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UPPER CRETACEOUS TECTONIC ACTIVITY ON LINEAMENTS IN WESTERN SOUTH DAKOTA

by

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ABSTRACT

Lineaments mapped on satellite images in western South Dakota define a geometry of basement blocks, and paleotectonic activity on these lineament-bound blocks is recorded in sedimentary rocks. Mapping on seven Landsat images in an area of about 100,000 km^2 reveals that lineaments are best developed along azimuths of N. 60° E. to N. 90° E. and N. 30° W. to N. 60° W. Although their exact structural nature and origin are not known, these features are visualized as major zones of weakness that subdivide the crystalline Precambrian basement into discrete blocks. Several of the most prominent surface lineaments can be related to basement faults. The blocks bounded by these lineaments constitute low-relief uplifts that define the southern margin of the Williston Basin.

During deposition of the Upper Cretaceous Pierre Shale, lineaments were the sites of tectonic activity. Members of the Pierre are relatively continuous throughout the area and are well dated by biostratigraphic zonation. The base of the Mobridge Member is the highest structural datum available for regional mapping. Northeast-trending surface lineaments near the White and Cheyenne Rivers have a clear expression on a subsurface structural map of this horizon. The Ardmore Bentonite Bed lies approximately 300 m (980 ft) below the Mobridge; subsurface structure contours on this datum show the active lineaments trending northwest. Isopach maps of two rock-stratigraphic units between the Ardmore and Mobridge reflect the shift in tectonic activity from early northwest sets of lineaments to later northeast trends.

INTRODUCTION

Lineaments mapped on satellite images in western South Dakota appear to have been the sites of tectonic activity during the Cretaceous. The high plains between Cretaceous outcrops in the Black Hills and along the Missouri River (fig. 1) are generally characterized by few outcrops and low relief. This portion of the northern Great Plains is well suited for interpreting paleotectonism along lineaments for several reasons. Prominent linear features are well displayed on Landsat images and structural features are not masked by glacial deposits. It is possible to relate surface lineaments to features in the Precambrian basement because the cover of Cretaceous sediments is not thick. Subsurface stratigraphic data from oil and gas exploration is available within the study area and biostratigraphic zonation in the Cretaceous has been completed in outcrop belts bounding the study area.

This report describes lineaments mapped on satellite images and relates these lineaments to features mapped on the surface and to geologic features of the crystalline basement. Paleotectonism along the lineaments is interpreted from the envelope of Cretaceous sedimentary rocks between the basement and the surface.

This study by the U.S. Geological Survey was funded by the U.S. Department of Energy. The lineaments are being employed in regional studies seeking nuclear waste disposal sites and are being tested as an exploration tool in the search for shallow biogenic gas. The technical assistance of W. S. Larson is gratefully acknowledged.

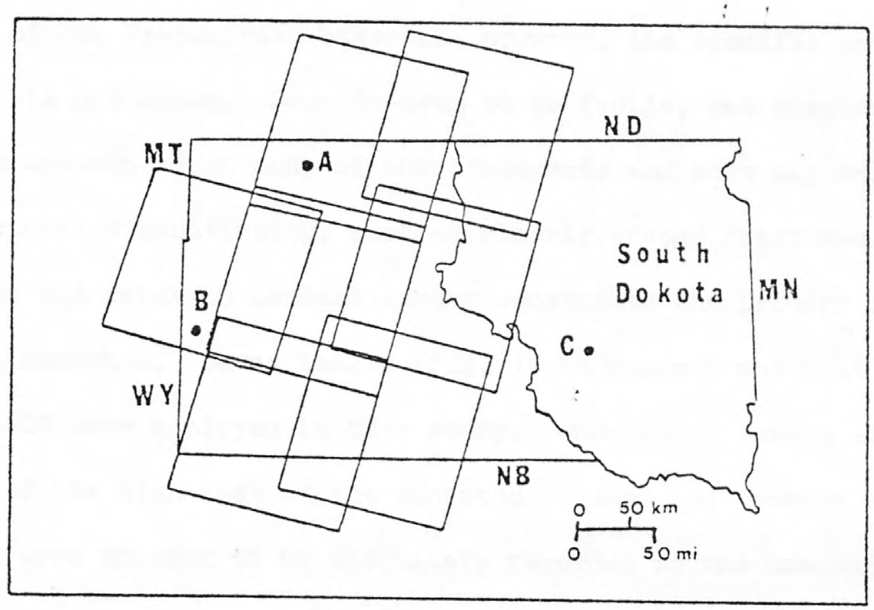

Figure 1.--Index map of South Dakota showing location of seven Landsat images employed in this study. Position A marks the approximate location of the Williston Basin, B is the Black Hills, and C is the Sioux Ridge.

LINEAMENT MAP

The term "lineament" is employed in this report to describe long, continuous linear features on the Earth's surface which can be observed on satellite images. The lineaments are interpreted to reflect structural aspects of the Precambrian basement; however, the specific nature of these features is not known. Some do seem to be faults, but displacement has not been documented on many of the lineaments and most may only be zones of structural discontinuity, such as closely-spaced fractures.

Tone and color on Landsat images constitute the primary data utilized to map lineaments. Seven images (fig. 1) in bands 5 and 7 at a scale of 1:1,000,000 were employed in this study. Unenhanced images were used because of the high cost of the enhanced product and because major features were thought to be adequately recorded in the unenhanced product. Linear features were mapped on the basis of linear tone and color patterns, and these patterns probably represent landscape components such as drainage, cover, and topography. Two populations of linear features were observed: long linear features averaging 40 km (25 mi) in length, but ranging up to 100 km (62 mi), are concentrated in limited zones; short linear features averaging 10 km (6.2 mi) in length and as short as 3 km (1.9 mi) are distributed within and between the zones of long linear features.

Long linear features were used to produce the lineament map for western South Dakota (fig. 2). All of the long linear features compiled from images were ranked in a hierarchy on the basis of frequency of observation. The most significant linear features were those observed by two workers on both band 5 and band 7; less important elements of the hierarchial ranking were those observed less frequently. Then, those

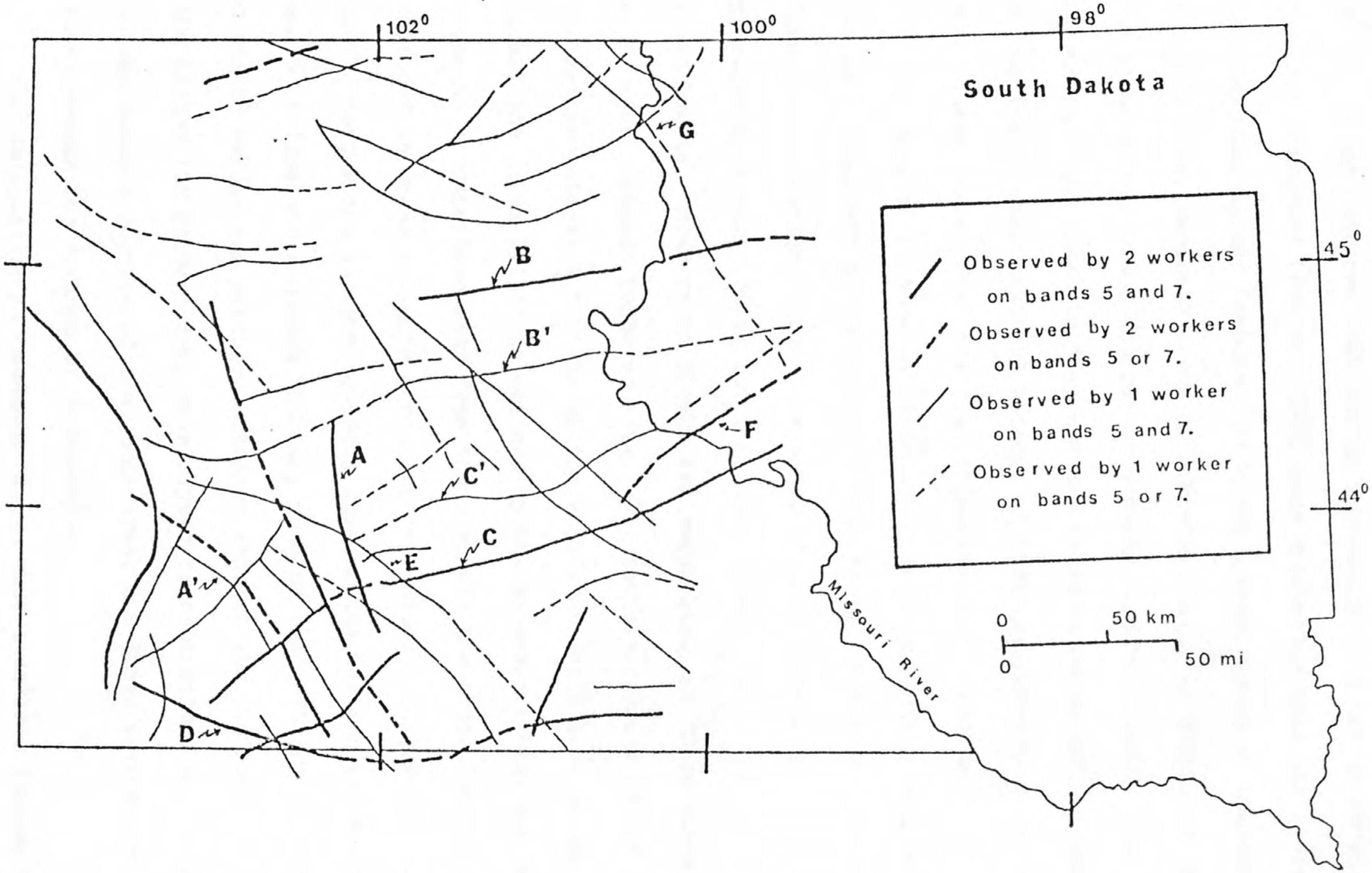

Figure 2.--Lineaments visible on Landsat images. Lineament pairs A and A^1, B and B^1, and C and C^1 define block boundaries. Mapped surface faults are present along lineaments D (Harksen and Haywood, 1969) and E (Raymond and King, 1976); inferred basement faults (Lidiak, 1971) correspond with lineaments F and G; lineaments B and C are components of a regional Precambrian structural feature (see fig. 5). The observations were made by the author and W. S. Larson.

ranked linear features that had no expression on a map of vertical magnetic intensity (Petsch, 1967) were eliminated from the hierarchy. The remaining linear features lie along linear trends of magnetic highs or lows, separate areas of different magnetic grain, or occupy positions along abrupt changes in contour line directions. All of the linear features shown in figure 2 are interpreted to reflect attributes of the Precambrian basement because of their expression on the magnetic map. These linear features are designated as lineaments.

The grid of lineaments is believed to be a surface manifestation of the arrangement of structural blocks in the Precambrian basement. This interpretation follows the model of lineament-block tectonics proposed by Thomas (1974) for the Great Plains just north of western South Dakota. Four major blocks are recognized and these correspond with major tectonic features (fig. 2): the Black Hills Uplift occupies the western block; a portion of the Williston Basin lies on the northern block; the Sioux Uplift is defined by the southern block; and the central block is a transition step from the basin to the arch. Specific lineaments that define these boundary zones are designated in figure 2: lineaments A and A^1 define the eastern boundary zone of the western block; lineaments B and B^1 define the southern boundary zone of the northern block; lineaments C and C^1 define the northern boundary zone of the southern block. Sawatzky and Raines (in preparation) have mapped concentrations of linear features in the central portion of the study area, and these correspond with block boundaries defined by lineaments.

The delineation of basement blocks from satellite images thus involves several levels of interpretation. Long linear features are interpreted from linear tone and color patterns on satellite images. Lineaments are ranked and interpreted from long linear features using a magnetic map and the frequency of observation. Block boundaries are interpreted from concentrations of lineaments. A final phase of interpretation, which would associate specific fault movement with block boundaries, has not been attempted in this study.

The proposed interpretation of the geometry of basement blocks is strengthened by a preliminary synthesis of observations on the population of short linear features. Figure 3 shows histograms of azimuths measured on short linear features in equal areas on the northern, southern, and central blocks. The core of the Black Hills was not mapped, although numerous linear features were observed there. Modes to the northeast and northwest are visible on all three blocks, but the northern block has a very well developed northwest mode. The distinctive population of short linear features, therefore, sets the northern block apart from other blocks.

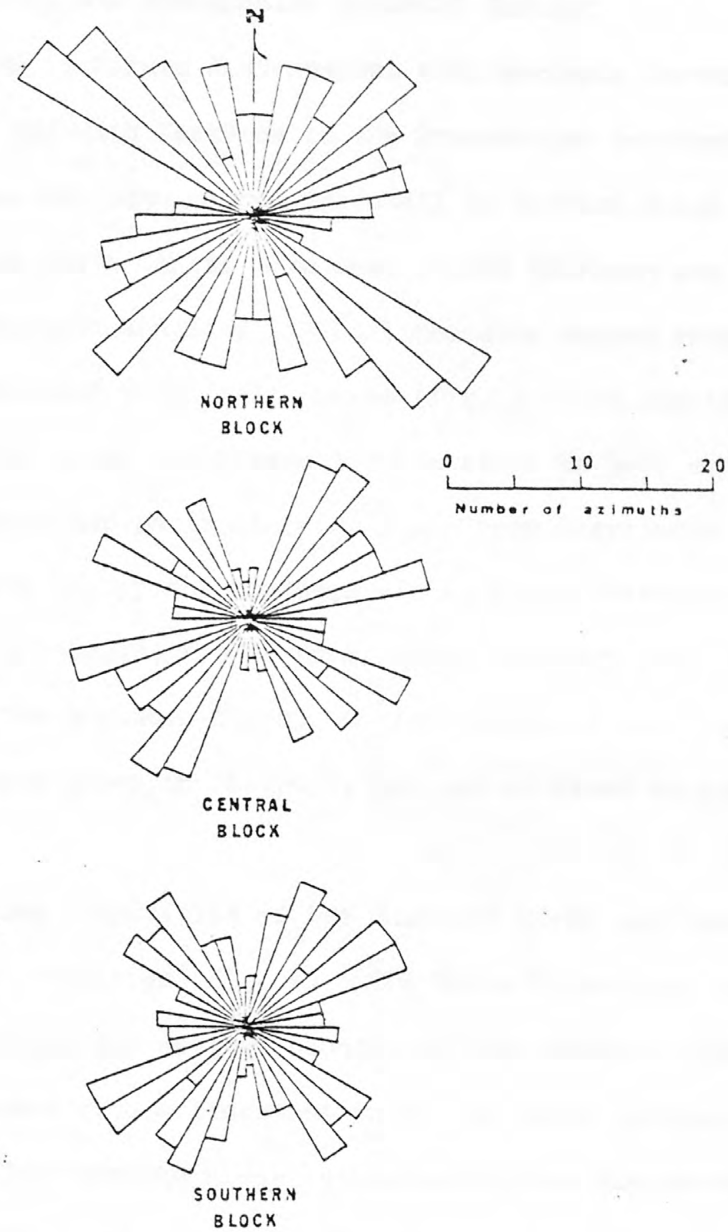

Figure 3.--Circular histograms of azimuths of short linear features visible on Landsat images. Azimuths were measured in equal areas on each of the three blocks and are shown here in 10° intervals. The orientation of 192 linear features was measured over portions of the northern block, 132 over portions of the central block, and 145 over portions of the southern block.

SURFICIAL AND PRECAMBRIAN BASEMENT GEOLOGY

Lineaments shown in figure 2 correspond with geologic features on the Earth's surface and with features in the Precambrian basement. Surficial geology has not been mapped in detail in western South Dakota; however, in two areas where faults have been mapped (Harksen and Haywood, 1969, and Raymond and King, 1976) lineaments mapped from Landsat imagery correspond with fault traces (fig. 2). In addition, the geometry of blocks bound by lineament zones seems to have expression in the general geologic map patterns (fig. 4): Upper Cretaceous units of the Williston Basin occupy the northern block; Upper Cretaceous Pierre Shale occurs throughout the central block; Tertiary formations are found mainly on the southern block. Outcrop patterns that define the Black Hills are not shown in figure 4, but are confined to the western block.

Major east-flowing tributaries of the Missouri River are found at or near the block boundaries (fig. 4). The White River lies along a portion of the southern and western boundary of the central block. The Bad River corresponds with a lineament in the southern portion of the central block. The Cheyenne River is located within the northern boundary of the central block; south of the mouth of the Belle Fourche River, the Cheyenne flows along the western boundary of the central and southern block. On the Missouri River, major meander loops are located near the lineaments bounding the northern and southern limits of the central block. These observations tend to support a recent suggestion (Potter, 1978) that regional fracture systems exert a fundamental control on big rivers. It seems highly likely that alignments of minor drainages in western South Dakota, which have been interpreted

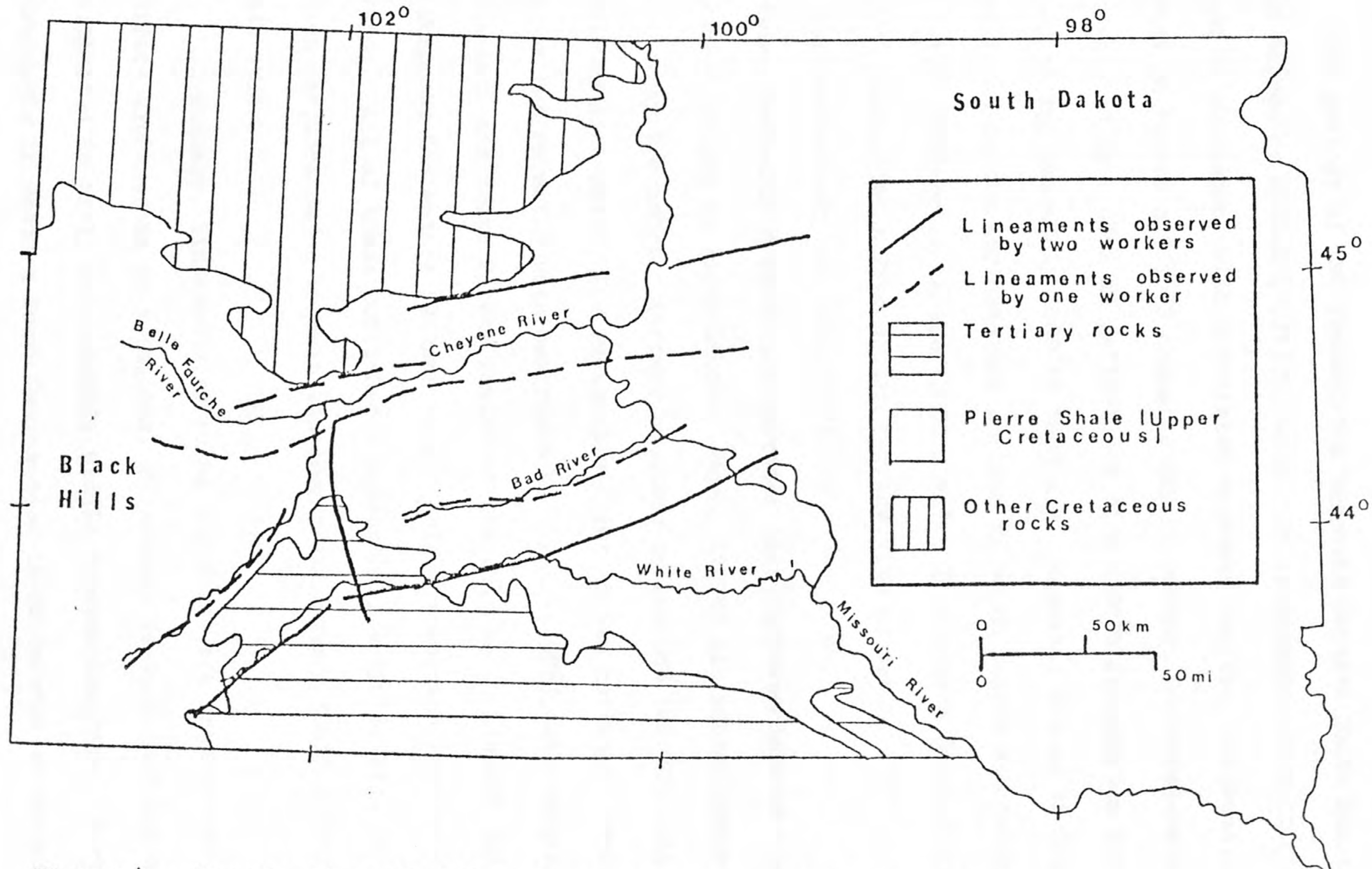

Figure 4.--Summary of surficial geology, major streams, and basement blocks of South Dakota. Geologic contacts generalized from Darton (1951). Geology of the Black Hills area is omitted.

to be the result of prevailing wind direction (White, 1961), are also fracture-controlled.

The geology of the Precambrian basement beneath South Dakota has been mapped by Lidiak (1971). Two of the lineaments shown in figure 2, F and G, correspond with postulated basement faults. Northwesterly trends on Petsch's (1967) magnetic map in western South Dakota are interpreted by Lidiak as reflections of a middle Precambrian terrane dated at approximately 1600 to 1800 m.y. Magnetic trends to the northeast found in the northeastern portion of South Dakota are believed to be early Precambrian in age (3500 m.y.). In southern South Dakota Lidiak (1971) postulates a Precambrian terrane with an age of 1430 to 1460 m.y. In Minnesota Morey and Sims (1976) have described a structural boundary between two early Precambrian terranes that corresponds with northeast basement faults in South Dakota. Morey (1976) has subsequently refined this early Precambrian terrane boundary to include two parallel faults trending northeast. The regional setting of the northeast-trending faults has recently been described by Warner (1978), who relates the Minnesota and South Dakota faults to the Colorado Lineament and interprets the entire feature as a middle Precambrian wrench-fault system. All of these published discussions are synthesized in figure 5, which includes major Landsat lineaments in western South Dakota from this study.

In summary, lineaments trending northeast are interpreted as surface expressions of a regional structural feature that may have originated in early and possibly middle Precambrian time. Northwest lineaments in western South Dakota seem to be related to structural elements that originated in middle Precambrian time. This structural

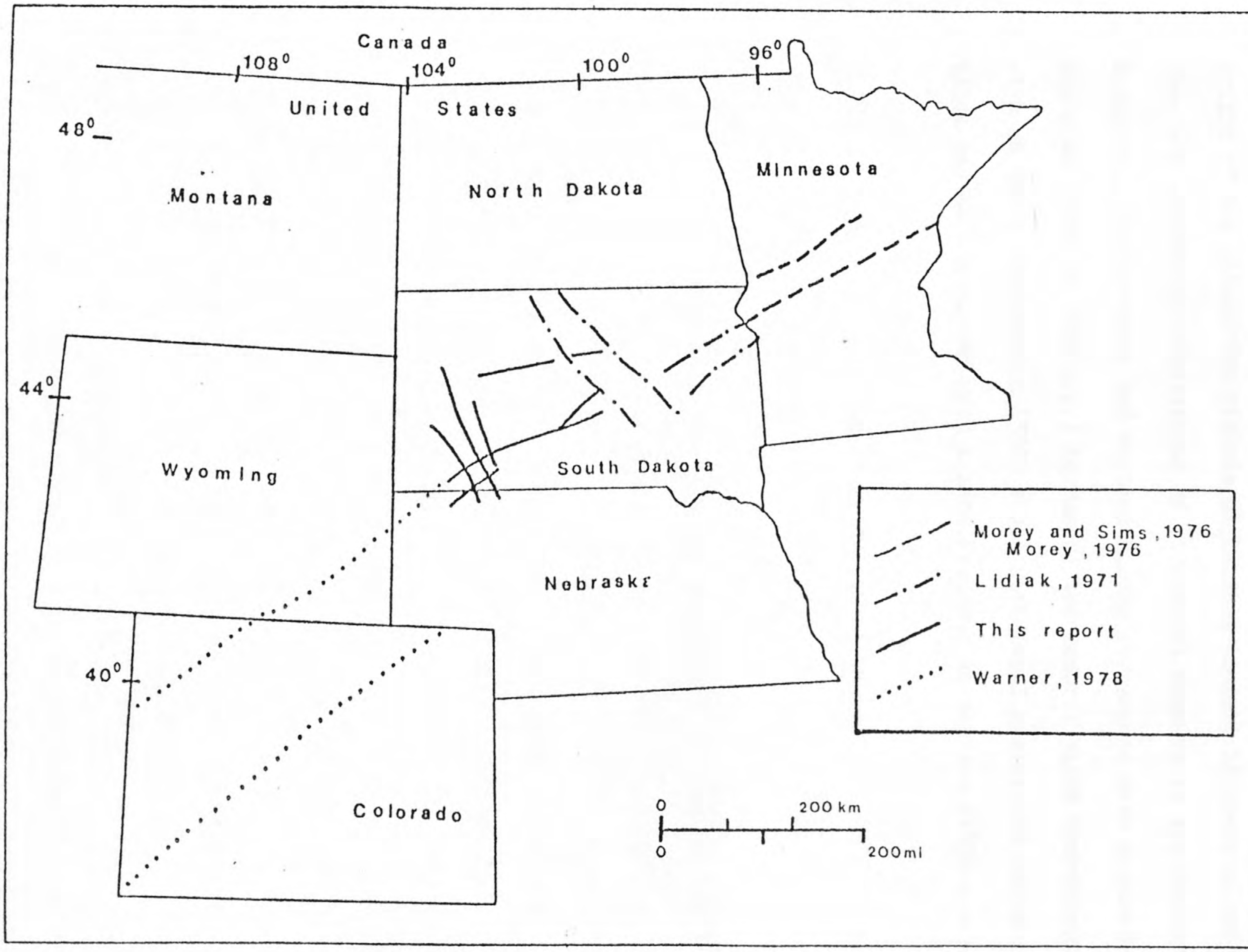

Figure 5.--Regional Precambrian structural features interpreted to be related to Landsat lineaments in western South Dakota. Specific elements of the Colorado Lineament (Warner, 1978) are not shown. Note that the northwest-trending faults appear to offset the northeast-trending zone of lineament.

domain overprinted and perhaps offset the throughgoing northeast structural grain of early or middle Precambrian age. Regardless of the specific origin of the lineaments visible on Landsat images, it seems clear that they are surface manifestations of structural aspects in the Precambrian basement. The northern and western blocks correspond with middle Precambrian (1600 to 1800 m.y.) terranes; the central block corresponds with an early Precambrian (3500 m.y.) structural grain; and the southern block may be associated with a late Precambrian terrane (1450 m.y.).

CRETACEOUS TECTONISM ON LINEAMENTS

Basement blocks bounded by lineaments control sedimentation because tectonism influences bathymetry, which in turn influences sedimentation (Shurr, 1975; 1979). Therefore, tectonic activity along lineaments is recorded in the envelope of sediment lying below the surface of the earth and above the crystalline basement. This discussion will emphasize the Cretaceous because it is the uppermost system continuous throughout the study area. The absolute ages employed are based upon the detailed biostratigraphic framework established for the Western Interior of the United States, which has been calibrated by radiometric dating. The uppermost rock-stratigraphic unit continuous throughout the study area is the Pierre Shale.

The configuration of the base of the Mobridge Member of the Pierre is shown in figure 6. This subsurface stratigraphic marker lies in the zone of Baculites baculus (Gill and Cobban, 1973) and the biostratigraphic zone is dated at 68 m.y. (Obradovich and Cobban, 1975). At several localites the stratigraphic marker is above the base of surface casing, and only minimum elevations can be determined. Still, the strong influence of the lineaments trending northeast is obvious. Tectonic activity must have occurred along these lineaments after deposition of the stratigraphic datum at 68 m.y.

A series of bentonite beds known collectively as the Ardmore Bentonite Bed is found 305 to 458 m (1000 to 1500 ft) below the base of the Mobridge Member. These are a part of the Sharon Springs Member of the Pierre (Gill and Cobban, 1973) and are dated at 78 m.y. (Obradovich and Cobban, 1975). A structure contour map constructed on the base of the Ardmore Bentonite Bed is shown in figure 7. Lineaments trending northwest seem to have

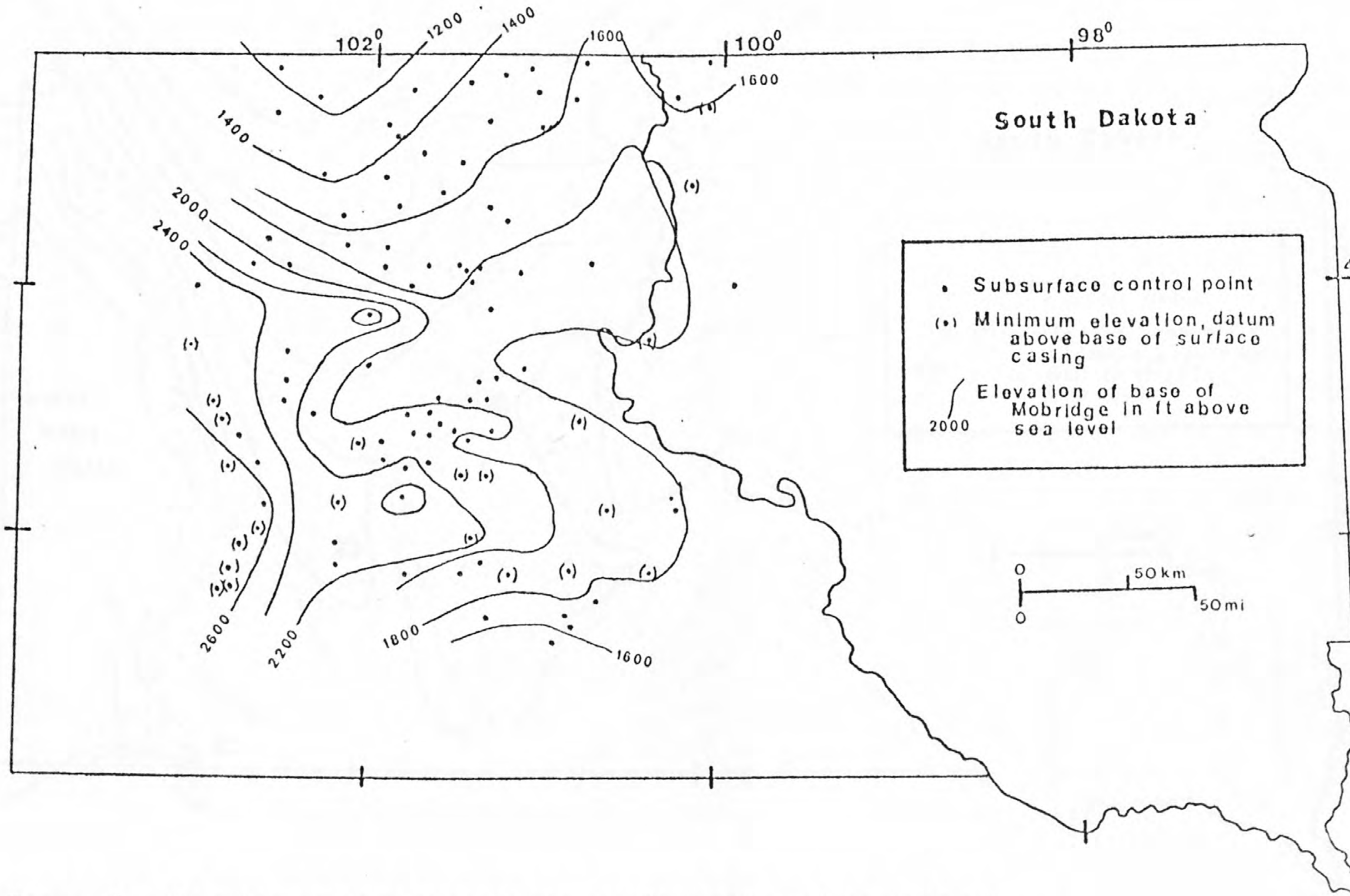

Figure 6.--Structure contour map showing configuration of the base of the Mobridge Member (68 m.y.) of the Pierre Shale. Lineaments trending northeast bounding the central block have expression on this map. Contour interval is 200 ft (61 m).

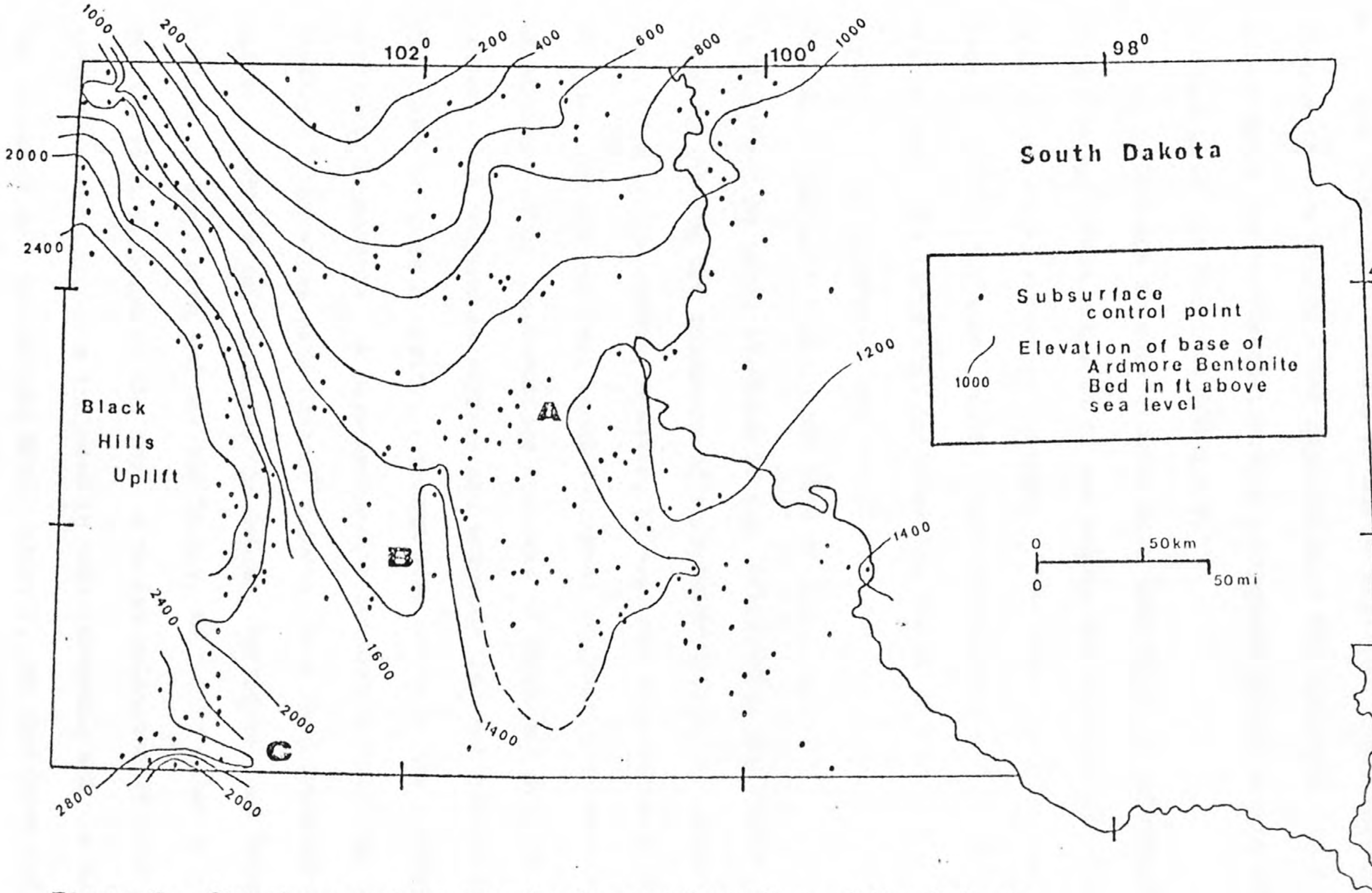

Figure 7.--Structure contour map showing configuration of the Ardmore Bentonite Bed (78 m.y.) of the Pierre Shale. Lineaments trending northwest are located near position A and B. A lineament near C corresponds with a mapped surface fault (see fig. 2). Contour interval is 200 ft (61 m), except on the edges of the Black Hills uplift where it is 400 ft (122 m).

expression on this map, which implies that a shift in tectonic activity must have taken place between 78 and 68 m.y. ago. Northwest-trending lineaments were active after deposition of the bentonite (78 m.y.), but subsequently the northeast-trending lineaments became active after deposition of the Mobridge (68 m.y.).

In an attempt to more closely date this shift in paleotectonism, thickness maps were prepared of two subsurface stratigraphic units between the dated structural datums. These maps are presented elsewhere (Shurr, 1978[b]), but some general observations will be included in this discussion. The lower unit includes the Sharon Springs and Gregory Members of the Pierre and has the 78 m.y. bentonite datum as its base. The top of the unit lies in the zone of Baculites scotti (Gill and Cobban, 1973), which is dated at about 72 m.y. (Obradovich and Cobban, 1975). Contours showing the thickness of this lower unit do not show clear expression of lineaments; however, if regional variations in thickness of this unit are removed, local thickness variations do seem to reflect lineaments. This trend-surface analysis of thickness data employs a second-order polynomial surface and suggests that the northwest lineaments dominated tectonic activity, although some activity was initiated on northeast lineaments. A paleogeographic reconstruction (fig. 8) incorporating lithofacies data further supports this interpretation. The upper subsurface unit includes the DeGrey, Verendrye, and Virgin Creek Members of the Pierre and has the 72-m.y. bentonite datum as its base and the 68-m.y. datum at the top. A facies relationship that is not completely understood is included in this interval, and the thickness map includes much incomplete data. However, the increased influence of lineaments trending northeast is clearly shown. Therefore, the shift

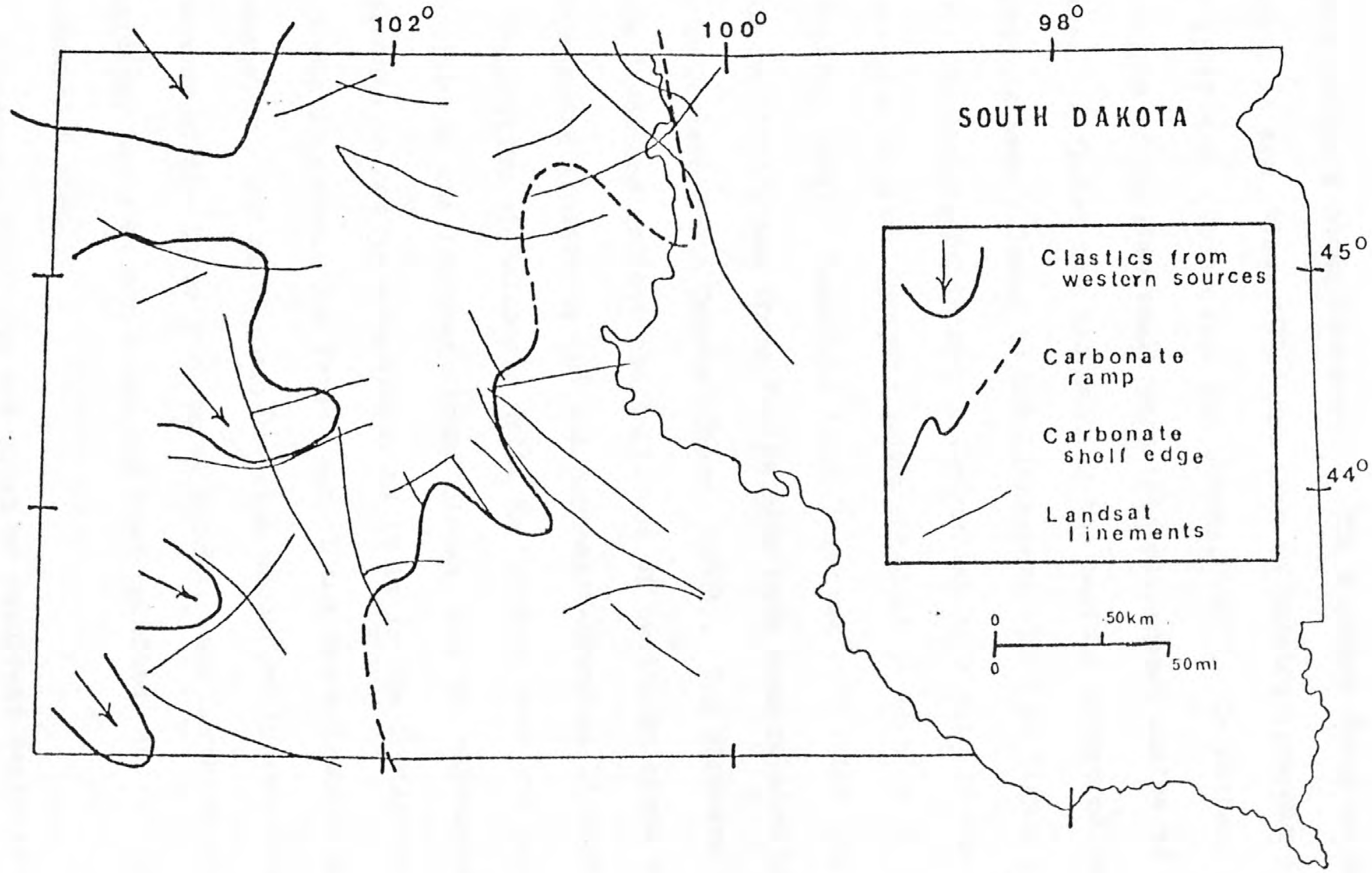

Figure 8.--Paleogeographic reconstruction for the time of deposition of the Sharon Springs and Gregory Members of the Pierre Shale. Lineaments shown are those having expression in trend-surface analysis of thickness data.

in activity from northwest lineaments to northeast lineaments must have taken place at approximately 72 m.y.

Cretaceous units below the Pierre Shale also show the effects of tectonic activity along lineaments. The Niobrara Chalk is Santonian to Coniacian in age (Rice, 1976) and lies in biostratigraphic zones dated at 78 to 87 m.y. (Obradovich and Cobban, 1975). In western South Dakota, two tongues of massive chalk pass into calcareous shales to the north and west. A facies map documenting the maximum extent of these chalk tongues has been related to the lineaments shown in figure 2 (Shurr, 1978[a]). The Dakota Sandstone is Cenomanian to Albian in age (Rice, 1976) and occupies biostratigraphic zones dated at 91 to 95 m.y. (Obradovich and Cobban, 1975). Sandstone interfingering with shale has been described by Schoon (1971), and these facies maps have been related to the lineament grid in western South Dakota (Shurr, 1978[a]). The Niobrara Chalk and the Dakota Sandstone reflect the influence of tectonism along both the northwest-trending lineaments and the northeast-trending lineaments.

Deposition of Paleozoic units in the study area was probably controlled by the lineament-bound blocks, but the expression of specific lineaments is not as unequivocal as it is in the Cretaceous. Figure 9 shows two examples. The facies map of the Pennsylvanian unit and the paleogeologic map of the sub-Devonian unconformity reinforce an interpretation of the three structural blocks: the northern block has been subsiding, the southern block has been uplifted, and the central block is a transition step.

Lineaments have been the sites of recurrent tectonic activity throughout the Phanerozoic. Some of the tectonism may be relatively recent because the lineaments correspond with modern topographic features.

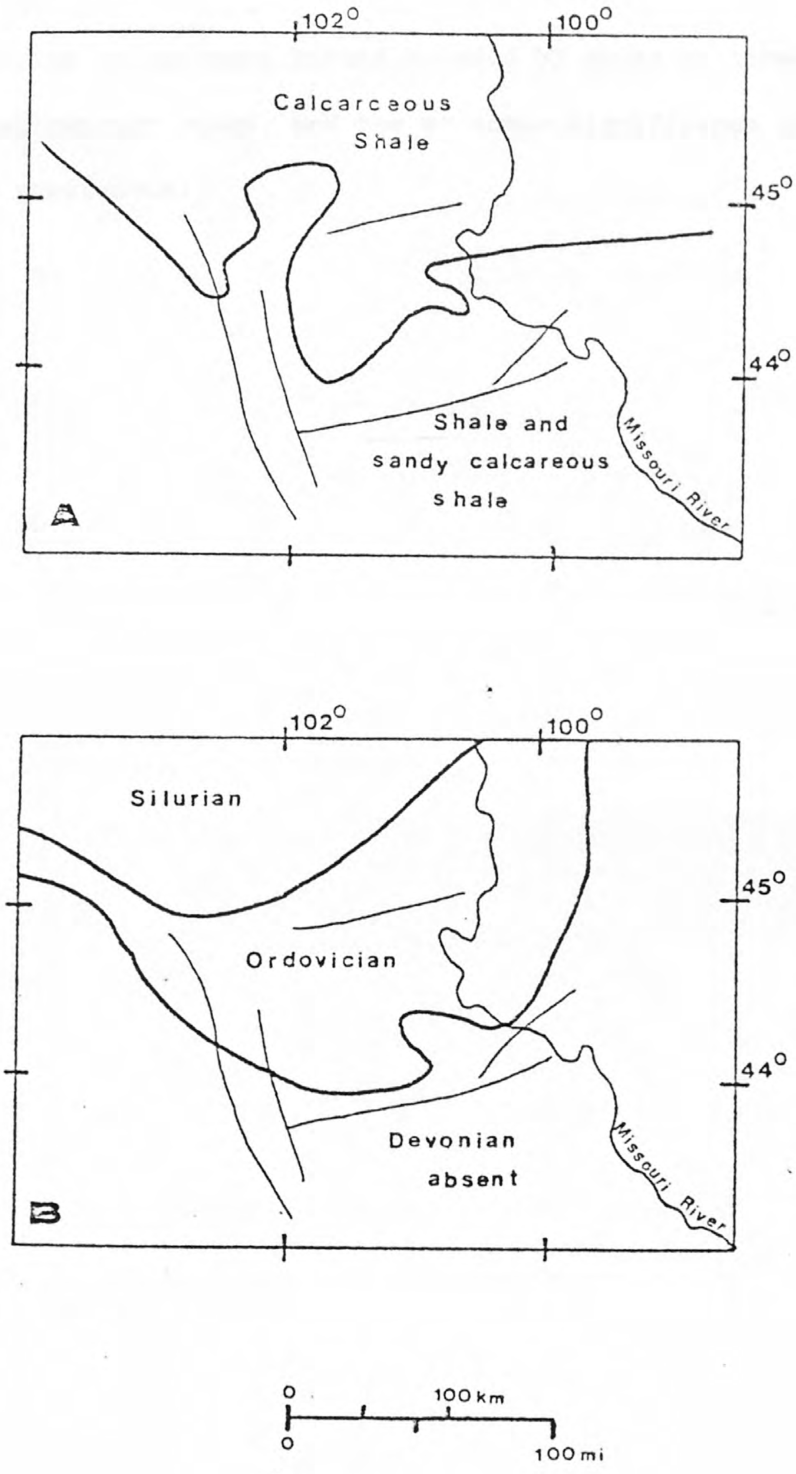

Figure 9.--Generalized subsurface maps of western South Dakota. Only lineaments related to block geometry are shown. A, Lithofacies in a portion of the Pennsylvanian and Permian Minnelusa Formation (Mallory, 1972). Coarse clastics increase onto the southern and western blocks. B, Paleogeology beneath the Devonian System (Baars, 1972). Central block is transition from down warped Williston on northern block and uplifted southern block.

Recurrent activity on basement blocks bounded by zones of lineaments is recorded in sedimentary rocks, and the economic significance of this conclusion is substantial.

ECONOMIC CONSIDERATIONS

Fracture porosity and permeability may locally improve the characteristics of hydrocarbon reservoirs near the lineaments, and the lineaments may thus act as vertical migration routes for formation fluids. Tectonism along lineaments controlled the facies and thickness of stratigraphic units that are reservoir rocks, source rocks, and seals for fluid hydrocarbon accumulations. Potentials for shallow biogenic gas are of particular importance in the study area, and a full discussion of lineaments employed in the exploration for this resource is available in a separate report (Shurr, 1978b).

REFERENCES CITED

Baars, D. L., 1972, Devonian System, in Mallory, W. M., ed., Geologic atlas of the Rocky Mountain region: Denver, Colo., Rocky Mountain Assoc. Geologists, p. 90-100.

Darton, N. H., 1951, Geologic map of South Dakota: U.S. Geological Survey map.

Gill, J. R., and Cobban, W. A., 1973, Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North and South Dakota: U.S. Geol. Survey Prof. Paper 776, 37 p.

Harksen, J. C., and Haywood, H. A., 1969, Geology of the Oelrichs, Lone Man, and Pine Ridge Quadrangles, South Dakota Geol. Survey unpub. field sheets.

Lidiak, E. G., 1971, Buried Precambrian rocks of South Dakota: Geol. Soc. America Bull., v. 82, no. 5, p. 1411-1420.

Mallory, W. M., 1972, Regional synthesis of the Pennsylvanian System, in Mallory, W. M., ed., Geologic atlas of the Rocky Mountain region: Denver, Colo., Rocky Mountain Assoc. Geologists, p. 111-127.

Morey, G. B., 1976, Geologic map of Minnesota, bedrock geology: Minn. Geol. Survey Miscell. Map 24.

Morey, G. B., and Sims, P. K., 1976, Boundary between two Precambrian W terranes in Minnesota and its geologic significance: Geol. Soc. America Bull., v. 87, no. 1, p. 141-152.

Obradovich, J. D., and Cobban, W. A., 1975, A time-scale for the Late Cretaceous of the Western Interior of North America, in Caldwell, W. G. E., ed., The Cretaceous System in the Western Interior of North America: Geol. Assoc. Canada, Spec. Paper 13, p. 31-54.

Petsch, B. E., 1967, Vertical-intensity magnetic map of South Dakota: South Dakota Geol. Survey Mineral Resources Investigations Map 4.

Potter, P. E., 1978, Significance and origin of big rivers: Jour. Geol. v. 86, no. 1, p. 13-33.

Raymond, H. E., and King, R. U., 1976, Geologic map of the Badlands National Monument and vicinity, west-central South Dakota: U.S. Geol. Survey Oil and Gas Inv. Chart OC-72.

Sawatzky, D. L., and Raines, G. L., in preparation, Geologic uses of linear-feature maps derived from small-scale images, in Proc. Third Internat. Conf. on Basement Tectonics: Durango, Colorado, Fort Lewis College, May, 1978.

Schoon, R. A., 1971, Geology and hydrology of the Dakota Formation in South Dakota: South Dakota Geol. Survey Rept. Inv. 104, 55 p.

Shurr, G. W., 1975, Marine cycles in the lower Montana Group, Montana and South Dakota: Missoula, Univ. of Montana Ph.D. dissert., 310 p.

__________, 1978a, Landsat lineaments in western South Dakota: U.S. Geol. Survey Open-File Reprot, 78-249.

__________, 1978b, Paleotectonic controls on Cretaceous sedimentation and potential gas occurrences in western South Dakota, in Williston Basin Symposium: Billings, Mont., Mont. Geol. Soc., September, 1978, p. 283-292.

__________, 1979, Lineament control of sedimentary facies in the northern Great Plains, United States, in Proc. Second International Conf. on Basement Tectonics: Newark, Delaware, Univ. of Delaware, July, 1976, p. 413-422.

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

Warner, L. A., 1978, The Colorado Lineament: A middle Precambrian wrench fault system?: Geol. Soc. America Bull., v. 89, no. 2, p. 161-171.

White, E. M., 1961, Drainage alignment in western South Dakota: Am. Jour. Sci., v. 259, no. 3, p. 207-210.