UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Isopach and Structure Contour Mapping of Thin Bentonite and Shale Beds in an Area of Mapped Lineaments, Central South Dakota.

by

Alan F. Chleborad[1]

Open-File Report 86-414

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

[1]U.S. Geological Survey, Denver, Colo.

1986

CONTENTS

ILLUSTRATIONS

Results of Isopach and Structure Contour Mapping of Thin Bentonite and Shale Beds in an Area of Mapped Lineaments, Central South Dakota

By

Alan F. Chleborad

ABSTRACT

Isopach and structure contour maps were constructed using outcrop measurements of thin bentonite and shale beds in the Virgin Creek Member of the Pierre Shale in central South Dakota. The maps were developed as part of a study to evaluate lineaments as a guide to the distribution of faults and fractures in the Pierre Shale. Knowledge of the distribution of tectonic faults and fractures is needed to evaluate the shale as a potential medium for toxic waste disposal. The isopach and structure contour mapping has demonstrated the usefulness of the thin but continuous bentonite and shale beds for purposes of stratigraphic and structural interpretation over a 600-mi^2 area underlain by the Pierre Shale. Thickening of the bentonite and shale beds across part of a mapped lineament, within the study area, indicates lineament control of paleodepositional conditions possibly related to paleotectonic activity as suggested by Thomas (1974) and Shurr (1978). The abrupt thickening of sediments across the northwest-trending lineament identifies the lineament as a possible block boundary that may have been tectonically active prior to deposition of a 68-m.y.-old datum, but after a postulated shift of tectonic activity from northwest to northeast-trending lineaments 72 m.y. ago. Similar isopach patterns for the bentonite and intervening shale beds indicate depositional control by a continuous long-term factor. The abrupt thickening of bentonite beds across the northwest-trending lineament indicates possible water transport of the original volcanic ash after deposition in a Late Cretaceous epeiric sea. Results of the mapping give direction to future work needed to better define stratigraphic and structural relationships in areas of mapped lineaments for the purpose of evaluating lineaments as a guide to tectonic fracturing and faulting in the Pierre Shale of central South Dakota.

INTRODUCTION

Information on the nature and distribution of faults and other fractures in shales is needed to predict the response of that material to deep engineering excavations as part of a geotechnical evaluation of shales as a medium for toxic-waste disposal. As part of the effort to generate needed information, field investigations were undertaken in a 600-mi^2 area in central South Dakota underlain by the Pierre Shale Formation (fig. 1).

Mapped surface lineaments appear, in some cases, to be faults, fault zones, or zones of intense fracturing. A potential tool for predicting the distribution of tectonic faults and related fractures in the Pierre Shale of western South Dakota is provided by a model of lineament-block tectonics developed by Thomas (1974), Shurr (1979), and Slack (1981). The lineament-block tectonic model developed by Thomas (1974) for parts of the Williston-Blood Creek Basin of North Dakota and Montana visualizes a block framework of northeasterly and northwesterly trending basement-weakness zones represented at the surface by lineaments. It is postulated that paleotectonic activity along lineament-basement-block boundaries was an important control on paleotopography and, consequently, on paleodepositional conditions. Thickening and thinning of beds, for example, may occur across lineament-basement-block boundaries due to block framework control of paleotopography.

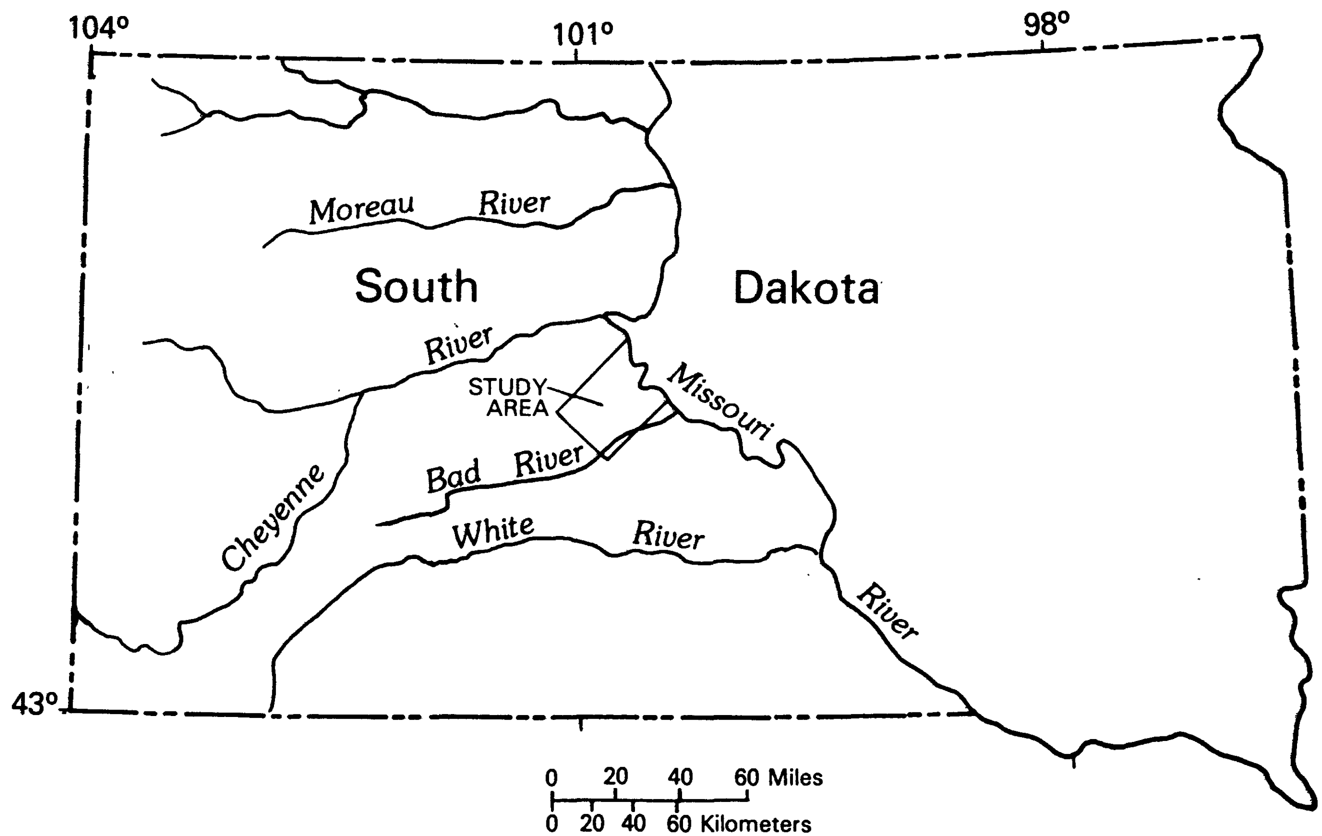

Figure 1.--Index map of South Dakota showing the location of the study area.

A lineament map (fig. 2) of western South Dakota was constructed by Shurr (1979) using Landsat imagery. Following Thomas' model, Shurr defined lineament-bounded blocks and correlated lineaments with the results of stratigaphic and structural studies. Structure contour maps were developed by Shurr (1979) from subsurface control points on two structural datums in the Pierre Shale: the Ardmore Bentonite Bed at the base of the Sharon Springs Member (78 m.y.) and the bottom of the Mobridge Member (68 m.y.) (fig. 3.) On Shurr's structure contour maps, northwest-trending lineaments have expression in the older 78-m.y.-old datum, whereas northeast-trending lineaments have expression in the younger 68-m.y.-old datum (base of the Mobridge Member). It was concluded by Shurr that the northwest-trending lineaments were active prior to the 68-m.y.-old datum, but apparently were not active during tectonic activity that deformed the 68-m.y.-old datum, reflecting a possible shift in tectonic activity from the northwest-trending lineaments to northeast-trending lineaments. Thickness maps of two subsurface stratigraphic units between the Ardmore Bentonite Bed and the Mobridge Member were also developed by Shurr (1978), in an effort to more closely date the apparent shift in paleotectonism. The upper unit with a 72-m.y.-old bentonite datum base and a 68-m.y.-old datum top, includes the DeGrey, Verendrye, and Virgin Creek Members of the Pierre Shale (fig. 3). According to Shurr (1979), the thickness map for that unit clearly shows the increased influence of lineaments trending northeast. In contrast, the thickness map of a lower and older unit that includes the Sharon Springs and Gregory Members of the Pierre Shale, shows a northwesterly trending lineament influence. Shurr concluded that the shift in tectonic activity must have taken place at about 72 million years ago. Data presented in this report suggest the possibility of tectonic activity along a northwest-trending lineament after deposition of the 72-m.y.-old datum.

Two lineaments mapped by Shurr (1979) cross the study area, one northwest trending and one northeast trending (fig. 2). The northwest-trending lineament, which is approximately 100 mi long, passes just south of Hayes, South Dakota, and appears to coincide, in part, with Plum Creek, a tributary of the Bad River in the southwestern part of the study area. That northwest-trending lineament was shown by Shurr (1979) to have expression on the structure contour map of the Ardmore Bentonite Bed (78 m.y.) and the northeast-trending lineament was shown to have expression on the structure contour map of the base of the Mobridge Member (68 m.y.) of the Pierre Shale.

Kolm and Peter (1984) also mapped lineaments in western South Dakota using a variety of images including low-sun-angle Landsat images that enhanced subtle topographic features and drainage patterns for the purpose of evaluating lineaments as a tool for locating areas of increased ground-water leakage through confining layers. In the study, six basement blocks were identified, well-defined by northeast-trending lineaments, but not well-defined by northwest-trending lineaments. The northeast-trending Bad River lineament, with documented hydrochemical and geothermal anomalies, was also identified as a probable major block boundary. Lineaments identified by Kolm and Peter (1984), are mostly northwest trending and do not cross drainage divides. There is disagreement with some lineaments common to Shurr's map; however, the parts of two lineaments mapped by Shurr that are within the area of the present study (fig. 2) appear to be represented on the Kolm and Peters lineament map as well.

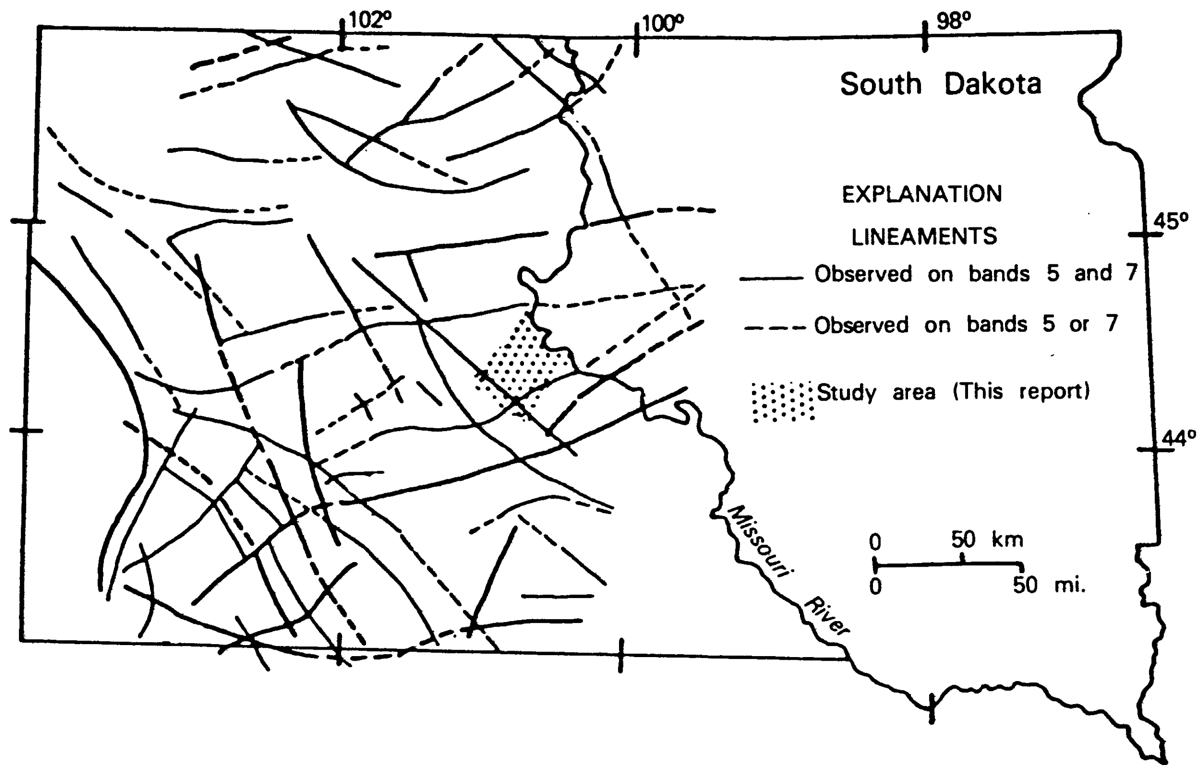

Figure 2.--Map showing location of the study area in relation to mapped lineaments in western South Dakota. Lineaments were delineated from Landsat imagery and vertical intensity magnetic data (Shurr, 1979). Area of this report (stippled pattern) is crossed by prominent northwest-trending and northeast-trending lineaments in the central part of the State.

Hell Creek Formation
Fox Hills Sandstone
Pierre Shale
- **Elk Butte Member**
- **Mobridge Member**
- **Virgin Creek Member**
- **Verendrye Member**
- **DeGrey Member**
- **Crow Creek Member**
- **Gregory Member**
- **Sharon Springs Member (including Ardmore Bentonite Bed at base)**
- **Gammon Member**

Niobrara Formation
Carlile Shale
Greenhorn Formation
Belle Fourche Shale
Dakota Sandstone

Figure 3.--Stratigraphic section of Cretaceous units in western South Dakota (from Shurr, 1979).

PURPOSE

The purpose of the study, of which this report is a part, is to evaluate lineaments as a guide in predicting the nature and distribution of faults and other fractures in the Pierre Shale. An understanding of the nature of faulting and fracturing in shales is needed to evaluate potential problems that might be expected in the siting of engineering works involving deep excavations for toxic-waste disposal.

USE OF STRATIGRAPHIC MARKERS IN THE VIRGIN CREEK MEMBER

A stratigraphic marker consisting of a group of thin bentonite beds in the lower-middle part of the Virgin Creek Member of the Pierre Shale was recently identified in the study area (Nichols and others, in press). The marker, named the Government Draw Bentonite Beds after an exposure in Government Draw west of Pierre, South Dakota, was originally defined as a group of three closely spaced bentonite beds (B1, B2, and B3 in fig. 4). A fourth bentonite bed (B4 in fig. 4) was not orginally identified as part of the stratigraphic marker because preliminary observations indicated that only bentonite beds B1, B2, and B3 (fig. 4) were sufficiently recognizable to be included (T.C. Nichols, Jr., written communication, 1985). However, field investigations performed for this study indicated that the top bentonite bed (B4) is almost always present and descernible in the study area, and that it thickens considerably to the west, making it an important part of the total marker, especially for possible future stratigraphic studies to the west. The marker was subsequently redefined to include bentonite bed B4 (Nichols and others, in press).

The near-surface areal extent of the marker was established by the discovery of exposures in the Willow Creek drainage, 7 mi west of Pierre, South Dakota, and in the Frozen Man Creek drainage 26 mi to the west of that location (fig. 5). Prior to that, the usefulness of the grouping of beds, as a continuous marker recognizable in outcrops over a large area, was unknown and questionable. For example, similarly thin bentonite beds in Cretaceous sediments of western Kansas could, in some cases, be traced only a few miles (Hattin, 1965). The usefulness of the marker for structural interpretation over a large area was demonstrated by a comparison of elevations at the Willow Creek and Frozen Man Creek datum locations that indicates a drop of 185 ft or approximately 7 ft/mi from west to east. The drop in elevation is consistent with the finding of Crandell (1958) who reported a possible eastward dip of 5 ft/mi for the base of the overlying Mobridge Member in an eastern part of the same area.

Figure 4 depicts a measured exposure of a stratigraphic interval in the Plum Creek drainage (SW 1/4 sec. 21, T.4 N., R.26 E.), southwest of Hayes, South Dakota, that includes the marker-forming group of four bentonite beds. For the purpose of this report, the total stratigraphic interval from the top of bentonite bed B4 to the bottom of bentonite bed B1 (fig. 4) is referred to as the Plum Creek interval. The individual bentonite beds are themselves isochronous stratigraphic markers, and are herein given the individual datum designations B1, B2, B3, and B4. Since each bentonite bed in the Plum Creek interval is also a time datum, thickness changes of the intervening shale beds

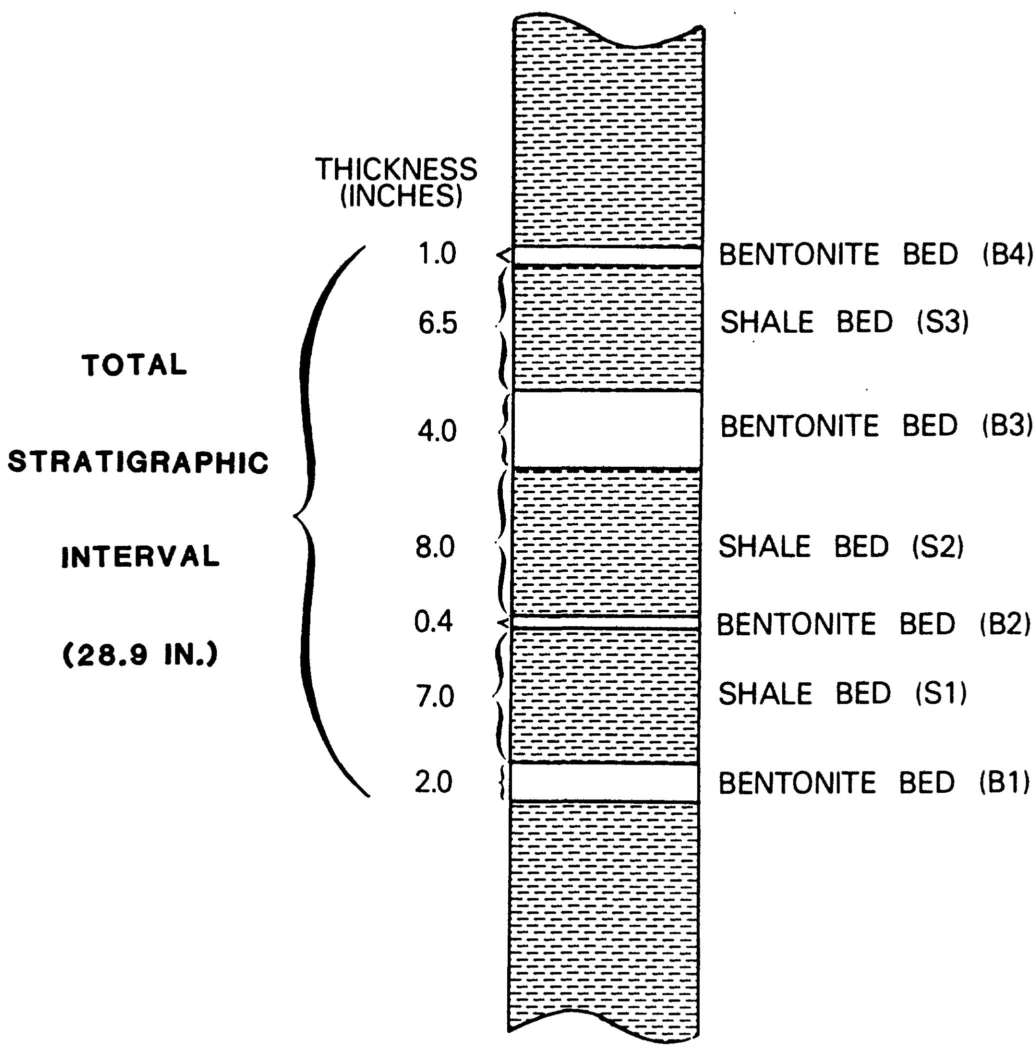

Figure 4.--Stratigraphy of the Plum Creek interval located in the Virgin Creek Member of the Pierre Shale. Thicknesses shown were measured at an exposure in the Plum Creek drainage SW 1/4 sec. 21, T.4N., R.26 E., southwest of Hayes, South Dakota. Bentonite beds B1, B2, B3, and B4 comprise the Government Draw marker identified by Nichols and others (in press).

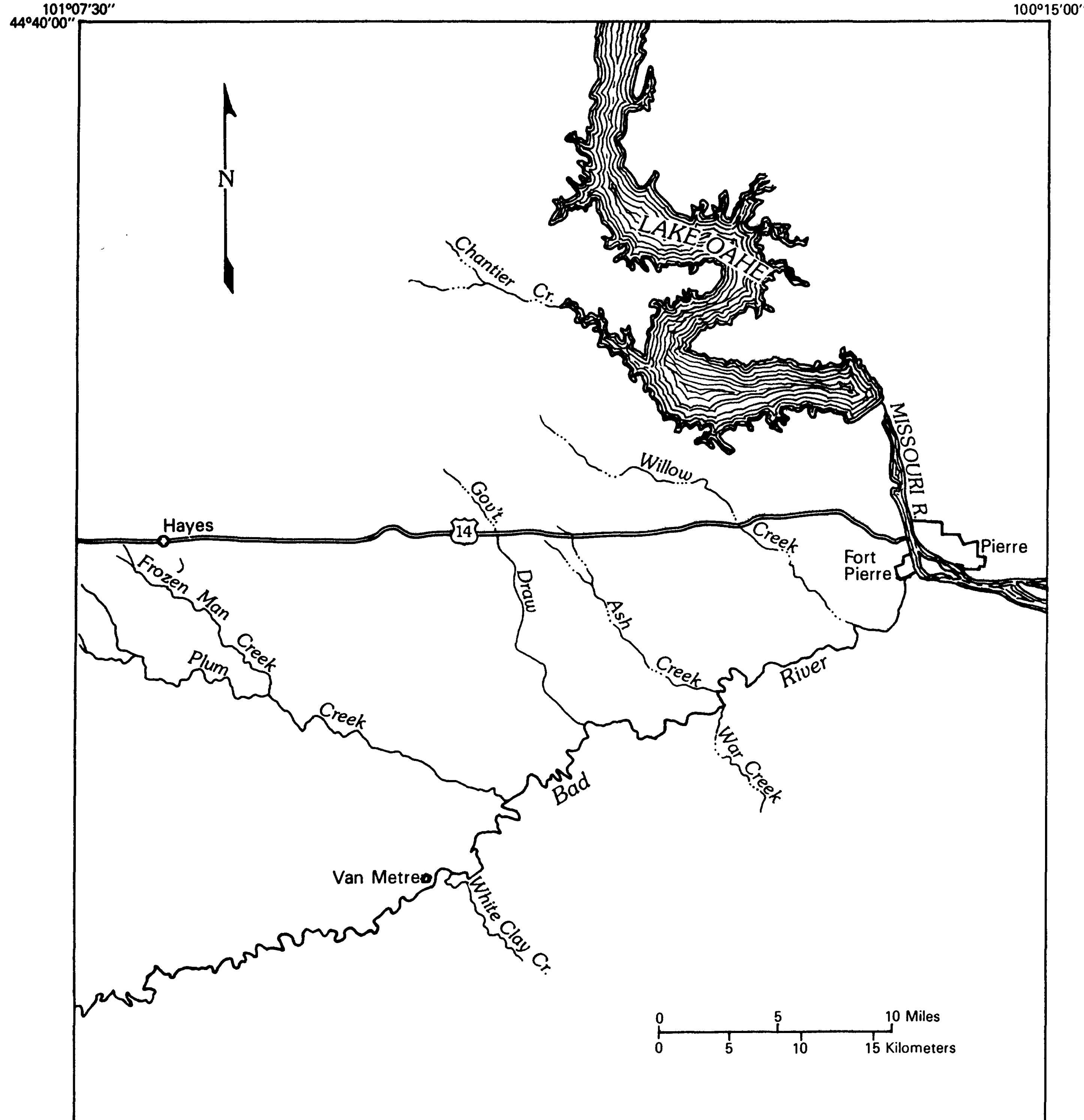

Figure 5.--Map of the study area showing selected physiographic and cultural features.

S1, S2, and S3 are independent of time and can be related to other paleodepositional factors. Isopach mapping of the total Plum Creek interval and the individual bentonite and shale beds that comprise it was undertaken in order to examine thickness changes in these units and the relation of those changes to mapped lineaments within the study area.

METHODS

The extensive near-surface occurence of the Plum Creek interval within the study area provided an opportunity to examine stratigraphic and structural trends along and across the previously discussed lineament areas mapped by Shurr (1979) and Kolm and Peter (1984). This was accomplished by developing isopach maps of the total interval and of the individual bentonite and intervening shale beds as well. Additionally, a structure contour map was developed for the area of the lineaments using the top of the Plum Creek interval (bentonite bed B4, fig. 4) as a datum.

The elevation and thickness of the Plum Creek interval and the thicknesses of the individual beds comprising the interval were determined at outcrop locations along and across lineament areas and at other locations throughout the 600-mi^2 study area. The amount and extent of local thickness variability was first checked by excavating and making preliminary measurements at points several feet to either side of a proposed data-collection site. After measuring strike and dip, the ground was excavated with a shovel to expose 2 or 3 ft laterally of the complete interval at right angles to the dip. Bed thickness measurements were then made with a steel tape measure to the nearest tenth of an inch.

Elevations were first determined by locating the exposed datum on a 1:24,000-scale topographic map and estimating an approximate elevation using map contours (maps with 10 ft, 20 ft, or 5 m contour intervals were used). To check the estimate, a Jacob's staff with Abney level was used to measure the vertical distance from the river, creek, or gully bottom directly up to the top of the exposed datum. If the elevation of a nearby topographic high was given on the topographic map, the vertical distance between the datum and the topographic high was likewise measured. Roads and other easily located cultural features were also used as elevation checks.

Faulting and other features were noted and described and color photos were taken of each exposure as additional documentation and for future reference.

Slope failures that have disturbed the elevation of surface exposures as much as several tens of feet are common in the study area. Crandell (1958) estimated that 75 percent of the material exposed in valley walls of the Missouri and Bad Rivers and their tributaries in the Pierre, South Dakota, area have been moved to some extent by mass-wasting processes, most commonly by a combination of slumping and flowage. Because of the high incidence of slope failure, potential data-collection sites were first examined for evidence of surface instability. Scully (1970) listed surface features indicative of landslides and areas with high landslide potential in the Pierre Shale. These features and others were used to identify areas affected by slope failure. Areas so identified were eliminated as elevation data-collection sites if original undisturbed elevations could not be determined by evidence of stratigaphic displacement.

RESULTS

Isopach maps that cover the eastern part of the study area as well as the lineament areas in the western part are presented in figures 6a through 6h. Figure 6a shows thickness changes for the total Plum Creek interval. Figures 6b through 6h show thickness changes for each of the beds that comprise the Plum Creek interval. Isopach maps of bentonite beds B2 and B4 (figs. 6d and 6h) were constructed, despite their extreme thinness, primarily to show their continuity over the total study area. Remarkably, even these very thin beds show isopach trends similar to those of the thicker beds.

Several observations can be made by inspection of the isopachs presented. There is a general increase in thickness of the beds from northeast to southwest. There also appears to be a fairly abrupt increase in thickness of nearly all of the beds from northeast to southwest across the northwest-trending lineament area, primarily in the northwest corner of the map area. The few data points along the northeast-trending Bad River lineament show no clear trend that can be related to that lineament.

A structure contour map showing the configuration of the Plum Creek interval in the area of the lineaments involved in this study is presented in figure 7. Lineament areas common to Shurr's (1979) and Kolm and Peter's (1984) mapping are superposed for comparison. A drop in elevation of the datum is evident from a high of 1905 ft in the northwest corner to 1750 ft in the southeast corner of the map area. A part of the northwest-trending lineament may have expression in the structural contouring as a northwest-trending trough, as suggested by the structural highs on either side of the lineament. However, due to the limited number of data points, supporting data from within the map area and beyond are needed to verify that tentative interpretation.

Collection of detailed information on faulting and folding was not attempted in this initial phase of the lineament evaluation. However, numerous faults, both normal and reverse, were observed in and near the lineament areas. Vertical components of fault displacements of at least as much as several feet are common. Some larger displacements could not be estimated because of limited exposures. Apparent drag folds and shear zones of unknown extent were observed at outcrops along or near the northwest-trending lineament. Several sudden changes in the stream direction of Plum Creek from southeast to northeast and east, along segments of considerable length, were noted in the vicinity of abrupt sediment thickening along the northwest-trending lineament (figs. 5, and 6a-6h). Such changes in stream direction may be an indication of extensive faulting or other structural control.

DISCUSSION

The isopach maps clearly show an abrupt thickness increase across a portion of the northwest-trending lineament in the study area. Assuming the validity of the lineament-basement-block model, this can be interpreted as additional evidence supporting Shurr's (1979) contention of paleotectonic control of depositional conditions along northwest-trending lineaments prior to deposition of the 68-m.y.-old base of the Mobridge member datum. However, the abrupt thickening of the post-72 m.y.-old and pre-68 m.y.-old Plum Creek interval also suggests the possibility of significant paleotectonic activity along the northwest-trending lineament at a time (post 72 m.y.) of postulated increasing northeast-trending lineament influence.

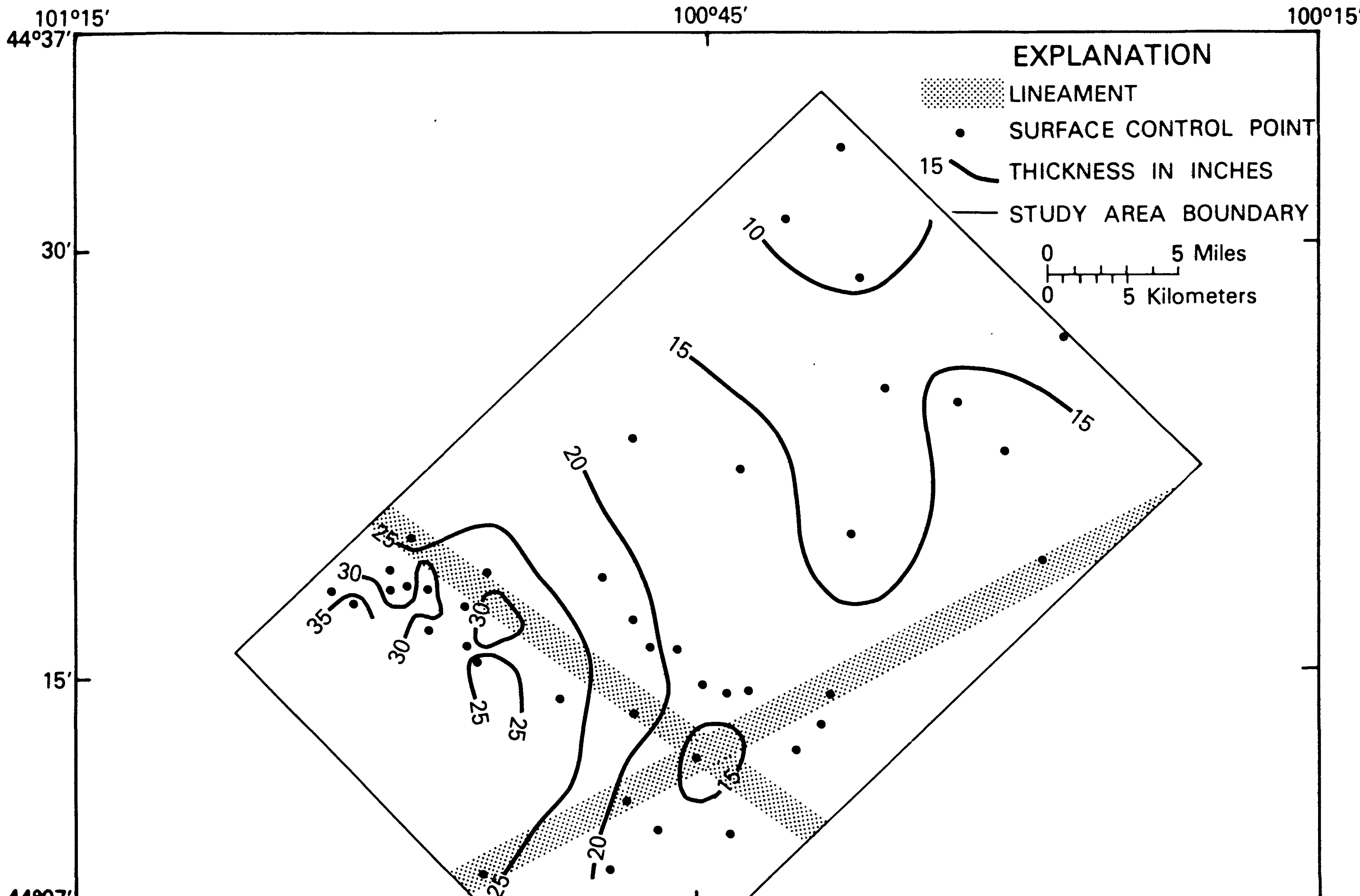

Figure 6a.--Isopach map of thickness of the Plum Creek interval; contour interval is 5 inches.

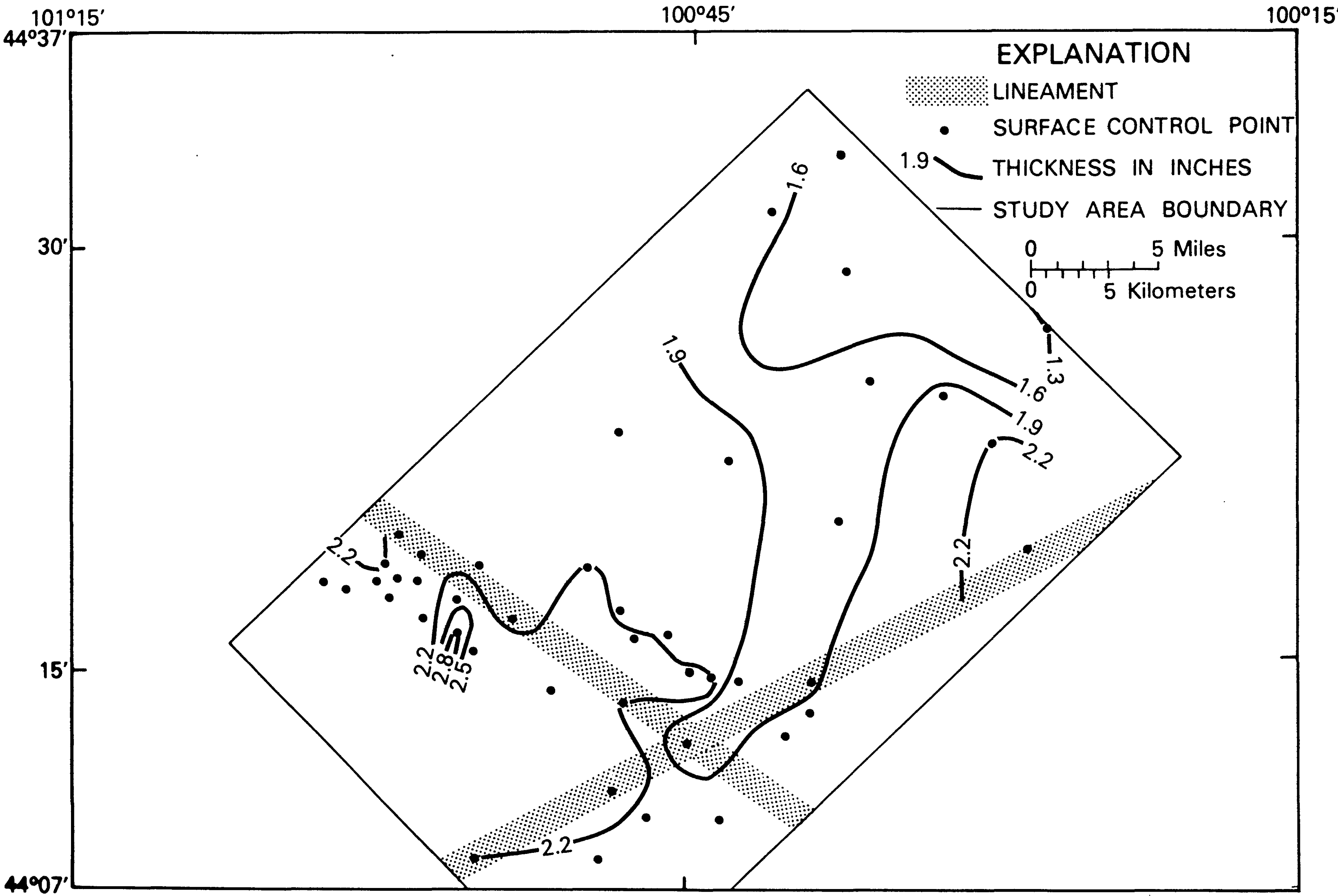

Figure 6b.--Isopach map of thickness of bentonite bed B1; contour interval is 0.3 inches.

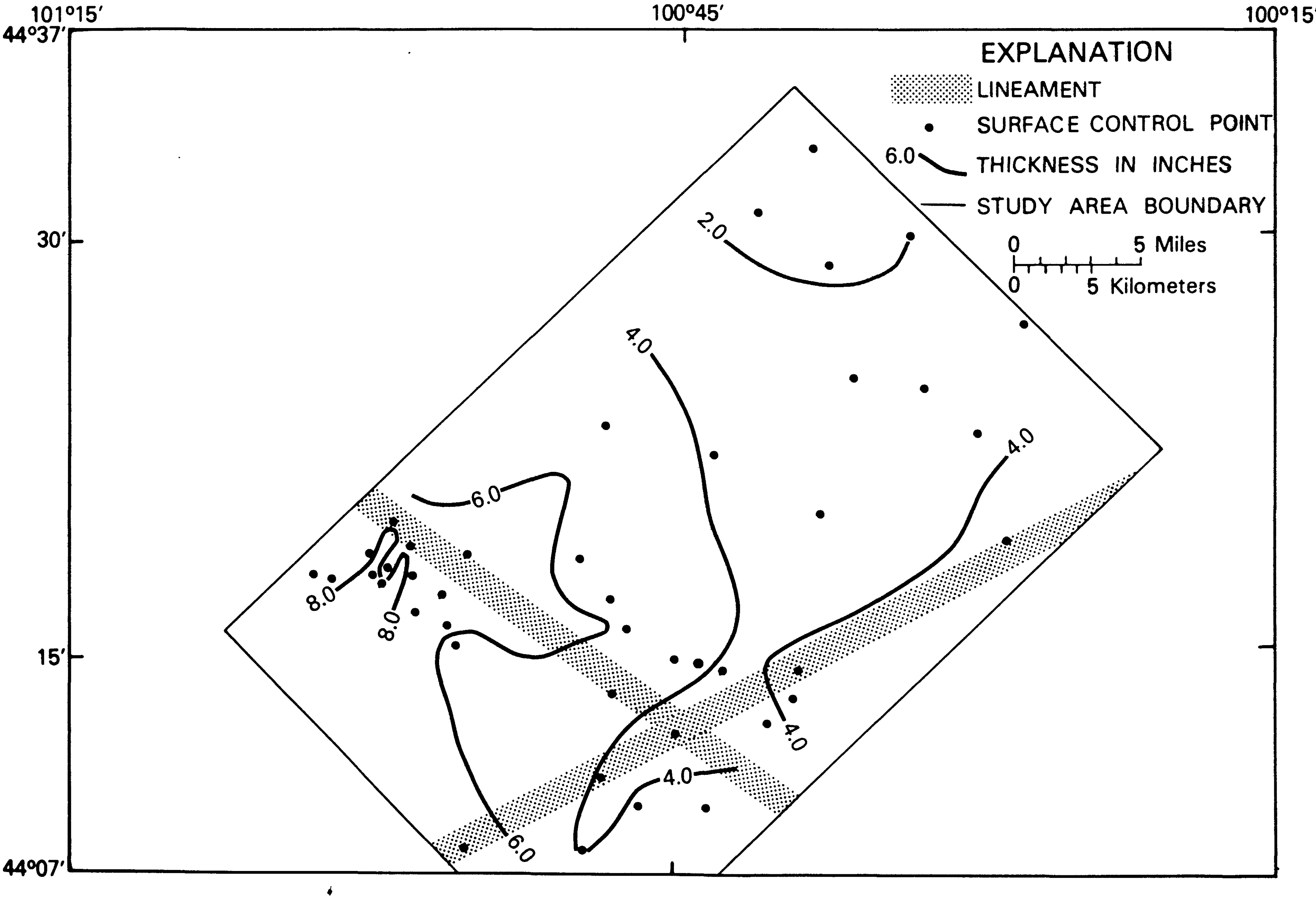

Figure 6c.--Isopach map of thickness of shale bed S1; contour interval is 2.0 inches.

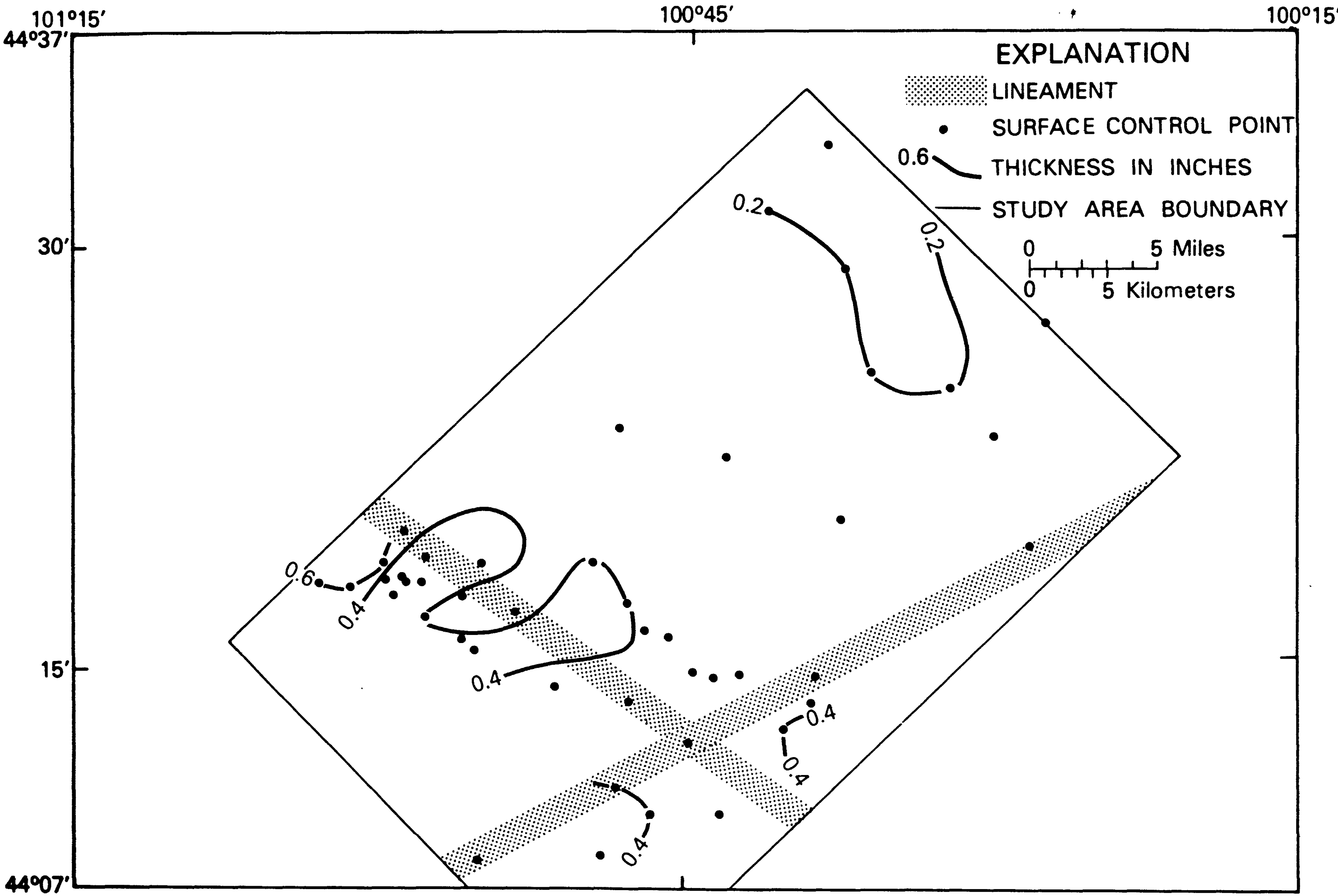

Figure 6d.--Isopach map of thickness of bentonite bed B2; contour interval is 0.2 inches.

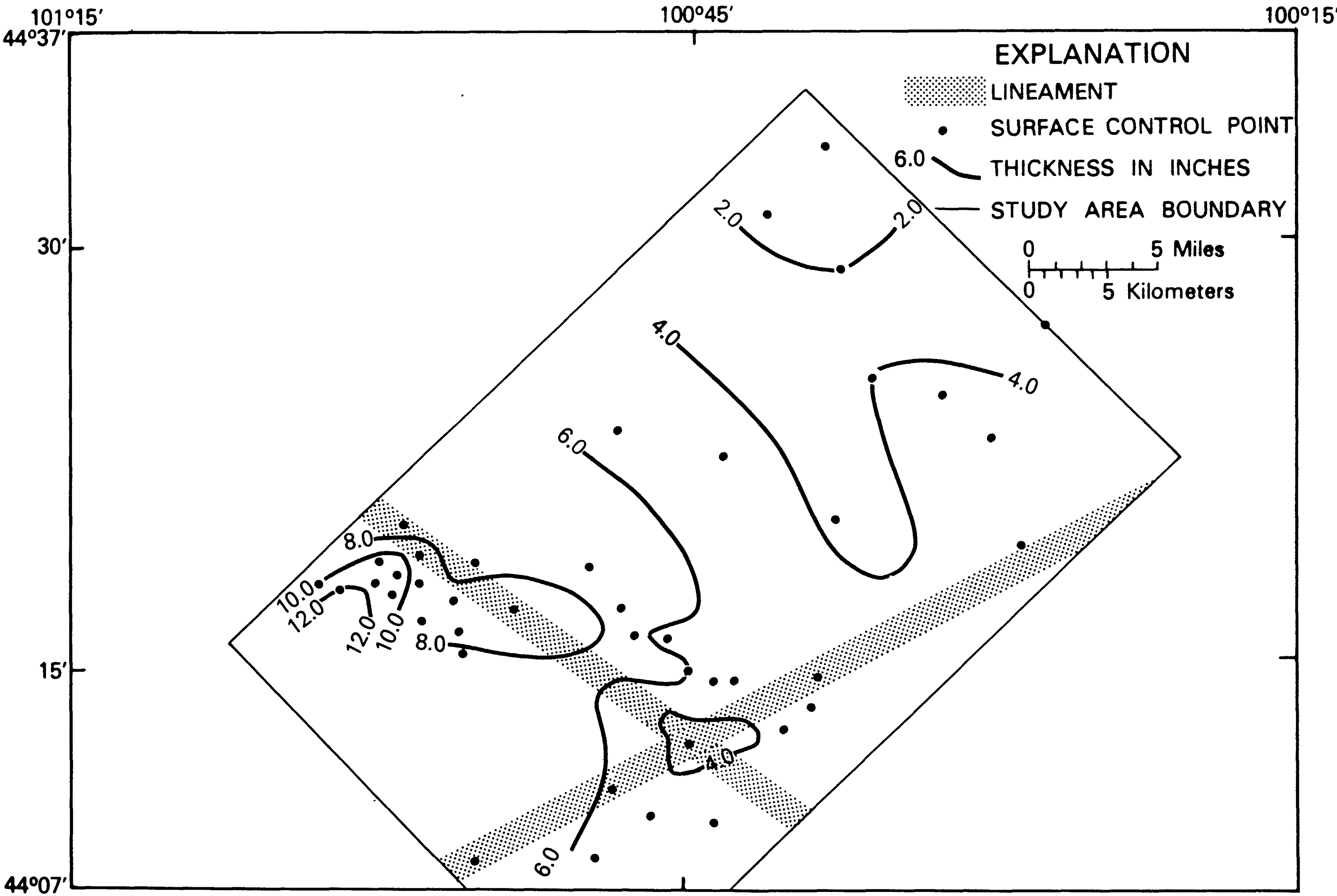

Figure 6e.--Isopach map of thickness of shale bed S2; contour interval is 2.0 inches.

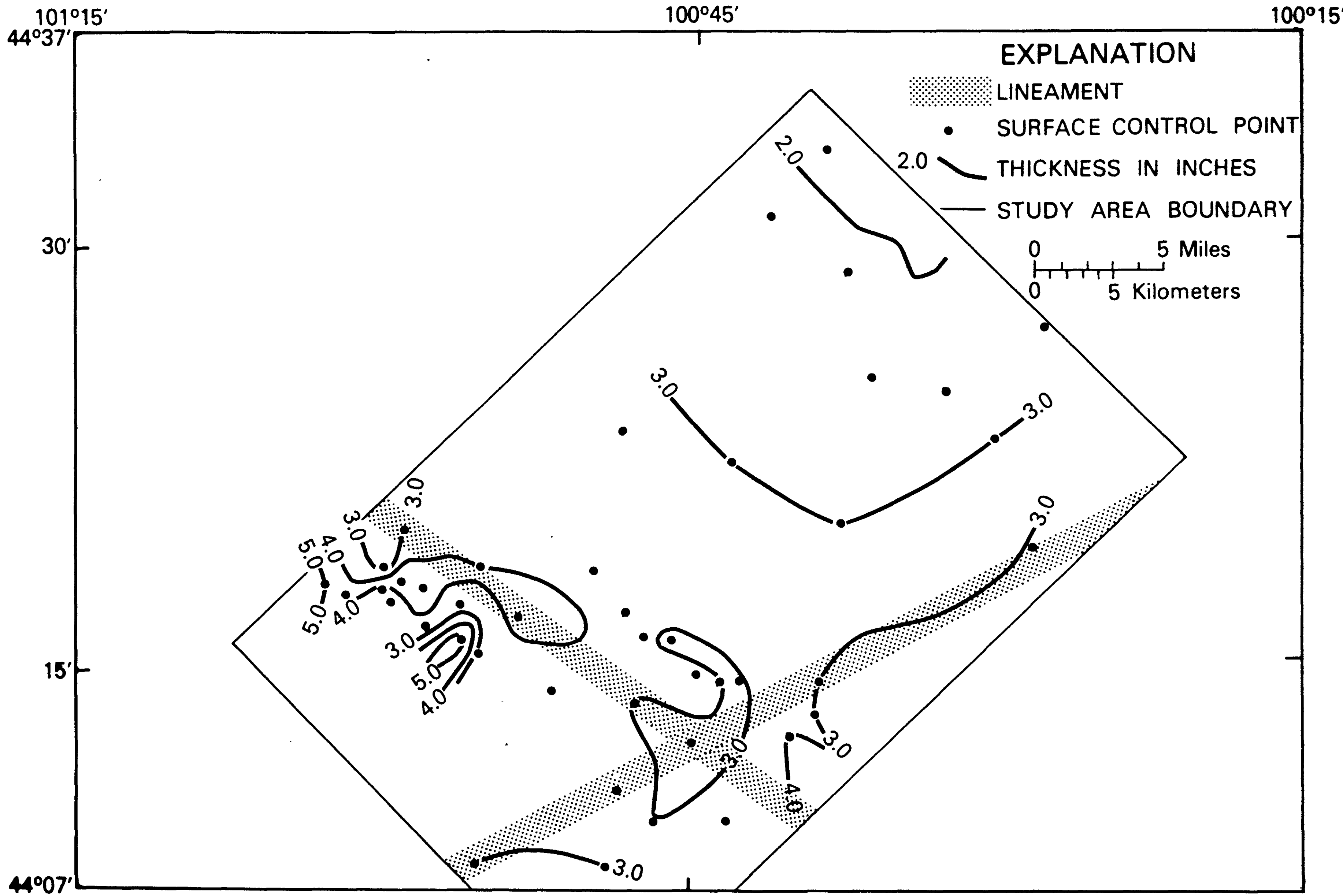

Figure 6f.--Isopach map of thickness of bentonite bed B3; contour interval is 1.0 inches.

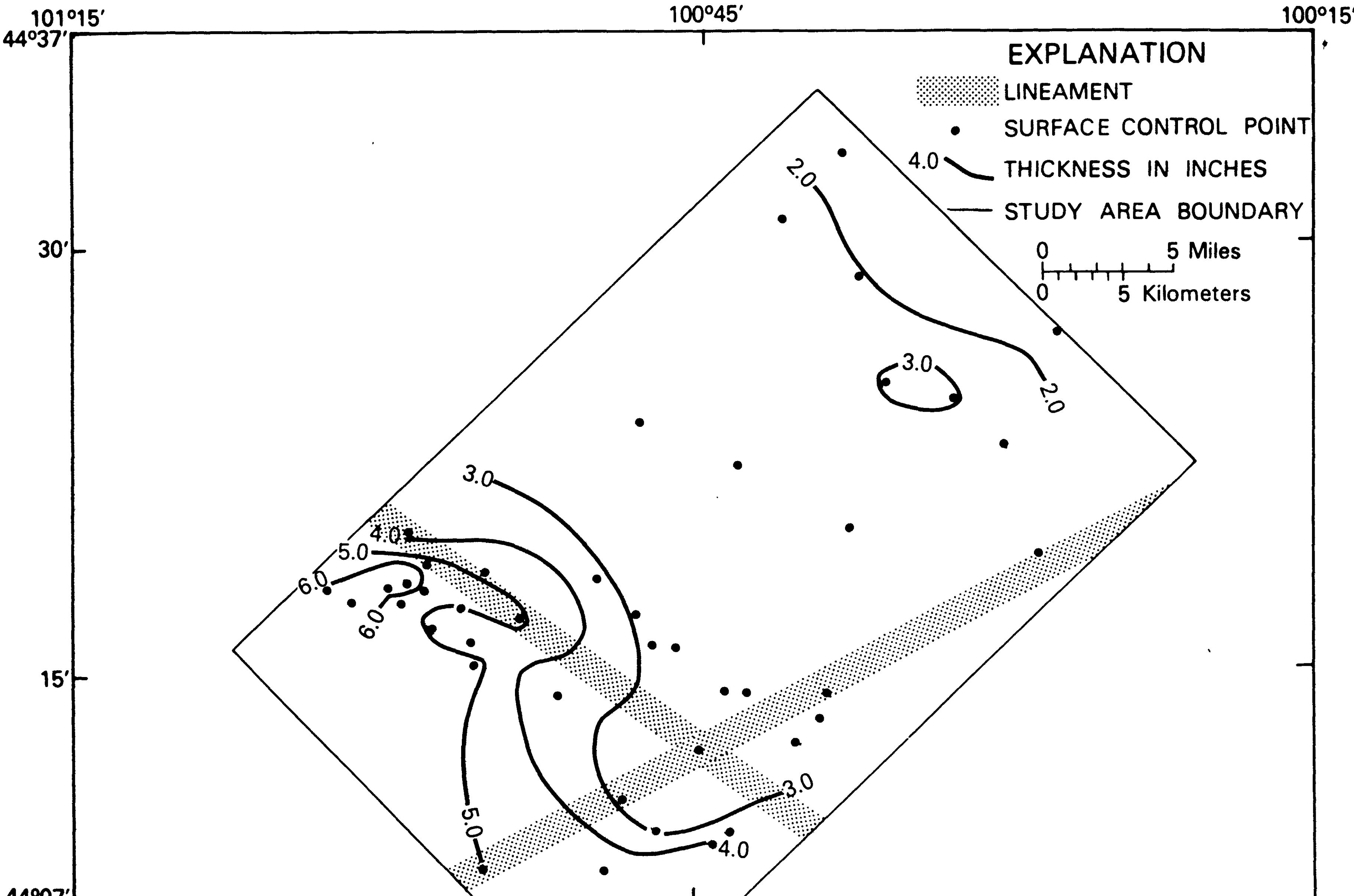

Figure 6g.--Isopach map of thickness of shale bed S3; contour interval is 1.0 inches.

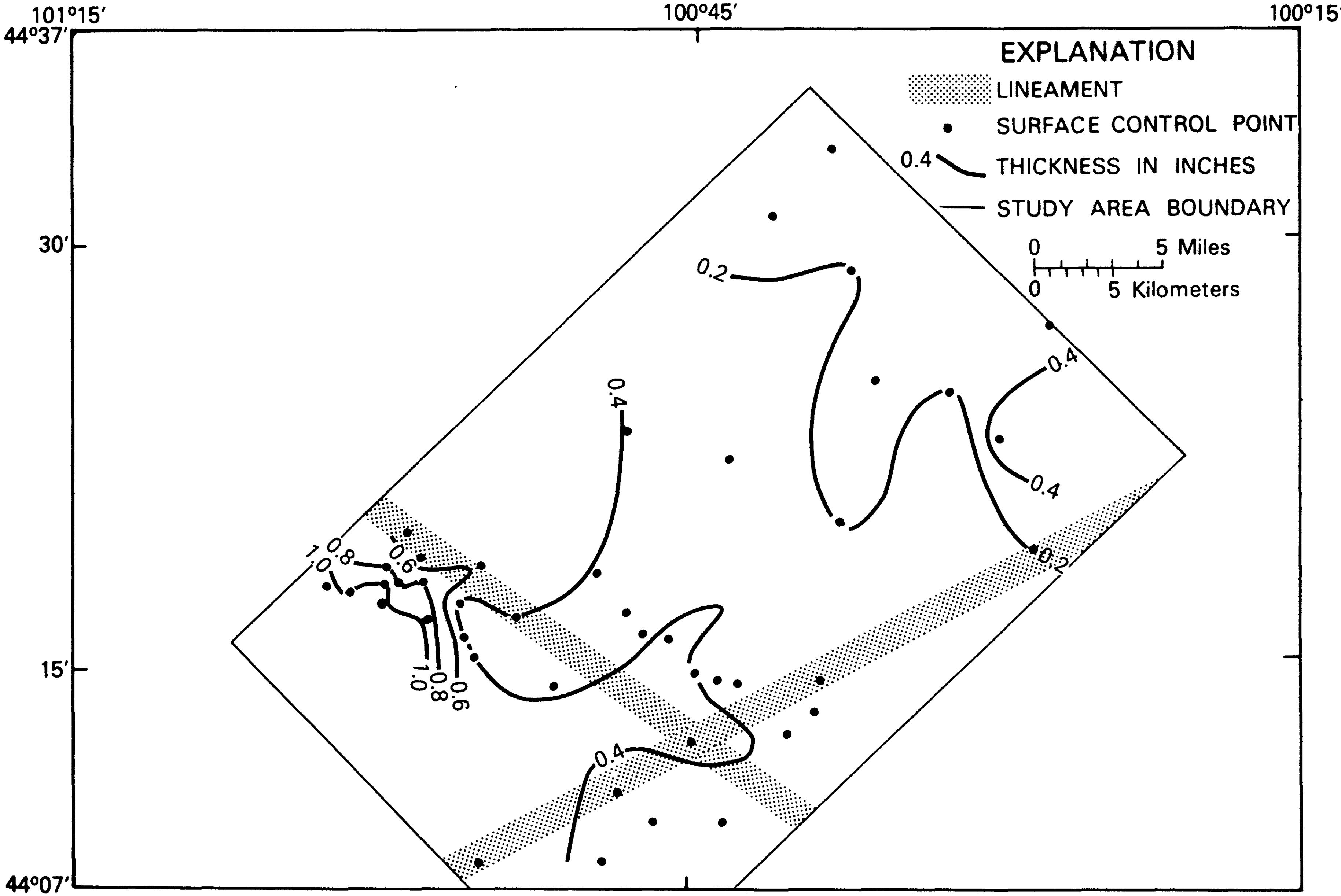

Figure 6h.--Isopach map of thickness of bentonite bed B4; contour interval is 0.2 inches.

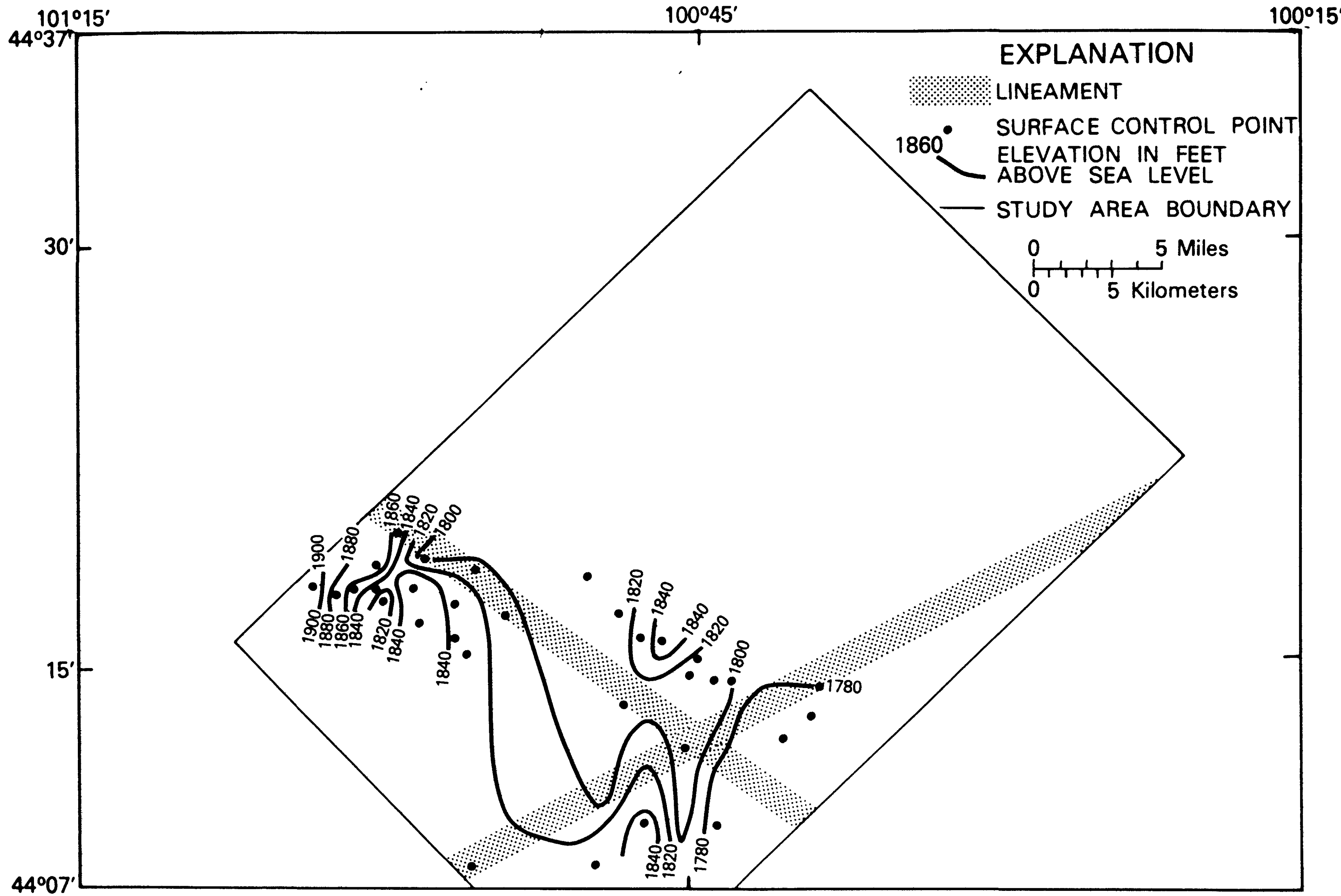

Figure 7.--Structure contour map of bentonite bed B4 (upper bentonite bed of the Government Draw Bentonite Beds group marker and top of the Plum Creek stratigraphic interval). Contour interval is 20 ft.

The Virgin Creek Member of the Pierre Shale, in the area of this study, was deposited in a Late Cretaceous epeiric sea some 200 to 300 mi west of the eastern shoreline (Crandell, 1958). Although the Plum Creek interval is relatively thin (maximum measured thickness in the study area is approximately 29 in.), it may represent as much as 30,000 yrs of deposition (average rate of sedimentation in central South Dakota during the late Cretaceous was approximately 60 to 80 ft per million years (Gill and Cobban, 1973). As pointed out by Shurr (1979), many factors other than topography may influence sedimentation patterns, such as current systems, availability of clastics, and storm frequency. However, the similarity in depositional patterns of the beds in the Plum Creek interval, representing thousands of years of deposition, suggests predominant depositional control by common and continuous long-term factor(s), such as paleotopography. The sharpness of contact and purity of many of the bentonite beds suggests that the original volcanic ash falls settled to the sea bottom rapidly after deposition on the water surface (Crandell, 1958). However, the abrupt thickening of the bentonite beds across a part of the northwest-trending lineament area suggests water transport of the ash.

A comparison of thickness change in shale bed S1 (fig. 6c) to that of shale bed S2 (fig. 6e), across the study area, reveals nearly identical thicknesses and thickness changes from east to west until the northwest-trending lineament area is reached. Interestingly, shale bed S1 (fig. 6c) increases in thickness approximately 25 percent across the lineament, while the stratigraphically higher and younger shale bed S2 (fig. 6e) increases approximately 40 percent in thickness across the same lineament area. The increased thickening of shale bed S2 compared to that of shale bed S1 suggests possible renewed paleotectonic activity along that lineament area prior to or during the deposition of shale bed S2 and after deposition of shale bed S1. In the study area, 45 bentonite beds between 0.1 in. and 9.0 in. thick were counted in the lower part of the Virgin Creek Member, including the four bentonite beds in the Plum Creek interval. Additional stratigraphic and structural studies involving these many potential marker beds may yield important information on the frequency of faulting and may be helpful in reconstructing the tectonic history of that portion of the Late Cretaceous.

The results of this study give direction to possible future work needed to evaluate lineaments as a guide to the distribution of faults and fractures in the Pierre Shale. Additional mapping is needed along and across the northwest-trending and northeast-trending lineaments, within the study area and beyond, to better define structural configurations, isopach trends, and the distribution of fractures. Stream-direction changes along Plum Creek, in the northwest part of the study area, coincident with the northwest-trending lineament and the abrupt thickness increase of the Plum Creek interval, identify it as being in an area where additional study may define important stratigraphic and structural relationships.

CONCLUSIONS

It has been demonstrated in this study that the Government Draw Bentonite Beds stratigraphic marker is a useful near-surface tool for stratigraphic and structural investigations in a 600-mi^2 area of central South Dakota.

Isopach mapping of the Plum Creek interval and the bentonite and shale beds that comprise it provide evidence of an abrupt thickening of those post-72 m.y.-old and pre-68 m.y.-old sediments across a portion of the previously mapped northwest-trending lineament, indicating the lineament may be an important northwest-trending block boundary.

The abrupt thickening of the post-72 m.y.-old and pre-68 m.y.-old sediments across the northwest-trending lineament suggests the possibility of tectonic activity along the northwest-trending lineament after a postulated 72-m.y.-old shift of tectonic activity from northwest- to northeast-trending lineaments.

The bed-thickness changes across the northwest-trending lineament suggest the existence of a paleotopographic low southwest of the lineament and a relative paleotopographic high northeast of the lineament.

Similar sedimentation patterns of the Plum Creek interval beds indicate dominant depositional control by a continuous long-term factor, such as paleotopography. Isopach patterns of the bentonite beds reflect trends similar to those of the shale beds across the study area, revealing a probable common dominant depositional control for both the slowly deposited shale beds and the rapidly deposited, volcanic-ash-derived, bentonite beds.

Abrupt thickening of the volcanic-ash-derived bentonite beds across part of the northwest-trending lineament indicates probable water transport of the volcanic ash after falling to the surface of a contemporaneous Late Cretaceous epeiric sea.

Structure contour mapping on the Plum Creek interval in the lineament areas of this study shows a southeasterly trending reduction in elevation of the datum of about 155 ft. Structural lows are indicated along the northwest trending lineament; however, the data are few and must be considered inconclusive for purposes of detailed structural interpretation. Additional data are needed to better define the structure and faulting in the study area.

REFERENCES

Crandell, D. R., 1958, Geology of the Pierre area, South Dakota: U.S. Geological Survey Professional Paper 307, 83 p.

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

Hattin, D. E., 1965, Stratigraphy of the Graneros Shale (upper Cretaceous) in central Kansas: State Geological Survey of Kansas Bulletin 178, 83 p.

Kolm, K. E., and Peter, K. D., 1984, A possible relation between lineaments and leakage through confining layers in South Dakota: Proceedings of the First C.V. Theis Conference on Geohydrology, p. 121-132.

Nichols, T. C. Jr., Chleborad, A. F., and Collins, D. S., in press, Government Draw Bentonite Beds; a newly identified stratigraphic marker in the Virgin Creek member of the Pierre Shale, central South Dakota.

Scully, John, 1970, Location of areas with high landslide potential in the Pierre Shale: Landslide Studies in South Dakota, Report No. 1, South Dakota Geological Survey, 76 p.

Shurr, G. W., 1978, Paleotectonic controls on Cretaceous sedimentation and potential gas occurences in western South Dakota: Williston Basin Symposium, Montana Geological Society, 24th Annual Conference, p. 283-292.

______1979, Upper Cretaceous tectonic activity of lineaments in western South Dakota: U.S. Geological Survey Open-File Report 79-1374, 23 p.

Slack, P. B., 1981, Paleotectonics and hydrocarbon accumulation, Powder River basin, Wyoming: American Association of Petroleum Geologists Bull., v. 65, no. 4, p. 730-743.

Thomas, G. E., 1974, Lineament-block tectonics--Williston-Blood Creek basin: American Association of Petroleum Geologists Bull., v. 58, no. 7, p. 1305-1322.