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Seismic Profiling of Geologic Structures Near Pierre, South Dakota

By

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ABSTRACT

The data obtained from a commercial seismic-reflection profile and a U.S. Geological Survey high-resolution seismic-reflection profile are not sufficient to conclusively demonstrate that near-surface faulting in the Cretaceous Pierre Shale is directly related to faulting in the underlying Precambrian rocks. The seismic data show fault displacements of as much as 70 ft in the Cretaceous sedimentary rocks at a depth of 2,130 ft; these displacements disrupt overlying rocks and appear to extend into the lower part of the Pierre Shale. Basement faulting affected depositional processes and deformed overlying deposits through Paleozoic and into late Mesozoic time. The structures found in Paleozoic and Mesozoic sedimentary rocks can be explained either by low-amplitude folding and faulting or sedimentary processes occurring after Precambrian time.

INTRODUCTION

Field studies supported by the State of South Dakota, in an area located approximately 22 miles west of Pierre, S. Dak., adjacent to and north of U.S. Highway 14 (fig. 1), have revealed surface evidence of at least 150 ft of stratigraphic throw or structural relief in the Pierre Shale over a distance of less than a mile along Lance Creek (fig. 2). The structural relief is thought to result from the vertical displacements on faults in the shale. To evaluate the possible cause of the deformation, it is first necessary to determine if basement structures are interacting with those near the surface. Thus, we use seismic-reflection techniques to determine the interaction, if any, between basement and near-surface structures.

FIELD INVESTIGATIONS

A structure-contour map (fig. 2) of the top of the Government Draw Bentonite Beds (Nichols and others, 1986), stratigraphic marker beds in the Virgin Creek Member of the Pierre Shale, shows an elevation drop of more than 150 ft along Lance Creek from the southeast corner of section 23 to the northeast corner of section 14. Along the same traverse, we have mapped only those faults with sufficient stratigraphic evidence to determine offsets. Other observed faults with indeterminable offsets or those that were too inaccessible to measure were not mapped.

Two approximately south-to-north-oriented seismic-reflection profiles provide important stratigraphic and structural information. The eastern profile (figs. 1 and 2) was conducted as part of a commercial venture, whereas the shorter western profile (fig. 2) was obtained by the U.S. Geological Survey (USGS) for this study (Williams and others, 1989). Four exploration drill holes provide stratigraphic control (fig. 1) along the two profiles, with only the Prince No. 23-14 and No. 1 Stanley drill holes within the study area shown on figures 1 and 2. On the 7½-mile-long commercial profile, the part containing stations 19-29 in section 14 is the most important because it

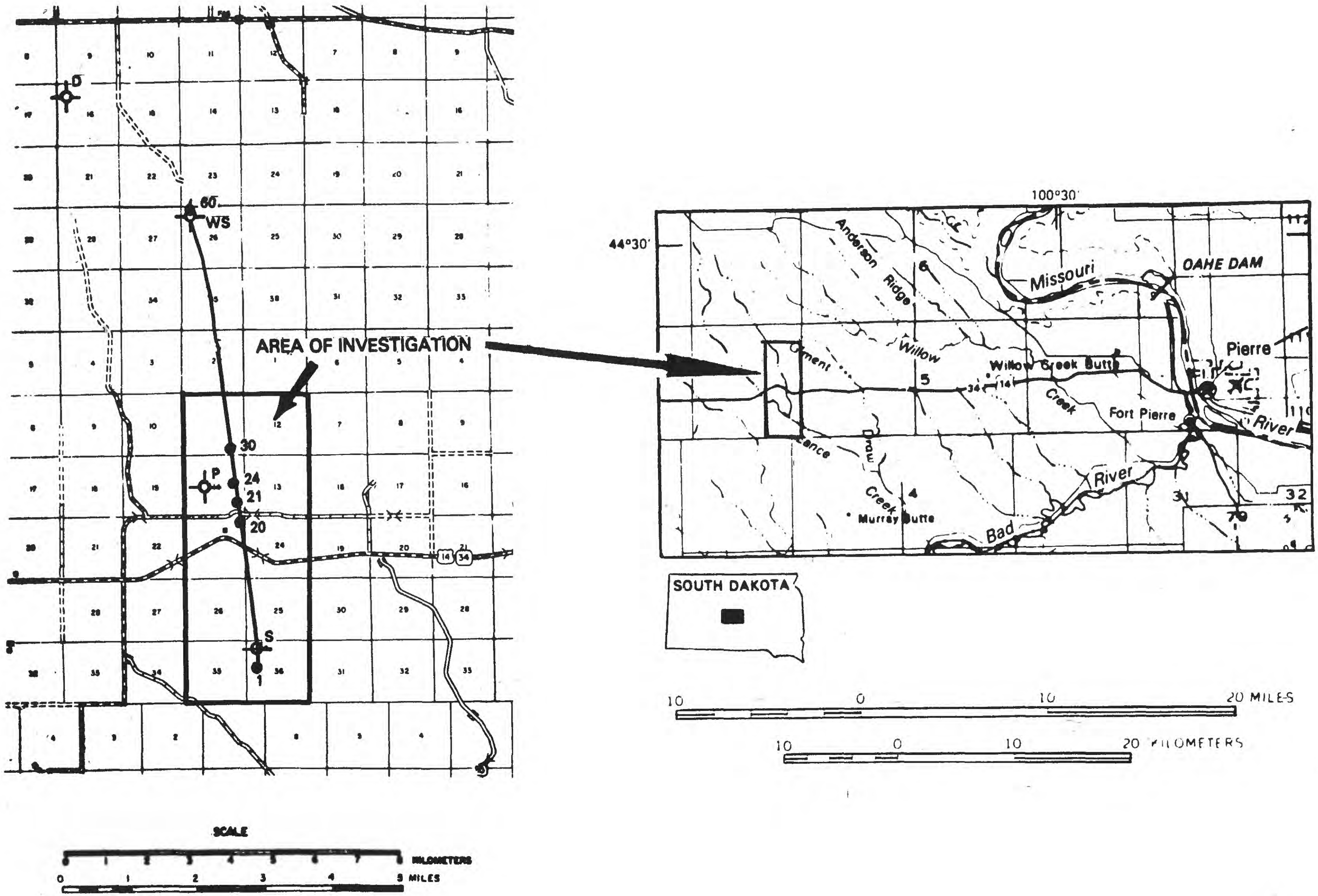

FIGURE 1.--Map showing locations of the commercial seismic-reflection profile; profile stations 1, 20, 21, 24, 30, and 60; and four drill holes (D, #1 Dakota; S, #1 Stanley; P, Prince #23-14; and WS, #1 Wyly Shaffner). Map modified from South Dakota Department of Transportation highway map, south half Stanley County. Index maps show study area with respect to Pierre and the State of South Dakota.

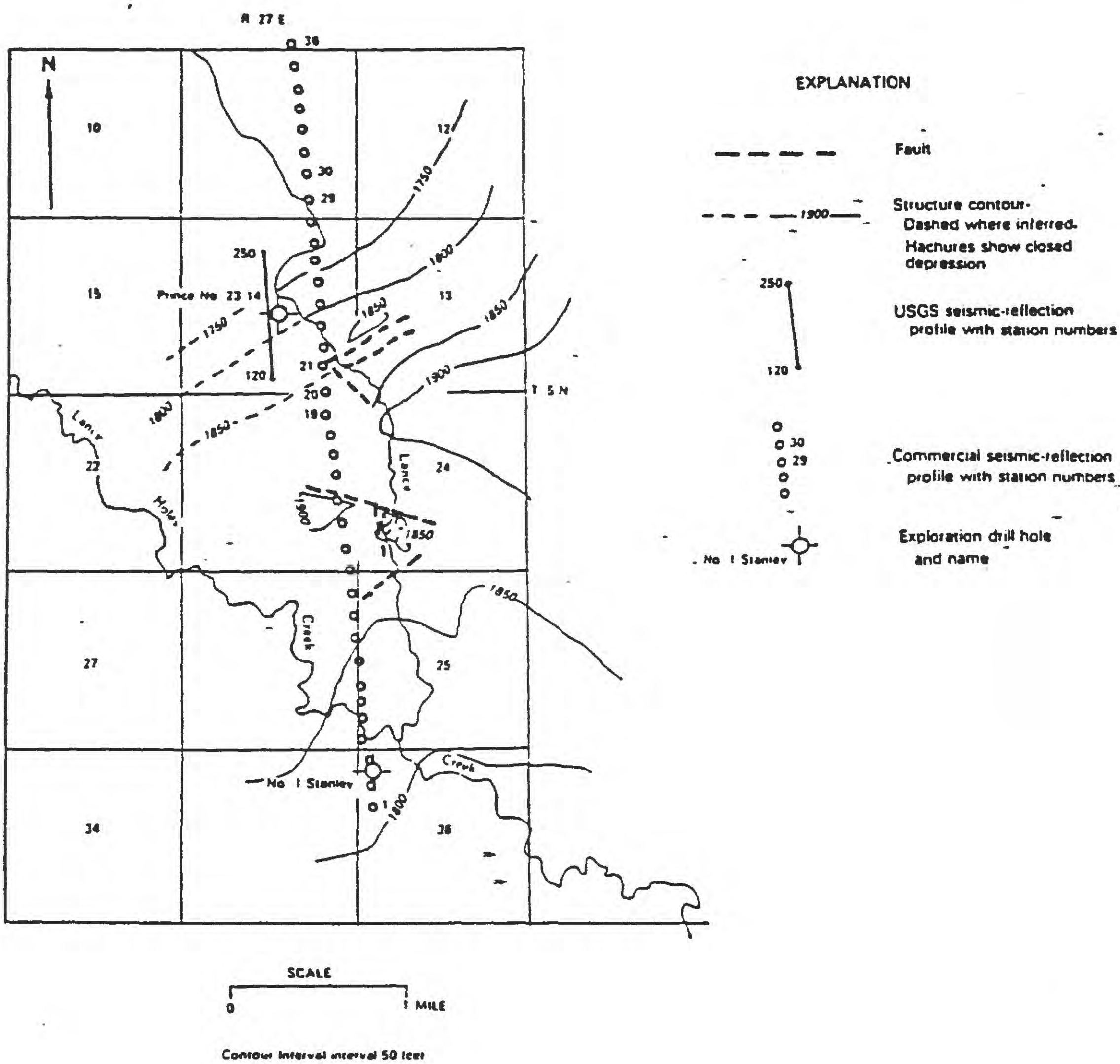

FIGURE 2.--Structure contours drawn on top of the GDBB (Government Draw Bentonite Beds, Virgin Creek Member of the Pierre Shale in the vicinity of Lance Creek. Locations of U.S. Geological Survey seismic-reflection profile and a part of the commercial profile are shown along Lance Creek.

coincides with a structural dip that indicates probable faulting. This part of the profile (fig. 3) shows seismic reflections from the Mesozoic and Paleozoic rocks that are correlated with the stratigraphic section described by Schoon (1971) on figure 4, and the top of the underlying Precambrian rocks. The position of these reflectors on the section were determined by using drill-hole logs from the four drill sites (figs. 1 and 2) and from a velocity model accompanying the seismic section. The following stratigraphic units, ages, and depths in table 1, taken from interpretations of geophysical-log data at the Prince No. 23-14 drill hole (R.A. Schoon, South Dakota Geological Survey, unpub. data, 1987), were correlated to velocity determined depths of reflections on the profile under station 23 and 24. The depths are corrected to a 1,700-ft datum which is used as the zero (0) time on the reflection profile.

The USGS profile (fig. 5) shows reflections only from Cretaceous rocks because the reflection data do not penetrate sufficiently deep to image the deeper Paleozoic and Precambrian strata. These reflections, identified in table 2, are based only on stratigraphic interpretations of geophysical drill-hole logs of Prince No. 23-14 hole (R.A. Schoon, unpub. data, 1987) adjacent to station 195, and the stacking velocities from refraction and reflection data from the USGS profile (Williams and others, 1989). The estimated depths for the reflecting horizons below a 1,900-ft-elevation datum plane are based on correlating the velocity determined depths of observed reflections to lithologic depths interpreted on geophysical (self potential, resistivity, and conductivity) drill-hole logs (R.A. Schoon, unpub. data, 1987). At each depth picked, there were distinct lithologic variations interpreted to have sufficient velocity contrasts to generate reasonable reflected horizons. Therefore, the reflector depths do not correspond exactly to the stratigraphic contact depths chosen by Williams and others (1989).

Because a higher frequency source was used in collecting the USGS data, possibly some of the reflections on this profile are from horizons other than those seen on the commercial profile; that is, those horizons with thickness and (or) lithology that enhance constructive interference of the higher frequency-shorter wavelength energy became more dominant reflecting strata.

DISCUSSION

Data from the commercial seismic-reflection profile under stations 23, 24, and 25 show a large basement fault and northward stratigraphic thickening of lower Paleozoic rocks above the fault (fig. 6). The reflection from the Precambrian Sioux Quartzite shows evidence of normal-fault displacement and a northerly dip on the Precambrian surface, accounting for nearly 500 ft of vertical relief in a distance of 1 mile. Additional northward tilting of the Precambrian rocks between stations 23 and 31 accounts for another 130 ft of stratigraphic relief, a total of more than 600 ft. The seismic profile shows an increased number of reflectors directly above the northern downdropped Precambrian rocks (Sioux Quartzite or granite) not observed above the higher block to the south (fig. 3), implying an abrupt northward thickening of the overlying sedimentary section. However, the overlying Pennsylvanian Reclamation Formation and reflectors above it are continuous across the faulted area but show a small increase of dip that indicates possible small local deformation over the faulted area. Thus, the thickening sedimentary section under the Reclamation Formation suggests that the north block was a topographic low in pre-Pennsylvanian time.

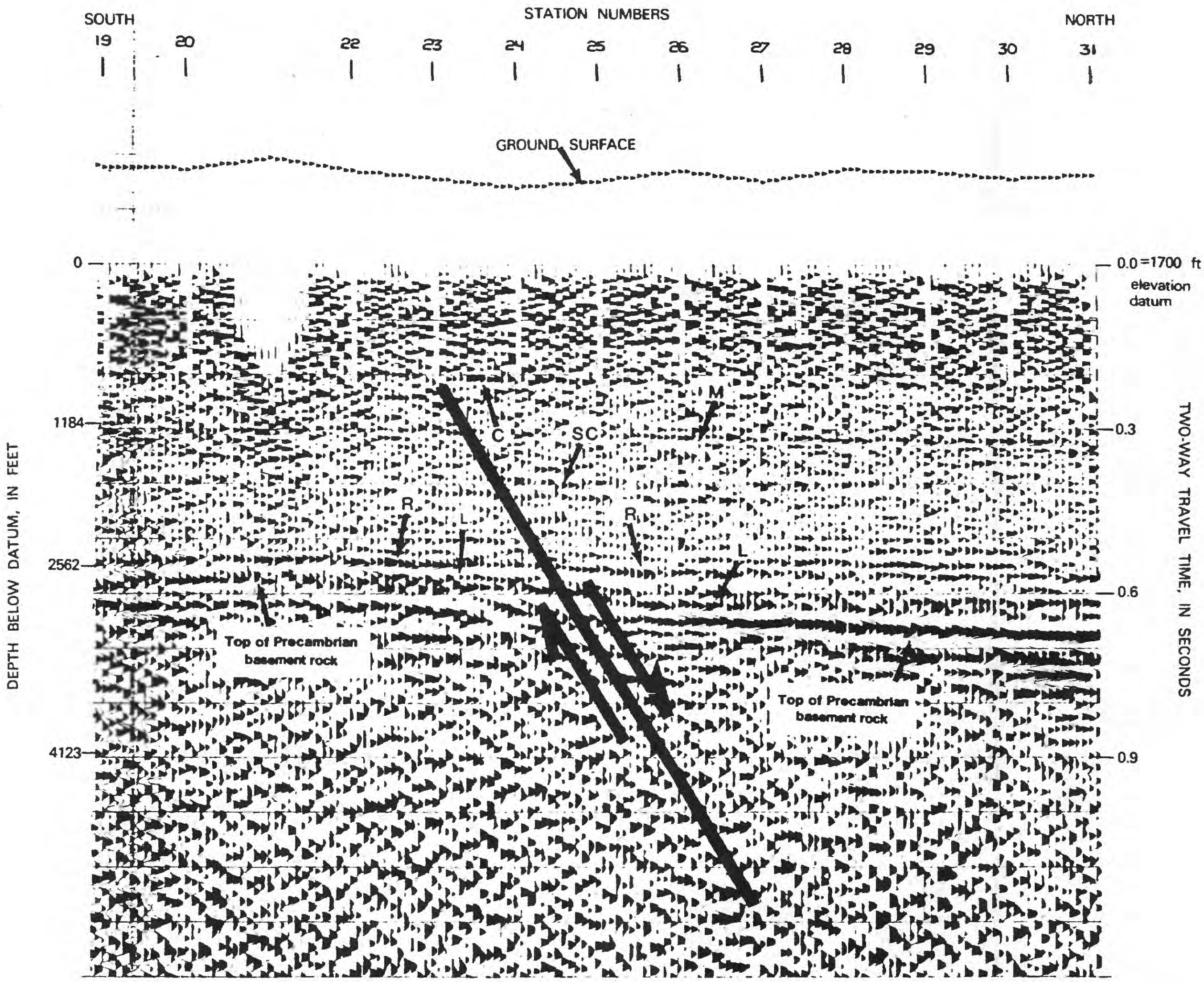

FIGURE 3.--Commercial seismic-reflection profile showing fault cutting Precambrian, Paleozoic (L and R), and Mesozoic (D, M, and C) reflectors. C, Carlile Shale; M, Mowry Shale; SC, Skull Creek Shale; R, Reclamation Formation; L, Lodgepole Formation.

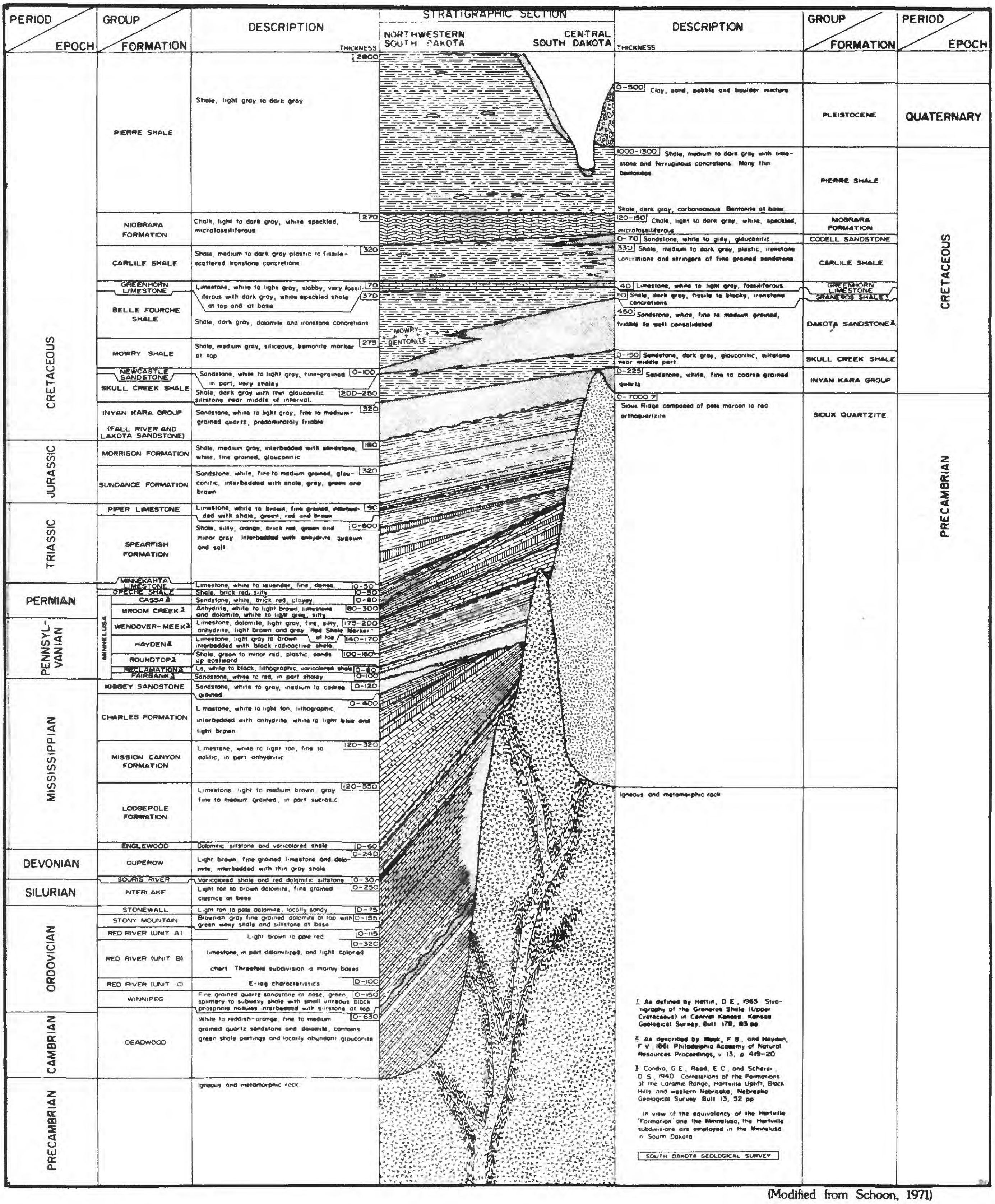

FIGURE 4.--Stratigraphic section of northwestern and central South Dakota. (Modified from Schoon, 1971.)

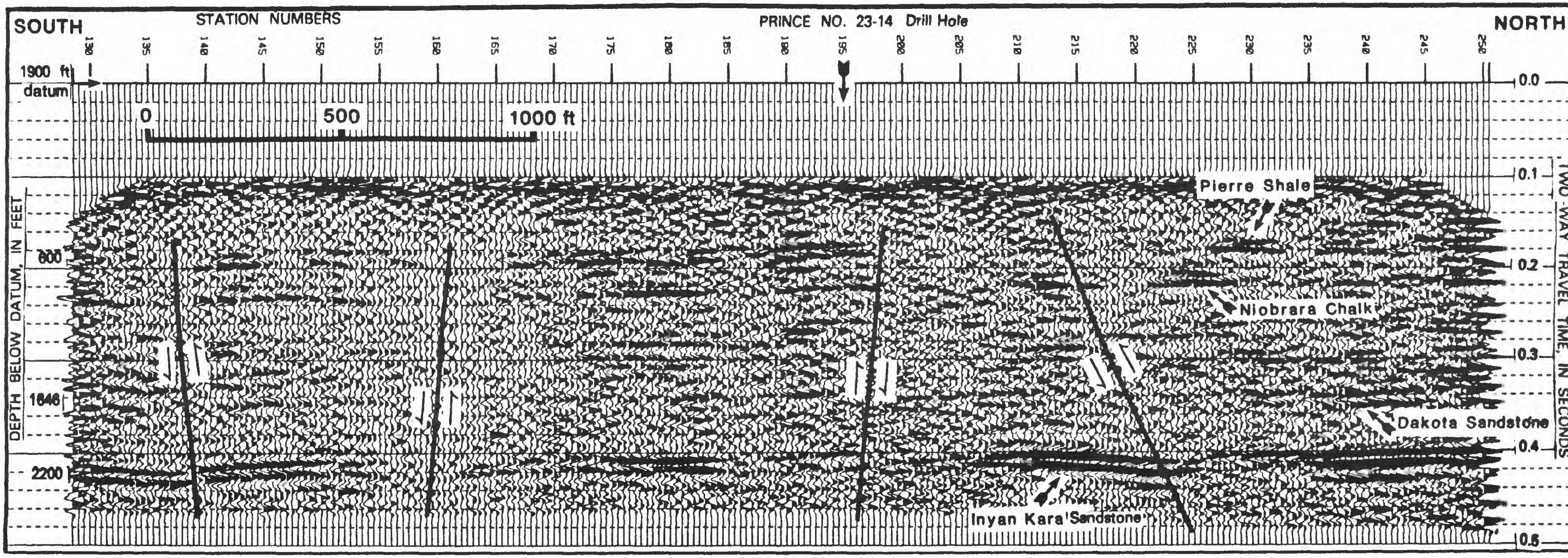

FIGURE 5.--U.S. Geological Survey seismic-reflection profile showing faults cutting the Cretaceous Pierre Shale, Niobrara Chalk, Dakota Sandstone, and Inyan Kara Group reflectors. These horizons were determined from core-log data acquired from the Prince #23-14 drill hole located at station 195.

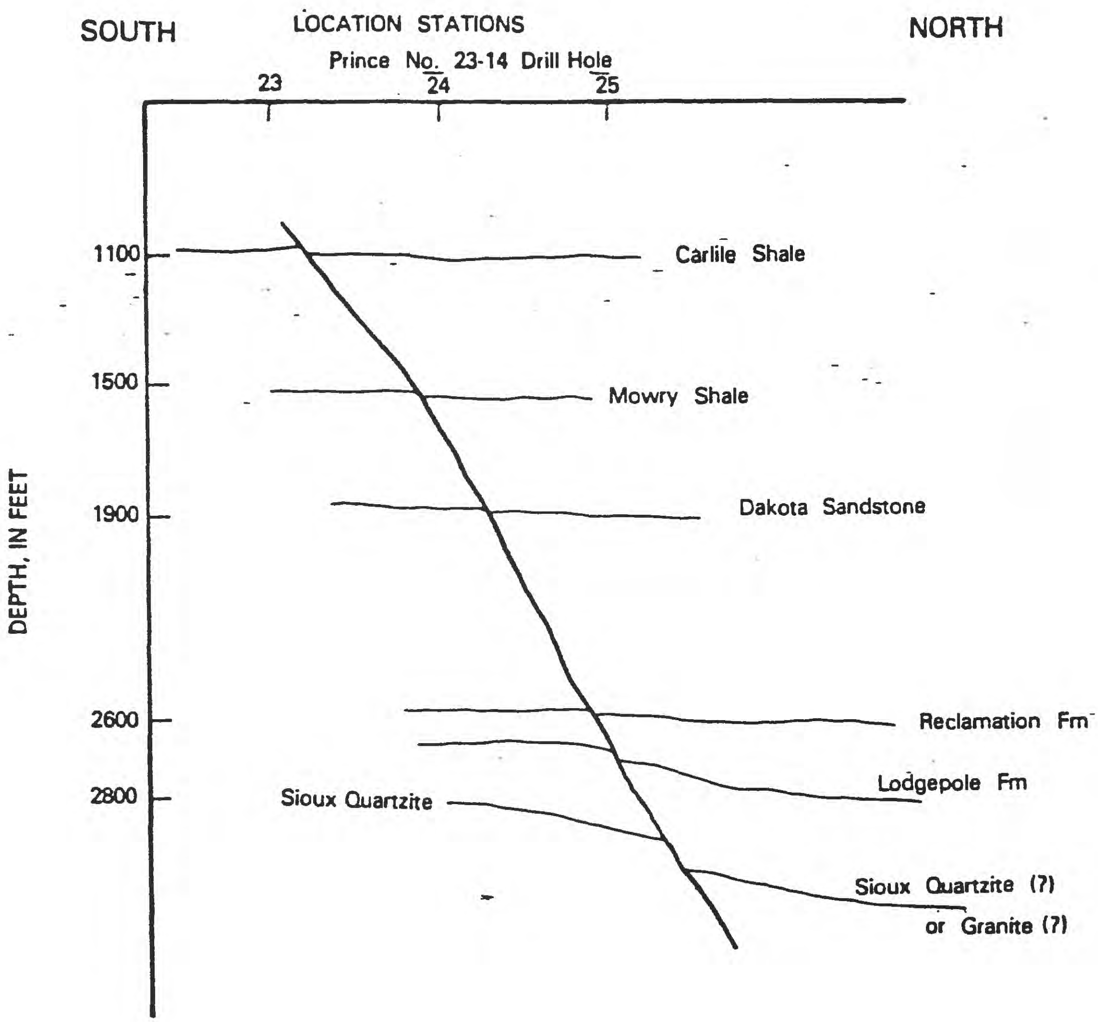

FIGURE 6.--Cross section of stratigraphic beds cut by fault as interpreted under stations 23, 24, and 25 from the commercial seismic-reflection profile.

TABLE 1.--Stratigraphic horizons identified as reflectors on commercial profile of Prince 23-14 drill hole

Era	Period	Formation and (lithology)	Depth below 1,700-ft-elevation datum (feet)
Precambrian		Sioux Quartzite (quartzite).	2,582
Paleozoic	Mississippian	Lodgepole (limestone).	2,366
Do	Pennsylvanian	Reclamation (limestone.	2,300
Mesozoic	Cretaceous	Skull Creek Shale (shale).	1,643
Do	....do	Mowry Shale (shale).	1,259
Do	....do	Carlile Shale (shale).	814

TABLE 2.--Stratigraphic horizons identified as reflectors on U.S. Geological Survey profile of Prince 23-14 drill hole

Era	Period	Formation and (lithology)	Depth below 1,900-ft-elevation datum (feet)
Mesozoic.....	Cretaceous......	Inyan Kara Group (sandstone).	2,122
Do.........	....do..........	Dakota Sandstone (sandstone).	1,646
Do.........	....do..........	Niobrara Chalk (chalk).	902
Do.........	....do..........	Pierre Shale (shale).	584

Logs from the Prince No. 23-14 drill hole (R.A. Schoon, unpub. data, 1987) (fig. 2) show that the Mississippian Lodgepole Formation is unconformable on Precambrian Sioux Quartzite. Logs from the No. 1 Wyly Shaffner drill hole (R.A. Schoon, unpub. data, 1987) located 4.3 miles to the north (fig. 1), show that the Lodgepole Formation has thickened considerably northward from station 24 and overlies at least 500 ft of lower Paleozoic rock (Cambrian through Devonian) above Precambrian rock. The drill hole did not penetrate Precambrian rock even at a depth of 3,461 ft below the 1,700-ft datum. A little more than 6 miles to the north-northwest of station 24 the Dakota No. 1 hole (fig. 1) penetrated more than 540 ft of pre-Lodgepole sedimentary rocks before drilling into Precambrian granite (Sioux quartzite was missing in this hole) at a depth of 3,729 ft below the 1,700-ft datum. However, 2.6 miles to the south of the fault at station 24, logs of the No. 1 Stanley drill hole (Schoon, unpub. data, 1987) (fig. 2) show that the Lodgepole Formation has thinned southward from station 24 and unconformably overlies the Sioux Quartzite at a depth of 2,546 ft below the 1,700-ft datum. The Pennsylvanian sedimentary rocks lie unconformably on the Lodgepole Formation both to the north and south of the fault (Brown and others, 1984), and the drill-hole logs show the Cretaceous Inyan Kara Group to lie unconformably on the Pennsylvanian rocks. North of the fault, the Sioux Quartzite is no longer present and the Precambrian rock surface has dropped nearly 1,200 ft.

From the above described relations of the commercial reflection profile and the stratigraphic information in the faulted area, we believe that the fault in the Precambrian rocks coincides with the north boundary of the Sioux Quartzite and that the Precambrian rock, nearly 1,200 ft deeper in the downfaulted block to the north of the fault, is granite. The fault was active during early Paleozoic time, allowing downdrop and sedimentation on the northern block. The southern block was emergent through lower Paleozoic until Mississippian time when the Lodgepole Formation was deposited. This interpretation agrees with the depositional history of the area reported by Brown and others (1984) who show evidence of uplift and downwarping that influenced sedimentation from the Paleozoic through the Mesozoic along the northwest-trending Nesson-Pierre structural element that extends into our study area (fig. 7). Brown and others (1984) show an abrupt thickening of Lodgepole equivalent and lower Paleozoic sedimentary rocks north of an emergent highland spur (part of the Pierre-Nesson element) in the area of our study and suggest that early Paleozoic and Mississippian-age tectonism, possibly related to the Siouxia Uplift, is responsible for the thickening. The uplifted block of Sioux Quartzite south of the fault is interpreted as the northern edge of this emergent highland spur. The absence of lower Paleozoic sedimentary rocks over the uplifted Sioux Quartzite indicates that the area must have been an eroding highland during this time. Repeated downdropping of the rocks north of the inferred fault under station 25 on the commercial profile probably occurred prior to and during Mississippian time, followed by regional subsidence during late Paleozoic time. The scarcity of Triassic and Jurassic rocks on all well logs indicates a long period of reemergence and erosion or nondeposition across the region prior to Cretaceous deposition.

Although there appears to have been repeated uplift and subsidence during the local depositional history, most of the displacement on the fault under station 25 occurred prior to Cretaceous deposition. Because the resolution of the reflections is so poorly defined, it is possible that the small offsets described for the shallower beds may not be real. The total surface

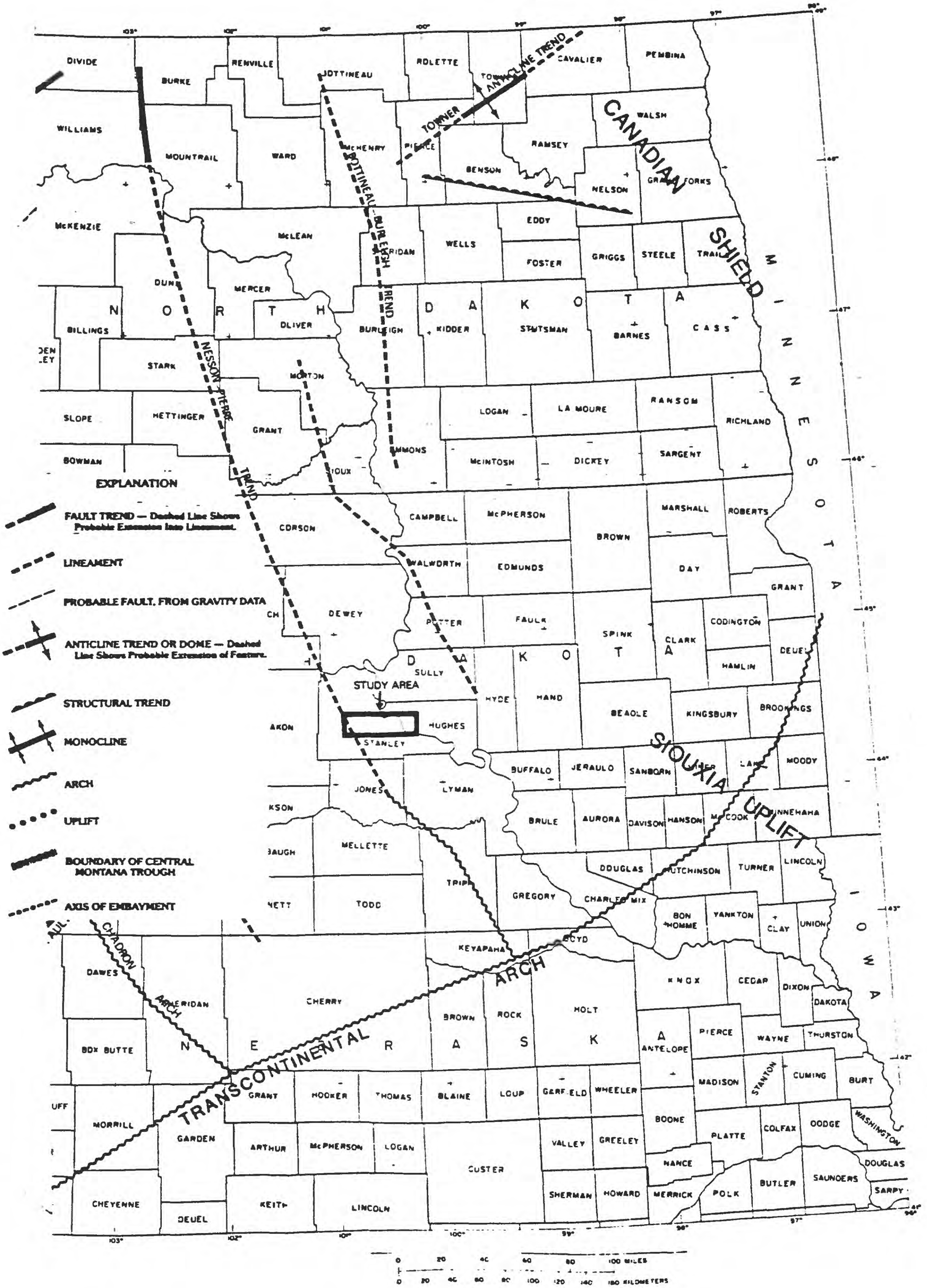

FIGURE 7.--Map showing some of the major Paleozoic structural elements in South Dakota (Brown and others, 1984). Rectangle in Stanley County shows location of study area on the Nesson-Pierre trend.

stratigraphic relief of 120 ft, therefore, may be the result of dip alone and may reflect sedimentation conforming to underlying surface dips rather than to repeated fault movements. The quality of the low-frequency reflected energy (45-65 Hz) on the commercial profile is very poor for the shallow Cretaceous rocks. However, there is evidence of a small offset and minor warping of the strata north of the fault that occurred during Cretaceous time and later. The reflections from the Reclamation Formation, Skull Creek Shale, Mowry Shale, and Carlile Shale, are displaced approximately 40-50 ft across the fault above the projected fault trace, based on the profile velocity model and traveltime displacements of the reflections, and are slightly tilted to the north. These calculated displacements are consistent with those observed in surface faults. The total structure relief for each of these beds from stations 21 to 31 is approximately 120 ft, which is similar to the stratigraphic relief over the same distance at the surface. However, this is much less than the 600 ft of relief for the Precambrian rocks. Thus, it appears that some movement may have occurred on the fault after deposition of the Cretaceous beds.

The USGS profile (fig. 5) compared to the commercial profile was obtained using a seismic source with a higher dominant frequency, higher natural frequency geophones, a short digital data time sampling interval, and severe low-cut recording filters to improve the resolution of reflections from the shallow stratigraphic horizons (Williams and others, 1989). In addition, the line was positioned parallel and as close to the commercial profile as the terrain would permit (fig. 2), hoping to image the same geologic features seen under station 25 of the commercial profile. The high-frequency reflections (>100 Hz) on the USGS profile provide better resolution than those seen on the commercial profile in a comparable time interval, but, in some intervals, similar reflections from both profiles are sometimes interpreted to be reflecting from different stratigraphic horizons. The deepest identified reflection is from the Inyan Kara Group at a depth (below 1,900-ft datum) of 2,112 ft, and there are good-quality reflections from unidentified strata at a depth (below 1,900-ft datum) of approximately 2,316 ft, only 457 ft above the Precambrian rock surface. Therefore, if the structural relationship in Precambrian rocks on the commercial profile is present below the reflecting horizons on the USGS profile, these reflections should mimic the structure of the Precambrian rocks interpreted on the commercial profile. However, the USGS profile does not show much similarity to the commercial profile, and because there are no reflections from the Precambrian surface to indicate otherwise, it seems likely that the USGS profile does not intersect the fault shown under station 25 of the commercial profile.

Our interpretation of the USGS profile suggests that the structure in the Mesozoic sedimentary rocks consists of boundary faults that accommodate mechanical adjustments between massive rock sections with opposing shallow dips. Some of the faults appear to extend from below the Inyan Kara Group upward into the Pierre Shale near the surface. In addition, the deepest reflector from the Inyan Kara Group, shows several broad, low-amplitude monoclines that rise from south to north. From stations 135 to 250, this reflection rises approximately 160 ft in elevation as a result of fault displacements and updip rise. The Cretaceous reflectors above the Inyan Kara show the same general structural trend, with the shallowest reflecting horizon at the base of the Pierre Shale, rising to the north approximately 80 ft between the same locations. This structural trend is opposite the trend of Government Draw Bentonite Beds mapped on figure 2. The area is extensively faulted and may contain local structural anomalies not present on the

Government Draw Bentonite Beds structure map. In addition, because of the low density and wide spacing of surface marker-bed sampling in this area, the location of structure contours (dashed) is tenuous.

The throws on faults on the USGS profile, similar to those on the commercial profile, are greater at depth than they are near the surface with a maximum vertical displacement of more than 70 ft. Only the component of vertical displacements can be estimated from the profile; therefore, the true sense of faulting is unknown. Also, the relation of these faults to deeper structures in the Precambrian rocks is unknown without deep-reflection data. Thus from this interpretation, faulting at depths of at least 2,112 ft may extend into the Upper Cretaceous Pierre Shale, indicating that faulting occurred through much of the Mesozoic sedimentary rocks at least in Late Cretaceous time.

Four examples of possible faulting are at stations 195-200, 215-225, 135-140, and 160-165 on the USGS line. These examples are discussed by Williams and others (1989), in light of limitations of the geophysical data and, here, in light of our observed geologic field data.

The best evidence of faulting is at stations 195-200 and 215-225 (fig. 5) where the reflection data indicate approximately 70 ft of vertical relief in less than 200 ft horizontally in the Inyan Kara Group and Dakota Sandstone. Above these horizons, the displacements diminish in the reflections from the Niobrara and Pierre Formations. In the vicinity of faulting, a "dead zone" occurs and the data quality from these shallow horizons is too poor to identify reflecting horizons. Throw on the faults is defined by projecting the dips and elevations from strong reflections on both sides of the faulted area. For instance, at stations 195-200 the basal Pierre Shale reflection has about 7 percent apparent dip to the south of the fault, whereas the Inyan Kara reflection has slightly greater than an 8 percent apparent dip to the south. Near the fault, the basal Pierre Shale reflection is obscured from station 196 to near station 210. Over the same part of the section, the fault vertically displaces the Inyan Kara reflection nearly 70 ft. At station 210, however, gradual northward folding flattens the dip and brings the bed to approximately the same elevation as the upthrown strata to the south of the fault. Similarly, the Pierre Shale reflection that is present under station 210 is approximately at the same elevation as on the upthrown south side of the fault under station 195. Because of the similar style of deformation of the deep and shallow reflections, and because the shallow reflected energy probably is absorbed by the fractured shale, it is interpreted that the fault also may have deformed the basal Pierre Shale either by folding or by numerous small displacement faults or both.

At stations 215-225 (fig. 5), vertical displacements on the order of 50 ft seen on the Inyan Kara reflection are larger than the displacements on the Niobrara and basal Pierre Shale reflections. Vertical displacements on these shallow horizons are as much as 17 ft and, as at stations 195-200, the reflections are partially obscured and difficult to interpret. Thus, the offset of the Inyan Kara reflection appears to project upward into the Pierre Shale, but the style of deformation is obscure and the amount of offset is not large enough to confidently measure.

At stations 135-143, the Inyan Kara reflection is vertically offset approximately 40 ft and has a sharp change of dip direction. South of the fault, reflections above the Inyan Kara are poorly developed but to the north fault these reflections are much more coherent and more easily traced. The Niobrara reflection is the only shallow horizon that can be crudely traced across the fault zone and has a vertical offset of approximately 30 ft.

Again, the faulting at depth seems to affect shallower horizons but poor-quality data make it difficult to accurately determine the amount of offset.

Finally, at stations 160-165 (fig. 5) the only evidence of faulting is a reversal of dip and a zone of very poor reflection data that obscures all of the reflectors on the section. The zone may be an area of deformation that includes low-amplitude folding and faulting but the poor quality of data also may be the result of near-surface absorption of the seismic energy (Williams and others, 1989).

The data from the USGS profile suggest that the faults expressed in the older Cretaceous rocks apparently extend upward into the basal beds of the Pierre Shale. The faulting at depth is accommodated in the shale either by minor faulting or small-amplitude folding. Structurally, the observed profile (fig. 5) apparently consists of large coherent blocks, each with a unique dip that results from displacements along bounding fault surfaces. However, locally the dip may be different than the regional dip because the blocks have been tilted by faulting. This interpretation is consistent with surface faults mapped in nearby outcrops of the Pierre Shale (fig. 8 and table 3).

The characteristics of many of the more prominent faults (table 3) are typical of near-surface faulting in the Pierre Shale. Larger faults in the shale outcrops exposed along incising stream valleys, commonly parallel to the valleys, may have vertical displacements of as much as 105 ft and can be traced to two-thirds of a mile. The high-angle (>45°) faults form boundaries between large tilted blocks of shale; the bedding in these blocks dips at low angles (0°-15°), commonly in different directions in adjoining blocks. Folding within the blocks is usually absent or very minor, except adjacent to faults where sharp drag folds have formed. Thus, the surface expression of faulting in the shale is similar to the style of block faulting interpreted on the seismic-reflection profile. The blocks are separated by faults with relatively small vertical displacements in the Cretaceous sedimentary rocks.

A possible but unlikely alternative interpretation of the geologic structure on the USGS profile is that the faults in the Inyan Kara Formation do not extend into the Upper Cretaceous Niobrara and Pierre Shale Formations. In this interpretation, the faulting may have occurred prior to or during deposition of the Pierre and Niobrara beds, with the relative offset either having become nonexistent or diminished upward in the sedimentary section through soft sediment ductile deformations. In either case, the dip of the upper horizons which roughly parallels the Inyan Kara Group may be explained by sedimentation processes, and the surface faulting may result from large-scale listric faulting caused by slumping during the deposition of the shale. The surface evidence for this type of faulting is lacking.

Although the commercial and USGS profiles are nearly parallel and less than one-third of a mile apart, there is no obvious structural relationship common to both profiles other than the fact that they both show high-angle faults that have less displacement upward. Because the USGS profile does not extend deep enough to observe Precambrian reflections, we cannot speculate on the connection between the underlying structures in Precambrian rocks to those seen on the commercial line. Furthermore, the general southerly dip of Mesozoic rocks on the USGS profile is opposite to the northerly dip of strata on the commercial profile. However, as previously discussed, the structure on the USGS line may be a local perturbation within a densely faulted terrain, and (or) the structure contours may not be accurately located because of sparse surface sampling. Available information is insufficient to confidently correlate the structures between the two lines.

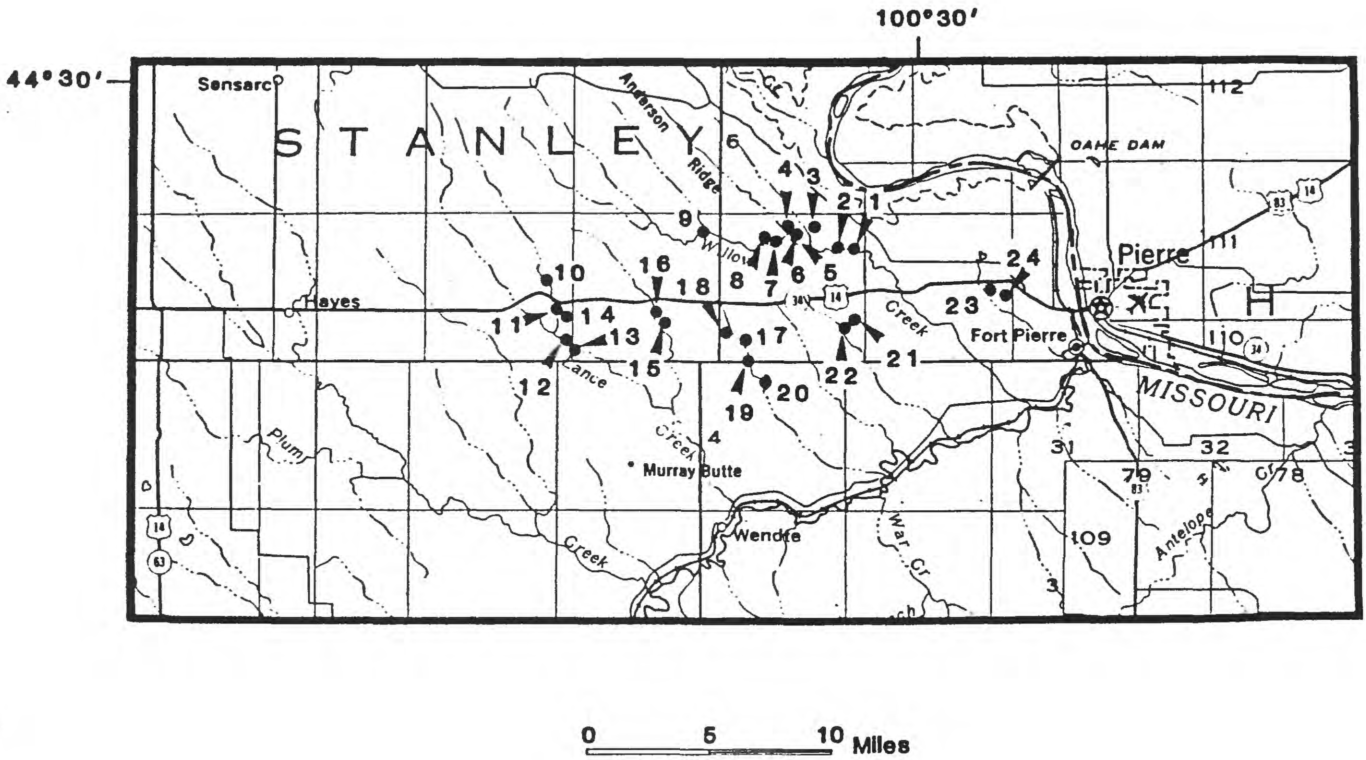

FIGURE 8.--Map showing locations of prominent faults described in table 1.

TABLE 3.--Characteristics of prominent faults

[Leaders (----) indicate no data available. FPL=fault parallel to stream course, FP=fault perpendicular to stream course. FO=fault at oblique angle to stream course]

Map location No.	Section	Township	Range	Valley drainage	Strike	Dip	Fault to stream orientation	Vertical displacement (m)	Sense of displacement	Fault characteristics	Lateral extent (m)	Description of scarp	Breccia zone width (m)	Valley wall height (m)
1	NW¼ 12	5 N.	29 E.	Willow Creek	N. 80° E.	40° SE	FPL	35	Thrust (low-angle reverse).	Well-developed scarp face; fault breccia source material for a 15-m-wide debris flow.	415	Fault scarp; height 21 m.	15	20
2	NE¼ 10	5 N.	29 E.	..do..	N. 65° E.	50° NW	FP	19	Normal......	Fractured bedrock adjacent to fault.	---	None.........	---	6
3	NE¼ 3	5 N.	29 E.	True Draw	N. 60° W.	----	FP	24	Reverse.....	Debris flow.......	820	....do.......	---	6
4	SE¼ 4	5 N.	29 E.	Willow Creek	N.25°-35° W.	48° SW	FPL	15	Normal......	Brecciated rock in gouge, 17 cm thick; well-developed mullion on scarp face. Junction zone of NW- and NE-trending faults.	400	Fault-line scarp; height 20 m.	---	5-20
5	SE¼ 10	5 N.	29 E.	..do...	NE	----	FP	23	Covered, junction zone of NW-NE-trending faults.	Covered by debris flow.	---	None.........	---	5-20
6	NW¼ 10	5 N.	29 E.	..do...	N. 15° E.	65° NW	FPL	16	Normal.......	8- to 13-cm fault gouge-bounding brecciated zone; 3-5-cm-thick bentonite beds ductiley drawn out.	---	....do.......	3-5	15
7	NE¼ 8	5 N.	29 E.	..do...	N. 5° E.	----	FPL	27	....do.......	Mullion well developed.	---	Fault-line scarp.	---	15
8	NE¼ 7	5 N.	29 E.	..do...	N. 40° W.	----	FPL	12	....do.......	Mullion well developed on highly fractured bedrock surface.	---	....do.......	---	9
9	NW¼ 3	5 N.	28 E.	..do...	N. 65° E.	55° SE	FP	32	Reverse......	....do...........	---	Fault scarp..	---	4
10	SE¼ 14	5 N.	27 E.	Lance Creek	N. 65° E.	59°	FP	19	....do.......	----	---	None.........	---	5-30
11	SW¼ 13	5 N.	27 E.	..do...	N. 40° E.	45° SW	FPL	14	----	Fractured bedrock, less than 3-cm-thick gouge.	---	....do.......	---	5
12	NW¼ 25	5 N.	27 E.	..do...	N. 35° W.	44° NE	FPL	12	Normal.......	Fault breccia well developed, >1 m thick; mullion well developed; at least two periods of movement.	100	Fault-line scarp; height 15 m.	1	15
13	SW¼ 25	5 N.	27 E.	..do...	N. 85°W.	60° SW	FPL	24	....do.......	Fault zone........	370	....do.......	---	5-25
14	SW¼ 24	5 N.	27 E.	..do...	N. 15° W.	36° NE	FP	16	....do.......	Gouge 3-5 cm thick	---	----	---	2-10
15	NE¼ 27	5 N.	28 E.	Government Draw	N. 45° E.	42° SE	FPL	>17	....do.......	Mullion developed on highly fractured bedrock surface.	---	----	---	----
16	NW¼ 22	5 N.	28 E.	..do...	N. 70° E.	45° NW	FO	14	....do.......	Gouge 3 cm thick; breccia 20 cm thick.	---	None.........	0.2	5-8
17	NW¼ 32	5 N.	29 E.	Ash Creek	Approximate NE direction.	----	---	22	----	Covered..........	---	....do.......	6	6
18	SW¼ 30	5 N.	29 E.	..do...	N. 25° E.	65° NW	FPL	13	Normal.......	Highly brecciated rock; 5-cm-thick gouge along fault plane.	400	....do.......	---	2
19	SW¼ 32	5 N.	29 E.	..do...	----	60° NW	FPL	25	....do.......	----	1,000	....do.......	---	3
20	SE¼ 4	4 N.	29 E.	..do...	EW	----	FPL	18	Reverse......	Highly brecciated, rock on fault plane; well-developed mullion.	150	Fault scarp; height 20 m.	>30	3-20
21	SW¼ 30	5 N.	30 E.	Powell Creek	Approximate NE direction.	----	FO	11	----	Highly brecciated, fault mostly covered.	---	None.........	---	2-5
22	SW¼ 25	5 N.	29 E.	..do...	Approximate NE trend.	----	FP	21	----	Covered..........	----	....do.......	---	21
23	NE¼ 24	5 N.	30 E.	Dry Run	N. 50° W.	75° NE	FP	24	-----	13-cm-thick gouge developed.	---	....do.......	9	20
24	NE¼ 24	5 N.	30 E.	..do...	N. 40° E.	37° NW	FP	13	Normal......	8-cm-thick gouge; 9-m-thick breccia.	---	....do.......	---	12

CONCLUSIONS

The seismic-reflection data used for this study are not sufficient to conclusively demonstrate that near-surface faulting in the Cretaceous Pierre Shale is directly related to faulting in Precambrian rocks. Vertical fault displacements of as much as 70 ft are present in the Cretaceous sedimentary rocks at depth of 2,112 ft (below 1,900-ft datum); these faults disrupt many of the overlying rocks and appear to extend into the base of the Upper Cretaceous Pierre Shale. Where observed, basement faulting extends into the Paleozoic rocks and possibly into the overlying Cretaceous rocks. However, both the USGS and commercial seismic profiles lacked clear evidence that basement faulting is related to surface faulting. Even though the structural relation between the two profiles cannot be determined, similarities between the profiles provide some idea of the past geologic history common to both profiles. The area has been one of repeated submergence and emergence at least through Early Cretaceous time. Faults that extend upward through Cretaceous rocks with diminished displacements in the Pierre Shale, indicate that small-magnitude faulting associated with small-amplitude folding probably occurred at least until Late Cretaceous time. It is possible that the Upper Cretaceous sediments were deposited during or after faulting and conformed to the underlying deformational features.

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