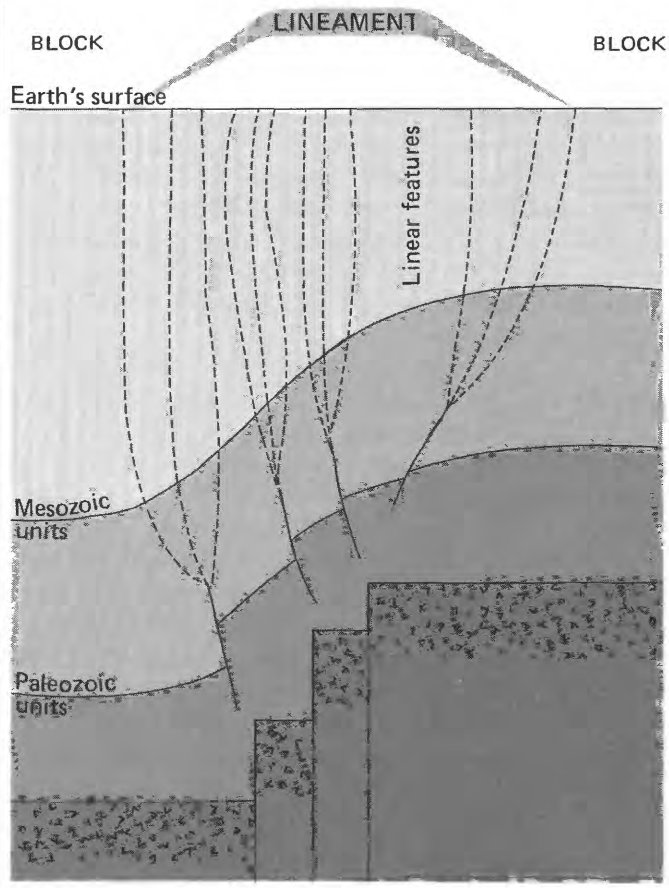


FIGURE 12.—Landsat lineaments and constituent linear features as the surface expression of basement fault zones, their component faults, and associated structures. No horizontal or vertical scale implied. From Shurr, 1982.

TECTONIC FRAMEWORK

Interpretations of the subsurface data resulted in recognized linear patterns of sediment geometry and texture that were mapped as subsurface lineaments. Interpretation of surface lineaments was based on linear trends of thicknesses of six chronostratigraphic intervals, on the relationship of thickness variations between successive chronostratigraphic intervals, and on linear trends of sedimentary texures of sand units within the chronostratigraphic intervals. Data for these interpretations were obtained mostly from drill-hole information and from geophysical logs; a composite map of the major lineaments of all the intervals is shown on plate 13. Composite lineaments systems or zones (El-Etr, 1976, p. 486) were defined in areas where lineaments recurred in most of the chronostratigraphic intervals. The lineaments were then treated as fractures, so that the standard fracture-analysis technique proposed by Thomas (1974) could be applied.

STRESS ANALYSIS

The orientation of observed linear patterns in the study area generally fits the theoretical angles associated with rock failure in a horizontal compressional system (fig. 16). As stated previously, rock failure is expressed in the form of grabens, horsts, half-grabens, monoclines; thrust or reverse, and normal faults; and shear zones. Each type of rock failure can result in one or more specific types of vertical and lateral sediment-deposition pattern. However, predicting a specific stress direction for Mesozoic and Cenozoic time is difficult if deformation of the basement during Precambrian time resulted from stress oriented in a different direction than was operating during Mesozoic and Cenozoic time.

Structural deformation of rocks during anorogenic events is subtle compared with deformation during orogenic events. Because the subsurface linear patterns described in this paper are expressed by rocks deposited during anorogenic events (at least in the immediate geographic area), structural deformation is subtle, yet the linear patterns have a regularity that cannot be attributed to random deformation. Moreover, the regional extent and orientation of the linear patterns indicate that the stress controlling the extent and orientation of the linear patterns is a single stress mechanism distributed over the entire region. The structural complexities that can arise from a single-stress (pure-shear stress) field are shown in figure 17. Surface linear patterns and orientation indicate that the same single-stress mechanism that was operating during pre-Laramide time was also operating during the Laramide orogeny (Thomas, 1974). Only the expression of the stress differs (shown by the type of structure produced by the stress): folding and large scale thrusts characterize Laramide structures; whereas, pre-Laramide structures are predominently grabens, half-grabens, and horsts.

It is postulated that the stress mechanism that produced the observed lineaments is horizontal compression rather than vertical isostatic adjustments. This premise is an important consideration when attempting to predict geologic and hydrologic features in areas of little or no control.

Vening-Meinesz (1947) postulated that a worldwide system of shear planes exists in the Earth's crust. This theory of compression assumes that most faults, fractures, and lineaments are incorporated into a worldwide shear pattern. This pattern, later named the regmatic shear pattern by Sonder (1947), is based, in general, on the observation and mapping of linear topographic, geologic, and geophysical trends of great extent that are consistently oriented either northeast or northwest around the Earth (Thomas, 1976).

Thomas (1976, adapted from Carey, 1958) postulates that the incipient stages of compression forces from the southwest were due to movement of the North American megaplate toward the East Pacific ridge initiated as early as Pennsylvanian time. Thomas (1976) also states that lineaments were intermittently active into the craton region to the northeast. The new stress direction reactivated existing basement shears, created a coupling (torquing) or simple-shear effect between Precambrian blocks, and initiated or enhanced fractures in west-northwest and east-northeast directions (figs. 18 and 19). The relative magnitude of the pure-shear system compared with the simple-shear (direct stress, no torquing) system is not known.

During Late Cretaceous time, increased westward motion of the North American megaplate, along with accelerated rates of northeast-southwest convergence

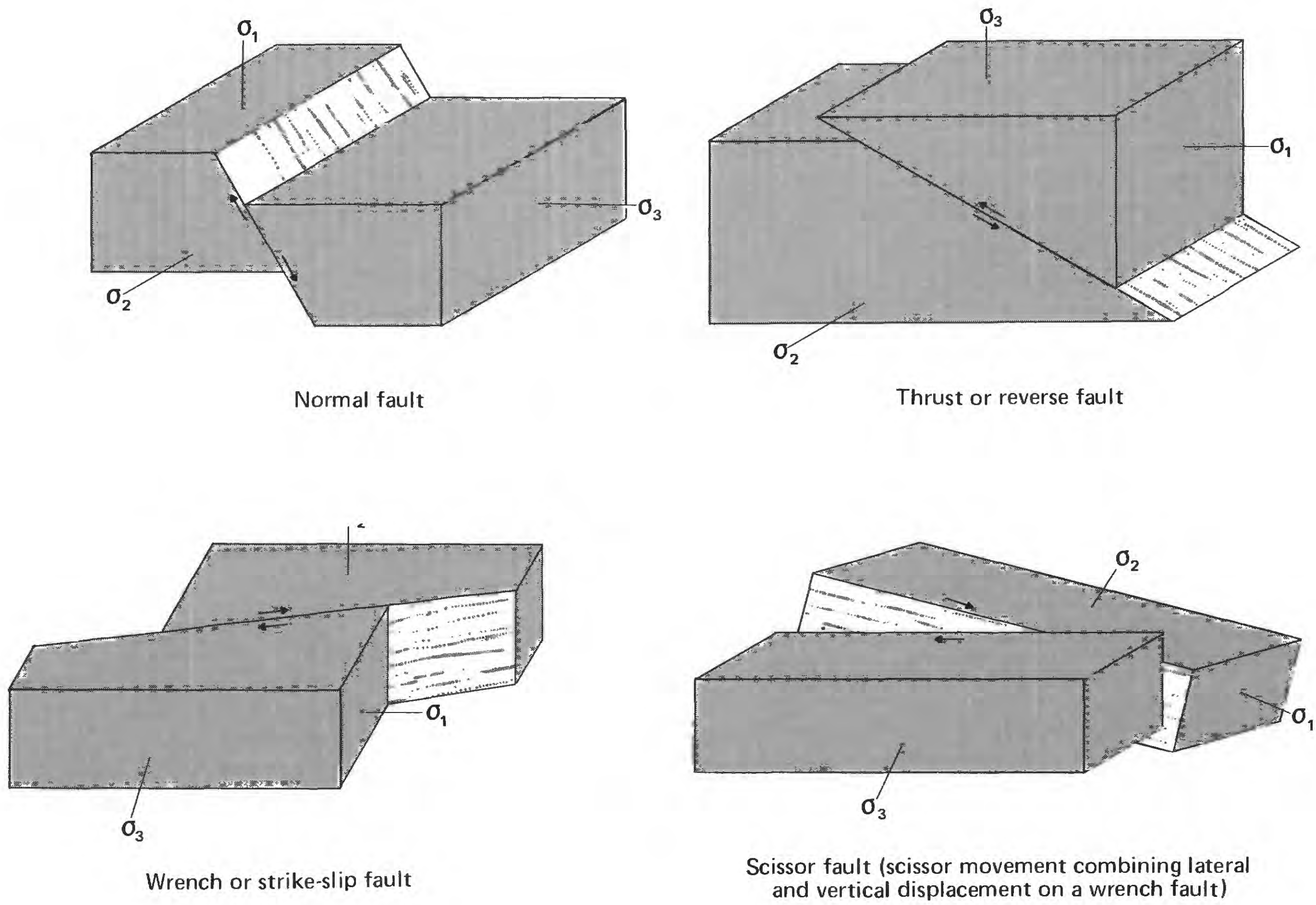


FIGURE 13.—Fault types and associated stress (σ) directions. σ indicates stress, with $\sigma_1 > \sigma_2 > \sigma_3$.

with the Farallon plate, marked the beginning of the Laramide orogeny (Coney, 1975, p. 1035). In the Northern Great Plains, reactivation of pre-existing Precambrian faults by east-west or northeast-southwest compression resulting from plate movement created Laramide features. In Montana and Wyoming, a large-scale Laramide lineament pattern of the Northern Great Plains interpreted from Landsat imagery fits comfortably with the simple-shear stress system. Thomas (1976) and Smith (1965) have theorized a simple-shear stress system during the Laramide orogeny for Montana and Wyoming.

Reches (1978) summarized that the Palisades monocline (drape fold) and other monoclines in the Colorado Plateau area were developed from compressional forces. His evidence is based on petrofabrics, fault orientations, and fold-axis orientations of small-scale features (fig. 14). Map view of these features indicates they are oriented between 20° to 30° to the direction of maximum compression (fig. 20). This orientation indicates that horizontal stress could have produced drape folds (monoclines) thought to be present in Mesozoic time in the Northern Great Plains.

INFLUENCE ON GROUND-WATER FLOW

The movement of ground water through rock is a function of many parameters, the hydraulic characteristics, and the vertical and lateral permeability distribution within sediments. Hydraulic conductivity can be measured directly from the rock itself. Vertical and lateral permeability distribution are also measured directly at the outcrop or are measured indirectly at a point source from geophysical logs; however, permeability distribution between point sources must be interpreted.

Secondary permeability in the form of fractures or dissolution features can greatly enhance the ability of a rock to transmit water. If, as postulated here, horizontal compressional forces operating during Mesozoic and Cenozoic time were responsible for the sediment deposition patterns described in this report, then the type and general orientation of faults, shears, or frac-

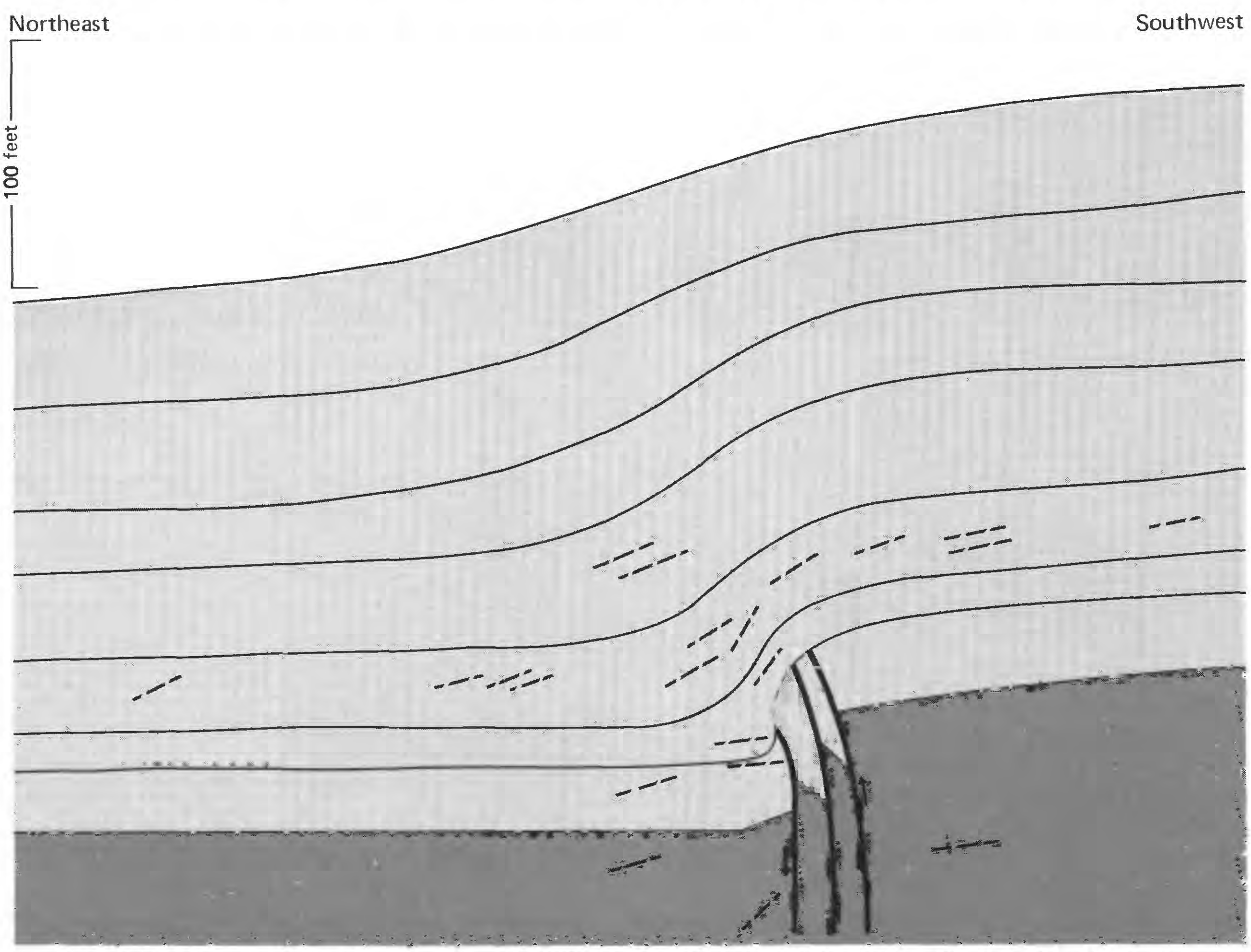


FIGURE 14.—Accurate composite cross section of the Palisades monocline. Short broken lines are directions of maximum compression according to petrofabric, fold axes, and fault orientations of small scale structures. Modified from Reches (1978).

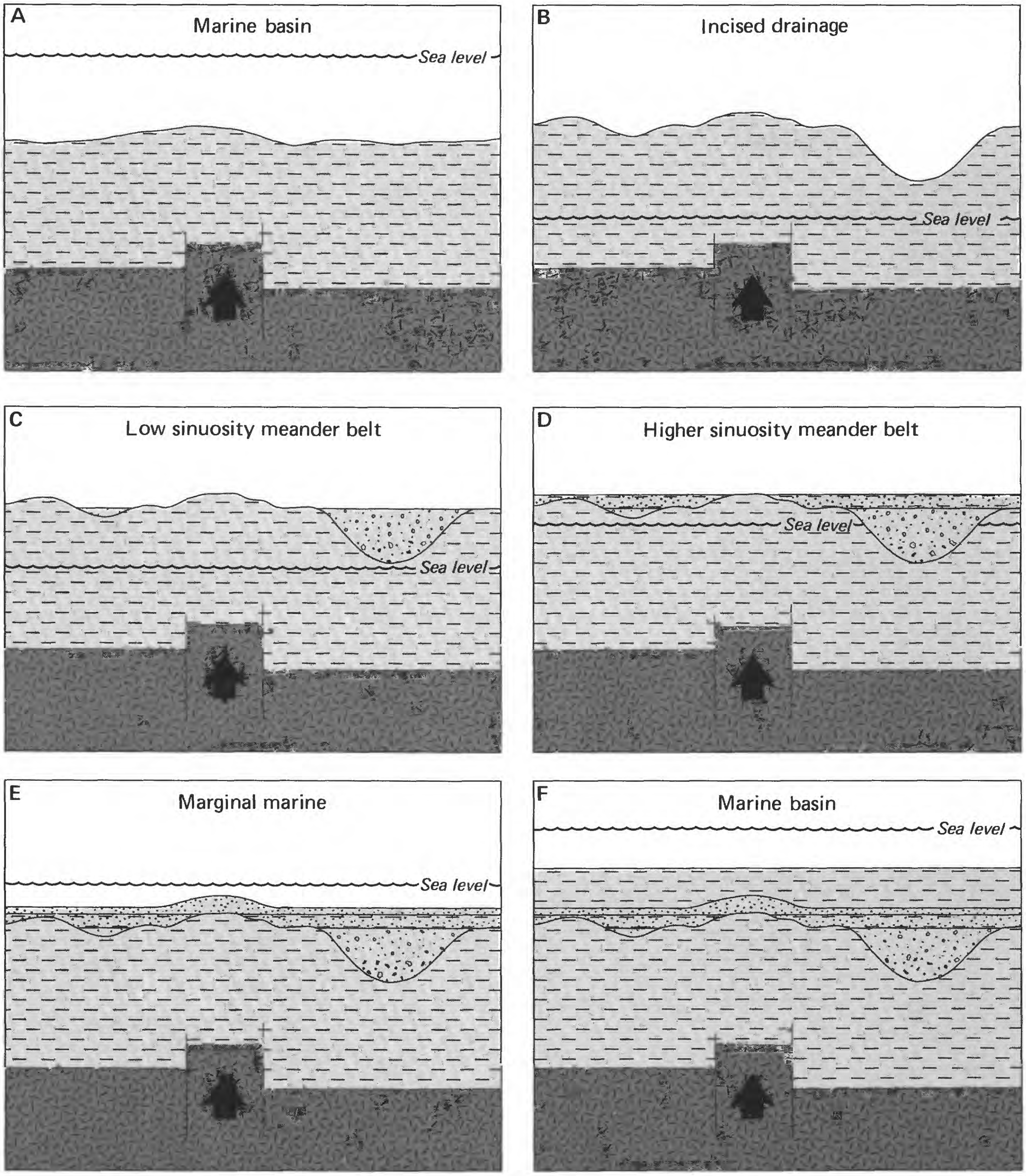


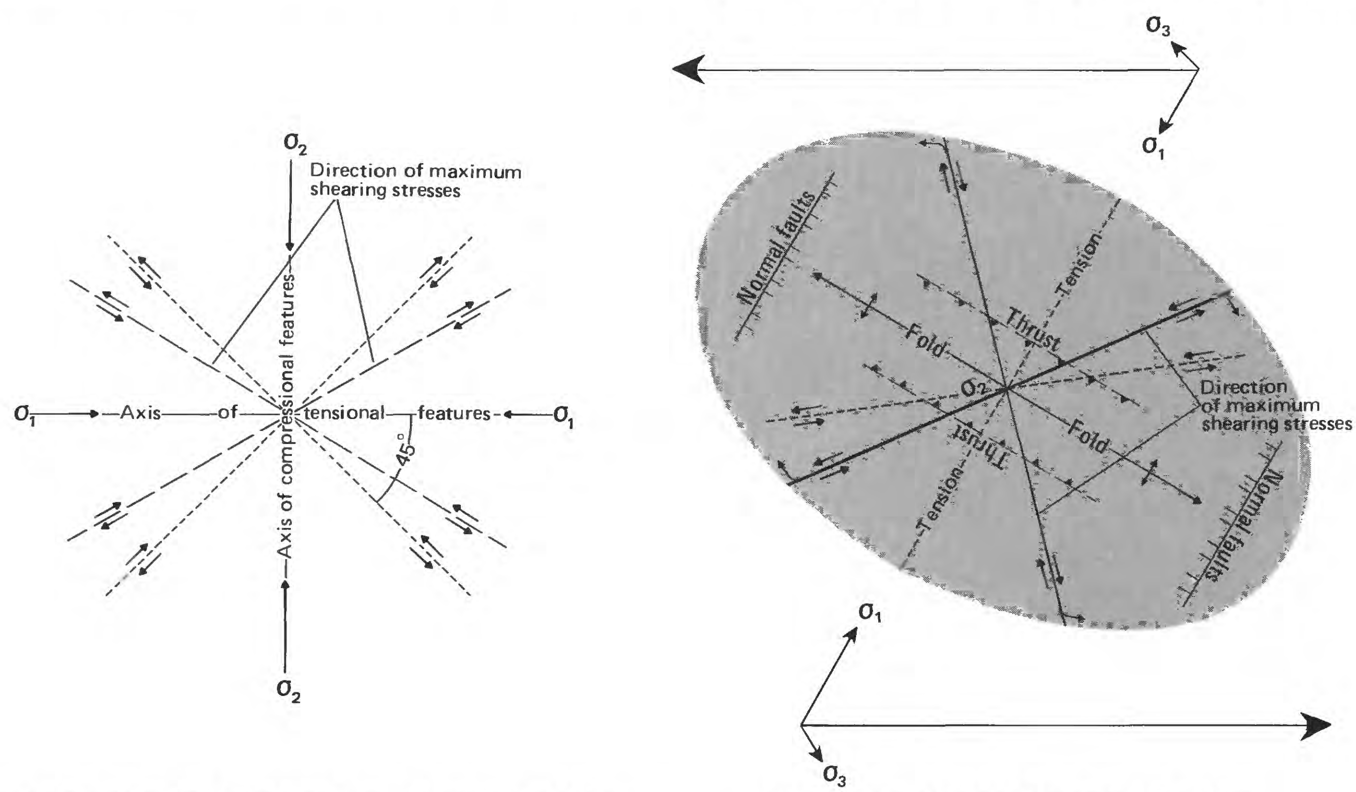
FIGURE 15.—Postulated sedimentary response to structural adjustment for one cycle of sea-level fluctuation in a classic environment. Modified from Weimer and others (1982).

tures that produced the depositional patterns is predictable (fig. 19). Because faults, shears, or fractures largely determine the secondary water-transmitting properties of the rock, it follows that secondary permeability distribution is also predictable.

It is assumed that the primary horizontal stress direction during Mesozoic and Cenozoic time was approximately east-west to northeast-southwest. Therefore, the direction of tensional structural features that parallel the major stress direction should be generally east-west to northeast-southwest, and the direction of compressional structural features should be approximately at right angles to the tensional features, that is, northwest-southeast. Tensional features in rocks could promote ground-water flow by enhancement of secondary porosity or permeability. Accordingly, ground-water flow volumes may be greater in a general northeast-southwest direction (fig. 21). Conversely, compressional features could decrease secondary porosity or permeability; thus, northwest-southeast-trending features could be effective barriers to northeast- or east-flowing ground water, or, perhaps, they could be partial barriers that deflect the water from its original flow path (fig. 21). This theory applies to both vertical and lateral movement.

Assuming that tensional features create conduits and compressional features create barriers to ground-water flow, the question arises: Is the process operating on a regional scale, on a local scale, or both? It appears that the northwest-trending Cedar Creek anticline is a particular barrier to east-flowing ground water (Downey, 1982). Where easterly or northeasterly trending structures intersect the Cedar Creek anticline, ground water crosses the anticline. When computer simulating ground-water flow, Downey often used the conduit-barrier technique to balance the simulation when other geologic parameters could not do so. The theory of structural control on ground-water movement is certainly inexact and cannot be applied to all cases. For example, in western South Dakota, potentiometric and geochemical data indicate that both northeast- and northwest-trending lineaments act as barriers to vertical and lateral flow. However, in general, the highest permeability zones are oriented northeast-southwest (Ken Kolm, U.S. Geological Survey, oral commun., 1982).

The process of porosity and permeability reduction due to compression, as postulated above, is neither well documented nor properly understood. The process may be mechanical, or chemical, or a combination of the two.



Pure shear. Modified from Moody and Hill (1956, p. 1210). Simple shear. Modified from Harding (1974).

FIGURE 16.—Theoretical fracture patterns associated with pure- and simple-shear stress; σ_1, σ_2, σ_3 are respectively maximum, intermediate, and minimum effective principal stress.

The process may be totally effective, totally ineffective, or only partially effective, depending on other geological factors.

SUMMARY

In the Northern Great Plains, during Jurassic and Cretaceous time, the dominant depositional environment was marine; in Tertiary time, the dominant environment was continental. Various pre-Jurassic paleostructural features, such as the Williston basin, the Cedar Creek anticline, and the Alberta shelf, continued as structural elements in Jurassic and Cretaceous time. The Laramide orogeny enhanced these features and created numerous other structural features approximately in their present-day configuration.

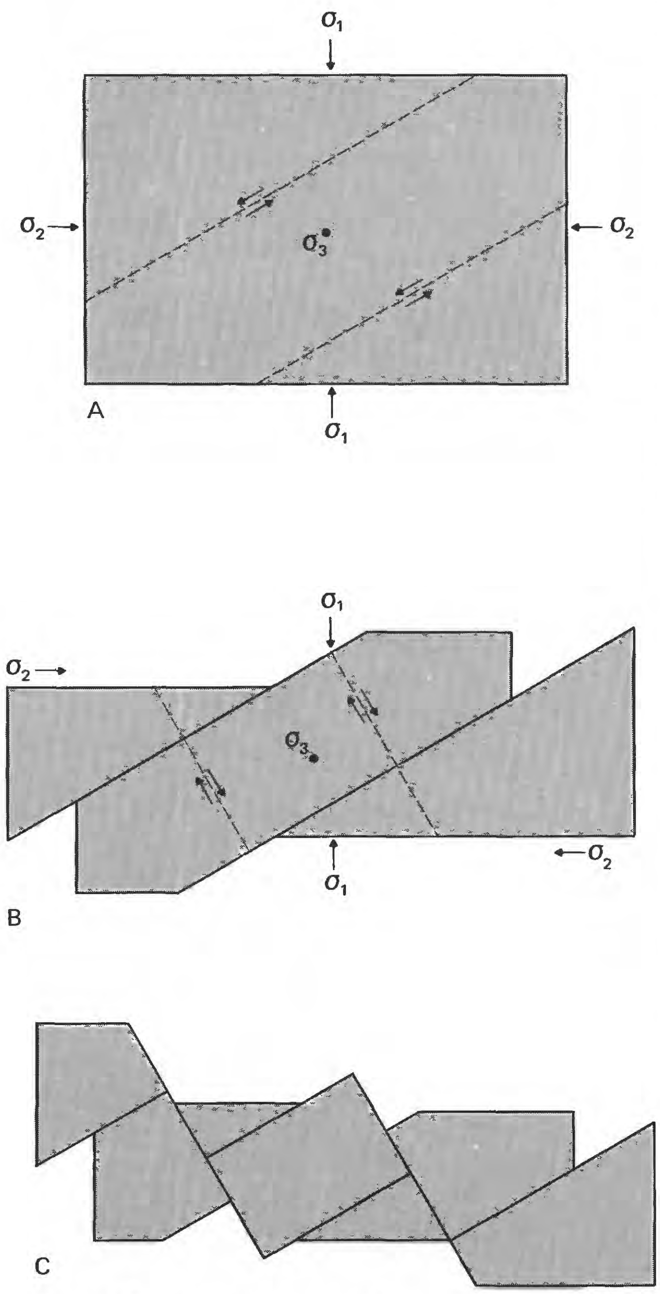


FIGURE 17.—Possible structural configurations in map view of Earth's crust as a result of pure-shear stress. $\sigma_1 > \sigma_2 > \sigma_3 >$.

The Nesson, Piper, and Rierdon Formations and equivalent rocks (Jurassic), consisting mostly of anhydrite, carbonate, and shale, were combined into chronostratigraphic Interval 1. Thick and thin linear patterns of the total interval thickness show a general northeast and northwest alinement.

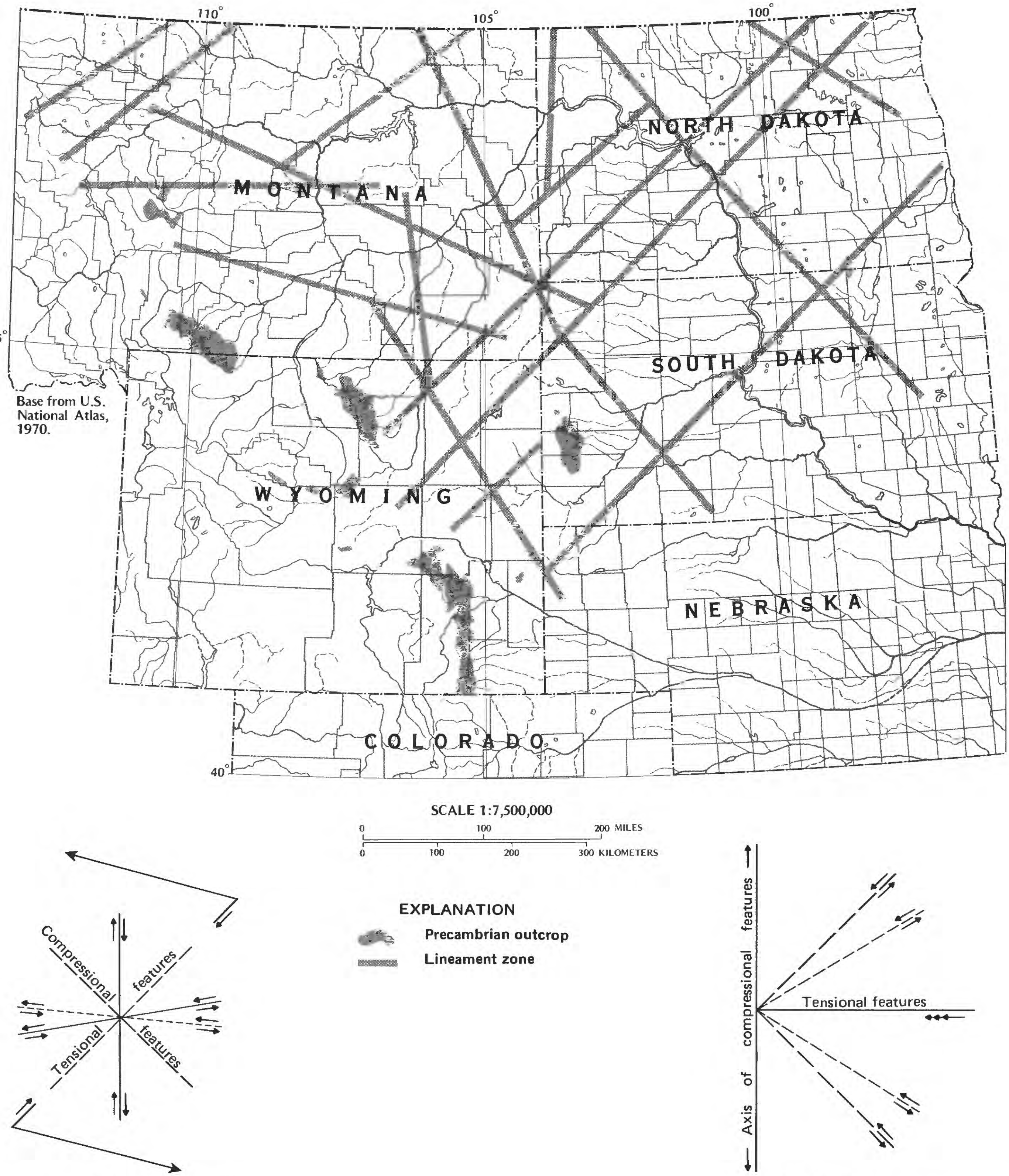
The Swift and Morrison Formations and equivalent rocks (Jurassic), which form chronostratigraphic Interval 2, consist mostly of marine and continental shale, siltstone, and sandstone, Contour patterns on isopach, net sand-thickness, and sand-texture maps of Interval 2 show lineament features that generally trend northeast and northwest.

The Lakota and Fuson Formations and the Fall River Sandstone of the Inyan Kara Group and the basal silt of the Skull Creek Shale and equivalent rocks (Early Cretaceous) comprise Interval 3. The Lakota and Fuson Formations consist of continental sandstone, siltstone, and shale; the Fall River Sandstone consists mostly of marine sandstone and siltsone. Contour patterns on an isopach map of Interval 3 show lineaments that generally trend northeast; contour patterns on net sand-thickness and sand-texture maps of the interval show lineaments that generally trend northwest.

The interval that extends from a regional silt marker bed and into the upper parts of the Skull Creek Shale, Newcastle/Muddy Sandstone, Mowry Shale, and equivalent rocks makes up Interval 4. The Skull Creek Shale consists of marine shale and siltstone; the Newcastle/Muddy Sandstone consists of marine and nonmarine sandstone, siltstone, and shale. Contour patterns on an isopach map of Interval 4 and net sand-thickness and sand-texture maps show lineaments that generally trend northeast.

The Belle Fourche Shale and Greenhorn Formation and equivalent rocks make up chronostratigraphic Interval 5. The Belle Fourche Shale is marine, and the Greenhorn Formation consists mostly of marine shale and limestone. Contour patterns on the isopach map of Interval 5 show lineaments that generally trend northwest with a northeast component.

The Carlile Shale, Niobrara Formation, and the Pierre Shale up to and including the Ardmore Bentonite Bed comprise chronostratigraphic Interval 6. The Carlile Shale is marine, the Niobrara Formation consists of marine shale and chalk, and the Pierre Shale is marine. The Eagle Sandstone and equivalent rocks in central Montana are included in the interval. The top of the Eagle is approximately time-equivalent to the Ardmore Bentonite Bed. Contour patterns on the isopach map of



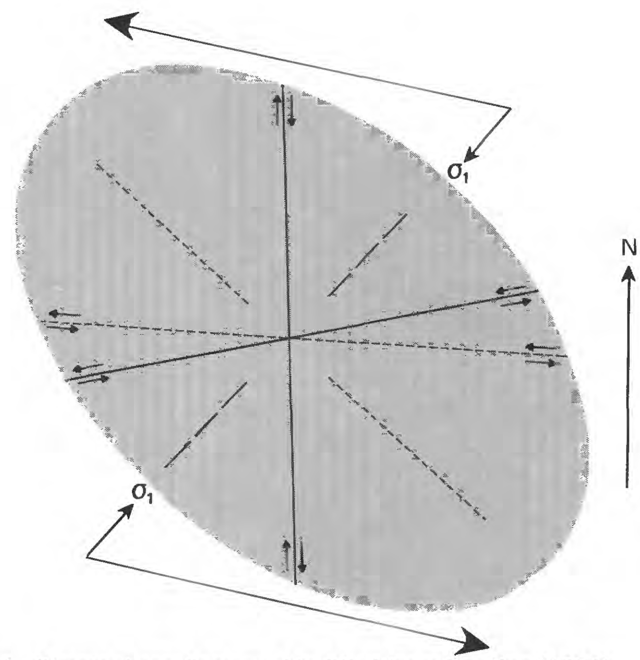
Simple-shear diagram.
Modified from Harding (1974).

Pure-shear diagram.
Modified from Moody and Hill (1956).

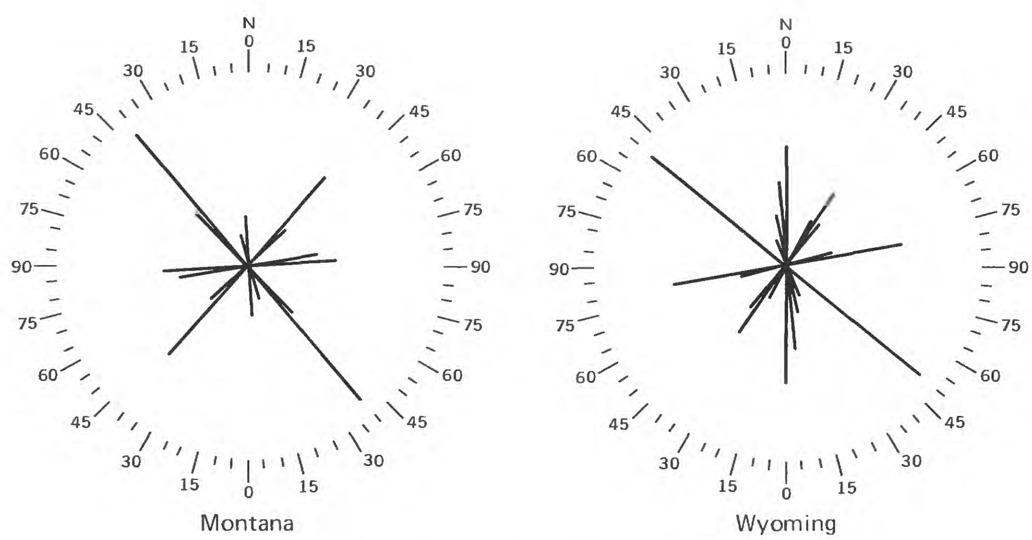
FIGURE 18.—Paleolineament map recognized from subsurface sediments, Northern Great Plains; pure-shear stress field operated primarily in North Dakota and South Dakota; simple-shear stress field operated primarily in Montana and Wyoming.

Interval 6 show lineaments that generally trend northeast with a northwest component. The distinct separation of the Williston basin from the Powder River basin begins in this interval.

Observed structures and their arrangement, orientations of lineament trends and patterns, and styles of deformation can be described best by a tectonic and sedimentation model that can be applied to at least Jurassic and Cretaceous units in the Northern Great Plains. This model consists of grabens, half-grabens, and horsts that influence the position of depositional environments. The effect of these structures is enhanced



A. Simple-shear diagram. Modified from Harding (1974).
σ_1 = maximum stress.



B. Rose diagrams with azimuths of linear trends from figure 10.

FIGURE 19.—Possible cause and effect relationship; simple shear (A) may produce lineament trends (B) as mapped in Wyoming and Montana.

by eustatic rise and fall of sea level. A horizontal style of stress system best explains the observed structural patterns.

Pure- and simple-shear stress was relatively active during Jurassic and Cretaceous time, activating movement of Precambrian fault-bounded blocks. The intensity of stress greatly increased during the Laramide orogeny, resulting in uplifts and the formation of mountain ranges and enhancing numerous older structural features and creating new ones.

Orientation of tensional and compressional structural features in the Northern Great Plains is predictable, assuming the style of stress described in this paper. Tensional features, oriented east-west and northeast-southwest, enhance secondary porosity or permeability and become partial conduits for ground-water flow. Compressional features, oriented generally northwest-southeast, decrease porosity or permeability and become effective barriers or partial barriers to ground-water flow.

The importance of the relationship between structure and stratigraphy cannot be overlooked in evaluating either regional or local ground-water systems. A hierarchy of predictability is possible because of the interdependency of transmissivity, permeability, secondary porosity, primary porosity, sedimentary texture and structure, sedimentary geometry and structure, and tectonics. All are directly or indirectly dependent on one another, and each needs to be evaluated on its own merit.

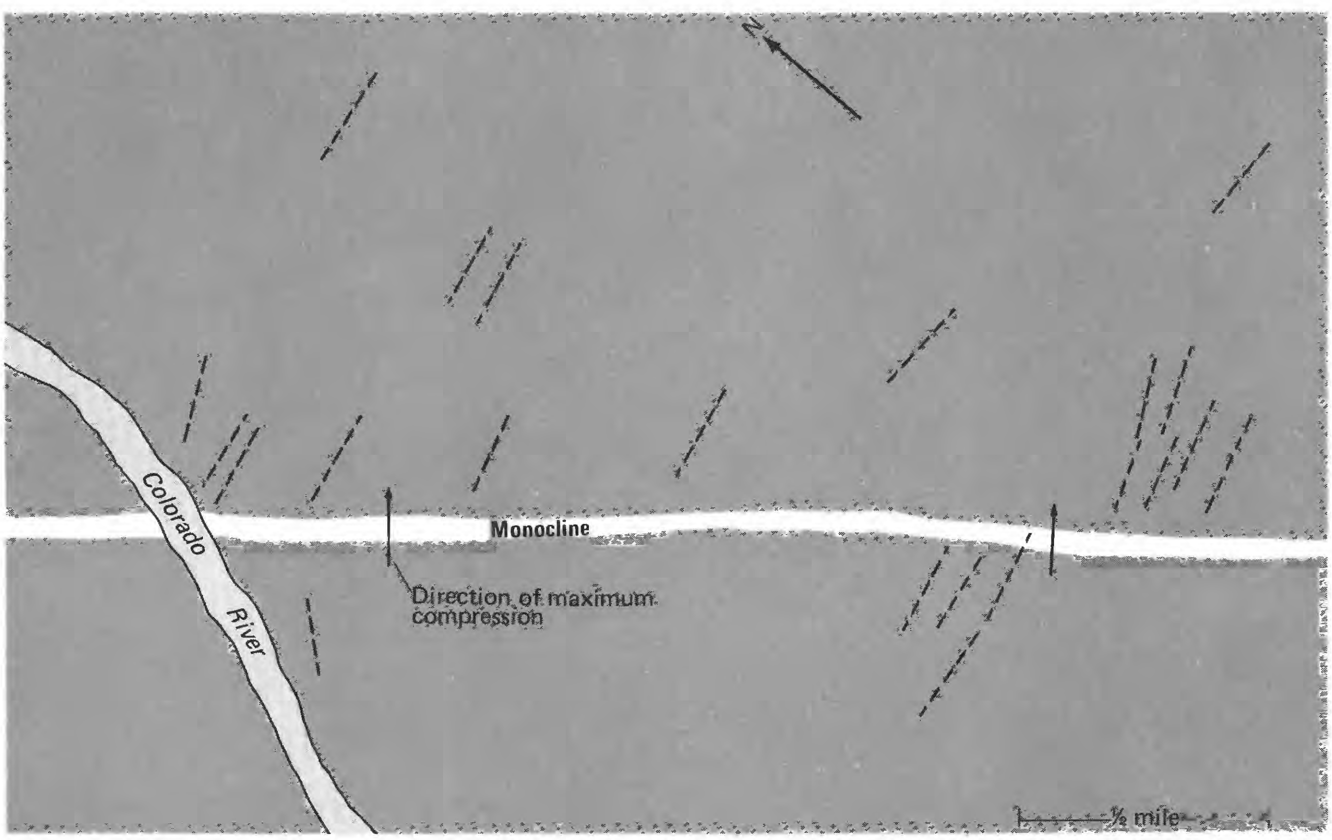


FIGURE 20.—Map view of direction of maximum compression in Palisades monocline. Compression axes from petrofabric, fold axes, and fault orientations of small scale structures. Modified from Reches (1978).

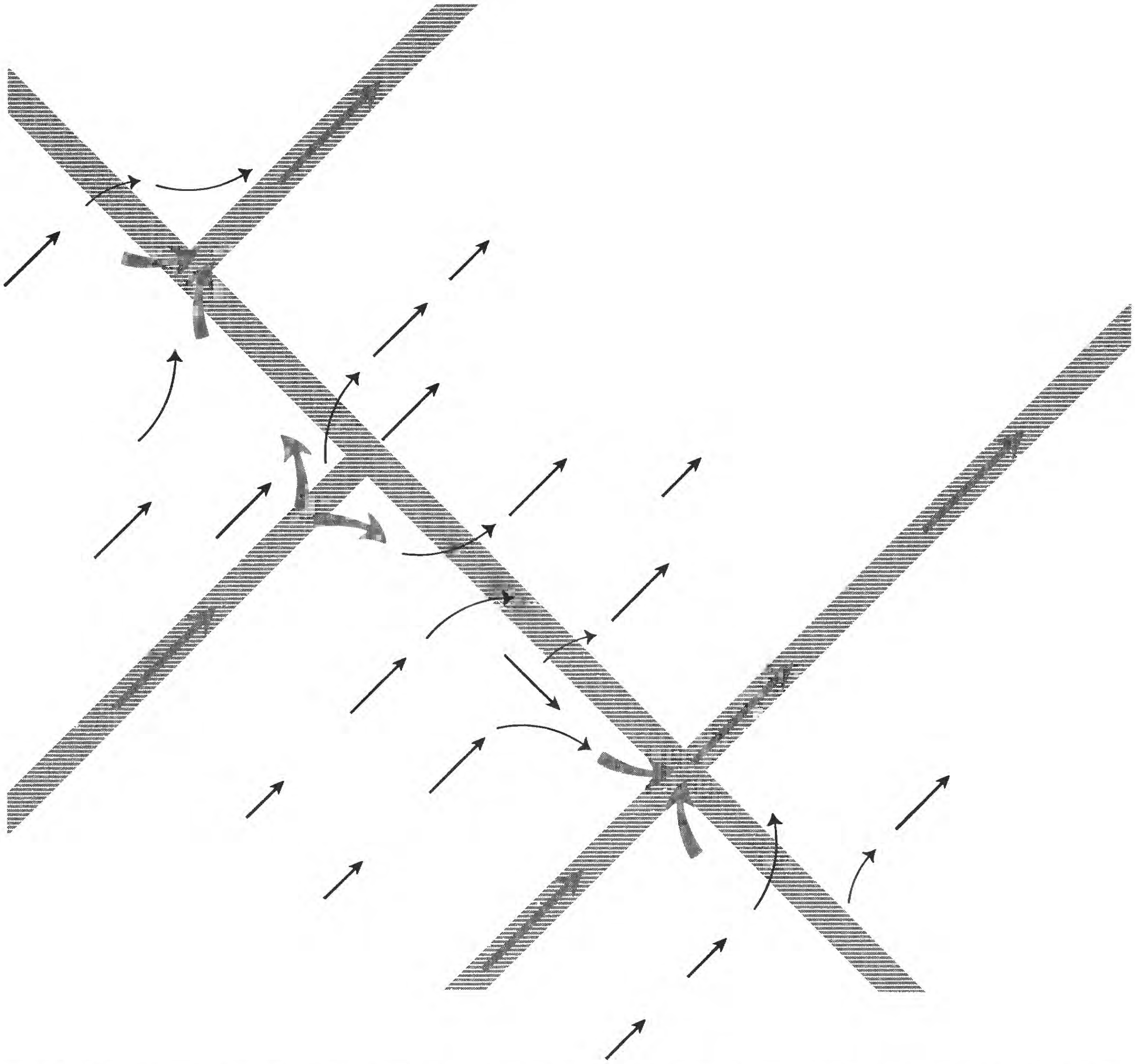


FIGURE 21.—Theoretical ground-water flow paths. Arrows indicate possible flow directions; large arrows indicate greater volume than small arrow. Shaded areas are theoretical lineament zones.

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