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CHADRON STATE COLLEGE

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Subtle Structures of the Pine Ridge Region, Northwestern Nebraska

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Abstract

The purpose of this study was to identify, map and describe geologic structures in the Pine Ridge near Chadron, Nebraska. Remote sensing and field techniques were employed during the course of this study which occurred over a 30-month period from September, 2008 to March, 2011. A total of 1147 lineaments were identified using Landsat-Thematic Mapper (Landsat-TM), National Aeronautic and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM) elevation data, and Digital Orthophoto Quads (DOQs) in a study area that was bounded by latitude 44° on the north, 40° on the south, longitude -105.5° on the west and -101° on the east . A forest fire in the Nebraska National Forest south of Chadron during the summer of 2006 removed vegetation and exposed previously covered rock outcrops suitable for geologic study. A total of 31 faults, with offset ranging from 0.14m to 60m, were mapped in a $20km^2$ intensive field study area on the north-south oriented ridge immediately south of Chadron. The differences between fault and closest lineament azimuths were analyzed using a goodness of fit statistic and difference frequencies were found not to be randomly distributed. The azimuth difference frequency with the greatest number of occurrences was the 0°-10° category. The 0°-10° category was considered a matching azimuth. The distance from points on fault planes and their closest lineament and the distance from random points and their closest lineament were analyzed using the difference of two means statistic. The mean distance from fault points to lineaments was found to be significantly closer to lineaments than random points. The conclusion drawn from both the azimuth difference and the mean distance to lineament tests is that within the intensive field study area lineaments represent faults.

Acknowledgments

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Table of Contents

Introduction

Identification and description of geologic structures provides the basis for understanding the geologic history of a region. Geologic mapping and study of structures is the foundation for understanding the region's tectonic geomorphology and recognizing geologic hazards. Discovering and protecting natural resources located within a region also requires understanding how the region's landscape has changed though time.

Slow-moving faults have been known to cause moderate to strong earthquakes. Basement fault reactivation might also result in earthquakes. Mapping and study of implied faults is as important as study of well exposed faults to accurately assess geological hazards. Structures such as faults, anticlines, arches and domes act as conduits and structural traps that provide opportunities for mineral, petroleum, uranium, and geothermal exploration, as well as groundwater storage or transmission. Discovery and subsequent management of natural resources depends upon knowledge of the location and age of geologic structures within a region (Lyatsky et al., 2004).

Understanding of the earthquake history in northwestern Nebraska is limited by several factors. First, the region was settled by Europeans roughly 130 years ago. Second, seismograph station coverage was not available until 1974 (United States Geological Survey [USGS], 2008) and active seismograph coverage remains sparse today. Third, because seismograph technology was not available until recently, the earthquake history relies upon newspaper accounts of damage and successful application of the Modified Mercalli Scale to estimate intensity of shaking caused by an earthquake (Von Hake, 1974).

An examination of published geologic maps indicates that geologic structures have been well mapped in Wyoming (Love & Christiansen, 1985) and South Dakota (Rothrock, 1949). Mapping in Wyoming and South Dakota is likely a result of resources and manpower provided by the oil, gas, and coal industries. In most cases, those projects did not extend into Nebraska; therefore, geologic mapping

ended at the Nebraska state line. The Nebraska Geologic Survey's emphasis on agriculture, soils, and groundwater research means that the structures are relatively unstudied.

Statement of the Problem

The discovery and management of natural resources are dependent upon knowledge of geologic structures within a region (Lyatsky et al., 2004). Tectonic geomorphology and structural geology combine to provide the basis for natural resource and hazard assessment. Mapping of faults is essential to accurately assess geological hazards. Geologic structures act as conduits and traps providing opportunities for mineral, petroleum, nuclear, and geothermal exploration, as well as groundwater storage or transmission. The purpose of this study is to identify, map and describe geologic structures in the Pine Ridge near Chadron, Nebraska.

Statement of Research Questions

A descriptive geologic survey is an observational study in which research questions are more appropriate than traditional hypotheses which are tested statistically.

Question 1

Paleogeographic, earthquake, and remotely sensed data indicate the presence and activity of geologic structures. It is unlikely that geologic structures and faults mapped in Wyoming or South Dakota simply stop at or near the Nebraska state line. Therefore, are lineaments identified on remotely sensed data geological structures or faults that can be verified and mapped on the ground?

Question 2

Geophysical data indicate the presence of subsurface structures. Well-log data exist for the region and can be used to identify tops of stratigraphic units in the subsurface. Do subsurface structures identified from subsurface configuration maps coincide with remotely sensed lineaments?

Question 3

The lithologies present within the study area are soft, volcaniclastic siltstones, sandstones, and shale. How are subsurface faults expressed in outcrop in the Pine Ridge region?

Review of Related Literature

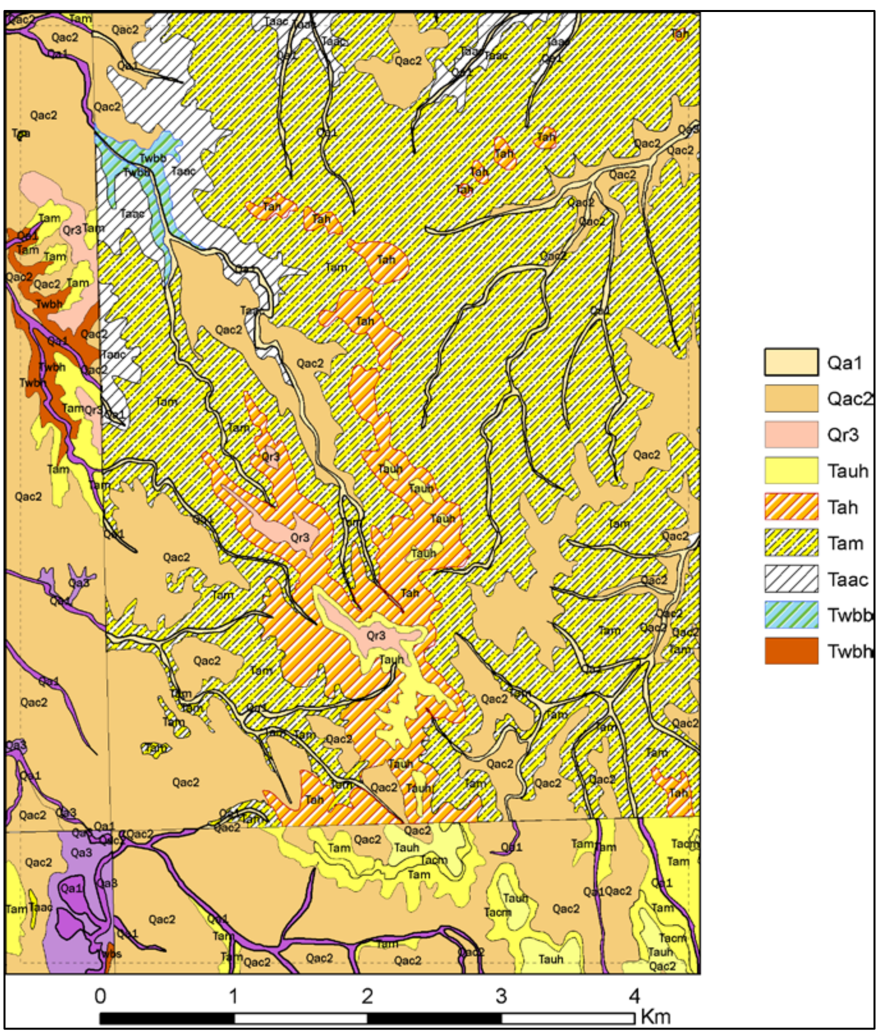
An accurate description of structural deformation requires a broad understanding of regional geology, regional continental assembly, regional tectonic activity, and structural geology. Ancient plate boundaries represent collisional zones where continental crust and island arcs were accreted onto or subducted beneath the cratonic crust. Gravity, magnetic and electrical conductivity anomalies form in the collision zones. Where subduction was involved, the subducted crust melted and provided a source for magma and igneous activity. The collision zone also produced metamorphic rocks in the subsurface and resulted in faults, which persist to today in the basement rocks. Unraveling the tectonic, structural, and geomorphic history of a region is complicated. It requires the methodical application of remote sensing technology, basin analysis, structural techniques, and the careful art of observation in the field.

Geology of Northwest Nebraska

In northwestern Nebraska, the Pine Ridge forms a north-facing south-dipping escarpment that has exposures of Ogallala, Arikaree, and White River Group rocks. The Pine Ridge Fault, identified by Swinehart et al., (1985) by correlating ash beds in cores, runs beneath the Pine Ridge Escarpment. The dip of the rocks and the shape of the Pine Ridge Escarpment indicate that it is part of the area deformed by the Black Hills uplift. The north slope of the ridge is steep and drained by tributaries of the White River. Meanwhile, the gentle south slope is drained by the Niobrara River Nebraska. Much of the area north of the Pine Ridge is covered by the Pierre Hills. The gently rolling Pierre Hills develop in areas where the Pierre Shale Formation is the bedrock. The Brule and Chadron Formations of the White River Group form badlands where they are exposed north of the Pine Ridge Escarpment. Older Cretaceous deposits are exposed at the Chadron Dome northeast of Chadron, Nebraska. Younger Quaternary deposits are generally found in the floodplains of the White River and its tributaries (Diffendal, 1994).

Quaternary eolian sediments were found filling the north-facing stream valley of the Hudson-Meng Bison Kill Site in northwestern Nebraska. The bonebed at the site rests on the lowermost paleosol and stream deposit dated at approximately 10,000yBP. The site documents rapidly evolving sequences of erosion and filling of small valleys with poorly cemented eolian sediments. The intermittent periods of landscape stability were punctuated by the development of paleosols (Balmat et al., 2007).

The tectonic and structural evolution of western Nebraska has been ongoing since Precambrian time. The earthquake history for the region shows sporadic weak earthquakes occur at depths of 5-15km within Precambrian basement rocks. In western Nebraska remotely sensed lineaments correspond to faults that are implied because accurate mapping has not been completed. The Black Hills uplift resulted in the deformation of the Pine Ridge. Fractures, joints and faults are typically associated with uplift deformation.



Map 1. Geologic map of Field Study area. Derived from LaGarry and Lagarry (1997).

Qa1 - Alluvium

Qac2 - Undifferentiated sandy alluvium and colluvium

Qr3 - Sandy residuum

Tauh – Anderson Ranch Formation, formerly Upper Harrison

Tah - Harrison Formation

Tam – Monroe Creek Formation

Taac – “Ash Creek” Beds

Twbb – Brule Formation

Twbh – Sharps Formation, formerly Horn Member

Structural Geology

Structural geology, while similar to tectonics, deals with the description, representation and analysis of moderate to small scale geologic features. Anticlines and Arches are convex up folds whose core contains stratigraphically older rocks. Faults are fractures or zones of fractures that have displacement parallel to the fracture (Bates & Jackson, 1984). Examination of the structures in a region will help determine how larger forces such as tectonics impacted the area's landscape evolution.

In Fall River County, South Dakota, the dominant geologic structure, found and mapped by E. P. Rothrock in 1931, is a southward dip of all beds caused by the uplift of the southern Black Hills. Superimposed on the dip are three southward plunging anticlines, the Cascade Anticline, the Chilson or Hat Creek Anticline, and the Cottonwood Creek Anticline. The Cascade and Hat Creek Anticlines have axes oriented north-south. They are asymmetrical with dips of 30 degrees on the west and 3-4 degrees on the eastern side. The Cascade Anticline plunges steeply below the ground surface well before the Nebraska state line; however, the Hat Creek Anticline is mapped to the state line. In the Ardmore, South Dakota, vicinity it assumes a symmetrical textbook shape of an anticline with both sides dipping at approximately 6 degrees. The Cottonwood Creek Anticline has an axis oriented southwest and forms an arc from Edgemont, South Dakota, to the Nebraska state line at the southwestern corner of Fall River County. This anticline is symmetrical and has small faults along its west flank with displacements of less than 50 feet. Rothrock's field crews mapping this anticline experienced an unreliable magnetic needle suggesting some kind of involvement of the basement geology. It is likely that a strong thrust was applied to the Black Hills north of Edgemont which caused a shearing thrust from the west with its intensity weakening toward the south. The result of the shearing force would cause the curvilinear direction of the Cottonwood Creek Anticline axis and the asymmetrical shape of the Hat Creek and Cascade Anticlines (Rothrock, 1949).

In western Nebraska, the most prominent basement feature is the northwest trending Chadron Arch. The Chadron Arch is part of the Chadron-Cambridge Arch system that extends from the Central Kansas uplift northwestward to the Black Hills uplift. However, the different parts of the arch system have been tectonically active at different times with a northwest progression of activity. A major pulse of tectonic activity on the Chadron Arch and the Black Hills occurred during the Mesozoic. Uplift along the better studied Cambridge Arch portion of the arch-system indicates activity from the early Ordovician through the Pleistocene and into the present with recorded earthquakes in Kansas. Recurrent uplift along the Chadron-Cambridge Arch system indicates a zone of weakness that has been in place at least since the Ordovician. However, according to Stix (1982) there are several lines of evidence that suggest older basement faulting. First, steep dips of were encountered in drilling that are not attributed to differential compaction because isopachous maps do not show thickening on the flanks or thinning along the axis. Second, there is greater fracturing of limestones where the dip is steep, further indicating fault development during epeirogenic movement on the arch. Third is the presence of steep aeromagnetic gradients in Precambrian basement lithologies. Lastly, the aeromagnetic gradient, steep dips and faults all trend in a general northwest direction which is parallel to the strike of the arch system. This would indicate that they are related to the arch and were created during as many as 9 episodes of uplift along the arch. A geothermal study indicates that granitic basement rocks in northwestern Nebraska, dated at 1710 +/-320 to 1720 +/-130 Ma, are producing a geothermal gradient which indicates the lithologies are producing radiogenic heat (Stix, 1982).

Faults can influence subsurface movement of fluids and water movement at the surface. The impact of faults on surface and near-surface processes is apparent in drainage systems, aquifer structure and vegetation distribution patterns. Some faults provide enhanced permeability for vertical groundwater flow. However, large faults generally act to inhibit horizontal groundwater movements (Bense et al., 2003). Secondary faults are more abundant than large faults and offer the probability of

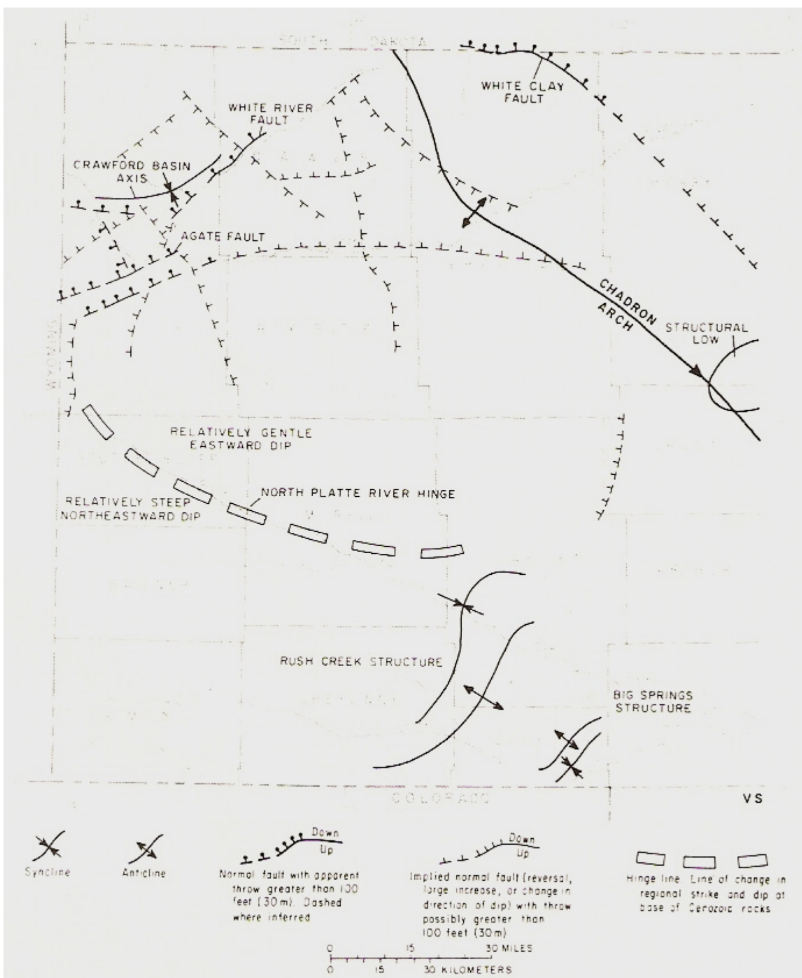
greater cumulative effect on the internal structure of geographically limited groundwater systems (Bense et al., 2003).

The Fannie Peak fault coincides with the Fannie Peak Lineament and extends from the Homestake Mine in South Dakota southward toward the Hartville uplift in Wyoming. East of Newcastle, Wyoming, this fault exhibits en echelon vertical faults within the fault zone and a maximum displacement of 130 meters. This fault parallels the Missouri fault located further west in Wyoming (Wulf, 1963). Folds in Precambrian rocks of the northern Black Hills closely parallel the Missouri and Frannie Peak faults. Major folds found in the northern Great Plains are related to the Precambrian basement fractures across a wide geographic area. Major anticlines in northeastern Wyoming indicate compression from the northeast and southwest. This regional compression produced broad northwest trending folds with low relief. The compression also reactivated the Precambrian basement fault system causing strike-slip movements along faults trending slightly east of north. Movements between the basement faults and the overlying sedimentary rocks produced small north-south trending anticlines. All of this deformation took place during the Paleozoic. Reactivativation of the faults occurred during the Laramide orogeny. During the Tertiary many of these faults served as the location for development of normal faults (Wulf, 1963).

Many of the mapped faults in Nebraska are located only approximately and may actually lie on lineaments (Diffendal, 1994). Normal faults in parts of the Pine Ridge may have controlled development of paleovalleys in which the Gering Formation (Miocene) was deposited. This regional uplift, faulting and folding took place after deposition of the Upper Harrison Beds, as the White Clay fault is post-Upper Harrison and has vertical displacements ranging from 91 to 213 meters. The Agate Springs fault in Sioux County, Nebraska, cuts the Upper Harrison and has vertical displacement of 70 meters. The White River fault in western Dawes County, Nebraska, has vertical displacement of 30-122 meters through White

River Group rocks (see Map 2). These three faults as well as others inferred to occur along the Pine Ridge and Niobrara River are a continuation of the Wyoming Whalen trend (Swinehart et al., 1985).

The White Clay Gravel bed is a part of the Miocene Ogallala Group found near the Nebraska-South Dakota state line outside of Whiteclay, Nebraska. The gravel deposit is the surface rupture of the White Clay fault and is found in a linear trench 20 meters deep and 300 meters wide (see Map 2). The channel tends to be straight with abrupt bends and steep sides which indicate structural control. The channel follows the fault rupture and is dated at 17.5 Ma using fossils found within the gravel deposits. The surface rupture and gravel deposits are evidence that points toward a Miocene reactivation of tectonics in the Black Hills (Fielding et al., 2007).



Map 2. Swinehart et al., (1985) map of geologic structures in western Nebraska.

Faults mapped at Toadstool Geologic Park in northwest Nebraska indicate that the main northeast-striking fault, Toadstool Fault, is linked to the Colorado lineament. Other faults mapped at the site strike northeast and north-northeast with subordinate faults that strike north, northwest, and east. Altogether 138 faults have been mapped within Toadstool Geologic Park. Most of the faults are filled with micrite, chalcedony, and calcite spar and occur in the Chadron and Brule formations of the White River Group (Moak et al., 2004).

Seismic Activity

Areas with slow-moving faults can be difficult to assess for geologic hazards because little or no seismic history is available. The characterization of faults in areas with low slip rates is important because large earthquakes can occur. Geomorphological and structural analysis can estimate relative dates of seismic events and determine if faults produced shaking that caused liquefaction (Masana et al., 2001).

Northwestern Nebraska has experienced at least two relatively strong earthquakes during its short recorded history. The first on July 30, 1934, centered in Dawes County, had an estimated Modified Mercalli Scale intensity VI. The second on March 28, 1964, centered in Van Tassell, Wyoming, had an estimated Modified Mercalli Scale intensity VII and a Richter Scale magnitude 5.1 (USGS, 2008). A search of the United States Geological Survey National Earthquake Database [USGS NEIC] historical and preliminary data, using the search criteria Latitude 44.0 – 40.0 degrees north and Longitude 101.0 - 105.5 degrees west, reports 31 earthquakes since 1975. All of the reported earthquakes had Richter Scale magnitudes ranging from 2.3 – 4.3 and occurred at depths of 5-15 kilometers (United States Geological Survey National Earthquake Information Center [USGS NEIC], 2008).

Paleoseismology is the study of fossil earthquakes. The analysis process requires the use of geological, geomorphological, and archaeological evidence for fault activity. The underlying premise of paleoseismology is that earthquakes produce permanent and recognizable effects within the

environment. Therefore, if a seismogenic fault has been active within the last few thousand years, it is likely that comparable shaking events happened in the past. There is no consensus within the geological community about how to identify soft-sediment deformation structures related to earthquake activity (Michetti & Hancock, 1997). However, Masana et al. (2001) described liquefaction features along the El Camp fault, observed two types of colluvial wedges during trenching, and buried fault scarps. The first type of colluvial wedge is described as a clast-supported conglomerate. The conglomerate formed post shaking in association with normal faults that exhibit localized extensional structures such as open fractures. The pre-existing fractures in the uplifted scarp are unstable after the earthquake and collapse. The second type of colluvial wedge forms a matrix supported gravel conglomerate which exhibits evidence of dissolution. This wedge formed after the earthquake uplifted the fault scarp. Weathering processes then gradually erode material from the elevated surface of the uplifted block and the upper edge of the fault scarp. The sediments are finer grained containing few cobble-sized clasts derived directly from the scarp wall (Masana et al., 2001).

Indicators of Quaternary structural and seismic activity along the Chadron Arch are seen by examining the Niobrara River. In southern Dawes County, the Niobrara runs parallel to the Runningwater paleovalley, then flows northeasterly crossing the Chadron Arch. It flows in deeply entrenched stream meanders near the White Clay fault and Quaternary alluvial fills are found high above the river in Sheridan and Cherry counties (Swinehart et al., 1985).

Basin Analysis

Post-Laramide basin filling continued along the western Great Plains throughout the Cenozoic. Consistent accumulation of 300-900 meters of sediment is seen in a broad area from western Nebraska through central Wyoming and into southern Montana. River gradients during the Neogene reached about 1 m/km in western Nebraska with basin fill deposits reaching 400 meters. Therefore, basin aggradation must have coincided with basin subsidence in order to maintain through-flowing rivers. A

tilt analysis by McMillian et al. (2006) of the tablelands of the western Great Plains in Wyoming and Nebraska revealed an average uplift of 680 meters. The uplift found in Wyoming and Nebraska is consistent with uplift concentrated under the Rocky Mountains beginning during the Miocene and continuing to present (McMillan et al., 2002).

Uplift occurred in the southern Nebraska Panhandle during the Oligocene. A structural 'hinge' in the vicinity of the North Platte River created an uplift of as much as 122 meters prior to deposition of the Gering Formation (see Map 2). Paleodrainages found within the Gering have a different orientation than the Eocene-age paleovalleys found within the Chadron Formation (Swinehart et al., 1985).

Geomorphology

Landform description, classification and analysis provide the basis for deciphering the landscape evolution of a region. The relationship between tectonic and fluvial geomorphology is apparent in regions with structurally controlled watersheds. Studying the drainage pattern and watersheds can provide insight to the tectonic geomorphology of the area. Stratigraphy often constrains the timing of tectonic activity which provides a timeline to landscape changes (Patidar et al., 2007).

A dense network of deeply incised streams and close spacing of range front to drainage divide provide strong indication for tectonically controlled drainage. Patidar et al. (2007) found during a study in the Katrol hill range, Kachchh, western India, tilting attributed to the uplift of a fault block and movement along the Katrol hill fault impacted the drainage systems of the Katrol hill range. Streams had rocky channels, steep gradients, and few alluvium deposits. Varying rates of incision coincided with areas where the stream crossed tilt blocks. Incised bedrock channels suggest tectonic uplift of fault blocks as the impetus for relatively narrow (1.5 – 4 meters) and deep (15 – 21 meters) gorge development (Patidar et al., 2007).

Ongoing stream incision occurs near tectonically active features of the Rocky Mountains (McMillian et al., 2006). Many streams stopped flowing across the Laramide uplift because the uplift

rate exceeded the incision rate. The stream segments later developed into separate drainage systems extending out from the uplift in opposite directions (Seeland, 1985).

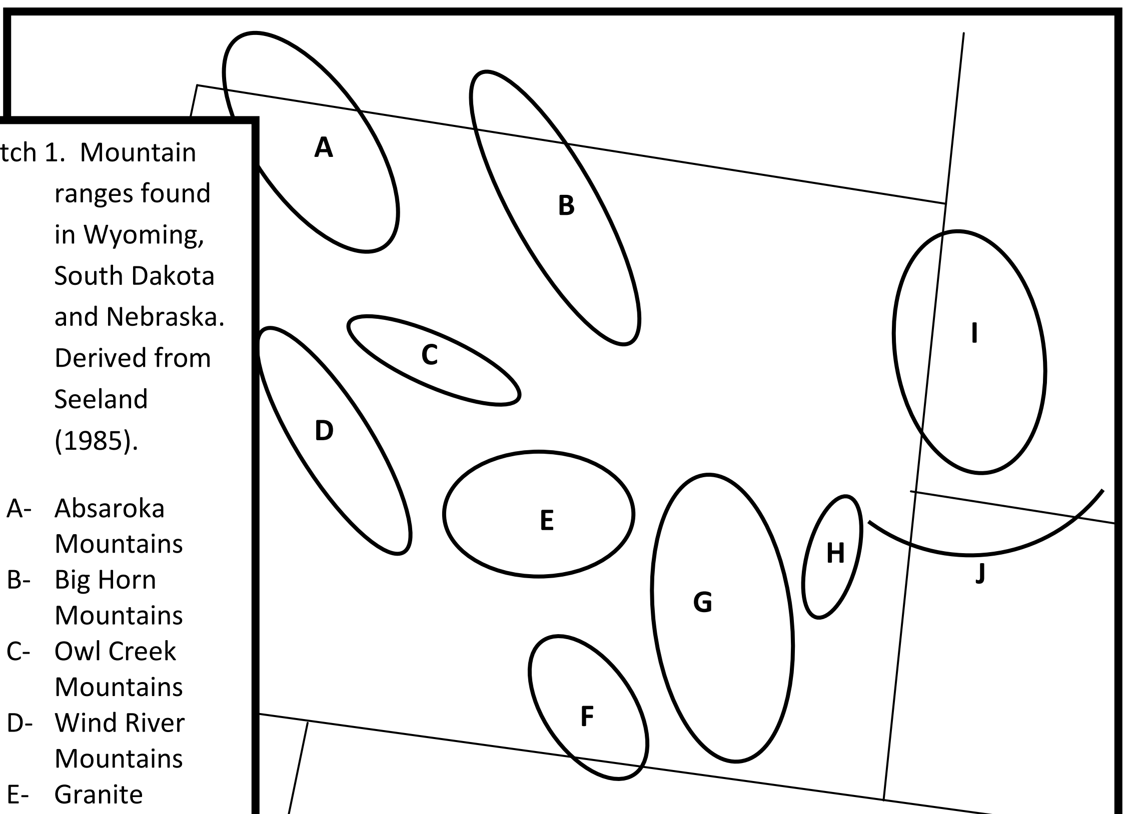
In the southwestern Nebraska panhandle, in the Denver Basin, an unconformity exists between pre-Oligocene and uppermost Eocene rocks. The unconformity was used by previous authors (DeGraw, 1969) to reconstruct paleodrainages. Seeland (1985) inferred paleodrainages for eastern Wyoming and the northwestern Nebraska Panhandle and joined them to the drainages identified by DeGraw. The paleodrainages may indicate that minor anticlines were actively forming topographic high points which diverted streams during the paleovalley incision (Seeland, 1985).

Anomalies, such as wind gaps and water gaps, found within drainage systems often correspond to locations with structural deformation. Anticlines are usually associated with topographic highs. The high points then lead to enhanced surface erosion and stream piracy (Ruszkiczay-Rudiger et al., 2006). The processes of folding and faulting often coincide. Many times the axis of a fold is mapped as a fault. This occurs as horizontal shortening produced a reverse fault with the hanging wall exposed during the anticline development. The lateral propagation of folds occurs above buried reverse faults as they accumulate slip and also propagate laterally. The lateral propagation of folds then provides evidence for the direction of fault propagation. The presence of two or more water gaps or wind gaps within one stream drainage provides positive evidence of lateral propagation (Keller et al., 1999). Water gaps develop in watersheds when uplift creates a diversion or stream capture by another stream. Wind gaps develop as a result of tectonic uplift downstream which leads to the progressive loss of the upper portion of the catchment (Boulton & Whittaker, 2008).

Regional Tectonic Activity

Unraveling the tectonic history of a region begins with a review of the known events and approximate occurrence times of those events. Tectonism in the western United States began with Precambrian strike-slip faulting. This was followed by the Pennsylvanian-Permian Ancestral Rocky

Mountain orogeny; Cretaceous-Oligocene Laramide orogeny; and Neogene extension in the southern Rocky Mountains (Wawrzyniec, et al., 2007). The Laramie Range, Hartville uplift, Bighorn Mountains, Black Hills, Absaroka Mountains, and the Owl Creek Mountains (see Sketch 1 below) are all considered part of the Laramide orogeny in the Wyoming, South Dakota, and Nebraska region. By the end of the Oligocene, the Arctic – Gulf of Mexico continental divide, which determined river drainage to the north or south, extended from the southern Absaroka Mountains to the eastern Owl Creek Mountains. The Oligocene continental divide then crossed the south end of the Powder River Basin, proceeded through the northern Black Hills, and continued eastward across South Dakota (Seeland, 1985).



Sketch 1. Mountain ranges found in Wyoming, South Dakota and Nebraska. Derived from Seeland (1985).

A- Absaroka Mountains
B- Big Horn Mountains
C- Owl Creek Mountains
D- Wind River Mountains
E- Granite Mountains
F- Medicine Bow Mountains
G- Laramie Range
H- Hartville Uplift
I- Black Hills
J- Pine Ridge Escarpment

An episode of Oligocene uplift of the Wind River Range, Granite Mountains, and the Uinta Mountains was due to hinge-like folding and the release of horizontal compression. The change in stress caused the reactivation of Precambrian shear zones and faults (Hall & Chase, 1989; Steidtmann et al., 1989). The uplifts are now supported by the strength of the rocks alone. Over time, uplifts supported by folding tend to collapse when the rock weakens (Hall & Chase, 1989).

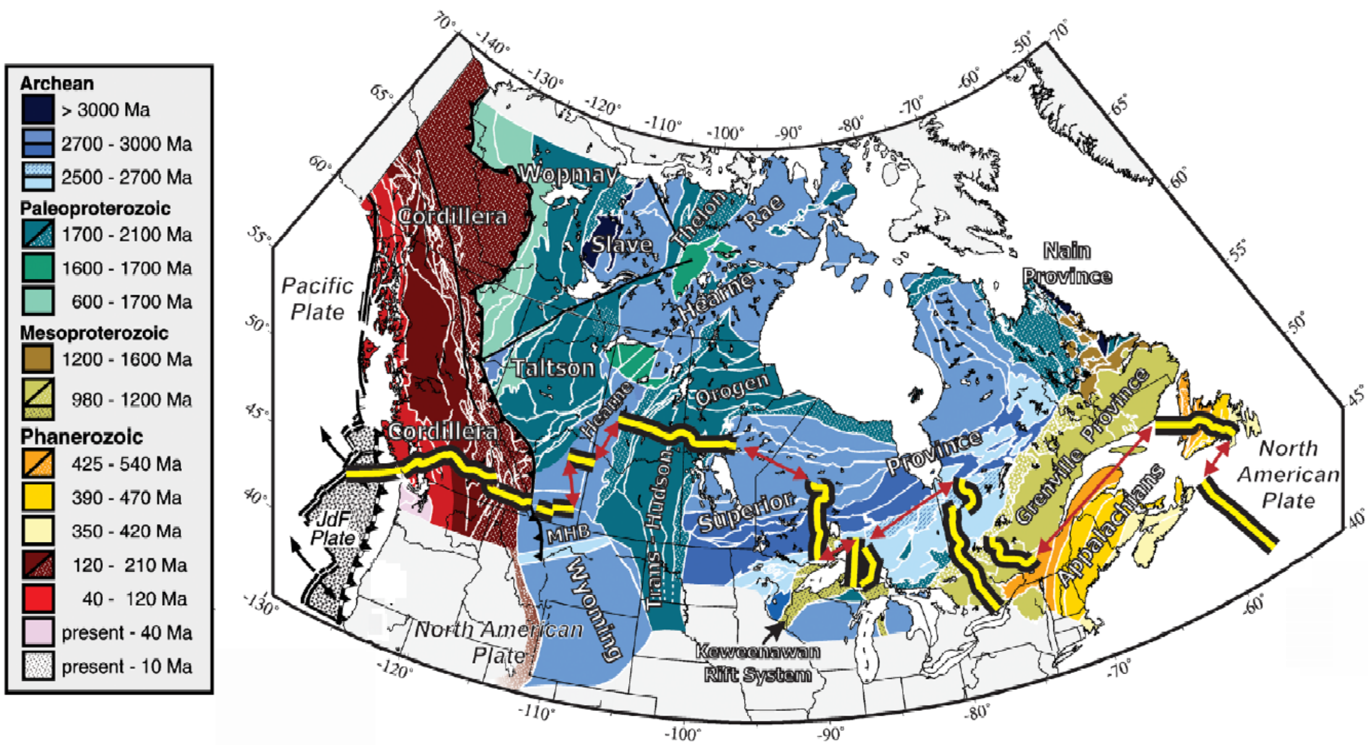
Zones of active normal faulting along the Rio Grande Rift cross the crest of the Rocky Mountains and extend into Wyoming. The amount of incision and the gradients of rivers flowing out of the Rocky Mountains and onto the Great Plains tend to decrease going from south to north and help to demonstrate the northward extension of the Rio Grande Rift over time (McMillian et al., 2006).

The Bear Lodge Mountains and the Black Hills form a north-northwest domal structure that is related to the Central Rocky Mountains and contain uplifted Precambrian granitic gneisses dated at 2,500 Ma. Younger Precambrian rocks form a complexly folded sequence with a north-northwest strike. The region comprising extreme northwestern Nebraska, east-central Wyoming, and the Black Hills-Bear Lodge Mountains is related to several tectonic and geophysical features. First, the North American Central Plains electrical conductivity anomaly, which is considered a possible Proterozoic plate boundary, extends northeastward from southeastern Wyoming to the east side of the southern Black Hills then turns north and continues into Canada. Second, the Black Hills uplift may be considered an extension of the Southern Rocky Mountains and related to the Rio Grande Rift. Third, a regional zone of high heat flow extends from the Rio Grande Rift in the south through the Black Hills and continues northward into Canada. Lastly, the Colorado Lineament, a combination of geological and geophysical trends that can be extended from the Grand Canyon past the southern tip of the Black Hills and across the Great Plains, falls in line with a major southwest trending Precambrian basement fault in South Dakota and a terrane boundary in Minnesota (Karner, 1981).

Regional Continental Assembly

Northwestern Nebraska, while located in the present-day heart of Laurentia, was the center of collision zones during Archean and Early Proterozoic times. The Archean provinces involved in these collisions were the Hearne, Superior, and Wyoming. These provinces have a granite-greenstone terrain or equivalent as a basement complex beneath deformed erosional remnants of platform facies. The Archean collision zones resulted in Early Proterozoic orogenic belts (Hoffman, 1988).

The collision zone between the Wyoming and Superior provinces extends in the subsurface from southeastern Saskatchewan to northwestern Nebraska and is generally interpreted, based upon geophysical data, as the southern extension of the Trans-Hudson orogen (see Map 3). The Trans-Hudson orogen, dated at 1860-1790 Ma, was followed by the Wyoming-Superior collision dated at 1770-1715 Ma. Island Arc accretion along the southern portions of the Wyoming province (Medicine Bow orogen) is dated at 1780 Ma (Dahl et al., 1999).



Map 3. North American continental provinces with time of attachment. Hammer et al., (2011)

The North American Central Plains conductivity anomaly is thought to represent Proterozoic collisional suturing. Arc-continent sutures occur in the Medicine Bow orogen, Cheyenne Belt dated at 1780-1740 Ma and in northern Saskatchewan dated at 1860-1845 Ma (Dahl et al., 1999). The Cheyenne Belt has been interpreted as an eroded, north-directed foreland thin-skinned thrust complex. The thrust complex moved northward over the Wyoming craton to the northern edge of present-day Granite and Laramie Mountains and north of the Black Hills. The Trans-Hudson orogen is truncated by the island arc terrains of the Central Plains orogen in northern Nebraska (Hoffman, 1988; Dahl et al., 1999).

The Precambrian crystalline core and Early Proterozoic continental margin rocks of the Black Hills are the only rocks exposed at the surface to have been affected by both the Trans-Hudson orogen and the Wyoming-Superior convergent zone. The Precambrian rocks indicate epicratonic rift basins in Wyoming province Archean basement rocks. The rift was filled with Early Proterozoic clastic rocks and mafic igneous rocks. Eventually, the rift basins were closed by the Wyoming-Superior collision (Dahl et al., 1999).

The Black Hills exhibit three fold nappes (Table 1). The first, shallow north-oriented folds interpreted by Dahl et al. (1999) as resulting from the thin-skinned thrust sheet which originated with island arc accretion along the Cheyenne Belt. The second, north-northwest trending nappes represent the Wyoming-Superior collision. Third, the steeply dipping, northeast-oriented cross folds represent the final stages of continental assembly or late-phase arc accretion to the south.

Folds	**Orientation**	**Interpreted Cause**
Set 1	Shallow, N	Island arc accretion and thin-skinned thrust sheet
Set 2	NNW	Wyoming-Superior collision
Set 3	Steeply dipping, NE	Final stages of continental assembly or late-phase arc accretion

Table 1. Black Hills Fold Orientations derived from Dahl et al. (1999).

Remote Sensing

Remotely sensed images are well suited to studying relationships between landforms and geologic features (Elachi, 1980). Many of Earth's features have unique and reliable multispectral light signatures that can be identified from satellite sensed data (Halbouty, 2008). Structures such as fractures, folds and faults that are not always expressed at the Earth's surface can be seen as lineaments which are lines, linear trends or tonal trends on remotely sensed images of the Earth (Anderson, 2008).

In locations where the surface of the earth is covered with cropland or badlands, identification of joints and faults can be difficult. Normal faults appear as linear structures on remotely sensed data, and satellite imagery can be used for reconnaissance of geologic structure locations. As an example, Arlegui and Soriano (1998) correlated mapped normal faults with lineaments identified using Landsat-TM images of the central Ebro basin in Spain. Later, ERS-1 SAR images detected small fractures with consistent orientation and reflectivity throughout the same study area. Arlegui & Soriano (2003) attribute detection of fractures with centimeters of offset to use of the radar system.

Photogeologic Lineaments

Topographic features referred to as lineaments likely reflect crustal structures (Bates & Jackson, 1984). Morphological features that are seen as lineaments often represent escarpments, mountains or streams. Tonal differences may be caused by the surface expressions of fractures, faults, and fault zones (Goetz & Rowen, 1981). Oftentimes, lineaments that exist over extended distances tend to represent fractures or shear zones (Hall, 1986). Two tasks involved in the evaluation of lineaments from remotely sensed data: the correlation of image data to field data interpretations and the establishment of equivalence between image data and field data (Csillag, 1982). A problem often arises when scientists attempt to judge the geological significance of features identified through remotely sensed processes because not all faults will exhibit surface expression. However, faults and fault zones may alter drainage patterns, have preferred vegetation patterns, or alter moisture patterns (Novak & Soulakellis, 2000). Because lineaments are linear features identified manually on remotely sensed images, it is necessary to

compare them with man-made linear features such as roads, fence lines, power transmission lines, and the edges of crop fields. This process is best accomplished using a Geographic Information System (GIS) for analysis.

As early as 1912, northwest-southeast trending lineaments, anticlines and synclines were identified in northwestern Missouri. During the 1960's members of the Missouri Geological Survey recognized that the anticlines projected downward into faults or fault zones in subsurface rocks with the area between being fault blocks. Further subsurface work carried out by the Missouri Geological Survey indicated that Precambrian basement rocks are dissected by fault zones identifiable in surface expression as lineaments. The lineaments correlate to previously mapped northwest-southeast trending anticlines (Gentile, 1968).

The Verdigris lineament is a major lineament in east-central Kansas comprising a series of smaller lineaments that correlates to well-known surface joint sets. The surface joints are related to deep faults in the crust. Lineaments are oriented northwest, north-northeast, and northeast. Most are identified by straight, continuous stream valleys, discontinuous valley segments or en echelon stream valleys. The linear stream valleys meet at angular junctions. Portions of creeks and rivers run in parallel trends or line up across drainage divides. The lineament represents a bedrock fracture pattern throughout east-central Kansas (Aber et al., 1997).

A lineament density study completed in the Williston Basin by the North Dakota Geological Survey found a spatial relationship existed between areas with high lineament density, lineament intersection, or lineament connectivity and wells producing oil. The study also found the dominant lineament orientations were NE to SW and NW to SE which is consistent with regional tectonic stress regimes and previous regional lineament studies (Anderson, 2008.)

Numerous oriented landforms and lineaments were identified by Diffendal (1994) from a digital shaded relief map of the United States and a synthetic-aperture radar map of the Alliance Nebraska 1 x

2 degree Quadrangle. Two dominant sets of lineaments exist: a northeast trending set that crosses drainages and a northwest trending set that parallels drainages. Additionally, circular features were identified in the northwest portions of the map; while chevron-shaped lineaments occur in the north-central portion. In western Nebraska some of the lineaments correspond to faults that are mapped as implied or buried faults. Other lineaments appear to coincide with extensions of faults mapped in Wyoming. Two prominent features extend from the central portion of the Alliance Quadrangle onto the North Platte Quadrangle appearing to disrupt the surface of dunes in the Sand Hills (Diffendal, 1994).

Aspect analysis on remotely sensed images of the southern Black Hills-Pine Ridge region revealed three dominant lineament trends: north, northeast, and northwest. A few possible explanations for the lineament trends should be evaluated. The north trend may be caused by the dominant steep north face of the Pine Ridge, regional slope or structural control. Major rivers within the study area flow southwest to northeast and thus may represent the northeast trend. Tributaries of the major rivers appear to line up with each other as well as with lineaments over long distances thus representing the northwest trend. As many faults and geologic structures are inferred on maps in northwestern Nebraska, remote sensing data can provide reconnaissance for ground verification and field mapping (Balmat & Leite, 2008).

Geophysical Lineaments

Geophysical data including seismic profiles, regional gravity, aeromagnetic, and electrical conductivity anomaly maps when integrated with geological studies can be used to understand subsurface structures and basement tectonic framework. When isostatic residual gravity maps are examined, most high anomalies can be explained by the presence of mafic rocks. Areas with low anomalies are often associated with sedimentary deposits, felsic rocks or to crustal downwarps. Most of the anomalies are found in areas of Precambrian tectonic activity and may be caused by the reactivation of those features. The gravity high extending northwestward from the Black Hills region is too large to

represent a basement upwarp associated with the Laramide. Instead, the gravity high may have an intrabasement source that is associated with the North American electrical conductivity anomaly, which extends to an exposed shear zone in Canada and likely is a Precambrian suturing of Proterozoic plate boundaries. Gravity anomalies that coincide with the northeast-trending Cheyenne Belt which is a Proterozoic suture support this interpretation. The Cheyenne Belt was reactivated during the Laramide resulting in gravity and electrical conductivity anomalies that converge with those of the Black Hills (Simpson et al., 1986).

Researchers in the Williston Basin successfully combined Bouguer gravity and high-resolution aeromagnetic anomaly maps to produce lineament maps that when combined with seismic profiles, borehole well-logs, and geological information resulted in the identification of six distinct basement structural zones and domains. Lineament orientations were reported as N-NE to SW and NW to SE (Li and Morozov, 2006).

Methodology

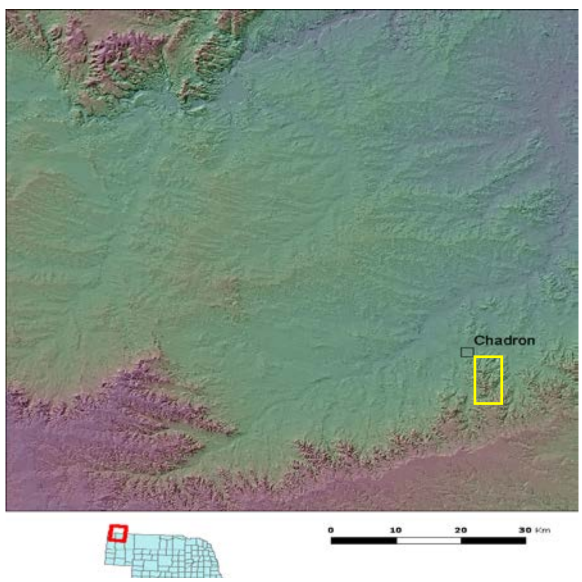
Research Design

The research design for this project is a descriptive structural geologic survey. Most university researchers restrict themselves to specialized methods and maps associated with their interests (Moseley, 1981). In this typical model, aerial photographs, satellite imagery, published literature, and existing maps are used for the initial planning stages. Once in the field, data collection consists of field notes, measured sections, sketches, and photographs. A structural survey will collect orientation and offset measurements of joints, faults and anticlines.

This project seeks to identify unmapped and implied geologic structures in the Pine Ridge region of northwestern Nebraska. Remote sensing and field techniques were employed during the course of this study. Methods used for remote sensing, lineament ranking, and field work are discussed in the following paragraphs.

Study Area

The remote sensing study area comprises northwestern Nebraska, southwestern South Dakota, and east-central Wyoming, which corresponds to the geographic area containing the Pine Ridge escarpment. It is bounded by latitude 44° on the north, 40° on the south, longitude -105.5° on the west, and -101° on the east (see Map 4). Data collected in the remote sensing study was used to help select the field study site.



Map 4. Remote sensing and subsurface study area. The Field study area, surrounded by the yellow box, is located on the north-south oriented ridge immediately south of Chadron.

A limited, yet lineament- and structure-dense area was selected for detailed study and mapping. The field study work focuses on the identification and description of faults, other geologic structures, landforms and sediments. The field study area is a 4 X 5 km region bounded by UTM coordinates (zone 13) 664000mE to 668000mE and 4735000mN to 4740000mN (see map 3).

Remote Sensing

The selection of remote sensing data was limited by data coverage and resolution available for the study area. In all cases, the finest scale available resolution data were selected. Automated lineament extraction software was not available; therefore lineaments were identified manually prior to beginning field work. The data used for remote sensing lineament identification in this study was obtained from the USGS Seamless Data Warehouse [USGS SDW], (2008), and included Landsat-Thematic Mapper (Landsat-TM), National Aeronautic and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM) elevation data, and Digital Orthophoto Quads (DOQs).

SRTM data with 1/3 arc second resolution were manipulated using ArcGIS. The data were resampled and reprojected to 10m spatial resolution, UTM projection. Hillshade was applied using the Spatial Analyst tool in ArcGIS. The default azimuth of 315° and zenith angle of 45° were used. The imagery was inspected at scales ranging from 1:5000 to 1:120,000. Lineaments were drawn manually and shapefiles created using the editing tool in ArcGIS.

Landsat-TM data with 30m resolution were manipulated in ArcGIS. Each Landsat band measures different light wavelengths (see Table 2 for descriptions of wavelengths and common uses.) Multiple band combinations were reviewed for visual suitability in lineament identification. Landsat bands 2, 4, and 7 assigned to red, green and blue respectively, were selected for use. The imagery was inspected at scales ranging from 1:500 to 1:120,000. Lineaments were drawn manually and shapefiles created using the editing tool in ArcGIS.

Landsat-TM Band 8 panchromatic data with 15m resolution were manipulated in ArcGIS. Cloud-free images were selected for May, 2008, and September 2008. The September image was subtracted from the May image. The resulting image displayed areas where vegetation had changed in the sampled inventory time as low values (dark). The imagery was inspected at scales ranging from 1:5000 to 1:120,000. Lineaments were drawn manually and a shapefile created using the editing tool in ArcGIS.

Landsat Band	Light wavelengths	Resolution	Common Applications
Band 1	0.45-0.52µm, blue-green	30m	Aquatic ecosystems, sediment in water, depth of water, coral reef mapping
Band 2	0.52-0.60 µm, green	30m	Vegetation and Band 1 items
Band 3	0.63-0.69 µm, red	30m	Vegetation, vegetation health
Band 4	0.76-0.90 µm, near infrared	30m	Water, land-water interface
Band 5	1.55-1.75 µm, mid-infrared	30m	Soil and vegetation moisture, clouds, snow
Band 6	10.40-12.50 µm, thermal infrared	60m 30m*	Surface temperature, geothermal, geologic processes, differentiate clouds from soils
Band 7	2.08-2.35 µm mid-infrared	30m	Soil and geology mapping
Band 8	0.52-0.90 µm panchromatic	15m	Geology

Table 2. Landsat bands with light wavelengths measured, resolution in meters and common monitoring applications for each band. * indicates data resampled by USGS after February, 2010 and available in either resolution. USGS Landsat Missions [USGS LM], (2011); Center for Biodiversity and Conservation American Museum of Natural History, (2011).

A natural-color DOQ with 1m resolution was manipulated using ArcGIS. The image was inspected at scales ranging from 1:50 to 1:12,000. Lineaments were drawn manually and shapefiles created using the editing tool in ArcGIS.

Lineament Ranking System

To achieve the study's goal, of assessing the structural significance of hundreds of candidate lineaments during a short field season, a series of criteria based upon remote sensing techniques and seismicity records were developed. Earthquake epicenters were obtained from the USGS Earthquake Search archives database [USGS NEIC], (2008). Table 3 presents the ranking criteria used to select field study locations.

Criteria	Yes	No
Lineament coincides with a mapped fault.	3	0
USGS Earthquake epicenter data point plots on lineament.	2	0
Lineament coincides with mapped implied fault.	2	0
Lineament crosses watershed/drainage system boundaries.	1	0
Lineament exists for distances greater than 10 km.	1	0
Lineament exhibits sharp bends.	1	0
Lineament identified on SRTM digital elevation model.	1	0
Lineament identified on Landsat image.	1	0
Lineament identified on topographic map.	1	0

Table 3. The weighted ranking system is used to identify locations where field verification of geologic structures has the greatest opportunity of success (Balmat & Leite, 2009).

Subsurface Study

The subsurface study area is bounded by latitude 44° on the north, 40° on the south, longitude 105.5° on the west, and 101° on the east (see Map 1). Subsurface well log data obtained from the State of Nebraska Oil and Gas Commission well-log database and the George Wulf well log card index at Chadron State College were entered into Microsoft Excel. A shapefile was created using the depth to the Greenhorn formation, an easily recognizable and widespread, limestone. A contour map of the surface of the Greenhorn formation was created using the Spatial Analyst tool in ArcGIS.

Geologic Field Study

Because remote sensing methods alone cannot accurately assess geologic features of a region, most studies also incorporate a field observations component. Remote sensing data were used to identify field study locations (Kervyn et al., 2006; Novak & Soulakellis, 2000). Deciphering structural geology and calculating the throw of a fault requires measuring sections and understanding the stratigraphic sequence, including key markers (Kottlowski, 1965; Moseley, 1981).

Field data were collected at sites within the field study area. The marker bed found within the study area is not described in current literature and is not mapped. Because it is significant to the study, a preliminary lithostratigraphic description will be completed. A provenance study and complete

lithostatigraphic description of the marker bed will aid in understanding the geologic history of the region; however, that study is beyond the scope of this project and designated for future work.

The instruments used for field data collection include Brunton compass for obtaining strike and dip measurements, rock hammer, tape measure, hand lens, dilute acid, collecting bags, permanent marker, field notebook, measured sections, topographic and geologic field maps, and camera.

Data Analysis

Fault and other geologic structure data collected in the field study area were documented in a field notebook. The data were then transferred to Microsoft Excel files. Lineament data managed in ArcGIS were exported to Microsoft Excel files. Fault data became sample 1 and random point data became sample 2 for statistical analysis. All statistical analyses were completed in Microsoft Excel.

Distance to Lineaments

To analyze distance from fault points to closest lineament a distance join was created in ArcGIS utilizing the spatial analyst tool join point to line. This process identifies fault points as centroids and locates the nearest lineament. Each centroid then has a distance and lineament identification associated with it. New fields are automatically created within the attribute table of the fault points shapefile that contain the distance in meters to the closest lineament and the lineament identification. The same procedure was repeated to join the random points shapefile with the closest lineament.

Analysis of distance from fault locations to closest lineament allowed the examination of the physical distribution or clustering of faults compared to lineaments. The combined lineament data sources were evaluated and each lineament data source was evaluated independently. In each case the null hypothesis and alternative hypotheses were the same. Null hypothesis: there is no difference in the mean distance of faults and random points to the closest lineament. Alternative hypothesis 1: the mean distance of fault to closest lineament is less than the mean of random point distance. Alternative

hypothesis 2: the mean distance of fault to closest lineament is more than the mean of random point distance. The difference between means was compared using the following statistic.

$$Z = \frac{(\bar{x}_1 - \bar{x}_2) - \delta}{\sqrt{(s^2_1/n_1 + s^2_2/n_2)}}$$

This test is used for sample sizes greater than 30. Delta represents a constant estimated from the population. When testing the null hypothesis of no difference between means, delta is set equal to zero. The remaining symbols in the equation represent the following: $\bar{x}_1$ is sample 1; $\bar{x}_2$ is sample 2; delta is the difference in population means; n is the number of items in the sample; and s is the sample standard deviation (Freund 1988, 311). Z scores were evaluated using the criteria described in Table 4.

Confidence Interval	Reject null Hypothesis if, otherwise accept the null hypothesis.
99.9%	z < -2.576 or z > 2.576
95%	z < -1.96 or z > 1.96
90%	z < -1.645 or z > 1.645
80%	z < -1.31 or z > 1.31

Table 4. The mean distance from fault points to closest lineament and the mean distance from random points to closest lineament were analyzed using the difference of two means. The resulting z-score was evaluated using the criteria in the table (Freund 1988, 311).

Evaluation at multiple levels of confidence began at the 80% interval and proceeded upward if criteria were met. This allowed the highest level of confidence to be determined depending upon the data set. Evaluation of each lineament data set independently may be valuable in the development of a remote sensing predictive model for fault location in the future.

Fault and Lineament Azimuths

The comparison of fault azimuth with lineament azimuth allowed evaluation of the relationship between physical faults and visualized lineaments. Fault azimuths were collected in the field. Lineaments intersecting the field study area and boundary as described previously were selected and azimuths were measured using an angle measuring tool in ArcGIS available from http://arcscripts.esri.com/details.asp?dbid=13543. A field for azimuth was added to the lineament attribute table. The lineaments were then joined to the fault shapefile using the ArcGIS join lines to

point tool. The differences between fault and nearest lineament azimuths were calculated. A ten degree difference range was selected, first to allow for any error in the remote sensing techniques; and second, to allow for the possibility that fault motion translated through a section of alternating soft and hard rock will have diffusion occur. Azimuth differences ranging from 0°-10° were considered matching; differences ranging between 80° and 90° were considered orthogonal.

A goodness of fit statistic based on chi-square criterion allowed for the comparison of the observed azimuth difference frequency with what would be expected if the azimuth difference frequency distribution were caused by random chance. The statistic to test for goodness of fit is represented by the following equation.

$$\chi^2 = \frac{\Sigma\,(o-e)^2}{e}$$

The observed frequency is represented by o and the expected frequency by e. The level of significance is determined from the degrees of freedom (k-m-1) where k is the number of terms in the $\Sigma\,(o-e)^2/e$ equation; m is the number of parameters of the probability distribution which have to be estimated from the sample data (Freund 1988, 368). In this application the probability is 0.11 as the data are separated into 9 azimuth difference frequency categories; and the value of m is zero. The confidence interval is 99.9% or p=.001 which gives a critical value of 26.125 at 8 degrees of freedom. The null hypothesis states the probability of each azimuth difference frequency is 0.11. The alternate hypothesis states the probability of each azimuth difference frequency is not 0 .11. Reject the null hypothesis if $\chi^2 > 26.125$, where degrees of freedom equal 8; otherwise state that the azimuth differences frequencies appear to be the result of random chance.

Results

Remote Sensing

Lineaments were identified on all selected imagery from November, 2008, to March, 2009.

Table 5 summarizes lineaments identified by imagery source and area.

Data Source	Lineaments Identified (total)	Lineaments Intersecting Field Study Area
SRTM	573	8
Landsat-TM Bands 2,4,7	490	8
Landsat-TM May-September	29	3
DOQ-1 meter	55	13

Table 5. Number of lineaments identified using each type of remote sensing imagery.

Lineament Ranking System

The lineament ranking system (see methods chapter) was applied and field tested during summer, 2009. Twenty-five lineament locations were studied in the field and no faults were identified. Three of the selected lineaments had USGS calculated earthquake epicenters less than 1 km away from them [USGS NEIC], (2008). Every field location consisted of a flat-bottom, steep sided, relatively narrow valley. On first inspection, the valleys appear to be dry stream channels. When valleys were located on USGS 7.5-minute quadrangle maps, they were found not to have streams flowing in them. Locations north of the Pine Ridge escarpment where the Pierre Shale and Chadron Formations are exposed had valleys that were several times wider than the sides were deep. This contrasts with locations south of the Pine Ridge escarpment where Quaternary loess and Miocene Arikarree formations are exposed at the surface. Southern locations studied had steep sided, flat bottomed valleys that were narrow, being only a few times wider than they were deep. Gravel deposits were found near 15 of the 25 valleys; in each case the gravels had been mined either privately or commercially.

One southern field location studied had a long lineament, segments of which appear on SRTM, Landsat bands 2- 4-7, and Landsat May-September images, also had a concurrent earthquake epicenter. The epicenter was located in the middle of a cultivated field. The lineament azimuth was coincident

with a straight low groove which had gently sloping sides. The north face of the Pine Ridge began across the county road from the field. The azimuth of a steep-sided ravine matched that of the groove in the field and the lineament.

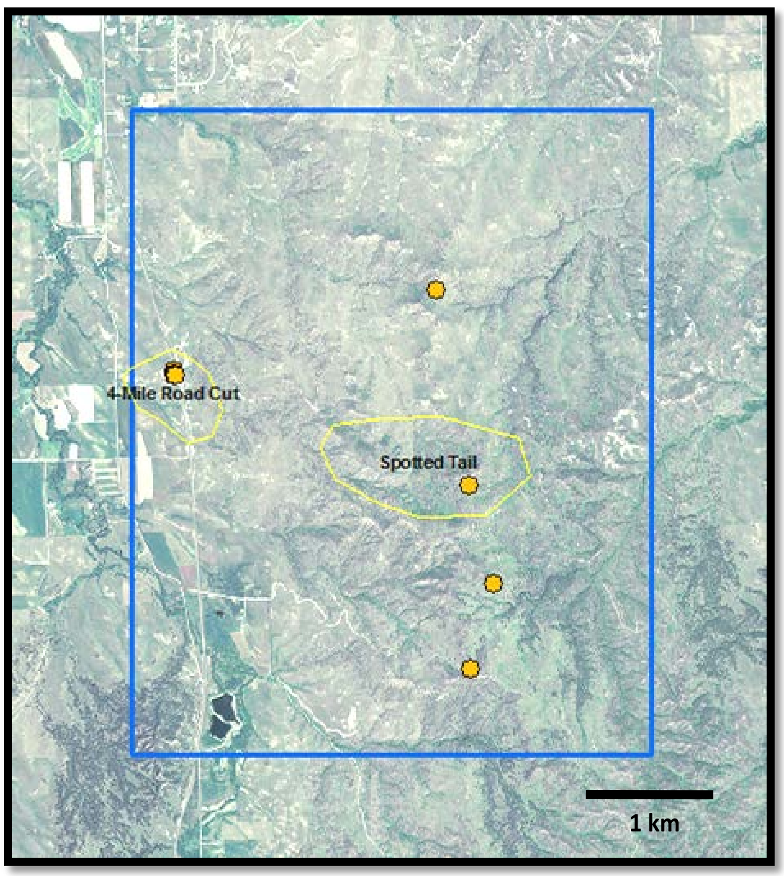
Subsurface Study

A contour map of the surface of the Greenhorn Formation was evaluated for structure and compared with faults identified by DeGraw (1969) using a hand contouring technique. Automated contours completed in ArcGIS were inconclusive because the automated contour tool does not consider the presence of faults. The map of the study area with well locations and depths to the Greenhorn Formation was printed and contoured by hand. Areas with large change in surface elevation over a small distance were considered faults. These areas coincide with the Bordeaux Creek, Bordeaux Segment, Chadron Creek, White River, and Pine Ridge Faults identified by DeGraw (1969).

Geologic Field Study

A preliminary lithostratigraphic description was completed on the ledge-forming fedspathic cross-bedded conglomerate and sandstone unit that crops out in many locations in the field study area and serves as a prominent marker bed for structural purposes. The upper contact is an unconformity at the base of the Quaternary loess upon which the modern soil is developed. Thickness of the conglomerate varies from 1-4 meters with 2 meters most consistently throughout its exposure. Sub-angular alkali feldspars with maximum grain size 12mm, rounded to sub-rounded plagioclase feldspars with maximum grain size 5mm, angular chert with maximum grain size 20mm, angular to sub-angular grains of quartz with tourmaline inclusions, andalusite, and hornblendes indicate a Black Hills source. The conglomerate does not contain reworked Pine Ridge derived rock and lacks the abundant presence of heavy minerals prevalent in the Arikaree Formation. The conglomerate does contain rare rounded conglomerate clasts with grain size 10-17.50mm. Within the field study area, the conglomerate grain size is largest to the north and becomes finer to the south. Paleocurrent indicators point to transport

from the north to the south with east-west channel migration. No fossils, carbon or ash deposits have been recognized that could be used for dating and correlation. The basal contact is an unconformity. The underlying lithology is the Anderson Ranch formation. Four measured sections were completed at 4-Mile Road Cut (see Map 5 for location) in a north-south transect along the road cut (see measured sections A-D and Image 1). Another four measured sections were completed in a north-south transect through roughly the middle of the field study area (see Field Study Area measured sections 1-4).

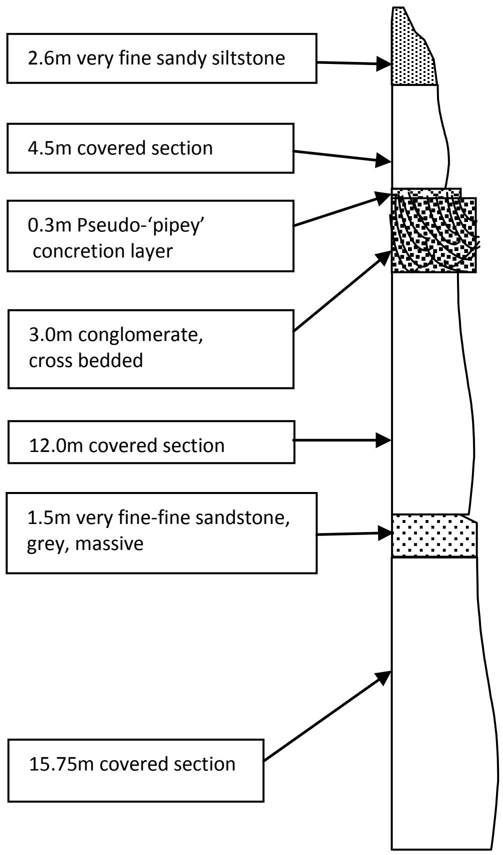


Map 5. Field study area south of Chadron, NE. Measured sections were completed at orange dots. Field localities with clusters of faults are outlined in yellow.

Field Study Area Measured Sections

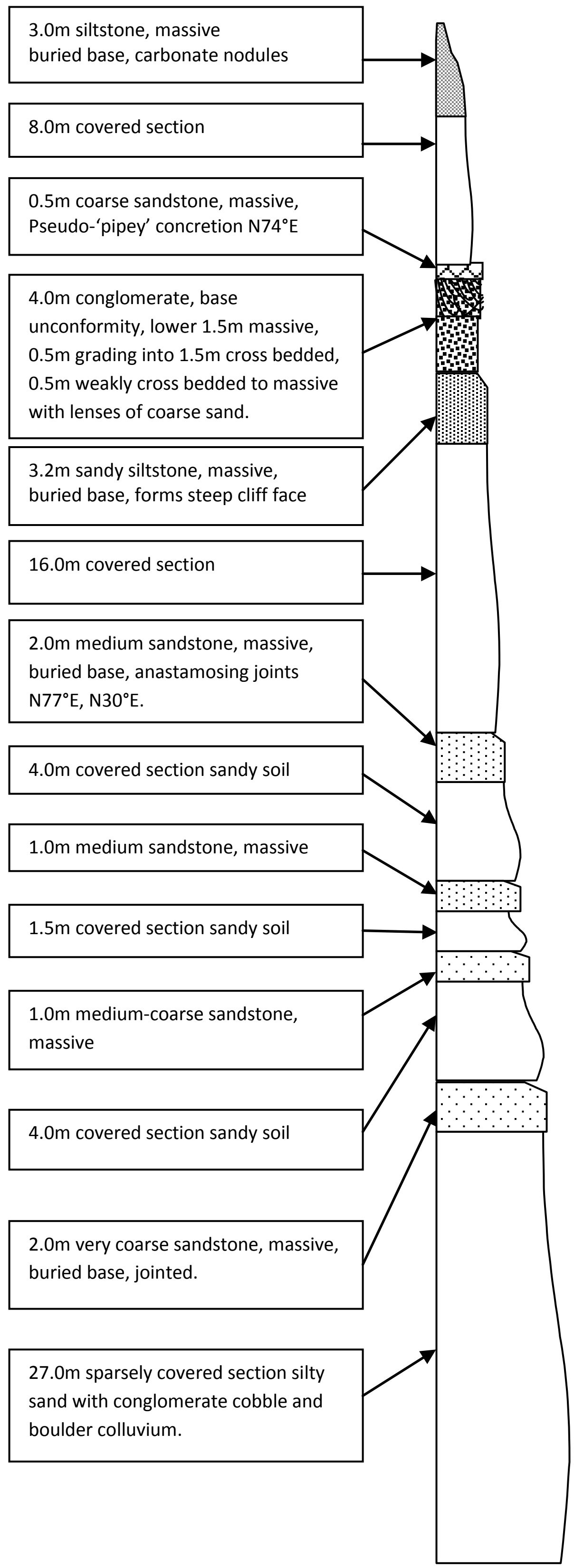
Measured Section 1 – Field Study Area

Base of section at UTM 666018mE 4736909mN, Zone 13T



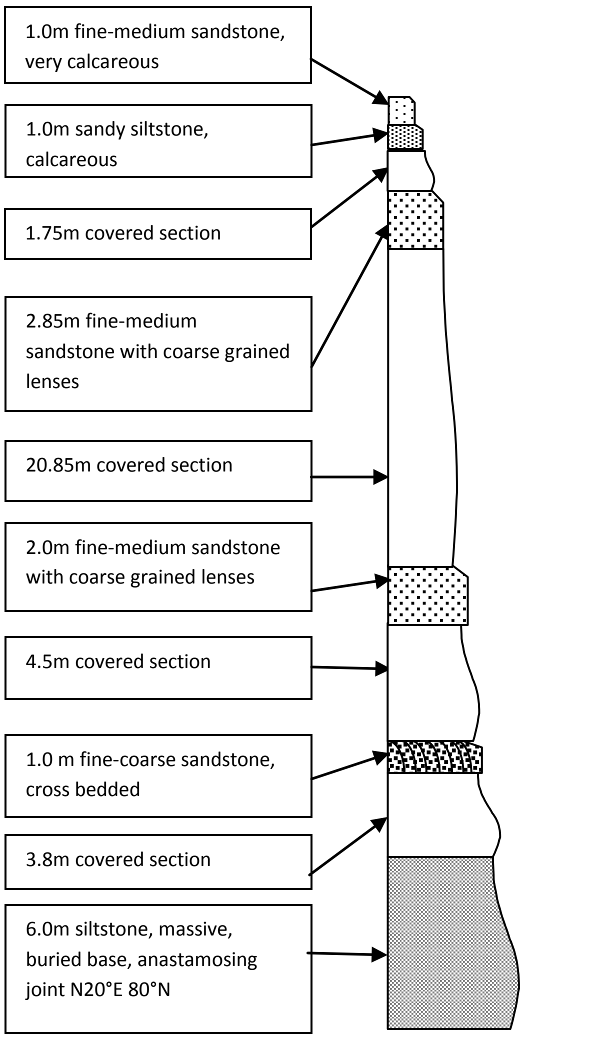
Measured Section 2 – Field Study Area

Base of section at UTM 0665658 mE 4739043mN, Zone 13T

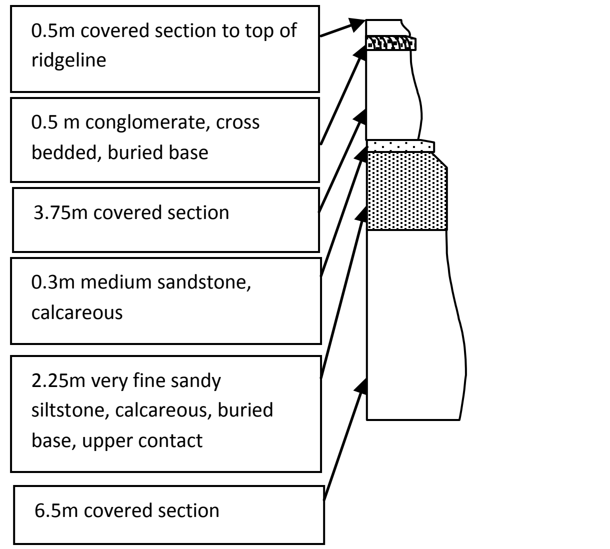


Field Study Area Measured Sections

Measured Section 3 – Field Study Area
Base of Section at UTM Zone 13T 0666288mE 4735846mN



Measured Section 4 – Field Study Area
Base of Section at UTM Zone 13T 0666044mE 4734924mN



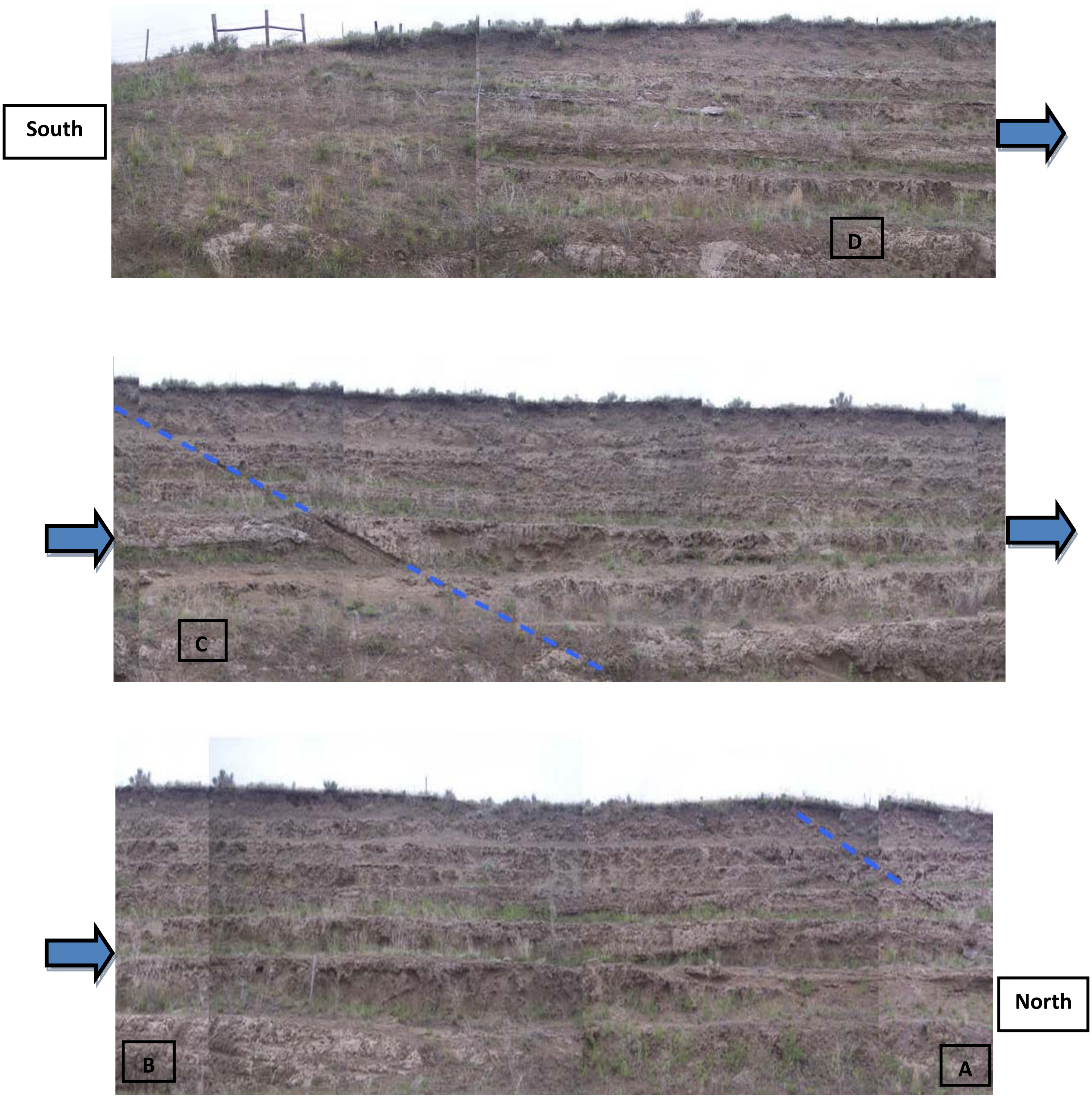
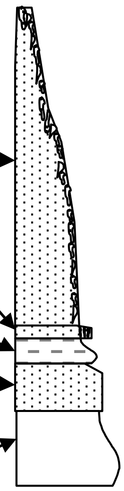


Image 1. 4-Mile Road Cut locality west exposure with measured section location identification. The 4-Mile Road Cut locality is approximately 4 miles south of Chadron on U.S. Highway 385.

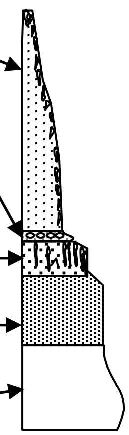
4-Mile Road Cut Locality Measured Sections

6.8m medium sandstone, 7.5YR 5/4, friable, not calcareous, weathering complex rounded nodular peds
0.20m medium sandstone, 7.5YR 5/4, friable, not calcareous, weathers to columnar peds
0.8m sandy shale, fissile, calcareous
1.0m massive medium sandstone, 7.5YR 5/4, not calcareous, no weathering peds, no concretions
1.60m covered section



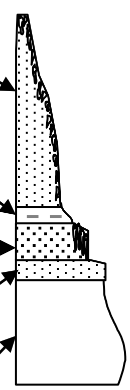
Measured Section D – 4 Mile Road Cut
Base of Section at UTM Zone 13T 662832mE 4738109mN

4.5m medium sandstone, 7.5YR 5/4, friable, not calcareous, weathering complex rounded nodular peds.
0.20m very fine clayey sandstone, 5YR 6/3, shale rip up clasts, very calcareous, fissile
0.75m medium sandstone, 7.5YR 5/4, not calcareous, weathering complex columnar peds, vertical burrows.
1.80m very fine sandstone, 7.5YR 5/4, clasts in upper 0.5m fine sand 10YR 5/4, not calcareous, no peds, no concretions
1.95m covered section



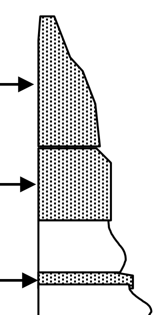
Measured Section C – 4 Mile Road Cut
Base of Section at UTM Zone 13T 662823mE 4738117mN

3.40m medium sandstone, 10YR 5/3, friable, not calcareous, weathering complex rounded nodular
0.40m very fine sandy shale, 5YR 5/6, fissile, very calcareous, upper and lower contact abrupt.
0.78m fine sandstone, 7.5YR 4/4, friable, not calcareous, weathering complex columnar peds.
0.48m fine-medium sandstone, 7.5YR 5/2, friable, not calcareous, no peds, no concretions
2.4m covered section

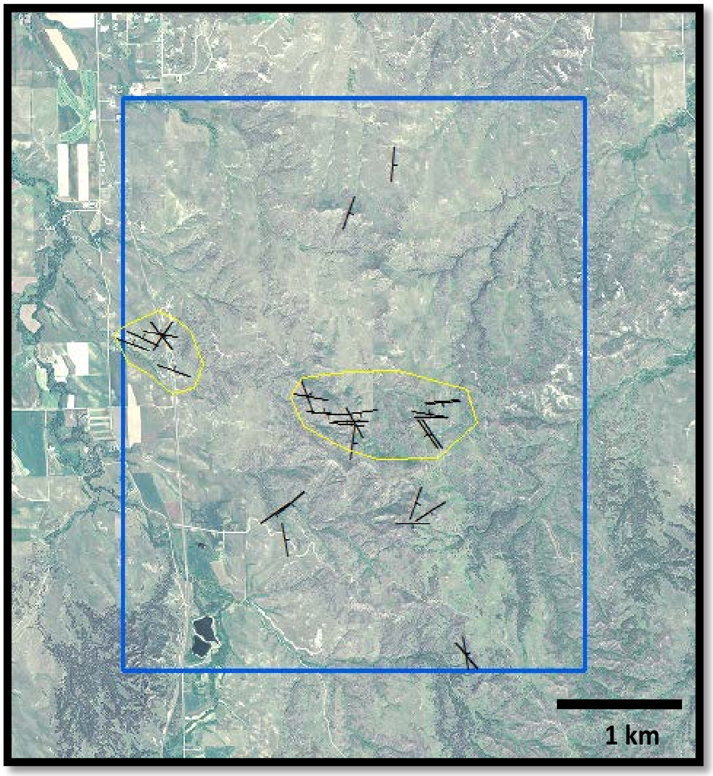


Measured Section B – 4 Mile Road Cut
Base of Section at UTM Zone 13T 662820mE 4738135mN

2.60m very fine sandstone, 7.5YR 4/4, not calcareous, no peds, no concretions, cementation decreases moving up from base.
1.70m very fine sandstone, 7.5YR 4/4, not calcareous, buried base, friable, irregular rounded peds. Upper contact gradational.
1.0m covered section
0.12m very fine silty sandstone, 7.5YR 5/2, calcareous
0.5m covered section



Measured Section A – 4 Mile Road Cut
Base of Section at UTM Zone 13T 662816mE 4738155mN



Map 6. Fault locations mapped within the field study area. Fault symbols are oriented to fault azimuth.

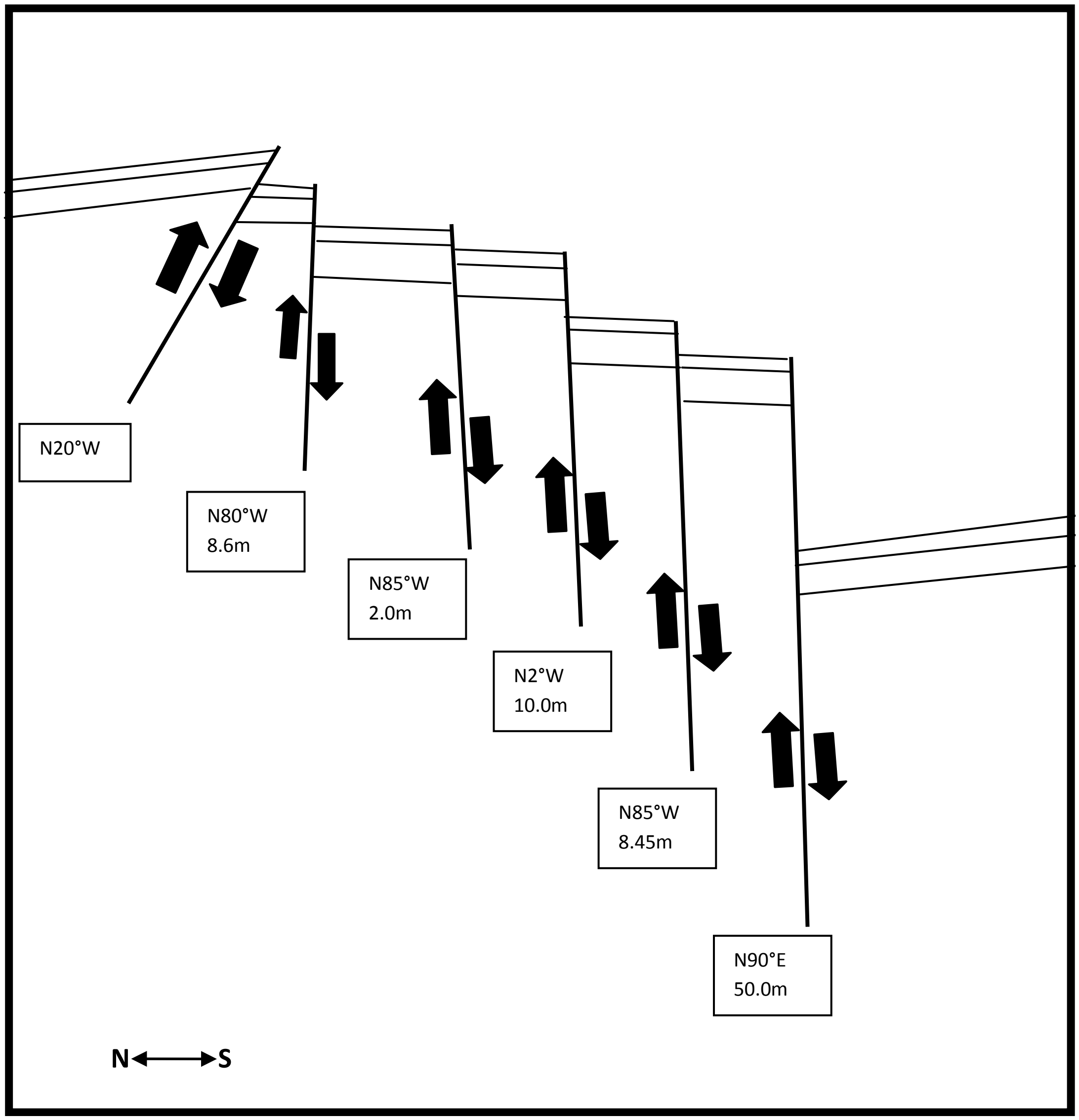
While individual faults occur throughout the study area, clusters of faults and joints were found in two major regions within the field study area: 4-mile road cut and Spotted Tail see Map 5 for locations. Locations of all faults are depicted in Map 6 and displayed along with orientation data in Table 4. Regions lacking outcrop exposure and /or that are heavily vegetated with grass cover could not successfully be surveyed for faults. Such regions occurred along the eastern side of the field study area and along the southwestern portion of the field study area. The presence of faults in these regions cannot be ruled out.

Meters Easting	Meters Northing	Strike	Dip
662826	4738072	N38W	78NE
662837	4738066	N34E	75SE
662824	4738122	N80W	40N
662465	4737995	N70W	13N
662611	4738071	N65W	64N
664361	4735604	N10W	70E
664200	4735910	N55E	70W
664432	4736028	N50E	72NW
664862	4737099	N92E	90S
665146	4737011	N90E	90S
664805	4737165	N85W	90S
664671	4737361	N80W	90S
664636	4737367	N20W	10SW
666126	4736882	S55E	90S
666072	4736879	S55E	90S
666263	4737234	N85E	90S
666254	4737262	N85E	90S
665205	4736777	N7E	*
666567	4734200	N40W	47SW
666577	4734212	N10W	42SW
665891	4735768	N90E	90S
665943	4736043	N20E	90S
666130	4737108	N90W	N90E
666114	4737149	N81W	89N
665200	4737032	N29W	90N
665095	4737023	N85W	85W
662949	4737681	N70W	68N
666128	4735915	N57E	2NW
665654	4740167	N5E	65E
665130	4739593	N20E	90W
665263	4737105	N82E	90S

Table 4. Fault location in UTM meters with fault orientation measurements recorded in the field. (*) measurement not recorded in the field.

Faults at 4-mile road cut west exposure are a series of low-angle faults with total offset of 1-2 meters. The faults extend from the base of the road cut to the base of the modern soil, are down to the south, and cut poorly defined horizontal beds of the Monroe Creek formation. Fault planes exhibit differential cementation with mineralization in the fault and demineralized zones around it. The mineralized rock does not display slickenlines. The normal fault found in the east exposure has approximately 0.2 m offset. It cuts cross-bedded sandstones of the Anderson Ranch Formation. The fault is not mineralized, is down to the north, and does not display slickenlines. Dips on the cross-bedded sandstone are to the north and become steeper upward through the outcrop.

The faults identified at Spotted Tail are a series of approximately vertical normal faults with near east-west and northwest-southeast strike that divide the north-south oriented ridge into a series of horsts and grabens. Fault scarps have eroded into narrow valleys that divide fault blocks (see sketch 2).



Sketch 2. Field diagram of north-south oriented ridge south of Chadron, Nebraska. Dips on beds are exaggerated. Diagram is not to scale. Relative motion and offset on faults depicted.

Data Analysis

Compiled field data was used to create a geologic structure map of the field study area. Each type of lineament data and fault data were analyzed using ArcGIS. For this analysis, a boundary replicating the field study area with a 100 meter boarder was created. Lineaments that intersected the boundary were used in analysis. The field study area contained 31 fault points. The fault points became sample 1. Thirty-one random points were generated in ArcGIS and became sample 2. All measurements were made using tools in ArcGIS.

Distance to Lineaments

The combined lineament data set was used to test the null hypothesis that there is no difference between mean distance from faults to lineaments and mean distance from random points to lineaments. The null hypothesis was rejected at the 99.9% confidence level based on a z-score of -4.28 and the alternative hypothesis that the mean fault to lineament distance is smaller than that from random data was accepted.

Each lineament data set was then evaluated independently to test the null hypothesis of no difference between mean distance from faults to lineaments and mean distance from random points to lineaments. Z-scores were evaluated at the 80%, 90%, 95% and 99.9% confidence intervals. Table 5 displays test results. The null hypothesis stating no difference in the mean distances was rejected; and the alternative hypothesis that the mean fault distance to closest lineament is less was accepted for the May-September Landsat, SRTM, and DOQ-1m data sets.

Lineament Data Set Source	Fault Point to Lineament Mean Distance, meters	Standard Deviation	Random Point to Lineament Mean Distance, meters	Standard Deviation	Z-score	Confidence Interval	Accept or Reject Null Hypotheses
May-Sept Landsat	675*	562	1192	570	-3.59	99.9%	Reject
SRTM	506*	305	629	391	-1.38	80%	Reject
Landsat 2, 4 &7	330	268	361	313	-0.411	80%	Accept
DOQ- 1m	243*	216	348	220	-1.89	90%	Reject

Table 5. Difference of two sample means test results with confidence intervals all data were rounded after calculations.

Fault and Lineament Azimuths

When considering the four lineament data sets together, there were 29 out of 124 occurrences when the difference between the fault azimuth and the closest lineament's azimuth were in the range 0°-10°. Table 6 displays fault and lineament azimuth difference frequencies and probability of occurrence. The total frequency for each azimuth difference range was used for the goodness of fit statistic to test the null hypothesis that the frequency of azimuth difference is random chance. The null hypothesis was rejected at the 99.9% confidence level based upon a critical value of χ^2 = 26.125 and calculated χ^2 = 34.48. The alternate hypothesis that the azimuth difference frequencies are not attributed to random chance was accepted.

Fault & Lineament Azimuth Difference	Probability	Expected Frequency	FSA 1-m Observed Frequency	SRTM Observed Frequency	Landsat-1 Observed Frequency	May-Sept Landsat Observed Frequency	Total Observed Frequency
0°-10°	0.11	13.64	11	9	5	4	29
11°-20°	0.11	13.64	4	1	6	1	12
21°-30°	0.11	13.64	1	1	4	1	7
31°-40°	0.11	13.64	0	2	2	4	8
41°-50°	0.11	13.64	1	1	3	6	11
51°-60°	0.11	13.64	1	11	1	9	22
61°-70°	0.11	13.64	1	2	4	2	9
71°-80°	0.11	13.64	1	3	3	0	7
81°-90°	0.11	13.64	2	1	3	4	10

Table 6. Fault and lineament azimuth difference frequencies by lineament source. Total observed frequency used in chi-square calculations.

Discussion

The 4-mile locality consists of two road cut exposures separated by approximately 0.5 km. At the northern end of this locality the road cut faces east and the southern road cut faces west. The Anderson Ranch formation crops out at the eastern 4-mile road cut where it consists of thin bedded fine grained sandstone. Bedding plane dips are about 10° to the north at the base of the outcrop, decreasing to 8° near the top. This indicates that uplift was occurring to the south of this location contemporaneous with deposition of the sandstones. The upper contact of the Anderson Ranch Formation at this site is an unconformity that truncates cross beds and upon which the modern soil is developed. The base, or lower contact, is buried.

Meanwhile, the west exposure of the 4-mile locality does not display any crossbedded sandstones. Instead it consists of massive very fine to fine weakly cemented sandstone interbedded with sandstone ledges underlain with beds of clay clasts. The weakly cemented sandstones weather into columnar and rounded nodules reminiscent of soil structures; however, no obvious soil horizons were identified. The upper contact is an unconformity at the base of the modern soil. The lower contact is a discontinuity with a massive grayish to pale brown silty sandstone whose base is buried. The surface geology in this area was previously mapped as Monroe Creek formation by LaGarry and LaGarry (1997). The presence of the structures found in this exposure would suggest it corresponds to the thick layer of grey to buff colored fine to medium sandstone that contains “potato” and “pipey” concretions described by Shultz (1941); however, close inspection reveals that the ledges are isolated lenticular beds that lack internal bedding and no concretions are present indicating that the columnar and rounded structures exhibited are likely the diagenetic results of insect bioturbation and soil development. These interpretations, combined with grain size and color, indicate that the lithology at this exposure is the Harrison formation. Neither scenario matches well with Tedford et al. (2004) who described a regional disconformity which has the Monroe Creek formation and Harrison formation absent in outcrop; and

younger units, such as the Anderson Ranch, deposited on top of older rocks containing Sharps and Wooded Knee-type fauna near Chadron.

The western exposure of the 4-mile road cut also contains a series of small-scale thrusts with maximum offset of 2m, up to the north. Thin beds of clay nodules were used for determining offset because the lenticular sandstones were too variable to use as markers. The entire road cut contains jointing orthogonal to the faults. The small-scale thrusts suggest that a highland, shedding packages of the Harrison formation due to gravity, was situated somewhere north-northwest of the present day hill. The north-northwest location is now a valley drained by Chadron Creek, which was mapped as a fault by DeGraw (1969) based upon subsurface data. The west flank of the hill this site is located upon is cut by a steep-sided canyon whose azimuth is within 10° of the azimuth of the joints found in the road cut; at its base is a gravel deposit mined for municipal use. A normal fault with 14cm offset was also mapped on the western flank of the hill.

Moving south along US Highway 385, a lack of road cuts and outcrop exposures exists because the adjacent land consists of rolling hills vegetated with grasses and used for grazing. However, visible beyond the rolling hills to the east, is a prominent ridge extending from Chadron at its north end southward to join the main escarpment of the Pine Ridge. Its eastern side is flanked by Bordeaux Creek, which was also mapped as a fault by DeGraw (1969), and its tributaries. This highland or ridge is an area of inverted topography where former streams flowed from the west and south in lowlands depositing interbedded sandstones and floodplain sandy siltstones incised into the softer rocks of the White River Group. These sandstones were then topped with a stream deposit.

The younger stream deposit is different in several important ways. The first and immediately noticeable difference is grain size. The younger stream deposit is a conglomerate with clast grain size ranging from 1-20 mm. Its clasts are angular to subrounded. The grain size and lack of roundness of clasts indicate a nearby source for the sediment. The upper contact is an unconformity upon which

Quaternary loess is deposited. The basal contact is an unconformity at the top of the Anderson Ranch formation. The upper surface of the conglomerate is eroded and 3-dimensional troughs are visible in most exposures. Paleocurrent indicators suggest water was flowing from the north to the south. This is the opposite direction of water flow from the older Anderson Ranch formation which flowed from the south and west bringing fine grained sediments from a western source. The suite of minerals contained in the conglomerate, combined with grain size and paleocurrent indicators, suggest a Black Hills source for the sediments. The unit is between 1 and 4m thick, with 2m thickness occurring in most locations. Its upper contact has been eroded at most places. These observations do little to answer the question of the time it took to deposit this unit. The lack of fossils preservation within the unit and size of the sediment contained in the crossbeds are indicators of fast moving water.

The stratigraphic position of the conglomerate makes that unit stratigraphically equivalent to the Ogallala Group and an argument could be made to identify it as a new unit of the Ogallala Group. However, since Swinehart et al. (1985), describe the Ogallala Group as having a western source, the Black Hills source of the conglomerate does not fit lithologically with the formations of the Ogallala Group. Therefore it represents a period of time after Arikaree rocks had already been deposited as a blanket of sediments extending from the Rocky Mountains in the west and the Black Hills in the north out across the Great Plains of today. Much as the Ogallala Group rocks were valley and channel filling sands and gravels filling the basins south of the Pine Ridge, this conglomerate is the result of a similar, yet smaller scale, depositional environment occurring in the basin between the southern Black Hills and the Pine Ridge.

If we return our attention to the north-south oriented ridge south of Chadron, we can focus on the faults. The northern section of the ridge is divided into east and west blocks by a fault oriented approximately N20°E, down to the west, with 9 m offset. This NE-oriented fault is intersected by a smaller fault oriented N5°E and dipping 65°E with 0.5m offset down to the east. The N5°E fault is in

Quaternary alluvium, is not mineralized and has a clastic dike associated with it. The lineament associated with this fault extends southward stopping just north of the Spotted Tail locality and likely represents a buried fault and is expressed at the surface as a steep sided, flat bottomed valley.

The main fault at the Spotted Tail locality is an east-west striking (N90°E) fault with an associated lineament that extends eastward beyond the mapped fault. To the east is a hill isolated from the main north-south oriented ridge. Offset across the east-west fault is 25m at this location. The western series of hills are part of the main ridge that runs north-south. Offset was measured in two locations across the N90°E fault. Offset on the east side is 60m; and offset on the west side is 50m. Beds on the hill immediately south of this location dip to the north. Moving north from this location, the ridge is cut by four more faults N85°W with offset 8.45m dipping 85°W, N2°W with offset 10.0m ~90°S, N85°W with offset 2.0m dipping ~90°S , N80°W with offset 8.60m dipping ~90°S, and N20°W (see image 2 for view looking east from Highway 385). Beds north of the N20°W fault dip to the north. This reversal of dips occurs along a poorly exposed fault trending N20°W which would lead one to suspect reverse faulting or an asymmetrical anticline with normal faulting on the southern limb. This fault lies approximately 1km east-southeast of the 4-mile road cut west exposure where thrust faults strike N17°W and N16°W and 1km south-southwest of the Quaternary fault previously described. No lineaments or valleys connect the sites; however, it seems unlikely that there is no association at least with the thrust faults at the 4-mile road cut locality.

A common feature of all the normal faults is narrow, deep, steep-sided, flat-bottomed canyons across which the fault offset was measured using the conglomerate as a marker bed. When inspecting the remote sensing images it is apparent that many of the lineaments within the study area coincide with these valleys. This does not appear to be uncommon in the region. The White Clay fault rupture mapped by Fielding et al. (2007) found surface ruptures of the fault are relatively narrow, steep sided,

flat-bottomed valleys that had filled with sands and gravels transported by water. The gravel deposits were later mined for municipal use.

Peters et al., (1986) in a lineament and geochemistry study in South Dakota found that lineaments 16km or longer associated with the White River, the Cheyenne River and several other rivers, where actually geologic structures allowing the mixing of groundwater between confined aquifers. The Peters study stopped short of calling the lineaments faults, having never ground verified them as such. However, it seems apparent that the structures manifesting themselves as lineaments and capable of transmitting groundwater between confined aquifers must therefore, in that case, represent faults extending to deeply buried rocks. Near Crawford, Nebraska, the White River fault has 400ft of offset. That portion of the White River has a lineament that coincides with it. Another lineament coincides with the Bordeaux Creek fault which was identified by DeGraw (1969).

The statistical analysis of the mean distance difference from faults to lineaments and from random points to lineaments found that faults were significantly closer to lineaments than random points. This indicates that lineaments actually represent faults or that the faults are clustered near the lineaments. The conclusion that the lineaments actually represent faults is supported by the azimuth difference data. The orientation of surface faults correlate with and are likely caused by a reactivation of strain on buried faults. Other evidence that supports the conclusion that lineaments represent faults is that lineaments are long and cross regions of lithologic change as well as watersheds. Because the basement rocks beneath the Chadron area are shallow (approximately 5000 ft) the buried faults are likely associated with or in fact are basement faults.

The difference in azimuth data also hints at some interesting findings that would require additional research. Most of the joints identified in the fault regions were orthogonal joints. The azimuth difference data found 10 faults had azimuth orthogonal to the closest lineament. However, most interesting, is if we accept the premise that lineaments actually represent buried faults then, the

second most populated frequency was the 60° difference frequency. This would indicate that 22 faults had azimuth conjugate to the closest lineament azimuth thereby indicating a horizontal primary stress or thrust. This is tentatively supported by the thrusts found running along the north-central portion of the field study area. However, further study focused primarily on those locations would be essential to identifying and explaining the source of stress.

Interesting field findings that require additional study are the faulted Quaternary rocks with clastic dikes that at least preliminarily indicate two things: first, shaking strong enough to liquefy and suspend sediments causing them to inject into fractures in the rock along faults; and second, this strong shaking has occurred in the last 2 million years. Presuming the age of faulting is less than 2ma, questions of dating could be resolved using radiocarbon dating of soil horizons found in these areas.

The mapping of regions adjacent to this study's field study area may extend identified faults and/or produce more mappable structures. Mapping the extent, thickness, and paleocurrent indicators of the conglomerate used as a marker bed in the field study area along with a complete sedimentological and mineralogic assessment will provide valuable knowledge about the environment that existed in the basin during the time it was deposited as well.

More advanced remote sensing techniques and visualizations combined with well log identified structures can be correlated with lineaments, and mapped faults will aid in finding, ground verifying and mapping structures. While this process was started during this project by creating the Greenhorn Formation subsurface contour map, the inability to combine the well-logs with subsurface contour maps and surface remote sensing images in appropriate software, limited exploration of lineament and subsurface structure relationships.

Because of a lack of bedrock mapping in Nebraska, a published structural map of the whole state does not exist. Faults have been identified by various authors in the literature. The lack of a Nebraska structure map and the emphasis of South Dakota structure maps on the Black Hills, the

proximity of the South Dakota state line of which the White Clay fault runs along for several kilometers, the Sandoz Ranch fault which extends from the west end of the White Clay fault northwestward toward Olerichs, South Dakota, and the unpublished revised stratigraphy in Nebraska, has lead to several errors in fault names and location references in the literature. Swinehart et al., (1985) refer to the Pine Ridge fault as a subsurface fault identified by offset in buried ash beds. The fault lies north of the Niobrara River and south of the Pine Ridge escarpment. It was also identified by DeGraw (1969) using well logs. Unfortunately, this confusion could be made worse by the addition of the faults identified in this study. The confusion will likely continue in the literature until someone publishes a structure map for the state of Nebraska.

Conclusions and Implications

The first research question this project sought to answer was, "Are lineaments identified on remotely sensed data faults or other geological structures that can be verified and mapped on the ground?" The field study area results demonstrate that in 29 of 124 instances faults have azimuths that match, within 10°, the azimuth of their closest lineament. The frequency distribution of lineament and fault azimuth differences was found to be statistically significant and therefore not random. The mean distance from mapped points lying on faults to lineaments was demonstrated to be significantly closer than that of random points. Therefore I conclude that lineaments within my study site do represent faults.

The second question was, "Do subsurface structures identified from subsurface configuration maps coincide with remotely sensed lineaments?" Major structures identified in the subsurface by DeGraw (1969) include the Chadron Creek fault, Pine Ridge fault, Bordeaux Creek fault, and the Bordeaux Segment fault. The White River fault was identified by geologists mapping subsurface configuration at the Crow Butte uranium mine near Crawford, Nebraska. All of these faults identified using subsurface configuration maps were identified on my hand-drawn contour of the Greenhorn surface map; however, lineaments identified using remote sensing techniques could not be integrated with subsurface data in appropriate software. Lineaments were found to match the White Clay fault, portions of the White Clay surface rupture, the Sandoz Ranch fault and geologic structures in the southern Black Hills.

The third questions asked, "How are faults expressed in outcrop in the Pine Ridge?" The majority of faults identified and mapped in the field study area were expressed along narrow and deep (with widths approximately one-quarter to one-half as wide as the valley is deep), steep-sided (with slopes greater than 23%) valleys with relatively flat bottoms. Offset was measured across canyons using a prominent conglomerate as a marker bed. The presence of a reliable marker was vital to

measurement of offset in nondescript soft rocks common in the region. Thrust faults were the only faults in the field study area that were mineralized.

Multiple lines of evidence support the conclusion that there have been several periods of uplift on the Pine Ridge south of Chadron, Nebraska. Bedding plane dips that decrease upward through a section of faulted Anderson Ranch formation rocks indicates that uplift and deformation of rocks were taking place during deposition. The presence of an Ogallala equivalent cross bedded conglomerate with sediment source and paleocurrent indicators pointed toward a Black Hills source provide evidence that the Ogallala-equivalent sediment package extended from its present day limits north to the Black Hills. This conglomerate acts as a resistant ledge-forming rock that helps to hold up the north-south oriented ridge south of Chadron. The rocks in this ridge are cut by reverse and normal faults. Full kinematic understanding of the relationships between reverse and normal faults in these rocks would require more field data. This study's conclusions were restricted by limited data collection in areas with poorly exposed rock. Faulting and associated clastic dikes also occurs in Quaternary-aged rocks.

Deciphering the kinematics and dynamics that lead to repeated episodes of uplift along the Pine Ridge will require kinematic analysis of faults, continued mapping of faults, and some analysis of basin evolution. This study has also demonstrated that not all geologic processes work slowly as the landscape of northwestern Nebraska and southwestern South Dakota appear to have evolved rapidly in response to faulting.

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