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Wayne B. Freisatz

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Fracture-enhanced Porosity and Permeability Trends in the Bakken Formation, Williston Basin, Western North Dakota

by
Wayne B. Freisatz
Bachelor of Arts, Hope College, Holland, Michigan, 1975

A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
in partial fulfillment of the requirements
for the degree of
Master of Science

Grand Forks, North Dakota
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1991
This thesis, submitted by Wayne B. Freisatz in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

(Chairman)

This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

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Department Geology and Geologic Engineering

Degree Master of Science

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To Nancy
ABSTRACT

Fractures play a critical role in oil production from the Bakken Formation (Devonian and Mississippian) in the North Dakota portion of the Williston Basin. The Bakken Formation in the study area is known for its low matrix porosity and permeability, high organic content, thermal maturity, and relative lateral homogeneity. Core analysis has shown the effective porosity and permeability development within the Bakken Formation to be primarily related to fracturing.

In theory, lineaments mapped on the surface reflect the geometry of basement blocks and the zones of fracturing propagated upward from them. Fracturing in the Williston Basin is thought to have occurred along reactivated basement-block boundaries in response to varying tectonic stresses and crustal flexure throughout the Phanerozoic. Landsat-derived lineament maps were examined for the area between 47° and 48° north latitude and 103° and 104° west longitude (northern Billings and Golden Valley Counties, and western McKenzie County, North Dakota) in an attempt to identify large-scale fracture trends. In the absence of major tectonic deformation in the craton, a subtle pattern of fracturing has propagated upward through the sedimentary cover and emerged as linear topographic features visible on these large-scale, remote-sensed images.

The association of Landsat-derived lineaments and fracture density in the subsurface was demonstrated by a statistically significant relation between proximity of wells to lineament traces and the percentage of drill stem test shut-in pressures indicating fracturing. A statistically significant relation was also identified between Bakken thickness and fracture density.
INTRODUCTION

The Bakken Formation (Devonian and Mississippian) of the Williston Basin is part of a widespread depositional complex of organic-rich sediments spanning the North American craton. Its finely laminated black shales have been attributed to deposition in a stratified, inland-equatorial sea, in a low-energy anaerobic environment, during a period of high organic productivity and limited clastic input (Ettensohn and Barron, 1981). The Bakken Formation is a known hydrocarbon source rock and petroleum reservoir (Meissner, 1978; Webster, 1984). The high organic content and burial history of the Bakken determine its hydrocarbon-generating potential. However, the Bakken Formation lacks the degree of rock matrix porosity and permeability common to most petroleum reservoirs. Core analysis of Bakken samples yield average porosities less than 6 percent and permeability of the order of 0.01 millidarcys, for unfractured intervals (Meissner, 1978; Deans, Scherer, and Pulley, 1991). Fracturing of the Bakken has been postulated to account for the fluid storage capacity and drainage network necessary to recover oil from the zone (Meissner, 1978; Hansen and Long, 1991a; LeFever, 1991). This study seeks to identify potential fracture trends in the Bakken Formation, in terms of fracture-density distribution.

The Bakken Formation does not crop out in North Dakota, so direct measurements of fractures and their spatial distributions are not possible. Various sampling techniques and indirect measurements have been employed to decipher fracturing in the Bakken (Meissner, 1978; Hansen and Long, 1991a and 1991b; Sperr, 1991). Cores (including conventional, pressure sleeved, and oriented cores) of the Bakken have been taken by exploration companies to look for fractures and their
orientations. Some natural fractures (as opposed to coring-induced fractures) have been identified in cores from the Bakken. Coring has been employed in other formations to interpret matrix porosity development and distribution through the mapping of lithofacies (e.g. Kent, 1987; Lindsay, 1987). However, discrete sampling of a discontinuous phenomenon, such as fracturing, is more difficult to extrapolate than lithofacies. For similar reasons, the evaluation of geophysical log properties has had limited success in characterizing fracture distribution. Seismic techniques useful in identifying faulting have shown limited success in the Bakken due to the depth of the unit and the apparent lack of vertical offset on the Bakken fractures. The analysis of structural flexure as an indicator of fracture density was proposed by some workers (Murray, 1968; Meissner, 1978). In the areas of Bakken oil production away from the Nesson Anticline fields studied by Murray and Meissner, there is little evidence of sharp structural closure on the Bakken.

A potentially useful tool for investigating fracture orientation and distribution is the identification of fault traces and linear zones of weakness on the ground surface. Many workers have postulated an interconnection between features mapped at the land surface and structures in the subsurface (e.g. Mollard, 1957; Erickson, 1970a, 1970b; Thomas, 1974; Erickson et al., 1975; Shurr, 1978; Brown et al., 1984; Gerhard et al., 1987). Therefore, lineaments and lineament trends identified on Landsat photo-interpretations were investigated as potential guides to fracturing in the subsurface.

A study area was chosen between 47° and 48° north latitude and 103° to 104° west longitude, in western North Dakota, to test the hypothesis that Landsat lineaments delineate zones of increased fracture density in the Bakken Formation (Figure 1). A potential relation between Bakken thickness and fracture density was also explored.
Figure 1. Location of the study area. The outline of the study area is shown in a dashed line on the map of county boundaries.
BACKGROUND

Williston Basin

The Williston Basin is an intracratonic basin spanning at least 345,000 square kilometers (133,000 square miles) (Gerhard et al., 1990) located in portions of North and South Dakota, Montana and the Canadian provinces of Saskatchewan and Manitoba (Figure 2). The approximate geographic center of the basin is near Williston, North Dakota; with a maximum sediment thickness of 4,677 meters (15,340 feet) recorded in a well southeast of Watford City, North Dakota (Gerhard, 1986).

Several mechanisms have been postulated for the formation of the Williston Basin. A left-lateral shear between the Colorado-Wyoming and the Fromberg shear zones was proposed as the mechanism for the formation of the major structures in the basin and perhaps the basin itself (Gerhard et al., 1982). Aulacogen intersection (Shepard, 1991) or extensions (Gerhard et al., 1982) have also been invoked for the nucleation of the Williston Basin. Thermal models for the formation of the basin have been proposed, involving the cooling of a thermal mass emplaced deep in the lithosphere (Ahern and Mrkvicka, 1984). Fowler and Nisbet (1985) modeled basin subsidence with phase transition of a mafic subcrustal body, perhaps derived as a result of the mid-Proterozoic suturing event between the Wyoming and Superior cratons. An assemblage of small Archean and early Proterozoic plate remnants trapped by such a collision make up the basement below the Williston Basin and the adjacent northern Great Plains (Green et al., 1985). For a review and critique of these models see Nisbet and Fowler (1984), Fowler and Nisbet (1985), and Bally (1989).
Figure 2. Location map of the Williston Basin. After Gerhard et al., (1990). Shaded area is the Trans-Hudson orogenic belt of Green et al., (1985).
BAKKEN FORMATION

Type Section

The type section of the Bakken Formation was designated by Nordquist (1953, p. 72) as the "strata occurring between the depths of 9615 - 9720 feet [2930.7 - 2962.7 meters] in the Amerada Petroleum Corporation - H.O. Bakken No. 1 well SW 1/4 NW 1/4 sec. 12, T. 157 N., R. 95 W., Williams County, North Dakota" (Kume, 1963). Nordquist defined the Bakken Formation from cuttings and electric logs, as the Bakken Formation was not known to crop out. The Bakken Formation as proposed by Nordquist consisted of two black shales rich in organic material (the informal lower and upper Bakken shale members) enclosing a siltstone and silty carbonate (the informal middle Bakken member). The three informal members of the Bakken Formation show an apparent onlapping relation, with the lower shale the least extensive and the middle member and upper shale distributed in successively wider areas. Kume (1963) proposed a standard reference section for the Bakken Formation in the Socony Vacuum Oil Company - C. Dvorak No. 1 well (Figure 3), in the southeast quarter of the northeast quarter of section 6, Township 141 North, Range 94 West, Dunn County, North Dakota, between 10,035' and 10,095' [3058.7 - 3077 meters]. Kume presumably chose the section in the Dvorak No. 1 well as the reference section for the Bakken for its continuous core extending from the lower Lodgepole Formation through the Bakken and Three Forks Formations into the Birdbear Formation.
Figure 3. Bakken type section, Kume (1963).
Members

The lower Bakken shale in the study area is black (N1 of Goddard et al., 1948) to dark gray brown (SYR 4/1), organic-rich (11.3 average weight percent organic carbon, Webster, 1984) moderately hard, slightly-to non-calcareous, finely laminated, sub-fissile, with disseminated fine pyrite and occasional nodular pyrite, scattered quartz grains, and lacks significant visual (in hand specimen or under 10X binocular magnification) porosity or permeability except for fractures. Core-derived porosity averages less than 6 percent with permeability in the 0.01 to 0.2 millidarcy range (Meissner, 1978; Deans, Scherer and Pulley, 1991). Fracturing, where observed in core samples, ranges between 70 and 90 degrees from horizontal and may or may not be calcite-lined or cemented. Unfortunately, great difficulty exists in differentiating natural fractures lacking cement or lining mineralization from coring-induced fractures (or those weaknesses or breaks in the cored material that resulted from the mechanics of taking the core sample).

The middle Bakken member ranges from calcareously cemented siltstones, shales and silty-carbonates in the northeastern corner of the study area to slightly silty carbonates in the southwest. The middle member is variable in color depending on the percentages of argillaceous material, quartz, pyrite and organic material present, but is generally highly cemented with calcite or dolomite (Huber, 1986). Sedimentary structures in the middle member indicate a much higher-energy depositional environment than the enclosing shale members. Cores of the middle member contain examples of cross-bedding, ripple marks, scour-and-fill features, organic burrowing, and soft-sediment deformation. Thrasher (1987) subdivided the middle Bakken into three informal units based on lithologic variations and faunal content. These informal subdivisions are more easily discernable in the central basin and their lithologic identity becomes blurred toward the southwestern margin of the basin (and the study area). Although some matrix porosity
exists in the middle member lithologies, it is low (less than 6 percent) due to the effects of compaction and the high degree of carbonate cementation.

The upper shale of the Bakken is lithologically similar to the lower shale member. As with the lower shale, organic material is distributed throughout the shale rather than concentrated in laminae (Webster, 1982). The conchoidal breakage pattern observed in fresh core material from both the lower and upper shale is probably due to the degree of induration and the presence of detrital silica.

The three members of the Bakken Formation all occur within the study area. The basal Bakken black shale member is the least extensive. The middle member silty carbonates and carbonates onlap the lower shale and are slightly more extensive in their areal distribution. The upper Bakken black shale onlaps the middle member and is the most widespread unit of the Bakken Formation.

Underlying Unit

The Bakken Formation is everywhere underlain by the Three Forks Formation, which is Late Devonian in age. The Three Forks Formation reaches a maximum thickness of 81 meters (265 feet) in the present study area (east and south of the Nesson Anticline, Dumonceaux, 1984). In the area of the present study the thickness of the Three Forks ranges between 7.6 and 81.7 meters (25 - 268 feet). The Three Forks Formation consists of thinly interbedded gray-green and brick-red shales and dolomudstones, buff to gray dolostones, light gray to light brown dolomitic sandstones and siltstones, and scattered anhydrite. Dumonceaux (1984) recognized five lithofacies within the Three Forks based on varying sedimentary structures, lithologic composition, and fossil biota. The distribution of these lithofacies was attributed to migration of a series of depositional bands, concentric with the basin outline, as a result of fluctuating sea levels. Environments ranged from
supralittoral through littoral to low-energy sublittoral for deposition of the Three Forks. An occasional sandstone at the top of the Three Forks Formation, mainly along the eastern Nesson anticline, has been informally designated the "Sanish sand". The "Sanish sand" may contain effective matrix porosity and permeability in the limited area where the unit is developed (Meissner, 1978). The Three Forks-Bakken contact has been considered conformable in the central portion of the Williston Basin, but is an angular unconformity near the basin margins (Dumonceaux, 1984; Webster, 1984).

Overlying Unit

The Bakken Formation is conformably overlain by the Lodgepole Formation of the Madison Group (Mississippian). The Lodgepole consists of up to 275 meters (900 feet) of medium-gray to medium-brown limestone, which may be fragmental or fossiliferous or both, with occasional argillaceous intervals. The lower Lodgepole represents the continuation of the major transgressive event begun during Bakken time. The facies identified in the Lodgepole indicate a return to normal marine circulation in the Williston Basin following the restricted circulation or strong stratification of the Bakken sea. Lithofacies patterns indicate a regressive phase beginning with middle Lodgepole deposition (Heck, 1978).

Bakken Thickness

Bakken thickness in the study area reaches a maximum (28 meters or 93 feet) near the northeast corner of the area and thins to a feather edge in the southwest (Figure 4). The lower shale member exhibits the most regular isopach pattern, with a maximum thickness (8-9 meters or 29 feet) in an elongate area bordering the western margin of the Nesson Anticline (Figure 5). The lower shale thins rapidly away from its depocenter and reaches a feather edge slightly more than halfway across
Figure 4. Contour map of Bakken thickness in study area (contour interval = 2 meters). Study area in dashed outline and well control shown with dot symbols. A portion of the township - range grid shown overlapping the study area for reference.
Figure 5. Isopach map of thickness lower shale member (contour interval = 1 meter).
the study area. The isopachs of the middle Bakken show a less well-defined depocenter for this member within the study area, with a general thinning of the member from the northeast to the southwest (Figure 6). An elongate thin in the middle member extends from the northwest corner into the center of the study area. The edge of the middle member is difficult to locate precisely where remnants of the middle member directly overlie similar lithologies of the Three Forks Formation. The upper shale is the most extensive member of the Bakken both in the study area and in the Williston Basin as a whole. The upper shale reaches a maximum thickness in the study area of just over seven meters (23 feet), south of the Nesson Anticline. The upper shale generally thins toward the southwest and reaches a feather edge in Golden Valley County in the southwestern corner of the study area (Figure 7).

Source Rock Potential

The Bakken Formation is a known petroleum source rock that occurs over a wide area in the basin (Murray, 1968; Dow, 1974; Meissner, 1978; Webster, 1982; Schmoker, 1990). Bakken oils have been classified as "Type II" (Williams, 1974) generated by oil-prone, sapropelic, fatty, lipid-rich organic material of probable marine origin (Webster, 1982, 1984). The results of geochemical tests performed on samples of the Bakken Formation show a very rich organic content (average weight percent total organic carbon 11.3), consisting of predominantly amorphous kerogen attributed to marine planktonic algae or phytoplankton (Webster, 1984). The onset of hydrocarbon generation was calculated from the geochemical data to have begun at an average burial depth of 2,740 meters (9,000 feet) (Webster, 1982, 1984; Price et al., 1984; Price et al., 1986). Webster (1982, 1984) estimated the beginning of oil generation at 75 million years BP (Late Cretaceous), at a temperature of about 100° C. Initial expulsion of the oil from the Bakken source was postulated to have occurred at 70 million years BP.
Figure 6. Isopach map of thickness middle member (contour interval = 2 meters)
Figure 7. Isopach map of thickness upper shale member (contour interval = 1 meter)
The presence of micro-fractures and hence micro-porosity and permeability in the organic-rich Bakken shales within the area of thermal maturity has been suggested by Meissner (1978, 1991), LeFever (1991), Carlisle (1991), Druyff (1991), and others. The development of these micro-fractures is a consequence of the effect of pore fluid pressure on the effective stress in a rock. Increased pore fluid pressure in a material with a relatively small differential stress can lead to tension (extension) fracturing (Hubert and Rubey, 1959; Meissner, 1978). Elevated pore pressures in the Bakken shales are in part due to the conversion of organic material that supports the overburden to non-overburden-supporting hydrocarbons. There is also a volumetric increase inherent in the conversion of kerogen to hydrocarbons plus residue (Meissner, 1978; Webster, 1982, 1984). These elevated pore fluid pressures are trapped in the Bakken due to the relatively impermeable underlying Three Forks and overlying Lodgepole Formations.

The presence of the oil generation fractures in the Bakken of the study area is assumed, based on the interpretation of thermal maturity for hydrocarbon generation by Webster (1984), and the distribution of total organic carbon by Webster (1982, 1984). Webster’s results in the area of the present study do not indicate significant variability of either of these two parameters. Therefore, the effects of the oil-generation fracturing are taken as relatively constant for the study area.

The oil-generation fractures do provide some reservoir storage and transmissibility to the Bakken, but macroscopic and megascopic fractures interconnecting the microfracture network seem to be required for commercial fluid recovery (LeFever, 1991; Druyff, 1991; Sperr, 1991). In the tectonically quiescent Williston Basin, subtle indications of the
movements of deeply buried basement blocks may offer one of the few clues to the localization of macroscopic fracturing in the subsurface.
FRACTURES

Fracture is "a general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress" (Bates and Jackson, 1980, p. 244). Fractures can be readily identified in outcrops or mine exposures as faults, joints, or cracks. In the subsurface, fracturing may be observed indirectly in cuttings samples, or cores, or their presence may be inferred by geophysical methods or reservoir engineering (modeling).

Examples of fractured reservoirs or fracture-enhanced reservoir performance are known from around the world. For reviews of fractured petroleum reservoirs see Nelson (1985, Appendix A), Aguilera (1980, chapters 1, 5 and 8), and Kostura and Ravenscroft (1977). The impact of fractures on aquifers is discussed by Kolm and Peter (1983), Neuzil, Bredenhoeft and Wolff (1983), and Peter et al. (1988). Geothermal reservoirs with significant fracture-controlled permeability have been identified in California (Brophy, 1984).

In areas where the strata under investigation (or overlying rock layers) may be examined directly, fracture density and fracture orientations may be mapped and quantified. However, when dealing with formations that do not crop out, more indirect methods are needed to identify and characterize fracturing. One such method is lineament analysis of aerial photographs or satellite images.

Linear Features

In a paper evaluating the use of lineaments as guides to ore deposits Gilluly (1976, p. 1512) stated, "It is hardly too much to say that nature abhors straight lines—they are local and very rare on the
continents . . . ." Yet the use of high-altitude photography and satellite imagery has led many workers to recognize the apparent linear alignment of a wide range of features on the surface of the earth. Even before photographic coverage of large areas of the earth's surface was available, linear patterns and alignments were noted and interpreted by geologists. These linear features range from highly subjective tonal boundaries on photo images to undeniable scarps formed by fault displacement. Of particular interest to this discussion are those features that can be related to structural or tectonic origins and might be expected to have some continued physical expression beneath the land surface.

Terminology

Although terms involved in describing linear arrangements or features on the surface of the earth have been used in geologic literature, they have not been used consistently. The term "lineament" was coined by W. H. Hobbs to describe the reasonably straight alignment of topographic features such as "(1) crests of ridges or boundaries of elevated areas, (2) the drainage lines, (3) coast lines, and (4) boundary lines of formations of petrographic rock types, or of lines of outcrops" (Hobbs, 1904, p. 485). Hobbs later expanded the scope of "lineament" to include "ravines or valleys and visible lines of fractures or zones of fault breccia" (Hobbs, 1912, p. 227). The term "linear" was used as a noun to refer to individual lineaments by Sonder (1938). In Sonder's terminology, lineaments are regional trends composed of individual contiguous features, or linears (Dennis, 1972). The use of "lineal" as a replacement for the adjectival form of linear was proposed (Gross, 1951), but has not received wide acceptance. The definition of "lineation" was perhaps best stated by Cloos (1946, p. 1) when he said, "Lineation is a descriptive and non-genetic term for any kind of linear structure within or on a rock. It includes striae on
slickensides, fold axes, flow lines, stretching, elongate pebbles or ooids, wrinkles, streaks, intersection of planes, linear parallelism or minerals or components, or any other kind of linear structure of megascopic, microscopic, or regional dimensions." The various meanings and uses of the above-mentioned terms, describing linear features, were discussed in a paper by O'Leary et al. (1975). In their paper they proposed that the following definitions be adopted:

**Lineament** "is a mappable, simple or composite linear feature of a surface, where parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns or adjacent features and presumably reflects a subsurface phenomenon."

**Linear** "is an adjective that describes the linelike character of some object or objects."

**Lineation** "is the one-dimensional structural alignment of internal components of a rock, is imposed by external agents, and cannot be depicted as an individual feature on a map" (O'Leary et al., 1975, p. 1467).

Following the definitions of O'Leary et al., lineaments in this discussion are restricted to features of mappable scale, that are structurally formed or controlled. Lineament would therefore have a genetic connotation. Under this classification linear features known or assumed to be formed by glacial, eolian or other non-structurally controlled processes could not be considered lineaments. "Linear" is reserved as an adjective, to describe linelike appearance. "Lineation" is used only as a petrographic textural term. These restrictions should
help avoid the confusion of the overlapping or synonymous use of the words by some authors.

Lineaments

The use of linear features to show the structural fabric of the underlying "basement" has been proposed by many workers. Hobbs, in his early work in New England, used lineaments as indicators of "the hidden architecture of the rock Basement" (Hobbs, 1912, p. 227). Other workers also made note of the apparent structural significance of geomorphic lineaments in and on the crust of the earth. The existence of a world-wide system of fractures in basement rocks was discussed by Vening Meinesz (1947) and Sonder (1947). Sonder coined the term "regmatic fracture system" for this apparent phenomenon. To explain the existence of a global fracture system, several models of fracture generation were proposed. Polar wandering, with its associated area of polar flattening, was proposed by Vening Meinesz (1947) as a possible cause to torsional fracturing of the crust. Through this mechanism a "regmatic fracture system" would be produced, by the crustal response to the change in the shape (curvature) of the crust as the pole migrated. Paleomagnetic evidence supports the idea of polar shift (real or apparent, due to plate tectonics). Another postulated mechanism for production of a global fracture pattern was the force of the rotation of the earth on its axis. The flattening of the earth, by a north-south compression due to centrifugal force, would produce a set of north-south tensional and east-west compressional zones of weakness, as well as northwest-southeast and northeast-southwest shears. These zones of weakness would have been propagated throughout planetary history. The existence of such a fracture pattern was substantiated by observations of the moon and other planets (Katterfeld and Charushin, 1970). Possible variations in the rotational velocity of the earth were cited
by Stokyo (1932, 1936) and Esclangon (1932) to account for world-wide lineament patterns.

The effects of lunar tides on the crust of the earth have also been employed to explain the existence of a world-wide fracture system. Lunar effects can be subdivided into two components, the effect of the moon on the earth's crust when the earth and moon were much closer to each other (4.5 billion years before present, Kuiper, 1960), and the effects of the moon's elliptical orbit around the earth (Fielder, 1961). These mechanisms are primarily designed to explain the generation of a relatively homogeneous tectonic fabric for all the earth's crust, early in its history. This initial "regmatic fracture system" would then be rejuvenated and propagated into newer crustal material by subsequent stresses, both tectonic and tidal (terrestrial tides). New fracture systems, not related to the original "regmatic fracture system", could be generated under the influence of younger stress fields. It should be noted that stress can be relieved in the crust along pre-existing zones of weakness, even though not ideally oriented, more easily than new fractures can be generated in that stress field. That is, every tectonic stress (great enough to produce plastic or brittle deformation) does not necessarily produce a unique set of folds and fractures, oriented according to the rules of material strain. Rather than generating new fractures, the stress may be relieved along planes of weakness generated under previous stress environments.

"Wrench-fault Tectonics"

One of the most frequently cited explanations for lineaments is based on the "wrench-fault tectonics" of Moody and Hill (1956). The basic tenet of this model is that lineaments mark basement zones of weakness, developed as conjugate shear fractures during Precambrian orogenics. These shear fractures developed as a result of "pure shear" resulting first in two first-order wrench-fault patterns. After
movement on these first-order shears (lineaments), continued application of stress would cause reorientation of the stress field in the adjoining blocks to produce second-order shears. By the same mechanism a third-order system would develop. Duplication of the shearing directions would start to occur at the third-order and beyond, thereby restricting the system to eight major shear directions (Figure 8). Maxwell and Wise (1958) considered the possibility of simple-shear (translation and rotational components) as the means by which wrench faults are activated. Saunders et al. (1973) felt that lineaments represented the boundaries of fundamental crustal blocks, which move past each other in response to changing tectonic stresses. This movement would produce secondary shearing, drag folds, and tension fracturing within the blocks as they moved along the primary shears represented by the lineaments. The angular relationship between the primary and secondary shears would depend on the intensity of the stress (increasing stress - decreasing angle between primary and secondary features).

"Tectonic Heredity"

"Tectonic heredity" was coined by Wise (1964) to describe a set of directions (or orientations) of preferential weakness in the rocks of a region. Wise described eight recurring fracture directions in the basement rocks of Wyoming and Montana. These orientations were interpreted to be "set" into basement rocks soon after crustal solidification (Wise 1968), and subsequently reactivated by successive tectonic events. Evidence for the fundamental existence of the patterns of weakness was demonstrated by the apparent continuity of lineaments passing through differing tectonic provinces and deformational regions. The orientation of the pattern does not appear to vary when passing from the plains to the mountains (e.g., into the Black Hills from the South Dakota prairie, Shurr, 1982, or from the Atlantic coastal plains into the Appalachians, Gathright, 1981).
Figure 8. Theoretical shear directions. Modified after Badgley (1965, p. 250). Shown are the shear directions that develop in a homogeneous, isotropic material under simple, north-south compression. Directions duplicate beyond the third order, giving rise to only eight unique, shear-plane orientations.
State of Stress of the Crust

The alignment of the current stress field may be useful in the assessment of lineaments as indicators of fracturing and fracture-enhanced permeability. If lineaments represent movement in the sedimentary cover along pre-existing zones of weakness (in response to the stress field), we may be able to discriminate between lineament (fracture) orientations that should be in compression and those in tension. The current stress field in the northern Great Plains has been analyzed through the study of wellbore breakouts and hydraulic fracturing-stress measurements (Bell and Gough, 1979; Bell and Babcock, 1986; Zoback and Zoback, 1989). A wellbore breakout is a measured asymmetry in the shape of a normally circular, subsurface, drill hole. The hole elongation is attributed to the effect of differential horizontal stresses, with the elongation direction normal to the maximum horizontal stress direction. The maximum, horizontal, compressive-stress axis for the northern Great Plains is oriented between northeast and east. This orientation is characteristic of a large "midplate" stress province common to most of the central and eastern United States, Canada, and possibly the western Atlantic Basin (Zoback and Zoback, 1989). The stress field (Figure 9) has been tied to the relative motion of the North American plate. Considering this current stress field, Anna (1986a) proposed that lineaments oriented northeast-southwest and east-west would be tensional, therefore enhancing secondary (fracture) porosity and permeability. Northwest-southeast and north-south lineaments would be in compression and probably would not contribute to porosity and permeability enhancement. It should be noted that most of the data used to characterize the state of stress in the Williston Basin has been extrapolated into the area from the adjacent provinces of Canada. Narr and Burruss (1984) in a study of Mission Canyon Formation (Mississippian) fractures in the Little Knife Field (on the eastern side of the present study area) relied on hydrofracturing
Figure 9. Midcontinent stress field of North America. After Stauffer and Gendzwill (1987, p. 1093). Short decorated lines refer to maximum horizontal stress direction. Lines with square from Zoback and Zoback (1989); with circle after Fordjor et al. (1983) and Gought et al. (1983); diamond from Holst (1982); and arrows from Stauffer and Gendzwill (1987). Data not shown for areas outside of midcontinent region.
data from near Regina, Saskatchewan, to delineate stress orientation. Hydrofracturing studies estimate the principal stress field by observation of man-made fractures produced by high pressure fluid injection into an unfractured subsurface bed. The hydrofracturing data from near Regina suggested an east-west maximum horizontal stress.

Previous Studies using Lineaments

The use of linear features identified on the land surface in aerial photographs, or in later satellite images, to delineate zones of buried structure has more than a 30-year history in the Williston Basin and the adjacent northern Great Plains. Although ascribed with varying degrees of confidence, the connection between subsurface and even crystalline basement, zones of weakness and their postulated surface expression has been made by many workers. Early studies employed aerial photographs or aerial photograph mosaics to analyze linear features (Kupsch, 1957; Mollard, 1957; Nelson, 1958; Johnson, 1960; Haites, 1960; Hamen, 1961, 1964; Erickson, 1970a and 1970b). Kupsch (1957, p.66) stated, "Some structures are reflected at the surface through thousands of feet of sediment." Some of these early workers considered that the location and orientation of some glacial features may be related to underlying bedrock structures, through preferential control on ice movements and localization of linear disintegration ridges in the continental ice sheet and meltwater channels (Kupsch, 1957; Haites, 1960). Haman (1961) discussed potential effects on zones of basement weakness by post-glacial isostatic rebound. The association between mapped lineaments in the Interior Plains of western Canada and the "world wide regmatic shear pattern" was considered by Haites (1960) and Haman (1961). Haites also regarded the lineaments (or transcurrent faults) as preferential pathways for fluid migration in the subsurface. Johnson (1960) considered the possibility of lineaments controlling (or delineating the zone of) deposition of reservoir-bounding anhydrites in
Burke County, North Dakota oil fields. Both Johnson (1960) and Haman (1961, 1964) mapped lineament density and orientation to identify areas of enhanced fracture development. Erickson (1970a, 1970b) concluded the Nesson Anticline was the result of wrench fault displacement of a pre-existing Precambrian feature. Lineaments were considered the surface expressions of the basement-cored shear zones. The lineaments were also identified as bounding or terminating the extent of petroleum accumulations within the basin. Embracing the idea of "The New Basement Tectonics," Gay (1972, 1973) compiled examples of photo-geologic and aeromagnetic lineaments and discussed their significance in terms of a pervasive, orthogonal, fracture pattern in the crust of the earth. Thomas (1974) proposed a simple shear model for the formation of major structural features in the Williston Basin, as well as for localization of petroleum reservoirs. The predominant lineament trends through the Williston Basin were identified (northeast-southwest, northwest-southeast, north-south, and east-west) and ascribed to zones of weakness in the Precambrian basement that defined discrete basement blocks. Compressive stresses promote adjustment along these pre-existing zones of weakness and deformation in the overlying sediments coupled to the blocks.

With the beginning of availability of satellite imagery in the mid 1970's, identification of linear patterns proliferated. A cautionary note was already being sounded by Hoppin (1974) due to the confusion generated by inconsistent use of "lineament" terminology and the general use of lineaments as a panacea for all structural interpretation. Erickson et al. (1975) used satellite photos to identify lineaments, tonal boundaries and "hazy areas" that they then related to petroleum accumulations. They concluded that lineaments and tonal anomalies successfully delineated two out of the four oil accumulations in the test. Paleotectonic controls on sedimentation in the Cretaceous of northern Great Plains were explored by Shurr (1978, 1981, 1982; Slack,
1981; Shurr and Rice, 1986; Anna, 1986a and 1986b). In these studies, detailed stratigraphic mapping pointed out basement block structural control on depositional bathymetry and hence on facies and sediment-thickness distribution. Lineament geometries mapped from Landsat images were seen to bound lithofacies and isopach patterns, indicating a genetic relationship between the lineaments, paleotectonics, and depositional environments. Lineaments may reflect zones of weakness propagated up through the sedimentary cover from basement block boundaries. These basement features may result in multiple lineaments or a swarm of fractures (Figure 10), not necessarily single discrete "faults" (Shurr, 1982). Studies have found similar links between paleotectonics and sedimentation patterns in Paleozoic units (Brown, 1978; Weimer, 1980; Slack, 1981; Brown et al. 1984; Downey, 1984; Maughan and Perry, 1986). Shurr also postulated that lineament-defined, basement-block boundaries act as loci for enhanced reservoir fracturing. Lineaments have been used to identify prospective areas for gas exploration in the Devonian shales of the Appalachian Basin (Wheeler, 1980; Gathright, 1981). One method employed by Gathright was to examine the percentage of productive gas wells as compared to proximity to the nearest lineament trace. The relationship between lineaments and interformational fracture communication (leakage) was considered by Kolm and Peter (1983) and Neuzil, Bredehoeft, and Wolff (1983) for South Dakota and Downey et al. (1987) for North Dakota. Such leakage would have effect on hydraulic conductivity properties used for modeling of potentiometric surfaces, hydrochemistry, and geothermal gradients in the region. Cooley (1986) used lineaments along with recognized structures and gravity anomalies to delineate areas of enhanced fracture permeability in the northern Great Plains. Cooley's study was the culmination of a series of Landsat-derived lineament maps made for the states in the region (distributed as U.S. Geological Survey Open File Reports: Cooley, 1983a, 1983b, 1983c, 1983d).
Figure 10. Lineaments and basement block boundaries (Shurr and Rice, 1986, p. 196)
A left-lateral shear system, as a result of tear faulting in the western margin of the Late Precambrian North American craton (Figure 11), was postulated to control the development of structures in the Central Rocky Mountains and adjacent northern Great Plains (Gerhard et al., 1982). The major lineament trends of the Colorado-Wyoming Lineament and the Brockton-Froid-Fromberg Lineament delineate this master fault couple. Renewed movement or "tensing" of this couple was said to have led to the development of the folding and faulting in the Phanerozoic sediments through mobilization of pre-existing basement-block boundaries.
Figure 11. Shear couple in relation to the Williston Basin, (Gerhard et al. 1987, p. 339).
METHODS

Study Area

The present study is concentrated between 47° and 48° north latitude and 103° and 104° west longitude. This one-by-one degree area includes most of northern Billings and Golden Valley Counties, western and central McKenzie County, and a small portion of western Dunn County, all in North Dakota. This area was chosen for testing the thesis for the following reasons: (1) the Bakken Formation occurs throughout most of the area (except for a small region in southern Golden Valley County); (2) the Bakken Formation in the area ranges in thickness from a feather edge to 28 meters; (3) the area was chosen to exclude the Nesson Anticline, with its Sanish Sand member in the upper Three Forks Formation; (4) most of the area is covered with a single Landsat image; and (5) well control is good throughout the area.

Lineament Maps

Landsat-derived lineament data were gathered for the study area. An initial test of the thesis was performed using a lineament map for North Dakota (Cooley, 1983a). The lineaments from Cooley's map were digitized into AutoCAD® (Autodesk, 1987), a computer-aided drafting program. The AutoCAD® program permits data entry on multiple "layers" with a common coordinate system. The use of "layers" was especially suitable for this project. Separate "layers" were created for the various types of information relating to the study area forming in effect, a GIS (Geographic Information System). "Layers" were overlain to show the spatial relationships between various data sets. "Layers" were created for: (1) the latitude – longitude outline of the study
area; (2) the township - range grid overlapping the study area; (3) locations of wells with their identification numbers; (4) lineaments derived from Landsat images (with subset groupings on separate "layers" according to lineament length and orientation); (5) labeling information; (6) structure contours on critical subsurface horizons; (7) isopach contours of the total Bakken and of each member of the Bakken; (8) drill stem test pressures; and (9) postings of the values used to generate the contoured data. The AutoCAD® program also allowed for extraction of the precise location (in the user-defined coordinate system) of all elements of the drawing file. This information was manipulated in external computer programs, with processed results reinserted into the drawing file (and then into the drawing).

Following the test of thesis methods using the Cooley lineament map, it was decided a more rigorously derived Landsat interpretation would be beneficial to the reliability of the study. Although the Cooley data were generally useful, certain biases in his interpretation limited application to this study. Among the problems perceived in the Cooley map were: (1) investigator bias against north-south or east-west linear features (or orientations near those directions); (2) the manual or visual inspection method of lineament interpretation (drawing operator perceived lineaments on a Landsat composite photograph) rather than an unbiased computer manipulation of the raw data (using a computer to search for lineaments among the pixels that make up the Landsat image); (3) the small scale (large areal coverage) of Cooley's investigation; and (4) Cooley's inexperience (by his own estimation) in Landsat interpretation (Cooley, 1983a, and Cooley, personal communication).

A second Landsat interpretation of the study area was obtained from IntraSearch (1990). This interpretation was commercially processed by a national remote-sensing lab by experienced photo-interpreters. The Landsat imagery used was Multi-Spectral Scanner (MSS) scale 1:250,000.
dated 1976 and 1977. The linear features were picked from computergenerated and computer-enhanced, three-band (bands 4 - yellow, 0.5-0.6 micrometers; 5 - red, 0.6-0.7 micrometers; and 7 - infrared, 0.8-1.1 micrometers), false-color composites (color ratio plots, blue for MSS band 4, green for MSS band 5, and red for MSS band 7). The Landsat data was chosen from spring (May 2, 1976 and May 5, 1977) and fall (September 23, 1976) images, with low sun angles and no cloud cover. Only the interpreted maps were received for this study; no raw data or composite photographs were acquired due to the prohibitive cost.

The IntraSearch Landsat interpretation was received already digitized into an AutoCAD®-compatible drawing file. The interpreters classified the linear elements into two groups based on the continuity and length of the features. These were portrayed (Figure 12) on separate AutoCAD® "layers" and with different line symbols. The coordinates of the mapped lineaments were extracted from the AutoCAD® drawing file and analyzed for length, azimuth, and areal distribution. The IntraSearch Landsat lineament data were received oriented and plotted in the state plane coordinate system (North Dakota North Zone). The coordinate information for the individual straight line segments that defined the lineaments were extracted and recorded in a computer file for later processing with the well data.

Well Data

Detailed information was gathered from the files of the North Dakota Geological Survey and the North Dakota Industrial Commission Oil and Gas Division on all Bakken Formation penetrations in (and near) the study area. A total of 1056 wells that penetrated the Bakken in the study area were identified. Wells with deviated well-bores or wells lacking electric logs were not used in the generation of structure contour or isopach maps. Therefore, the contour and isopach evaluations were made with between 1032 and 1053 data points. The latitude -
Figure 12. Lineament map. Data plotted from Intrasearch (1990), using their subset designations: heavy line symbols for "mega" lineaments; single width line symbols for "minor" lineaments.
longitude coordinates for the wells were converted to the state plane coordinate system for overlaying with the lineament data in the AutoCAD® drawing. A program was written to insert the well data with identifying permit numbers into an AutoCAD® drawing "layer".

The data points collected for each well penetrating the Bakken in the study area included: (1) detailed location information: latitude - longitude, township, range, section, quarter-quarter-quarter section, footages from the section lines, and calculated state plane coordinates; (2) operator and well name; (3) kelly bushing elevation; (4) North Dakota Geological Survey and API (American Petroleum Institute) well identification numbers; (5) wellbore deviation information; (6) subsea elevations for the tops of the Bakken, its members, and the underlying Three Forks Formation; (7) thicknesses for the Bakken, its members and the underlying Three Forks Formation; and (8) the number and results of any drill stem tests (DSTs) that were performed over the Bakken. A computer data base was created and maintained to record and manipulate the data points for each well in the study area. Well data was posted in AutoCAD® and contoured with Quicksurf® (Schreiber Instruments, 1989) a gridding and contouring module designed to work within the AutoCAD® environment (Figure 13).

Data Analysis

Computer programs were written to analyze the distribution of the Landsat lineaments and any spatial relations between the compiled well data and the Landsat lineaments. The distributions of lineament lengths, lineament azimuths, and lineament lengths and azimuths for subsets of the data were recorded, plotted as histograms, and examined.

The spatial distribution of Landsat lineaments was examined and the resulting statistical parameters were compared to theoretical values for a random pattern of lines. The tests were performed following the methods outlined in Davis (1986). The length (l) of each lineament, the
Figure 13. Contour map on top of Bakken Formation (contour interval = 25 meters). Well control shown with dot symbols.
number of lineaments \( (n) \), and the total area \( (A) \) in the study were extracted from the AutoCad\textsuperscript{®} drawing. A line density parameter \( (\lambda) \) was calculated using:

\[
(1) \quad \text{line density } \lambda = \frac{\Sigma l}{A}
\]

A mean nearest-neighbor distance was computed for each lineament in the study area. This value was calculated by choosing a random point on each lineament and computing the perpendicular distance from all other lineaments to this point. The shortest distance between the point and another lineament was recorded as the nearest-neighbor distance for that lineament. The average nearest-neighbor distance for all the lineaments in the study was computed:

\[
(2) \quad \text{mean nearest-neighbor distance } = \overline{d}
\]

An expected-mean nearest-neighbor distance, expected variance, and standard error were calculated using the constants derived by Dacey (1967).

\[
(3) \quad \text{expected nearest-neighbor distance } = \overline{d} = \frac{0.31831}{\lambda}
\]

\[
(4) \quad \text{expected variance } \sigma^2 = \frac{0.10132}{\lambda^2}
\]

\[
(5) \quad \text{standard error } S_o = \sqrt{\frac{\sigma^2}{n}}
\]

From these values a Z statistic was calculated to test the significance of the difference between the expected and observed average nearest-neighbor distance. The level of significance for the test was chosen as 95 percent, yielding a critical value of ±1.96. If the calculated Z value was larger than the upper critical value or smaller than the lower critical value the observed distribution of lineaments varied significantly from a random pattern of lines of the same line density.
The Z statistic was calculated by:

\[ Z = \frac{\bar{d} - \delta}{S_0} \]  

A nearest-neighbor index (R) was calculated using the ratio of the observed to the expected mean nearest-neighbor distance.

\[ R = \frac{\bar{d}}{\delta} \]

The index (ranging from 0.0 to a maximum of 2.15) characterizes the spatial pattern of the lines. An index value of zero indicates coincident lines, 1.0 represents a random spacing of lines, and values approaching the maximum (2.15) indicate maximized mean nearest-neighbor distances (a regular patterned distribution).

The central test of the thesis was performed to find any correlation between the proximity of wells to Landsat lineaments and the percentage of wells exhibiting signs of fractures. Among the various data values collected, the one deemed most suitable as an indicator of natural fracturing was the drill stem test (DST), maximum shut-in pressure. The reasons for choosing the maximum drill stem test shut-in pressure as a measure of fracturing include: (1) the large number of DSTs performed on the Bakken in the study area (214); (2) the wide distribution of these DSTs across the study area; (3) the relative similarity (and therefore comparability) of DST techniques as applied to the Bakken; (4) DSTs are generally taken immediately following Bakken penetration, while drilling and before any artificial stimulation or completion has been attempted; and (5) the DST shut-in pressures value as an indication of the Bakken's ability to transmit pressure to the wellbore (hence an indication of the Bakken's permeability).

For each well with a Bakken DST the nearest-neighbor lineament was identified and the perpendicular distance between the lineament and the well, the orientation of the lineament, the bearing from the well to the
lineament, along with the DST maximum shut-in pressure were tabulated. The DST maximum shut-in pressures were examined and classified as low pressure (< 10 MPa) or high pressure (> 10 MPa). The percentages of high pressure DST shut-ins (y) within each neighbor distance class (x) were determined and plotted. The corrected sum of the squares and cross-products were computed and these values were used in the calculation of a correlation coefficient (r). The significance of the correlation coefficient was investigated with the Student's t test. A least-squares regression line was fitted to the well data to highlight the relation between the variables. The appropriateness of the regression line characterization of the data was tested by checking the goodness-of-fit (R^2) of the line to the data points and an ANOVA (ANalysis Of VAriance) of the regression versus the original data.
RESULTS

Lineament Data

The distribution of lineament lengths and azimuths were examined for the IntraSearch LandSat map. The map was received plotted in the North Dakota North Zone State Plain coordinate system, which is scaled in feet. The lineament lengths and the map area were converted to metric units using standard conversion factors. IntraSearch subdivided the lineaments in their interpretation into two arbitrary classifications designated "mega" and "minor". This distinction was based on the relative length and continuity of the individual lineaments. A summary of the line properties is given below in Table 1.

<table>
<thead>
<tr>
<th>Group</th>
<th>No. of lines</th>
<th>Max. (ft.)</th>
<th>Max. (m.)</th>
<th>Min. (ft.)</th>
<th>Min. (m.)</th>
<th>Avg. (m.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>1090</td>
<td>77,825</td>
<td>23,721</td>
<td>1,120</td>
<td>341</td>
<td>4,248</td>
</tr>
<tr>
<td>Mega</td>
<td>346</td>
<td>77,825</td>
<td>23,721</td>
<td>2,477</td>
<td>755</td>
<td>8,303</td>
</tr>
<tr>
<td>Minor</td>
<td>744</td>
<td>21,045</td>
<td>6,414</td>
<td>1,120</td>
<td>341</td>
<td>2,362</td>
</tr>
</tbody>
</table>

Histograms of the distributions of lengths for all lineaments, the "mega" lineaments, and the "minor" lineaments are given in Figures 14, 15, and 16, respectively.

The distributions of lineament azimuths for all lineaments, "mega" lineaments, and "minor" lineaments are given in Figures 17, 18, and 19, respectively. Because lineaments have orientation but not direction, all lineaments were projected into the north half of a compass circle (270°-360° and 0°-90°).
Figure 14. Frequency plot of all lineament lengths. Classes are 2 kilometer groupings (e.g., 2 kilometer bar represents the number of lineaments from zero to 2 kilometers in length).
Figure 15. Frequency plot of "mega" lineament lengths. Classes are 2 kilometer groupings (e.g., 2 kilometer bar represents the number of "mega" lineaments from zero to 2 kilometers in length).
Figure 16. Frequency plot of "minor" lineament lengths. Classes are 2 kilometer groupings (e.g., 2 kilometer bar represents the number of "minor" lineaments from zero to 2 kilometers in length).
Figure 17. Azimuth distribution of all lineaments. Azimuth classes are 15 degree groupings (e.g., the 285 bar represents the number of lineaments with azimuths between 270 and 285 degrees).
Figure 18. Azimuth distribution of "mega" lineaments. Azimuth classes are 15 degree groupings (e.g., the 285 bar represents the number of "mega" lineaments with azimuths between 270 and 285 degrees).
Figure 19. Azimuth distribution of "minor" lineaments. Azimuth classes are 15 degree groupings (e.g., the 285 bar represents the number of "minor" lineaments with azimuths between 270 and 285 degrees).
The frequency plots of the azimuths of all lineaments used in the study show three dominant directions. The most pronounced maximum was observed in the lineaments with orientation between 300 and 330 degrees. This node was observed in both the total lineament plot as well as the plots of "mega" and "minor" populations separately. A second clustering of lineament azimuths occurred near the north-south orientation (330 to 15 degrees). This peak was predominantly due to the influence of "minor" lineaments. A third, more diffuse, peak in azimuth frequency was observed from 45 to 75 degrees. This maximum was most apparent in the histogram of "mega" lineaments.

A statistical appraisal of the IntraSearch lineament map was made comparing the line distribution to a random pattern at the same line density. The total area of the lineament map was calculated at 10,960 square kilometers. The sum of the length of the 1,090 lineaments in the study area was found to be 4,630,606.26 meters, yielding a line density \( \lambda \) of 0.00042 meters per square meter. The mean nearest-neighbor distance for the lineaments within the study area was 1,439.5 meters. The expected nearest-neighbor distance for a random pattern of lines with the same line density would be 753.5 meters, with an expected variance of 567,696.6 and a standard error of 22.8. A 95 percent level of significance was chosen for the test of similarity between the map mean nearest-neighbor distance and the expected nearest-neighbor distance for a random pattern of lines. The critical values for the two-tailed test at 95 percent significance were \( \pm 1.96 \). The calculated \( Z \) statistic was 30.1; therefore, the IntraSearch lineament pattern varied significantly from a random distribution of lines. The nearest-neighbor index for the study area lineaments was 1.9, indicating a relatively ordered or structured arrangement of lines.
Well Data

A total of 1,056 wells penetrated the Bakken Formation in the study area. The distribution of these wells is shown in Figure 20. In the study area 214 wells had drill stem test (DST) results from the Bakken. Only mechanically successful tests with valid reservoir shut-in pressures were considered. The Bakken DSTs are plotted in Figure 21, with the size of the circle marking the DST location proportional to the magnitude of the maximum shut-in pressure. A histogram of the DST results grouped according to the maximum shut-in pressures is given in Figure 22. The 10 MPa level of shut-in pressure was chosen as the cut-off point between low pressure (less fractured) and high pressure (more fractured) Bakken Formation. Of the 214 DSTs considered 128 had maximum shut-in pressures in excess of 10 MPa.

A potential relation between thickness and fracture density was investigated for the Bakken in the study area. The dependence of fracture spacing on bed thickness has been well documented in the literature (Narr and Lerche, 1984; Nolen-Hoeksema and Howard, 1987; Narr, 1991). For the 193 wells in the study area with both DST and Bakken thickness data, the maximum shut-in pressures and thicknesses were compiled. The percentage of wells with shut-in pressures in excess of 10 MPa was calculated for a series of Bakken thickness ranges. These results are plotted in Figure 23, along with the regression line calculated through the data points. The data used in Figure 23 are summarized in Table 2, with the ANOVA of the regression shown in Table 3.
Figure 20. Bakken penetrations in study area (well control).
Figure 21. Bakken drill stem tests (DSTs) in study area. The diameter of the symbol is proportional to the magnitude of the maximum shut-in pressure.
Figure 22. DSTs grouped by maximum shut-in pressure. Maximum shut-in pressure classes are 5 MPa groups (e.g., the 5 MPa bar represents the number of wells with DST maximum shut-in pressures between zero and 5 MPa). The 128 wells with maximum shut-in pressures over 10 MPa represent "fractured" Bakken.
Figure 23. Bakken thickness versus percentage shut-in pressure >10 MPa. The Bakken thickness classes are 2 meter groupings (e.g., the 2 meter thickness point represents the percentage of wells with greater than zero and less than or equal to 2 meters of Bakken thickness that have DST maximum shut-in pressures over 10 MPa)
Table 2.--Bakken Thickness versus Maximum Shut-in Pressure > 10 MPa

<table>
<thead>
<tr>
<th>x^2</th>
<th>x</th>
<th>xy</th>
<th>y</th>
<th>y^2</th>
<th>ȳ</th>
<th>ȳ^2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td>78.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>171.4</td>
<td>85.7</td>
<td>7344.5</td>
<td>74.1</td>
<td>5492</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>230.4</td>
<td>57.6</td>
<td>3317.8</td>
<td>69.4</td>
<td>4820</td>
</tr>
<tr>
<td>36</td>
<td>6</td>
<td>346.2</td>
<td>57.7</td>
<td>3329.3</td>
<td>64.7</td>
<td>4191</td>
</tr>
<tr>
<td>64</td>
<td>8</td>
<td>517.6</td>
<td>64.7</td>
<td>4186.1</td>
<td>60</td>
<td>3606</td>
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<td>100</td>
<td>10</td>
<td>579</td>
<td>57.9</td>
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<td>55.4</td>
<td>3065</td>
</tr>
<tr>
<td>144</td>
<td>12</td>
<td>576</td>
<td>48</td>
<td>2304</td>
<td>50.7</td>
<td>2568</td>
</tr>
<tr>
<td>196</td>
<td>14</td>
<td>700</td>
<td>50</td>
<td>2500</td>
<td>46</td>
<td>2114</td>
</tr>
<tr>
<td>256</td>
<td>16</td>
<td>640</td>
<td>40</td>
<td>1600</td>
<td>41.3</td>
<td>1705</td>
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<tr>
<td>Σ</td>
<td>816</td>
<td>72</td>
<td>3760</td>
<td>4616</td>
<td>27934</td>
<td>27560</td>
</tr>
</tbody>
</table>

x = Bakken total thickness (m)
y = percentage wells with maximum DST shut-in pressures >10 MPa
r = correlation coefficient = -0.84274
t = t test for the significance of r = -3.83475
[t critical at 95 percent significance level = ±2.365]

B₀ = y-intercept of regression line = 78.8
B₁ = slope of regression line = -2.34405
R² = goodness of fit of regression line = 0.710219

Table 3.--ANOVA for Thickness versus Percentage Maximum Shut-in Pressure >10 MPa Regression Line

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Squares</th>
<th>F test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>923.086</td>
<td>1</td>
<td>923.086</td>
<td>F=14.7</td>
</tr>
<tr>
<td>Deviation</td>
<td>376.634</td>
<td>6</td>
<td>62.772</td>
<td>F crit.</td>
</tr>
<tr>
<td>Total Variation</td>
<td>1299.72</td>
<td>7</td>
<td></td>
<td>@95%=5.99</td>
</tr>
</tbody>
</table>
The results of the thickness versus DST shut-in pressure analysis suggest a significant inverse relation and a good fit to the calculated regression line. The fit of the regression line is significant at the 95 percent level. Based on the data in the study area, at a Bakken thickness of two meters or less the probability of encountering fractures in the Bakken is near 86 percent.

Lineament Distance versus DST Shut-in Pressures

The central test of the thesis compared the percentage of DST shut-in pressures greater than 10 MPa to the distances to the nearest lineament. A histogram of the numbers of DSTs within each distance class in the study is given in Figure 24. The distance classes were chosen at 200 meter increments, with the upper limit of the range given in the tables and graphs of the data (e.g., the 200 meter distance bar on the graph contains the information for wells between zero and 200 meters). Only the distance classes up to 1,200 meters were considered in the statistical analysis of distance versus percentage of high shut-in pressure wells. The 1,200 meter limit was chosen for three reasons: First, the limited numbers of wells within the distance classes greater than 1,200 meters (less than 12 per class). These small samples may not accurately reflect the nature of the general population. Second, the average lineament nearest-neighbor distance for the study area was 1,440 meters. Wells greater than 1,200 meters from the nearest lineament may be influenced by subsurface fracture domains not seen or expressed at the surface (e.g., an unidentified lineament zone). Thirdly, various test plots of the data showed a breakdown of linear correlation between distance and the percentage of high shut-in pressures for distances greater than 1,200 meters (perhaps due to some combination of the prior two reasons). Of the 214 wells with DST results, 166 were located within 1,200 meters of a lineament. Figure 25 shows the distribution of azimuths among the nearest-neighbor lineaments to wells with DST.
Figure 24. Distance from well to nearest lineament for wells with DSTs. The distance classes are 200 meter groupings (e.g., the 200 meter bar represents the number of wells with DSTs that were found within zero to 200 meters of a lineament).
Figure 25. Wells with DST results grouped by azimuth of nearest-neighbor lineament. Azimuth classes are 15 degree groupings (e.g., the 285 bar represents the number of wells with nearest-neighbor lineaments possessing azimuths between 270 and 285 degrees).
results. Lineaments with a northwest-southeast orientation predominate as nearest-neighbors to wells with Bakken DSTs. This may be a reflection of the general distribution of lineaments in the study area, where northwest-southeast is a dominant orientation. The bearing from wells with DSTs to their nearest-neighbor lineament was examined to check for potential bias in the data. There is a slight bias (53 percent) toward nearest-neighbor lineaments occurring to the east of the wells with DST results, but it is not considered significant.

Initially all lineaments in the study area were considered for potential nearest-neighbors to the wells with DST results. The data used to compare the percentage of shut-in pressures greater than 10 MPa to the nearest-neighbor distance to any lineament are summarized in Table 4. The ANOVA for the original data versus the regression line calculated through the data points is given in Table 5. The correlation coefficient between lineament distance and the percentage of DST shut-in pressures greater than 10 MPa was significant at the 95 percent level. The fit of the calculated regression line is also significant at the 95 percent level. A plot of the data and regression line is given in Figure 26.

A second test for a potentially significant relation between nearest-neighbor lineament distance and shut-in pressures was conducted with a subset of the lineament data. The same procedure was employed as used in the first test but only those wells with nearest-neighbor lineaments in the "minor" category were considered. Figure 27 shows a graph of the relation and Figure 28 is a map of the "minor" lineaments. The data used in the second analysis of distance versus shut-in pressures are in Table 6, with the ANOVA results given in Table 7.
Table 4.--Data for Percentage Maximum Shut-in Pressure >10 MPa versus Nearest-neighbor Lineament Distance (considering all lineaments)

<table>
<thead>
<tr>
<th></th>
<th>x²</th>
<th>x</th>
<th>xy</th>
<th>y</th>
<th>y²</th>
<th>ŷ</th>
<th>ŷ²</th>
</tr>
</thead>
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<tr>
<td></td>
<td>0</td>
<td>200</td>
<td>11760</td>
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<td>65.6</td>
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<td>62.9</td>
<td>3956.4</td>
<td>61.0</td>
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<tr>
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<td>38160</td>
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<td>4045.0</td>
<td>56.5</td>
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<tr>
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<td>51.9</td>
<td>2694</td>
<td></td>
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<td>1000</td>
<td>52200</td>
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<td>2724.8</td>
<td>47.4</td>
<td>2243</td>
<td></td>
</tr>
<tr>
<td>144000</td>
<td>1200</td>
<td>42820</td>
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<td>1274.5</td>
<td>42.8</td>
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<td></td>
</tr>
<tr>
<td>Σ</td>
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<td>325.1</td>
<td>18152</td>
<td>325.2</td>
<td>17978</td>
</tr>
</tbody>
</table>

x = nearest-neighbor lineament distance (m)
y = percentage wells with maximum DST shut-in pressures >10 MPa
r = correlation coefficient = -0.82183
t = t test for the significance of r = -2.88495
(t critical at 95 percent significance level = ±2.571)
B₀ = y-intercept of regression line = 70.11333
B₁ = slope of regression line = -0.02276
R² = goodness of fit of regression line = 0.675403

Table 5.--ANOVA for Lineament Distance (all lineaments) versus Percentage Maximum Shut-in Pressure >10 MPa Regression Line

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Squares</th>
<th>F test</th>
</tr>
</thead>
<tbody>
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<td>Regression</td>
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<td>362.52</td>
<td>F=8.32</td>
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<tr>
<td>Deviation</td>
<td>174.23</td>
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<td>43.56</td>
<td>F crit.</td>
</tr>
<tr>
<td>Total Variation</td>
<td>536.75</td>
<td>5</td>
<td>107.35</td>
<td>@95%=7.71</td>
</tr>
</tbody>
</table>
Figure 26. Percentage DST shut-in pressure >10 MPa versus distance to nearest-neighbor lineament. The distance classes are 200 meter groupings (e.g., the 200 meter distance point represents the percentage of wells within zero to 200 meters of a lineament that have DST maximum shut-in pressures over 10 MPa).
Figure 27. Percentage shut-in pressure >10 MPa versus distance to nearest-neighbor "minor" lineament. The distance classes are 200 meter groupings (e.g., the 200 meter distance point represents the percentage of wells within zero to 200 meters of a "minor" lineament that have DST maximum shut-in pressures over 10 MPa).
Figure 28. "Minor" lineaments in the study area.
Table 6.--Data for Percentage Maximum Shut-in Pressure >10 MPa versus Nearest-neighbor Lineament Distance (considering only "minor" lineaments)

<table>
<thead>
<tr>
<th>$x^2$</th>
<th>$x$</th>
<th>$xy$</th>
<th>$y$</th>
<th>$y^2$</th>
<th>$\hat{y}$</th>
<th>$\hat{y}^2$</th>
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</thead>
<tbody>
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<tr>
<td>40000</td>
<td>200</td>
<td>12500</td>
<td>62.5</td>
<td>3906.3</td>
<td>69.9</td>
<td>4885</td>
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<tr>
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<td>2894.4</td>
<td>51.6</td>
<td>2658</td>
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<tr>
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<td>800</td>
<td>36400</td>
<td>45.5</td>
<td>2070.3</td>
<td>42.4</td>
<td>1796</td>
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<tr>
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</tr>
<tr>
<td>1440000</td>
<td>1200</td>
<td>24000</td>
<td>20</td>
<td>400</td>
<td>24.0</td>
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</tr>
<tr>
<td>3640000</td>
<td>1400</td>
<td>165160</td>
<td>281.8</td>
<td>14828</td>
<td>281.8</td>
<td>14707</td>
</tr>
</tbody>
</table>

$x =$ nearest-neighbor "minor" lineament distance (m)

$y =$ percentage wells with maximum DST shut-in pressures $>10$ MPa

$r =$ correlation coefficient $=-0.961121$

$t =$ t test for the significance of $r = -6.961448$

[t critical at 95 percent significance level $= \pm 2.571$]

$B_0 =$ y-intercept of regression line $= 79.07$

$B_1 =$ slope of regression line $= -0.045857$

$R^2 =$ goodness of fit of regression line $= 0.923754$

Table 7.--ANOVA for Lineament Distance ("minor" lineaments) versus Percentage Maximum Shut-in Pressure $>10$ MPa Regression Line

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Squares</th>
<th>F test</th>
</tr>
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<tr>
<td>Regression</td>
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<td>$F=48.5$</td>
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<tr>
<td>Deviation</td>
<td>121.5</td>
<td>4</td>
<td>30.4</td>
<td>F crit.</td>
</tr>
<tr>
<td>Total Variation</td>
<td>1593.5</td>
<td>5</td>
<td></td>
<td>@95%=7.71</td>
</tr>
</tbody>
</table>
The second analysis for potential interrelation between shut-in pressure (as an indicator of fracturing) and "minor" nearest-neighbor lineament distance was even more encouraging. The correlation coefficient was large at -0.96, indicating a strong inverse relation between the variables. The test for the significance of the correlation coefficient (at the 95 percent level) was easily met. The fit of the regression line is significant at the 95 percent level.
DISCUSSION

The results of the current investigation show some promise for isolating factors controlling fracture distribution in the Bakken Formation. In particular, drill stem test maximum shut-in pressures (indicating fracturing) were found to have significant correlations to Bakken thickness and to lineament nearest-neighbor distance.

Lineaments

The lineament density and average nearest-neighbor distance within the study area were compared to theoretical values for a random distribution of lines. The results of this portion of the study indicated a statistically significant difference between the lineament pattern within the study area and a random line pattern. The non-random nature of the Landsat-derived lineaments suggests the presence of a controlling mechanism for their location. I attribute the lineament localization to underlying, crystalline, basement-block boundaries or to deformation of the sedimentary cover as a result of relative movement of these blocks.

There are some problems inherent in the use of remotely sensed data and discrete geographical point data. The remote sensing tool (in this case the Landsat satellite) samples large areas of the earth's surface with an array of digital and analog sensors. The data collected are subject to resolution limitation inherent in the sensors and the data transmission system. The Landsat data used in this study have a ground resolution of 79 meters by 56 meters per pixel (or 0.44 hectare per picture element). The Landsat sensor actually averages all of the reflectance within a 79 meter by 79 meter area (giving some sidelap) and
assigns one value to the pixel in the image (Lillesand and Kiefer, 1979). The images considered most suitable for lineament interpretation are acquired at times of low sun angle (early morning or late afternoon) to enhance shadow effects. These factors may influence the identification of lineaments due to the combination of pixel orientation and preferential shadow enhancement. The map location of remotely sensed data is also dependent on proper distortion removal and accurate registration of identifiable geographic features in the image to the map. Finally, the Landsat interpreter draws a line to represent the linear arrangement of like pixels in the image. This process may be quite subjective and accurate location of the lines (lineaments) on the map may be dependent on the map scale.

Well Data

The spatial distribution of the wells used in the study is not random. By the nature of data from wells drilled for oil and gas, the sampling method is not under the control of the researcher, and the samples may not accurately reflect the general population. The well information was filtered to remove values which might not reflect true formation pressures (e.g., tests indicating pressure leakage or recorder malfunction), but variables unknown or outside the control of the study may have affected the results. The location of wells drilled through the Bakken Formation was controlled by the various interpretations of exploration companies as to the distribution of structural or stratigraphic traps for hydrocarbons. Therefore, closed structural highs, anticlinal areas, and stratigraphic pinch-outs are preferentially sampled. The well density varies across the study area, with high density in regions of hydrocarbon production in the Bakken or deeper horizons. Well and DST density is lower in non-productive areas or in areas dominated by producing horizons shallower than the Bakken. The distribution of DST results also is not uniform. DSTs tend to be
clustered in or around areas of existing Bakken oil production. It should be noted that there are more DSTs in the region of thinner (generally 3 meters or less) Bakken than in the deeper basin where the Bakken is thicker.

Bakken Thickness versus Shut-in Pressure

There is a statistically significant correlation between Bakken thickness and the percentage of high shut-in pressure wells. The percentage of highly fractured Bakken wells (as indicated by DST shut-in pressures >10 MPa) is particularly great in the thickness range of the Bakken from zero to three meters. This may be indicative of a critical thickness for optimum fracture spacing, given the mechanical properties of the Bakken Formation. An attempt was made to remove the influence of the Bakken thickness factor from the analysis of shut-in pressures versus nearest-neighbor lineament distance. Wells with less than three meters of total Bakken thickness were removed from the sample and the statistical tests were rerun. However, this did not significantly alter the results of the tests.

Shut-in Pressures versus Lineament Nearest-neighbor Distance

The best correlation between the percentage of DST shut-in pressures >10 MPa and nearest-neighbor lineament distance was found when considering only "minor" nearest-neighbor lineaments. An inverse relation between the two variables was also seen when considering all lineaments and other subsets of the lineament data. A characteristic in common with almost all of the analysis of shut-in pressures versus lineament neighbor distance was the slightly to moderately lower percentage of higher pressure wells in the zero to 200 meter-distance class as compared to the 200 to 400 meter class. No satisfactory explanation for this phenomenon has been identified. The effects of Bakken thickness and of bearing from the well to the neighbor lineament
were explored without success. Another hypothesis considered but not proven is the leakage of pressure from the Bakken in the most intensely fractured zones.
CONCLUSIONS

1. The Landsat-derived lineament pattern in the study area is non-random and apparently related to basement block tectonics.

2. The mean nearest-neighbor spacing between lineaments in the study area is 1,440 meters (4,723 feet).

3. A significant inverse linear relation exists between the thickness of the Bakken and the probability of encountering fractures (as inferred by DST maximum shut-in pressures). The 10 MPa level of maximum shut-in pressure was chosen as the threshold between low pressure (relatively unfractured Bakken) and high pressure (more fractured Bakken). In the study area, at a Bakken thickness of two meters or less the probability of encountering fractures is near 86 percent.

4. A significant inverse linear relation also exits between the proximity of wells to Landsat lineaments and fracture density (or the probability of encountering fractures as indicated by the percentage of DST maximum shut-in pressures >10 MPa).

5. Knowledge of these trends in fracture-enhancement of the porosity and permeability in the Bakken Formation should be useful in the siting of conventional and horizontal, petroleum, exploration wells.
6. A link between basement-block discontinuities, Landsat lineaments, and fracturing of the intervening sediments could have impact on the understanding of the hydrodynamics and petroleum migration pathways in the basin.
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Peter, K. D., Kolm, K. E., Downey, J. S., and Nichols, T. C., Jr., 1988, Lineaments--significance, criteria for determination, and varied effects on ground-water systems--a case history in the use of remote sensing, in Johnson, A. I., and Pettersson, C. B., eds., Geotechnical applications of remote sensing and remote data transmission: Special Publication No. 967, American Society of Testing and Materials, Philadelphia, p. 46-68.


