FRACTURE ARCHITECTURE OF THE HIGH PLAINS AQUIFER, NORTHEASTERN TEXAS PANHANDLE: IMPLICATIONS FOR GEOLOGIC STORAGE OF CARBON DIOXIDE

By

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Abstract: Surface and airborne gas monitoring programs are becoming an important part of environmental protection in areas favorable for subsurface storage of carbon dioxide. Understanding structural architecture and its effects on the flux of fluids, specifically CO_2 and CH_4, in the shallow subsurface and atmosphere is helping design and implement next generation monitoring technologies, including unmanned aerial vehicles (UAVs). An important aspect of this research is using subsurface fracture data to inform the design of flight pathways for UAVs in the Farnsworth Oil Unit of the Anadarko Basin.

The High Plains Aquifer of the northeastern Texas Panhandle disconformably overlies Permian and Triassic redbeds and is dominated by weakly to moderately indurated sandstone in the Ogallala Formation. Ogallala strata are overlain by Quaternary strata that include chert and caliche caprock. The target zone for CO_2 storage and enhanced oil recovery in the Farnsworth Oil Unit is in upper Morrow sandstone at subsurface depths greater than 2,000 m. Field study reveals that indurated sandstone and chert contain numerous joints that provide crucial insight into aquifer architecture and subsurface flow pathways.

Properties of more than 1,700 joints were measured in the field and in high-resolution satellite imagery. The joint networks consist of well-developed systematic joints and cross-joints. In vertical section, the joints are typically curvilinear and strata-bound. Two distinctive joint systems were identified in the study area. Joint spacing follows a log-normal statistical scaling rule. These fractures appear to be the product of regional tectonic stress and may have a significant effect on flow in the High Plains Aquifer system. Based on the results of this research, design of UAV flight paths should be oblique to fractures in a way that maximizes the likelihood of CO_2 and CH_4 flux from systematic joints and cross joints. Geological risk of leakage from CO_2-enhanced oil recovery operations at Farnsworth is low, and multiple potential natural sources of CO_2 and CH_4 have been identified in near-surface formations. These near-surface sources are predicted to dominate shallow subsurface and atmospheric gas flux.

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INTRODUCTION

Ensuring safe, permanent storage of CO_2 is vital for the success of subsurface geologic CO_2 storage projects. The development of robust monitoring technology is vital for validating storage permanence, as well as for ensuring the integrity of storage operations. Accordingly, monitoring programs are considered essential for meeting the goals of CO_2 emissions reduction, environmental protection, and human health and safety (National Energy Technology Laboratory, 2012). This study is part of a larger investigation that aims to advance the state of the art of surface and airborne monitoring and includes the deployment of low-flying unmanned aerial vehicles (UAVs) for near-surface detection of CO_2 and CH_4 plumes emanating from the land surface.

The study area for this thesis is Farnsworth Oil Unit in the Anadarko Basin of the northeastern Texas Panhandle (Fig. 1). The Southwest Regional Carbon Sequestration Partnership (SWP) and Chaparral Energy, LLC, are conducting CO_2-enhanced oil recovery experiments in the Farnsworth Oil Unit. These experiments are being carried out at a depth > 2,000 m in the Pennsylvanian-age upper Morrow sandstone. Aquifer protection is the primary concern of underground injection regulations in the United States. The High Plains Aquifer is the primary underground source of drinking water (USDW) in the study area and consists primarily of the Ogallala Formation. Characterizing the geologic framework and fracture architecture in the

Farnsworth area will aid in the design and implementation of the surface and airborne monitoring program, as well as the interpretation of the monitoring results.

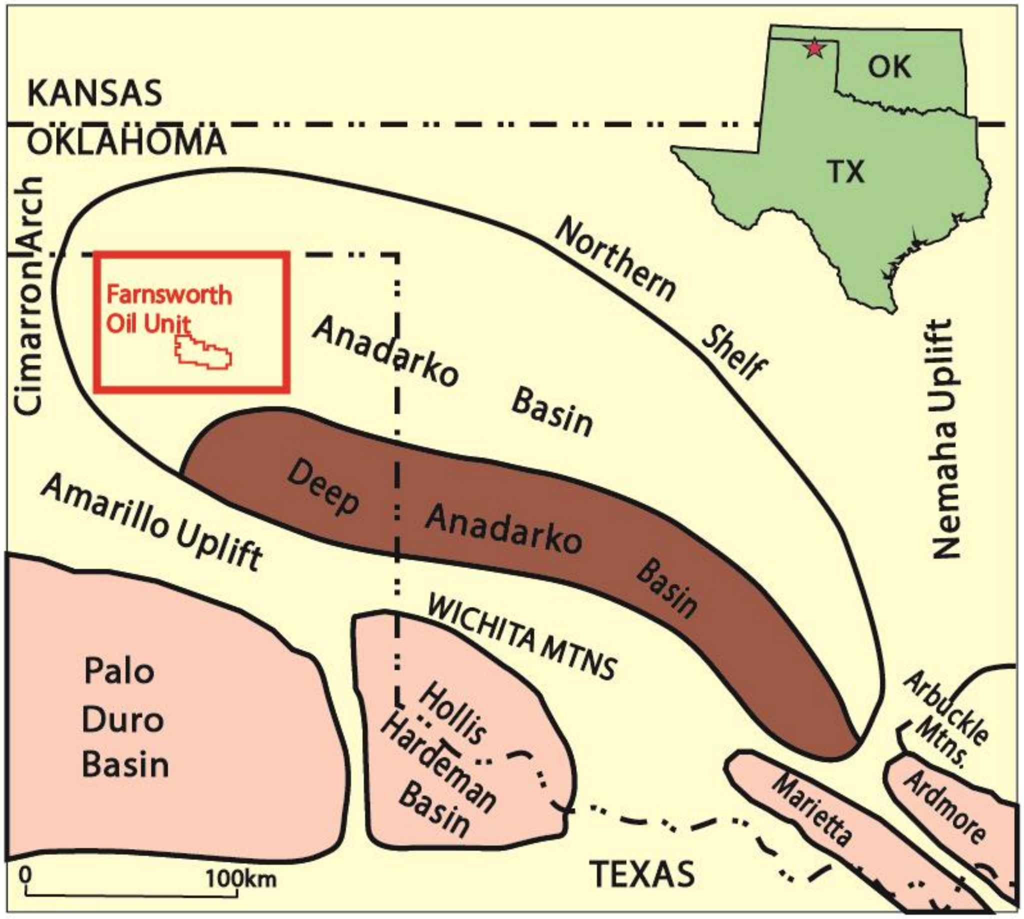

Fig. 1. Map showing location of the study area (red box) and the Farnsworth Oil Unit in the Anadarko Basin of the northeastern Texas Panhandle (modified from Carter et al., 1998).

Although several publications have discussed the general structural framework of the Texas Panhandle (Seni, 1980; Gustavson and Budnik, 1985; Gustavson, 1986), a need remains to examine the surface and shallow subsurface fracture architecture in the study area. To the author's knowledge, there has been no detailed description or quantitative analysis of the fractures in the High Plains Aquifer or the related strata in the northeastern Texas Panhandle. To help fill this gap, this study characterizes the stratigraphic framework, structural framework, and fracture architecture of the High Plains Aquifer and related strata in the Farnsworth area. This analysis will provide insight into the ways that fracture architecture may affect the movement of gas and water, and the results will be used to design and optimize surface and airborne monitoring programs.

The primary working hypothesis of the study is that Miocene-Quaternary formations in the study area contain numerous joints that affect subsurface flow, as well as the flux of CO_2 and CH_4 from the land surface to the atmosphere. Those joints are considered to be parts of regional fracture networks that are controlled by tectonic stress. Another hypothesis is that surface fluxes of CO_2 are more likely related to near surface processes than leakage from underground injection activities.

I.1 Goals and Objectives

Surface and shallow subsurface monitoring technologies are important parts of the pilot programs that have been and are being conducted by the Regional Carbon Sequestration Partnerships (RCSPs) (NETL, 2011). Two technologies that are now commonly employed are shallow groundwater monitoring and soil gas monitoring (Klusman, 2003, 2005; McIntyre et al., 2008; Wells et al., 2013). An area of rapid technological advancement is airborne monitoring, which includes aerial imaging and surveillance (Bateson et al., 2008; Male et al., 2010; Bellante et al., 2013). Many surface monitoring technologies, such as soil gas flux chambers, provide limited spatial coverage and thus under-sample areas of investigation. Soil flux monitoring is also labor-intensive, which adds to costs and can make long-term monitoring operations cumbersome. Emerging airborne sampling technologies with UAVs have the potential to improve spatial sampling over that of surface technologies. UAV technology can be deployed on demand, provide rapid data delivery, and minimize weather dependency through flexible flight planning. UAVs, moreover, can focus on specific locations, provide flexible spatial resolution, and can carry sensors for the direct detection of CO_2 and CH_4. The lower fuel costs and immediate deployability of UAVs should yield major cost savings while providing unprecedented flexibility in monitoring operations. Hence, the principal goal of this study is to provide the basic geologic information that helps advance the design and application of next-generation surface and airborne technology at the Farnsworth Oil Unit.

To test the hypotheses laid out in the previous section, this thesis focuses on identifying faults, fractures, and other geologic discontinuities that could serve as shallow subsurface flow paths that could affect the flux of water and gas, in and around the Farnsworth Oil Unit. Basic geologic data were compiled and used to characterize and analyze the stratigraphic and structural framework of the High Plains Aquifer in the test area. Surface strata were described and measured in outcrops near the Farnsworth Oil Unit. Subsurface analysis focused on characterizing the subsurface geologic framework and identifying any discontinuities that may be indicative of enhanced fracturing and small-scale faulting. Statistical methods were used to characterize the natural fractures at the surface.

To support the surface and airborne monitoring program, optimal flight pathways for UAVs were designed based on the subsurface fracture architecture characteristics. To facilitate this objective, two conceptual models have been developed to explain how shallow subsurface processes affect the flux of CO_2 and CH_4.

CHAPTER II

GEOLOGICAL SETTING

II.1. Anadarko Basin and High Plains Aquifer

The Anadarko Basin is one of the deepest and most productive petroliferous basins in the United States. The basin is a northwest-elongate, asymmetrical synclinorium extending from west-central Oklahoma into the Panhandle region of Oklahoma and northern Texas (Wang and Philp, 1997) (Fig. 1). It is bordered by the Nemaha Uplift in the east, the Amarillo-Wichita Mountains in the south, the Cimarron Arch in the west, and the central Kansas uplift in the north (Wang and Philp, 1997; Carter et al, 1998). The Farnsworth Field is developed in the southern part of the Anadarko shelf (Fig. 2), where the strata dip homoclinally southward at about 0.7 degree (12 m/km), and lack any major folds and faults. Also, the Farnsworth Oil Unit is north of the major overpressure region in the heart of the basin.

Paleozoic sedimentary rocks in the basin range in thickness from 3,000 m to about 12,000 m (Kennedy et al., 1982). The Paleozoic basin fill is at its thickest along the southwestern margin of the basin. Pre-Pennsylvanian strata of the Anadarko Basin consist primarily of shallow marine carbonate rocks interbedded with lesser amounts of sandstone and shale (Fig. 3).

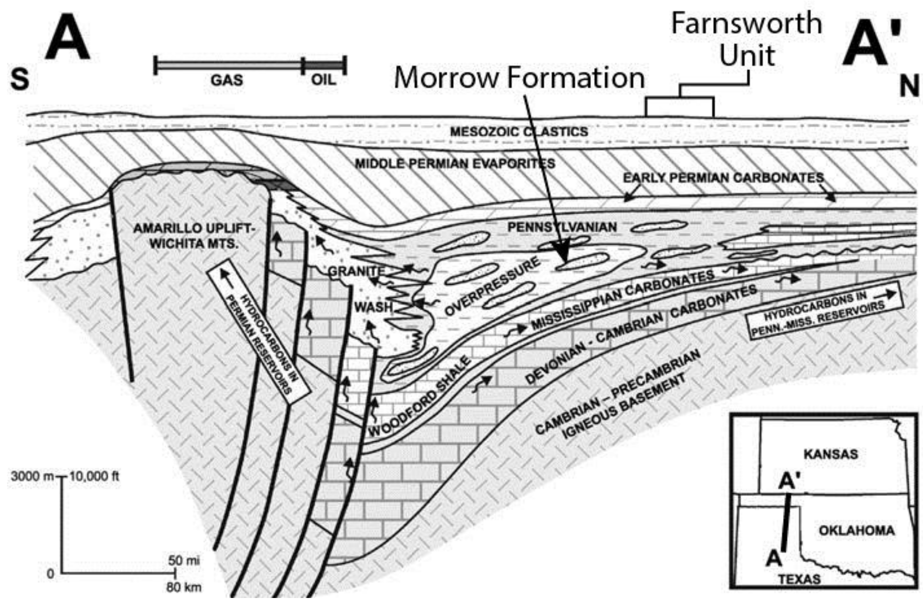

Fig. 2. Generalized subsurface cross section showing the geologic setting of Morrow sandstone in the Anadarko Basin (modified from Sorenson, 2005).

The Pennsylvanian strata of the northeastern Texas Panhandle consist of shale, sandstone, and conglomerate with subeconomic coal seams (Johnson et al., 1989) (Fig. 3). Morrowan (Lower Pennsylvanian) rocks are about 250 m thick in the Farnsworth Oil Unit and consist of shale, sandstone and limestone. The upper Morrow sandstone, which is the oil reservoir in the Farnsworth Oil Unit, is near the top of this section. The Thirteen-Finger Limestone (~ 36 m) overlies the upper Morrow section and forms the base of the Atokan Series in the Farnsworth area. Above the Atokan Series is the Cherokee Group, which is about 180 m thick and predominantly contains shale with thin intervals of limestone. The Cherokee is overlain by Marmaton Group, which contains about 90 m of interbedded shale and limestone in the Farnsworth area and is part of the Desmoinesian Series. Similar strata abound in the Missourian-Virgilian section (~ 600 m), which forms the top of the Pennsylvanian System.

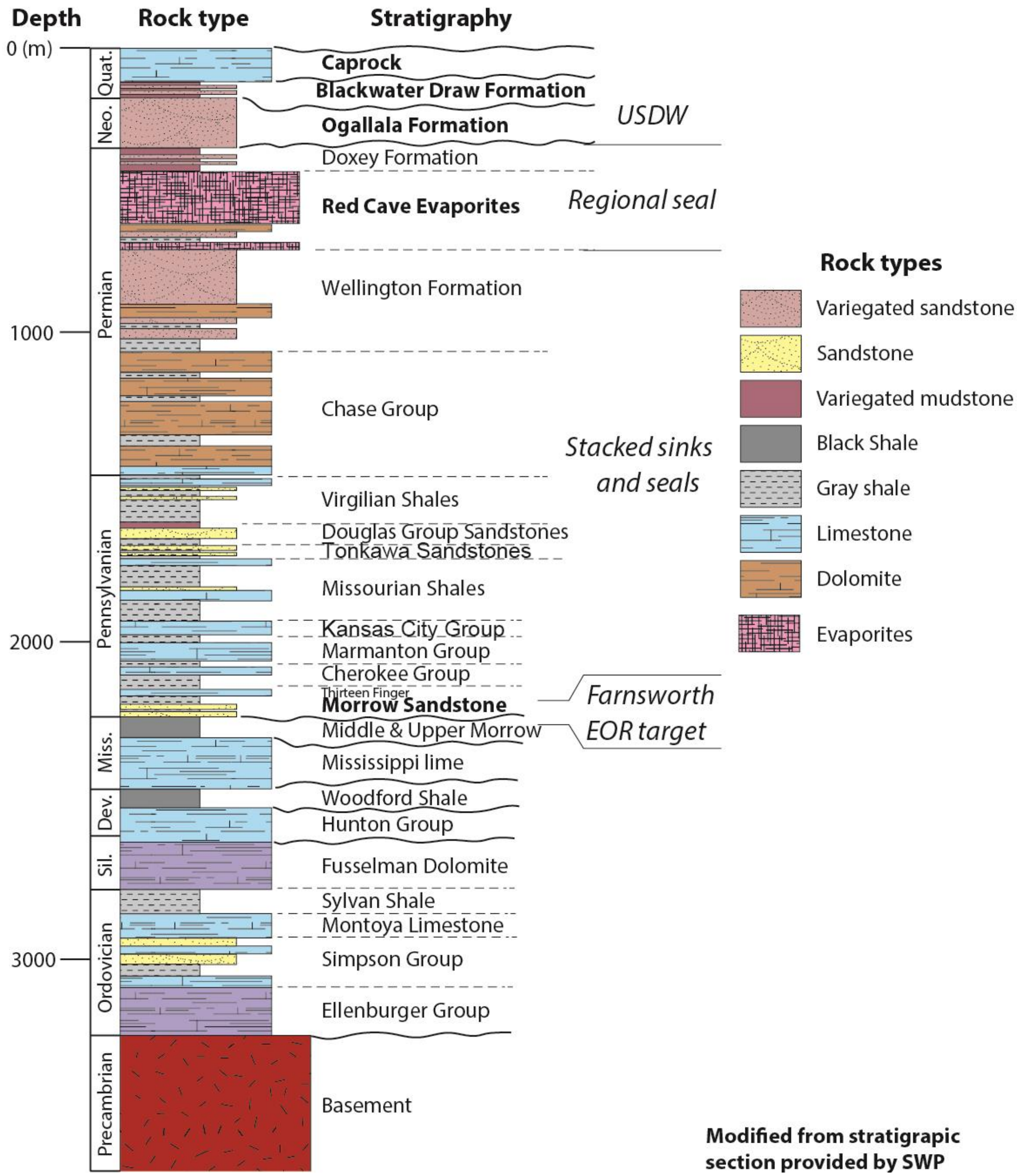

Fig. 3. Stratigraphic column of the Anadarko Basin in the Farnsworth Oil Unit showing the position of the Morrow injection target relative to the shale and evaporite seals and the USDW in the Ogallala Formation.

Permian strata in the Anadarko Basin include carbonate, shale, sandstone, anhydrite, and salt (Fig. 3). The Chase Group of the Wolfcampian Series consists predominantly of dolomite and shale and is up to 400 m thick in the Farnsworth Oil Unit. The Leonardian Series contains about 320 m of redbeds and evaporites. The Wellington Formation is the principal siliciclastic redbed unit in the Permian section and is composed of sandstone and shale. The Red Cave evaporite section of the Texas Panhandle includes about 180 m of intercalated dolomite, shale, sandstone, and evaporite strata (Handford and Fredericks, 1980). The Doxey Formation forms the top of the Permian section in the study area and mainly contains reddish sandstone and shale.

Neogene strata disconformably overlie Permian strata in the study area and are assigned mainly to the Ogallala Formation (Fig. 3), which is thought to be of Miocene to Pliocene age (Gustavson and Winkler, 1988). The Ogallala is the principal formation of the High Plains Aquifer, also called the Ogallala Aquifer, which is composed of poorly to moderately indurated calcareous sandstone (Gustavson and Winkler, 1988; Johnson et al., 1989; Gustavson and Holliday, 1999). The High Plains Aquifer is the largest aquifer in the Great Plains and extends from South Dakota into the Texas Panhandle. This aquifer is the primary underground source of drinking water (USDW) in the southern High Plains (Mehta et al., 2000), and is thus a resource that needs to be protected. The Ogallala Formation thickens westward from 100 m (300 ft) to about 275 m (800 ft) in the northeastern Texas Panhandle and covers the western third of the Anadarko Basin (Cunningham, 1961; Seni, 1980). Reeves (1972) and Gustavson and Winkler (1988) described lower Ogallala Formation as primarily consisting of laterally extensive, heterogeneous, vertically stacked, successions of gravel and sand. Thick sequences of very fine sand or loamy sand, silt, and clay composed the upper part of the Ogallala Formation. Ripple laminae and cross-bedding features have been reported in some outcrops (Gustavson and Winkler, 1988). Siliceous and calcareous root tubules (rhizocretions) and calcareous nodules (glaebules) are common in the Ogallala Formation. Quartz pebbles have been found locally in the Ogallala (Bretz and Horberg, 1949).

Pliocene and Quaternary strata in the area disconformably overlie the Ogallala (Fig. 3). Locally, the base of the Quaternary section contains loamy strata that can be difficult to distinguish from Ogallala strata and may be assignable to the Blackwater Draw Formation and other units (Gustavson and Winkler, 1988; Gustavson and Holliday, 1999). Gustavson and Holliday (1999) described Blackwater Draw as containing light brown to reddish-brown, very fine to fine sand and sandy mud, which is commonly mapped as loam.

A widespread caliche zone is present at the top of the section throughout the study area (Gustavson and Winkler, 1988). The caliche locally contains chert as well as some gypsum. The caliche ranges in age from Pliocene to Holocene, and the well-lithified Pliocene caliche section is commonly referred to as the caprock in the region (Reeves, 1970). The modern soil profile, consists of a dark, loamy epipedon that grades downward into the caliche, and supports a range of agricultural activities in the Farnsworth area.

Surface topography in the northeastern Texas Panhandle, appears generally flat, except for areas where streams dissect the caprock and the upper Ogallala Formation. The land surface slopes imperceptibly east-southeast and might have been controlled primarily by the elevation of the pre-Ogallala surface or local subsidence due to the dissolution of the Permian evaporites (Seni, 1980; Gustavson, 1986). Geologic structures in the Paleozoic fill of the Anadarko Basin do not appear to be expressed in the post-Permian section. So far, no literature has been identified on fracture networks in the northeastern Texas Panhandle. Fractures in the western Texas Panhandle, however, strike northeast and northwest and may be related to regional tectonic stresses (Gustavson and Budnik, 1985).

II.2. Farnsworth Oil Unit

The Farnsworth Oil Unit is located in west-central Ochiltree County, Texas, approximately 11 km south and 16 km west of the town of Perryton. The oil unit has produced more than 36 million barrels of oil and 27 billion cubic feet of gas since 1955 and is historically the most productive upper Morrow oil field in the Anadarko Basin (Munson, 1990). The thickness of the upper Morrow sandstone in the Farnsworth Oil Unit is 10 to 20 m, and the reservoir is composed of quartzarenitic sandstone and conglomerate (Fig. 4A). The sandstone is enveloped by shale containing siltstone laminae (Fig. 4B) and this shale forms the topseal for the upper Morrow oil accumulation and also is the principal confining unit for CO_2 injection.

Numerous shale units with thickness in the order of 100 m are present in the Middle and Upper Pennsylvanian sections and provide secondary confining units that help ensure the containment of injected CO_2. Pennsylvanian and Permian strata compose most of the overburden in the Farnsworth Field. In the Permian section, moreover, the Red Cave evaporites form a regionally extensive sealing stratum that helps isolate the High Plains Aquifer from development activities in the deep subsurface (Hill, 1984). Chaparral Energy began CO_2-enhanced oil recovery operations in the Farnsworth Unit in 2010, and this effort includes the large-scale Phase III field test being performed by the SWP. Phase III tests aim to verify safe, permanent capture, transportation, injection, and storage of CO_2 at scales on the order of 10^5 to 10^6 tons (NETL, 2013).

Fig. 4. Photographs of core from the upper Morrow section in the Farnsworth Oil Unit. A) Upper Morrow reservoir sandstone, which is the CO_2 injection target in the oil unit. B) Black shale with siltstone laminae, which is the primary topseal for the upper Morrow oil accumulation.

CHAPTER III

METHODOLOGY

The analytical approach for this research is divided into two parts: (1) Stratigraphic and sedimentologic analysis, and (2) structural analysis. This approach is designed to characterize the geologic framework of the Farnsworth area from reservoir depth to the surface. The results of this analysis were then used to formulate conceptual models that help guide the design and implementation of surface and airborne monitoring technologies in the Farnsworth Oil Unit.

III.1. Stratigraphic and sedimentologic analysis

Outcrop and laboratory analyses were performed to help characterize the High Plains Aquifer and associated strata in the Farnsworth area. No outcrops are available within the oil unit, where the topography is effectively flat and the bedrock is concealed below an agricultural landscape. However, the upper part of the Ogallala Formation and caprock strata are well exposed where streams have dissected the topography along Palo Duro Creek northwest of the oil unit and along Wolf Creek east of the oil unit, and the Canadian River south of the oil unit (Fig. 5). Field work was performed in the summer of 2014, when outcrops were described and sampled. Access to outcrops along the Canadian River is limited, and so most detailed work focused on Palo Duro Creek and Wolf Creek. Detailed descriptions were made using stratigraphic procedures, measured sections, photographs, and notebook sketches were made to characterize lithologic composition, Color, grain size, texture, thickness, and bedding, as well as physical, biological, and diagenetic sedimentary structures. Seventeen hand samples were collected for petrographic thin section analysis. Hand samples and thin sections were described to determine the color, grain size, texture, framework composition, cementation, and porosity. The standard Chayes point count method (Chayes, 1949, 1956) was employed for thin section analysis on a polarizing microscope. At least 300 points per thin section were counted to characterize framework composition and porosity. The results were then plotted on ternary diagrams to classify the sandstone.

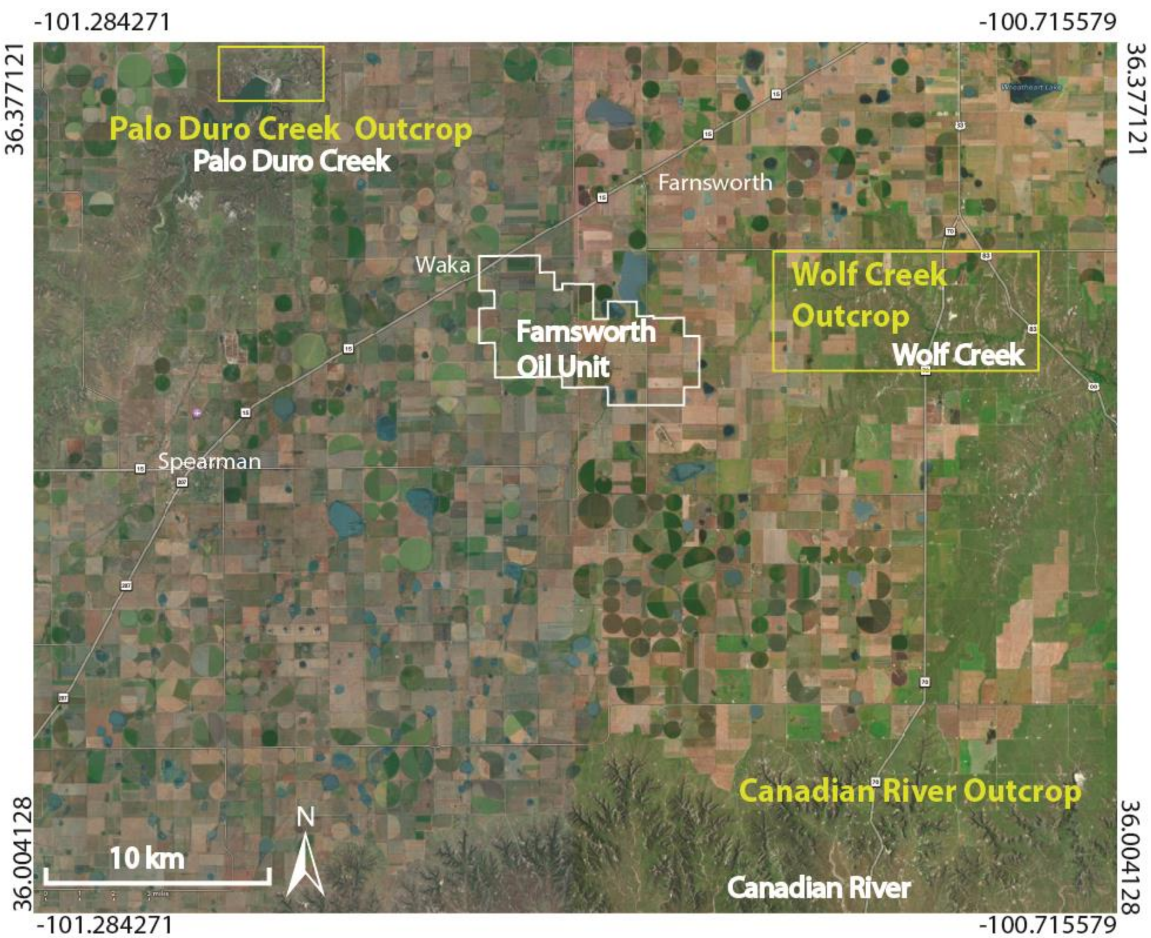

Fig. 5. Landsat Thematic Mapper (TM) image of the study area showing the location of the outcrop areas relative to that of the Farnsworth Oil Unit.

The shallow subsurface stratigraphic framework of the study area was investigated by studying water well records. Records from 147 water wells in the Farnsworth area (Fig. 13-17), including the adjacent outcrop belts, were provided by the SWP. The format and quality of these records vary substantially, and many record basic lithologic information, which were used to identify Permian redbeds, the Ogallala Formation, and caprock strata. Isopach maps of the Ogallala Formation and caprock strata were contoured to determine aquifer and caprock thickness based on interpretation of the water well records. The maps were constructed using ArcGIS and refined in Adobe Illustrator.

III.2. Structural analysis

Structural contour maps and a surface elevation map were constructed to identify any flexures or discontinuities that may be indicative of enhanced fracturing and small-scale faulting in the study area. Surface elevation data were derived from a digital elevation model (DEM) and mapped using ArcGIS software. A DEM from the U.S. Geological Survey- National Elevation Dataset with a 10 m (33 ft) grid spacing was used. Structural contour maps of the base and top of the Ogallala Formation that were also made based on an interpretation of water well records. The maps were constructed using ArcGIS and refined in Adobe Illustrator to develop a geologically viable interpretation of erosional relief at the Permian-Miocene disconformity surface.

Numerous fractures were observed in the field and in Landsat Thematic Mapper (TM) image imagery with the resolution of 30 m. Due to limitations of outcrop quality and accessibility, most fracture attribute data were collected from satellite imagery. Fracture orientation and spacing of more than 1,700 joints were measured, and cross-cutting relationships were analyzed using high-resolution (up to 0.5m) Texas Orthoimagery Program satellite imagery in Google Earth software. Fractures were measured where they are imaged clearly, and the orientation and spacing data were recorded in a spreadsheet. Fracture orientation, length, and spacing were measured using measurement tools in Google Earth. Fractures in the study area tend to be vertical, and so orientation was defined by the azimuth of the surface trace of each fracture.

Once the fracture data were recorded, they were analyzed using basic population statistics to characterize orientation and spacing. Structural analysis of fracture orientation data was accomplished using Stereonet software (Allmendinger et al., 2012) to generate rose diagrams and calculate directional statistics, including vector mean azimuth, vector magnitude, and angular standard deviation following the methods of Krause and Geijer (1987). Spacing of the joints was analyzed statistically using Microsoft Excel to identify the governing scaling rules. Due to incomplete exposure of long fractures, only partial length for systematic joints could be observed. Accordingly, no rigorous assessment of systematic fracture length could be made beyond evaluating the variability of fracture strike.

CHAPTER IV

RESULTS

IV.1. Stratigraphic and sedimentologic framework

Outcrops near the Farnsworth unit include exposures of Ogallala sandstone and caprock strata, including chert and caliche (Figs. 6-8). The best exposures, which offer panoramic views of these strata, are along the Palo Duro Creek in eastern Hansford County and along the Canadian River in Roberts County (Fig. 8). The eastern outcrops in the Wolf Creek drainage system have lower relief and are more weathered but also provide instructive exposures. Also, chert was only observed along Palo Duro Creek, whereas caliche rests directly on Ogallala sandstone in the Wolf Creek area.

Three lithofacies were identified in the Ogallala Formation: 1) massive sandstone lithofacies; 2) argillaceous sandstone lithofacies; and 3) indurated sandstone lithofacies. The massive sandstone lithofacies is best exposed in the lower part of the section along Palo Duro Creek (Fig. 6). The facies contains thickly bedded, pink to reddish yellow (7.5YR 8/4 to 7.5 YR 7/8; Munsell color, 1994), medium to fine grained sandstone. Grain size typically fines upward with the color of the sandstone becoming lighter. The sandstone is friable, poorly sorted and calcareous, and commonly contains pebble-size caliche nodules (Fig. 7A). Also, the sandstone is massive; sedimentary structures including cross-beds and horizontal laminae are observed locally.

Biogenic structures including root tubules and sparse meniscate burrows were identified in this facies. The massive sandstone lithofacies contains few natural fractures.

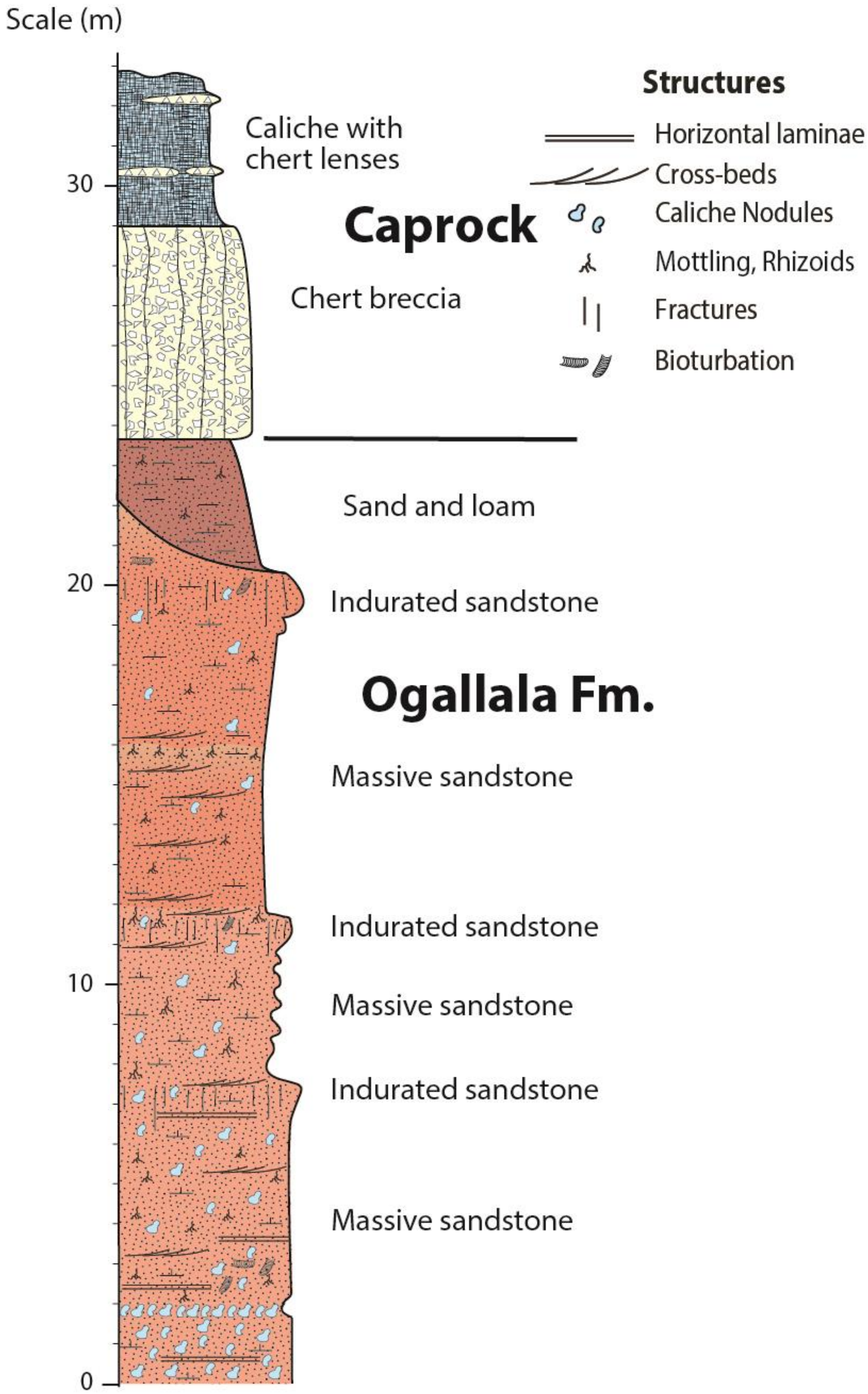

Fig. 6. Composite stratigraphic column showing the rock types and Ogallala sandstone lithofacies along Palo Duro Creek.

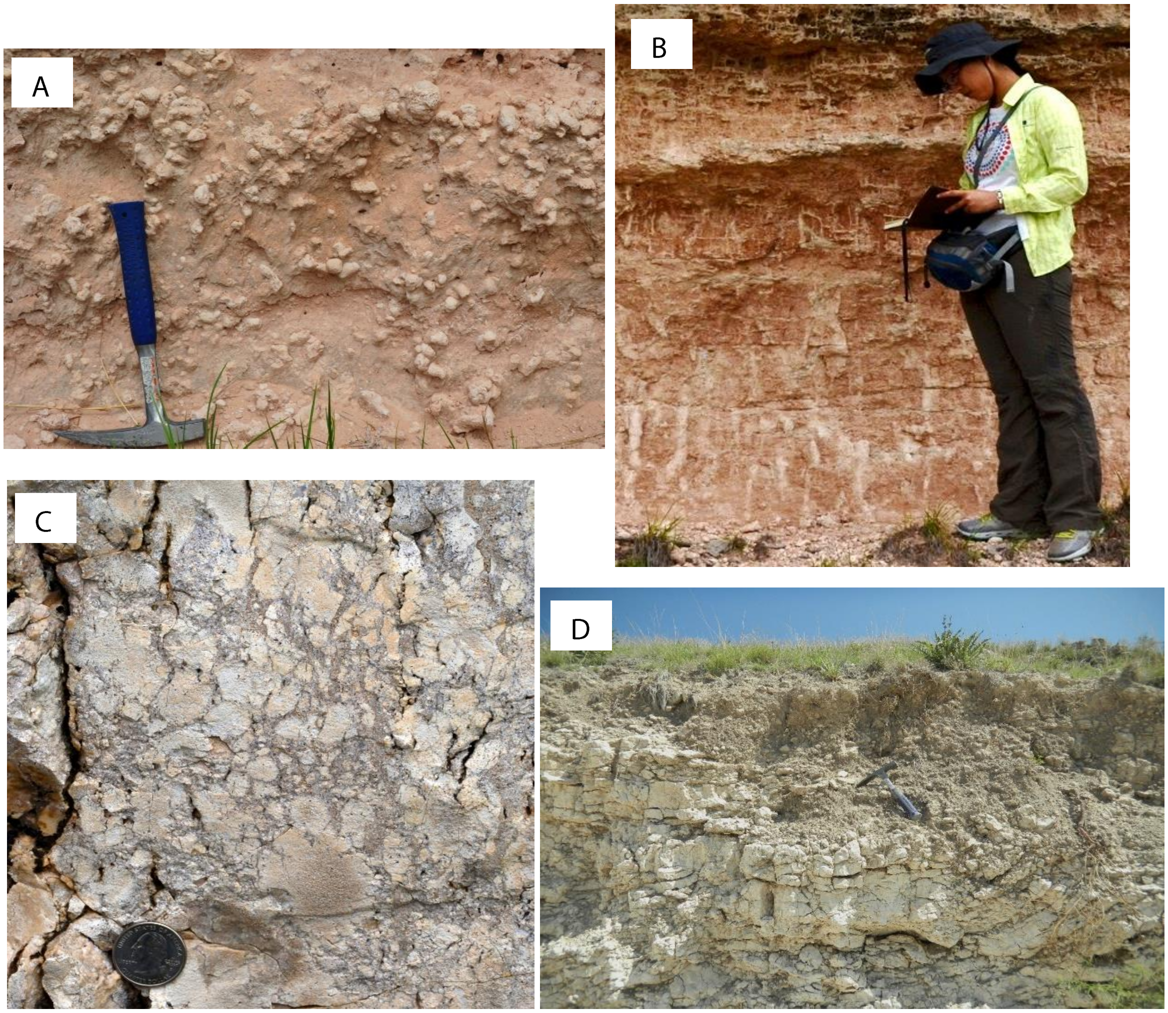

Fig. 7. Field photographs of Ogallala and caprock strata in the field area. A) Caliche nodules in the massive sandstone facies of the Ogallalla Formation, Palo Duro Creek. B) Subvertical, branching root tubules in the argillaceous sandstone facies of the Ogallala Formation, Wolf Creek. C) Chert breccia exposed along Palo Duro Creek. Open fractures are preserved in the breccia. D) Caliche overlain by modern argillaceous soil profile in the Wolf Creek outcrop area.

The argillaceous sandstone lithofacies is widespread in the Wolf Creek area and consists primarily of thickly bedded, pinkish white to pink (7.5YR 8/2 to 7.5 YR 8/4), fine grained, and silty sandstone. The sandstone is argillaceous and calcareous, friable and poorly to moderately sorted. Abundant calcite cemented rhizocretions (Fig. 7B) and pebble- to cobble-size caliche nodules are common in the sandstone. The argillaceous sandstone lithofacies contains few natural fractures.

The indurated sandstone lithofacies is resistant to weathering and forms distinctive ledges and pavements in the Wolf Creek area. The sandstone is thickly bedded (~ 1-2 m), white to pinkish white (7.5YR 8/1 to 7.5 YR 8/2), and fine to very fine grained. The sandstone is moderately indurated, calcareous, and moderately to well sorted. Pebble to cobble-sized caliche nodules and rhizocretions are locally abundant in this lithofacies. Abundant jointing is a salient feature of the indurated sandstone (Fig. 8A). The fractures are linear to curvilinear in plan view. In profile, the joints tend to terminate at the top of the indurated sandstone and extend downward into the more friable sandstone of massive and argillaceous sandstone lithofacies.

Some strata of indefinite affinity have been identified in the western outcrop area between the Ogallala Formation and the caprock succession. Light gray to red loamy deposits were identified that may be assignable to other stratigraphic units of Ogallala Formation (Fig. 6). These strata are generally thinner than 4 m and appear to be preserved as channel fills.

Caprock strata were subdivided into two lithofacies: 1) chert caprock and 2) caliche caprock. About 5 m of chert breccia sharply overlies the Ogallala Formation and forms a resistant layer that forms pronounced ledges in the western outcrop area along the Palo Duro Creek (Fig. 8B). The thickly bedded chert breccia is light grey to very pale brown (10YR 7/1 to 10 YR 7/3). Clasts in the breccia are angular, are of pebble to cobble size, and are cemented by silica (Fig. 7C). Abundant joints were observed in the chert breccia, and the fractures are curvilinear in profile (Fig. 8A).

Thick caliche overlies the chert caprock along Palo Duro Creek (Fig. 6), and overlies the Ogallala Formation along Wolf Creek. Exposures in the study area reveal the characteristics of the basal 8 to 15 m of the caliche, and drilling records in the area indicate that the caliche section is in places thicker than 60 m. The caliche is pale yellow to reddish yellow (2.5YR 8/2 to 7.5YR 8/6), thickly bedded, and micritic. The caliche section along the Wolf Creek is cracked (Fig. 7D). Chalky and friable caliche containing some gypsum was observed along Palo Duro Creek; two discontinuous medium to thick beds of chert occur in the caliche section. Sedimentary structures include horizontal laminae and desiccation cracks. Biogenic structures include abundant root tubules.

The modern soil profile is developed above the caliche and has a gradational basal contact (Fig. 7D). The soil is gray and loamy and appears to be a residuum derived from weathering of the underlying caliche. The soil supports a desert-like flora where streams dissect the caliche.

Several researchers have interpreted the depositional environments of the Ogallala-caprock succession in the Texas Panhandle (Seni, 1980; Winkler 1985, 1987; Gustavson and Winkler, 1988). Basal Ogallala deposits are not exposed in the study area; they include conglomeratic rocks that have been interpreted as fluvial deposits. The upper part of the formation, which comprises the three sandstone lithofacies described in the current study, has been interpreted mainly as eolian deposits resembling nonglacial loess (e.g., Gustavson and Winkler, 1988).

Abundant rhizocretions and caliche nodules in the upper Ogallala indicate that this part of the formation was a vegetated landscape in which the sand has been subjected to significant pedogenic alteration. Reddening of the sandstone, particularly in the argillaceous and massive sandstone lithofacies points toward oxic paleosol development, and the calcareous nature of the sandstone indicates widespread precipitation of pedogenic carbonate in a semi-arid to semi-humid climate. The cross-bedding in the sandstone is very faint and might be remnants of small eolian dunes or localized fluvial reworking of the sand. Whereas pedogenic carbonate is most abundant in nodules in the massive sandstone lithofacies (Fig. 7A) and in rhizocretions in the argillaceous sandstone lithofacies (Fig. 7 B). Indurated sandstone lithofacies contains more cements that forms a more resistant sandstone framework therefore becomes the main host facies for natural fractures.

The thick section of caliche indicates that a significant episode of carbonate sedimentation post-dated deposition in the Farnsworth area. Although much of the carbonate displays classic pedogenic features (Fig. 7D), the great thickness of carbonate may best be explained as a product of ephemeral playa lakes in the Southern High Plains (Haukos and Smith, 1992; Byerly, 1995; Hovorka, 1997). The chert caprock can be interpreted as a karstic collapse breccia, and the origin of the silica is undetermined that will be explained in the section that follows on petrologic analysis. Regardless of initial depositional, the bulk of the caliche contains abundant nodules with root tubules and desiccation structures and thus appears to be dominantly of pedogenic origin. The occurrence of gypsum in parts of the section, moreover, indicates a semi-arid environment. The evidence for regionally extensive calcic pedogenesis underscores the ephemeral nature of the lacustrine systems that may have the initial carbonate sedimentation in the Farnsworth area. The unusually flat topography in the Farnsworth area, moreover, may be a relict land surface left behind by the playa-caliche complex.

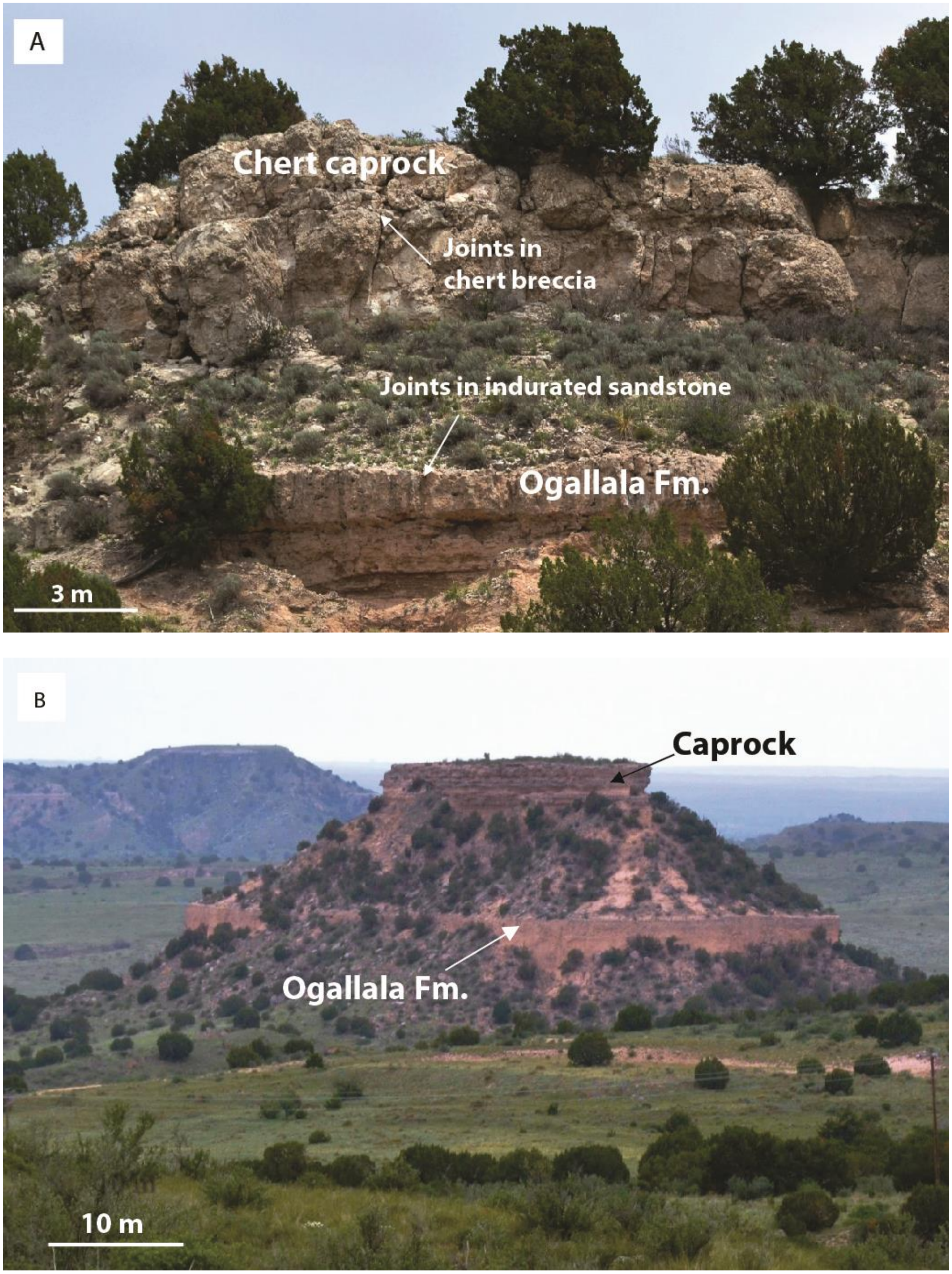

Fig. 8. Ogallala and caprock exposures in the Farnsworth area, northeastern Texas Panhandle. A) Chert caprock overlying the Ogallala Formation along Palo Duro Creek. Note closely spaced joints in the indurated sandstone lithofacies and more widely spaced joints in the chert caprock. B) Caliche caprock overlying the Ogallala Formation along the Canadian River valley south of the Farnsworth Oil Unit.

IV.2. Petrologic analysis

Thin section analysis shows all three lithofacies of Ogallala Formation consist of medium- to very fine-grained sandstone. Framework grains range in size from coarse sand to silt, and the sand grains are poorly to moderately sorted, angular to well rounded, and have variable sphericity (Fig. 9). Monocrystalline quartz is the dominant framework constituent, forming up to 95% of the sandstone. Feldspar generally accounts for less than 5% of the framework grains, but locally forms 17% of the sandstone. Sedimentary rock fragments generally constitute less than 1% of the framework grains. Plotting sandstone composition on the Quartz-Feldspar-Lithic (Q-F-L) ternary diagram of Folk (1980) indicates that sandstone is mainly subarkose with some quartzarenite (Fig. 10). The sandstone is texturally quite immature, suggesting recycling from nearby sources of sediment and minimal diagenetic alteration of the framework grains.

A mixture of clay and micritic carbonate cements Ogallala sandstone. The cement content ranges from 13% to 41% (Fig. 9). The clay-micrite mixture is typically expressed as grain coatings and interparticle cement. Interparticle porosity predominates in the sandstone, and point counting indicates that porosity ranges from 11% to 30%. Cement content is highest in caliche nodules, where framework grains commonly float in micritic matrix. Indeed, all cementation observed in the Ogallala appears to be associated with pedogenesis and caliche precipitation. Grain dissolution voids were observed in some thin sections and may be related to modern surface weathering in outcrop.

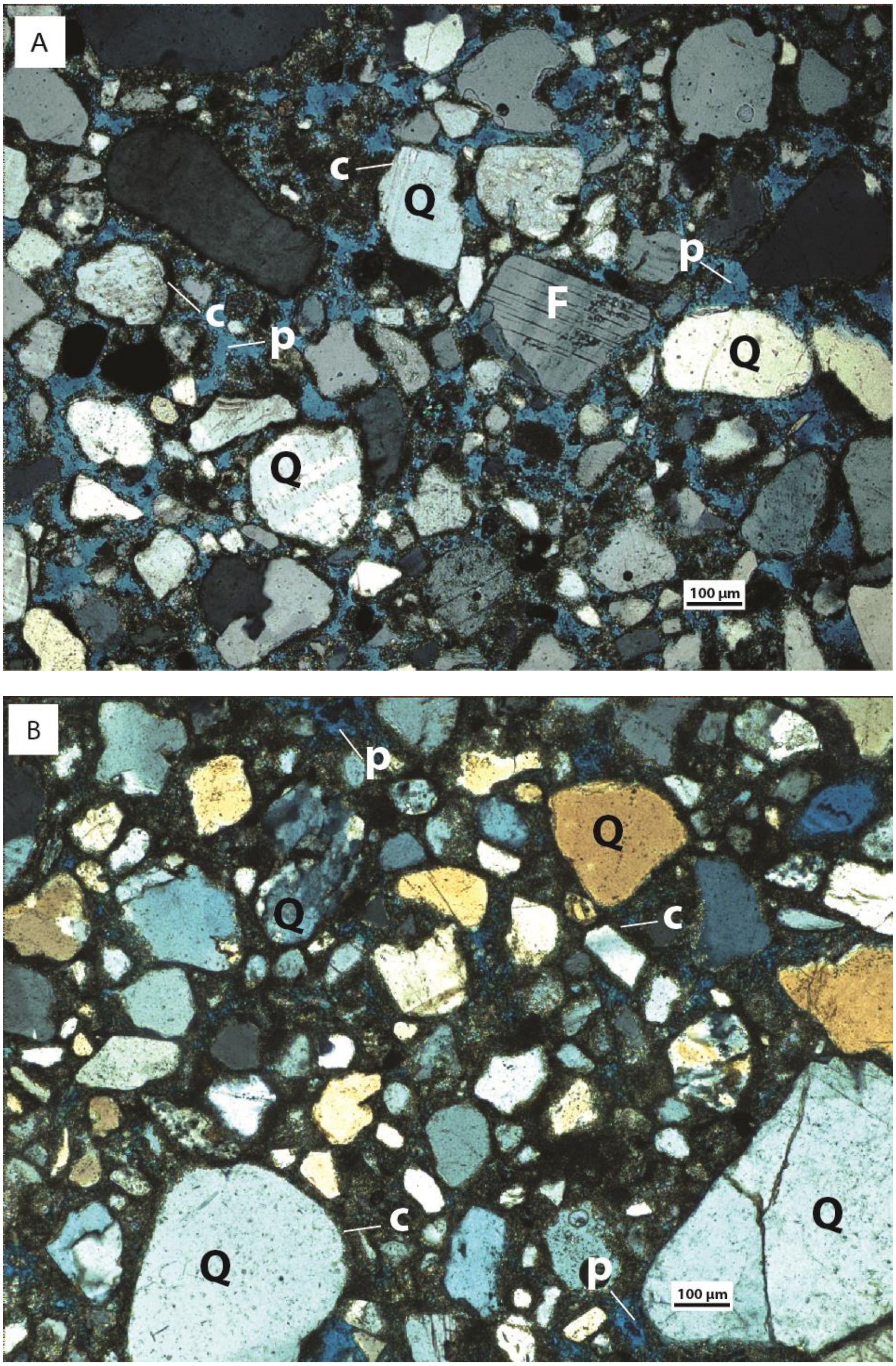

Fig. 9. Photomicrographs of Ogallala sandstone in cross-polarized light. A) Thin section of the massive sandstone lithofacies at Palo Duro Creek showing abundant primary porosity (p) and grain coatings and interparticle cement composed of a mixture of clay and carbonate (c). Note grains of quartz (Q), feldspar (F), primary porosity (p). B) Thin section of the indurated sandstone lithofacies at Palo Duro Creek showing abundant clay-micrite interparticle cement and grain coatings.

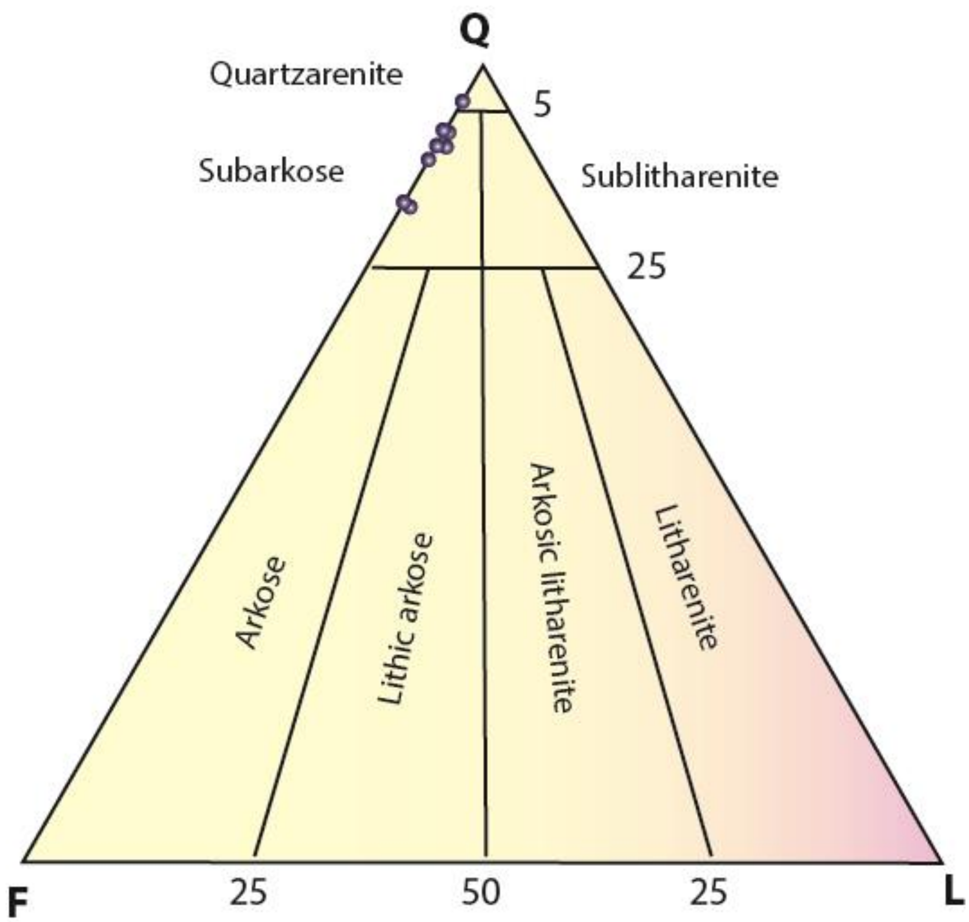

Fig. 10. Q-F-L ternary diagram of Folk (1980) showing subarkosic to quartzarenitic composition of Ogallala sandstone.

Figure 11 shows the thin section photomicrographs of the siliceous caprock along Palo Duro Creek. The chert is composed principally of cryptocrystalline silica (Fig. 11A), which appears to have replaced the micritic carbonate that is typical of the caliche caprock section. Diagenetic silica coats the voids in the chert and includes laminar silica, as well as a later phase of botryoidal silica (Fig. 11B). The caliche caprock primarily consists of micritic limestone (Fig. 12). Abundant root tubules were observed in some thin sections and are cemented by silica.

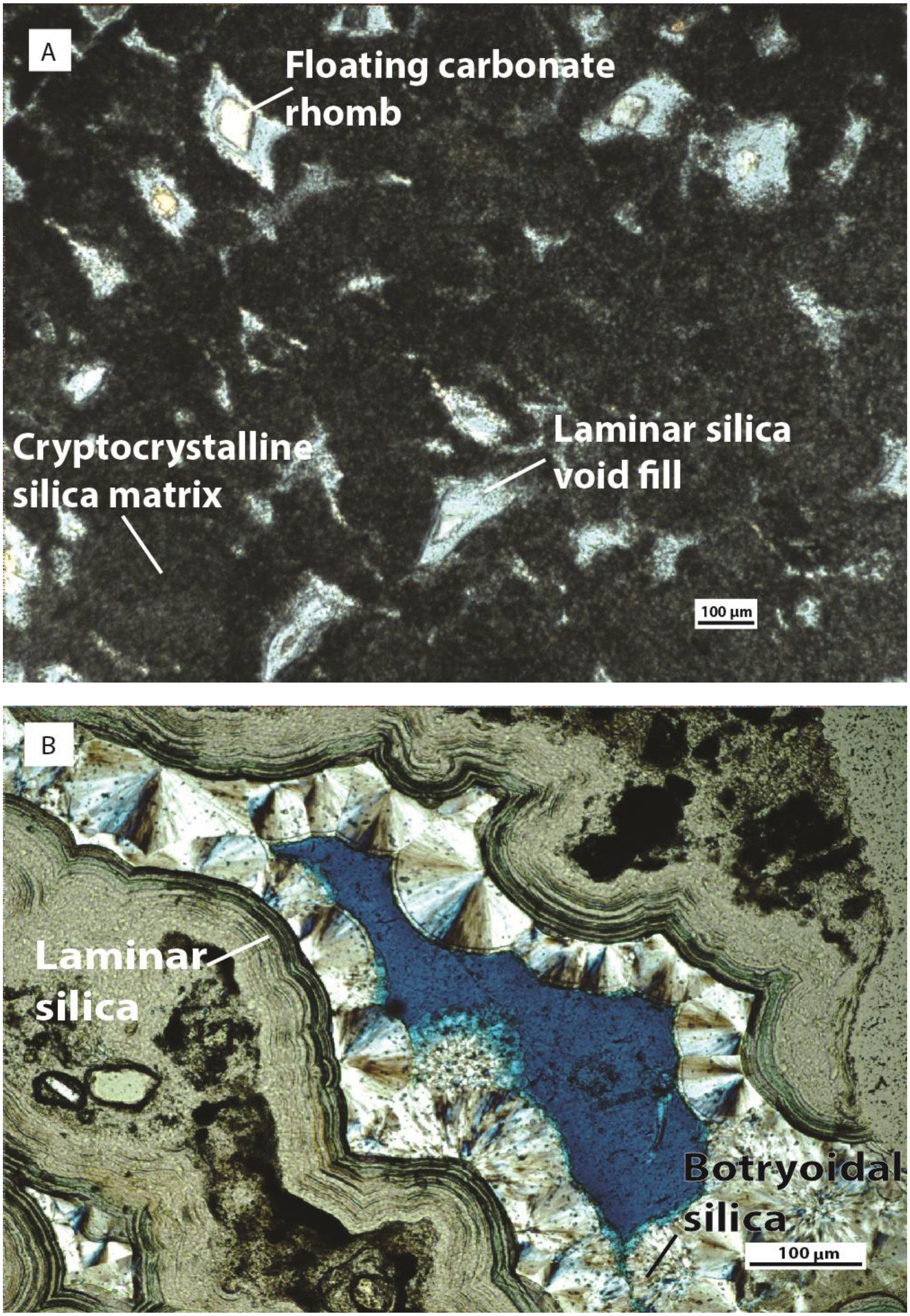

Fig. 11. Photomicrographs of the chert. A) Thin section of a chert bed within the caliche caprock at Palo Duro Creek showing typical fabric of chert. B) Thin section of the chert breccia at Palo Duro Creek showing the diagenetic features in a void fill.

The chert and micrite matrix contains floating detrital grains that are virtually identical to the framework grains in the Ogallala Formation. Accordingly, the silica forming the chert appears to be from a different source than the detrital grains, and one possibility to consider is that the chert-forming silica is volcanogenic. In summary, the chert appears to be silicified karstic collapse breccia that was derived from the parent carbonate that formed the caliche section. The presence of floating detrital grains suggests that eolian input of siliciclastic sediment continued into caprock deposition.

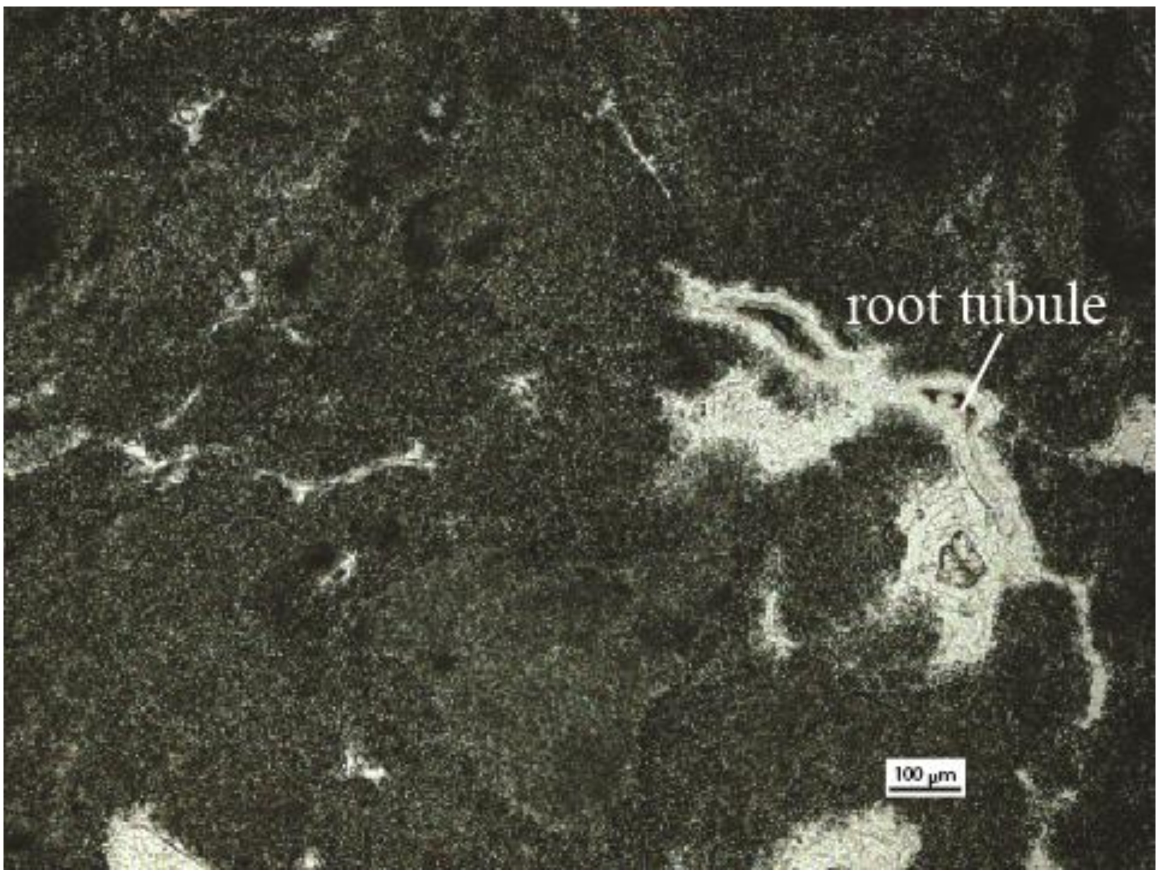

Fig. 12. Photomicrograph of the caliche caprock showing micritic limestone with mottled texture and root tubules filled by laminar silica cement, Palo Duro Creek.

IV.3. Shallow subsurface and surface structure and aquifer thickness

Drilling records from 147 water wells in the Farnsworth area provide a basis for characterizig subsurface structure and aquifer thickness. Table 1 shows the criteria that were used to pick the top and base of the Ogallala. Caliche is commonly noted in driller's records, although picking the base of the caprock succession is complicated by inconsistent terminology. Strata assigned to the chert caprock is typically described by drillers as hard sand rock or hard rock. The Ogallala Formation is distinctive in that it is composed primarily of sandstone and forms a fining-upward succession with conglomeratic strata at the base. Most of the water wells were drilled through the Ogallala into the Permian redbeds. Permian rocks beneath the Ogallala Formation are described as red, red clay or as redbeds, and drillers commonly note the relative hardness of these strata, which were instrumental for recognizing the base of the Ogallala Formation.

Table 1. Typical water well record describing geology in the Farnsworth Area.

Well number: 03-39-601
Driller: Buschman Drilling Company

Interval	**Depth (ft)**	**Description (interpretation)**
Caprock and soil	1 - 2.5	Soil
	2.5 - 3.5	Caliche (caliche caprock)
	3.5 - 50	Hard sand rock (siliceous caprock)
Ogallala Formation	50 - 65	Rock, sand, gravel (caliche nodules?)
	65 - 70	Hard sand rock
	70 - 80	Sand and gravel
	80 - 85	Hard sand rock
	85 - 95	Sand
	95 - 172	Sand and gravel
Permian undifferentiated	172	Red clay

Based on the water well records, the thickness of the Ogallala Formation ranges from 30 to 260 m (100 to 730 ft) (Fig. 13). Changes in thickness are controlled primarily by variations in the depth and elevation of the pre-Ogallala disconformity surface, and the Farnsworth Oil unit sits atop a paleotopographic high separating incised Ogallala paleovalleys (Fig. 14). The siliceous caprock is mostly distributed along Palo Duro Creek in the northwestern part of the study area, and a small patch of chert caprock appears to be present in the western part of the Farnsworth Oil unit (Fig. 15). The thickness of the caliche caprock varies from ~3 m (9 ft) to ~80 m (275 ft) in the study area and is anomalously thick near the town of Farnsworth (Fig. 16). Within the oil unit, however, the caliche is about 30 m (100 ft) thick, which is more typical of the region. Changes in thickness of the caliche caprock generally correspond with the structure of the top of the Ogallala Formation (Fig. 17).

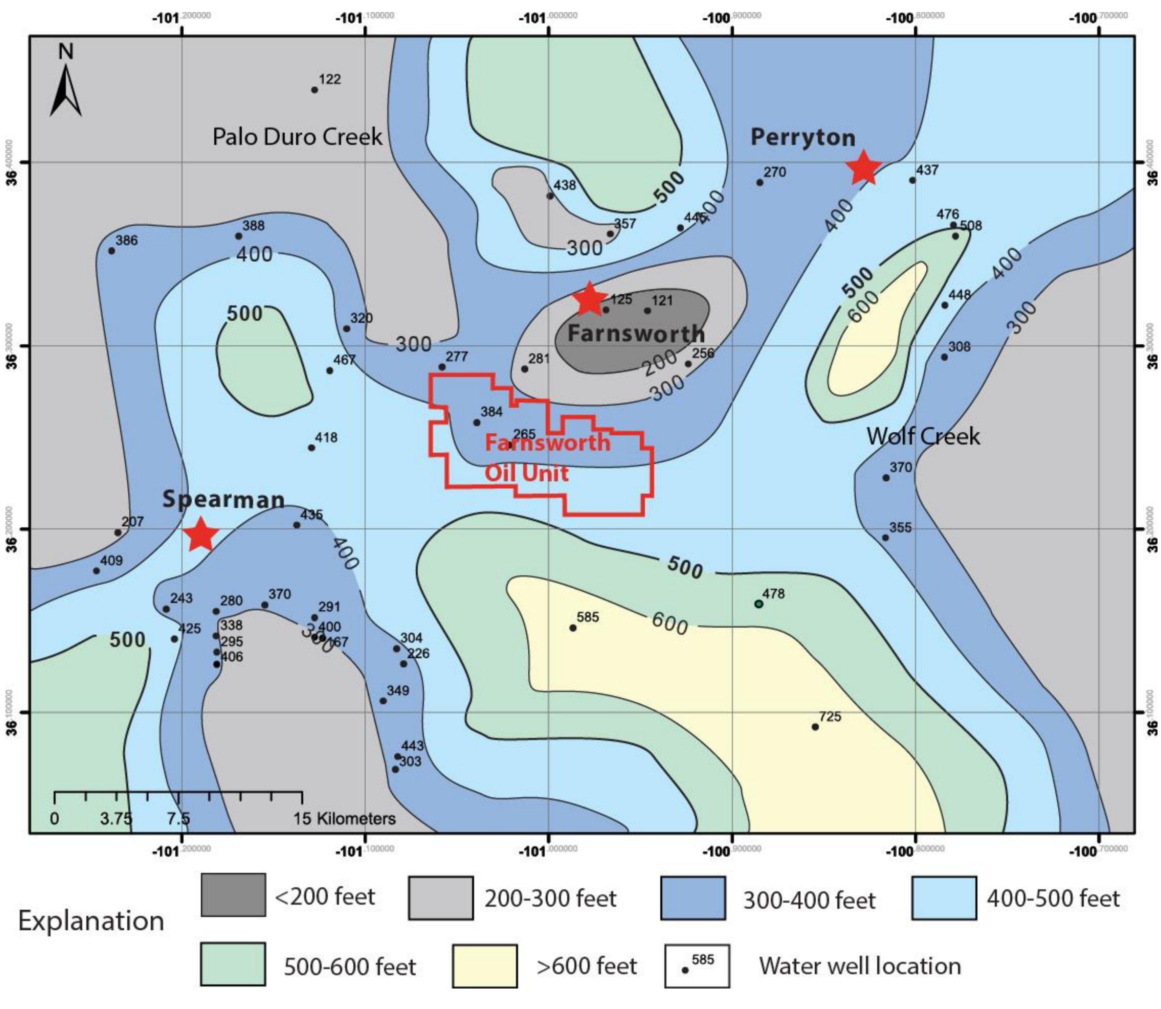

Fig. 13. Isopach map of the Ogallala Formation. Contour interval = 100 ft.

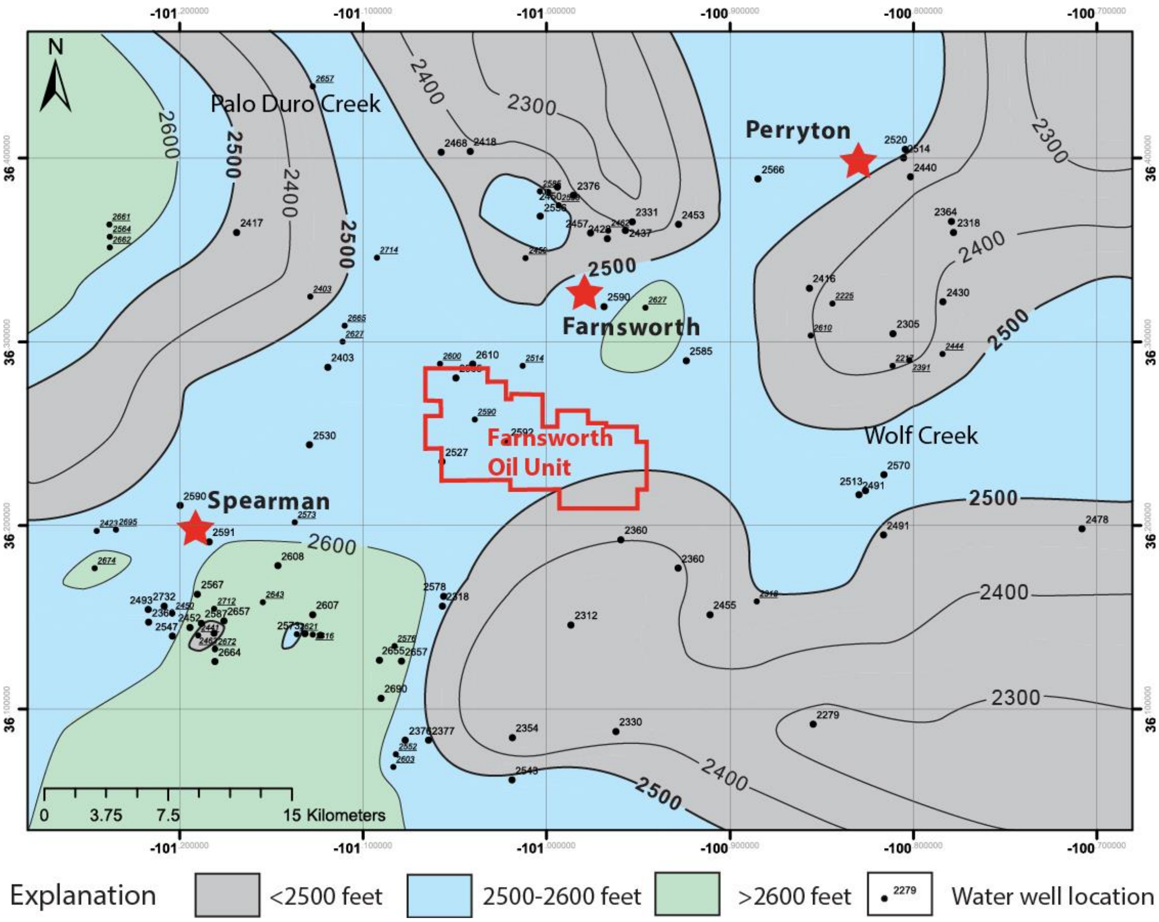

Fig. 14. Structural contour map of the base of the Ogallala Formation. Contour interval = 100 ft. Structural relief reflects paleotopography at the Permian-Miocene disconformity surface.

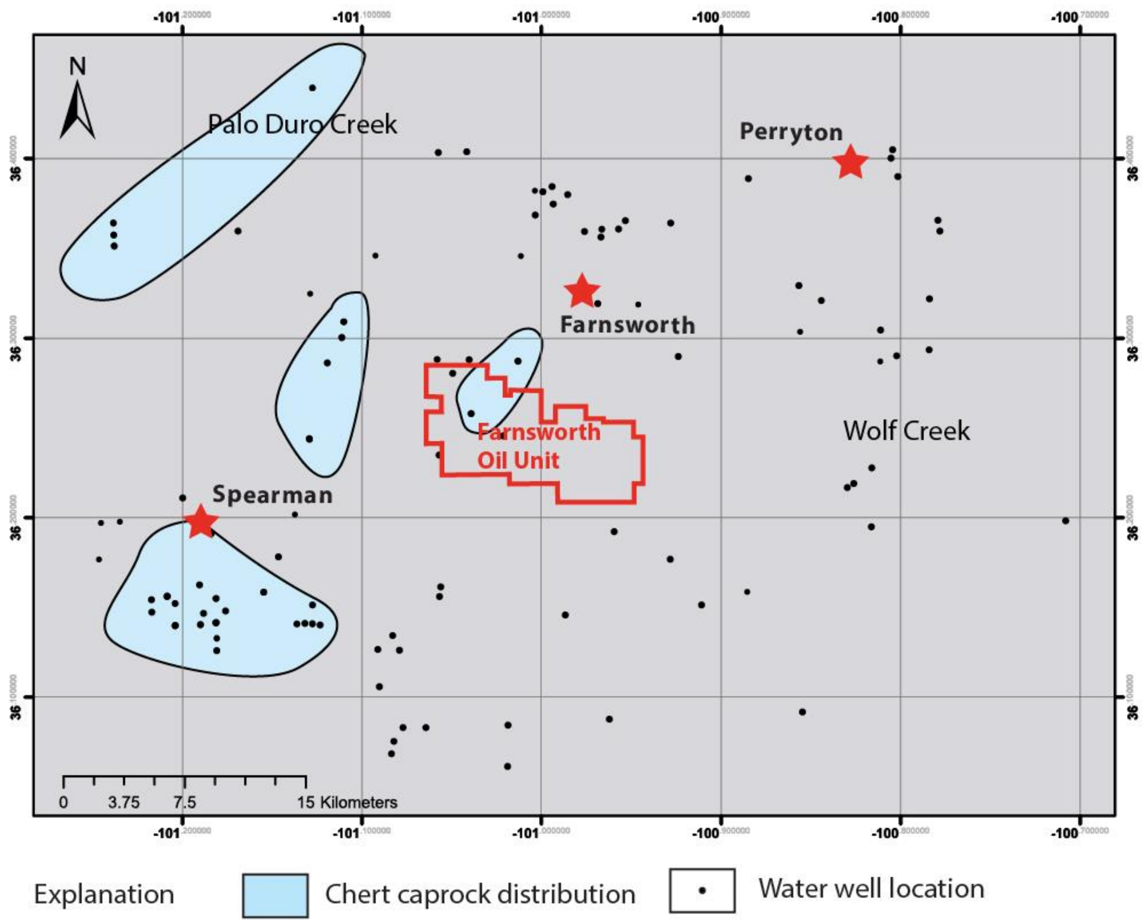

Fig. 15. Chert distribution showing the siliceous caprock appeared in the Farnsworth Oil Unit.

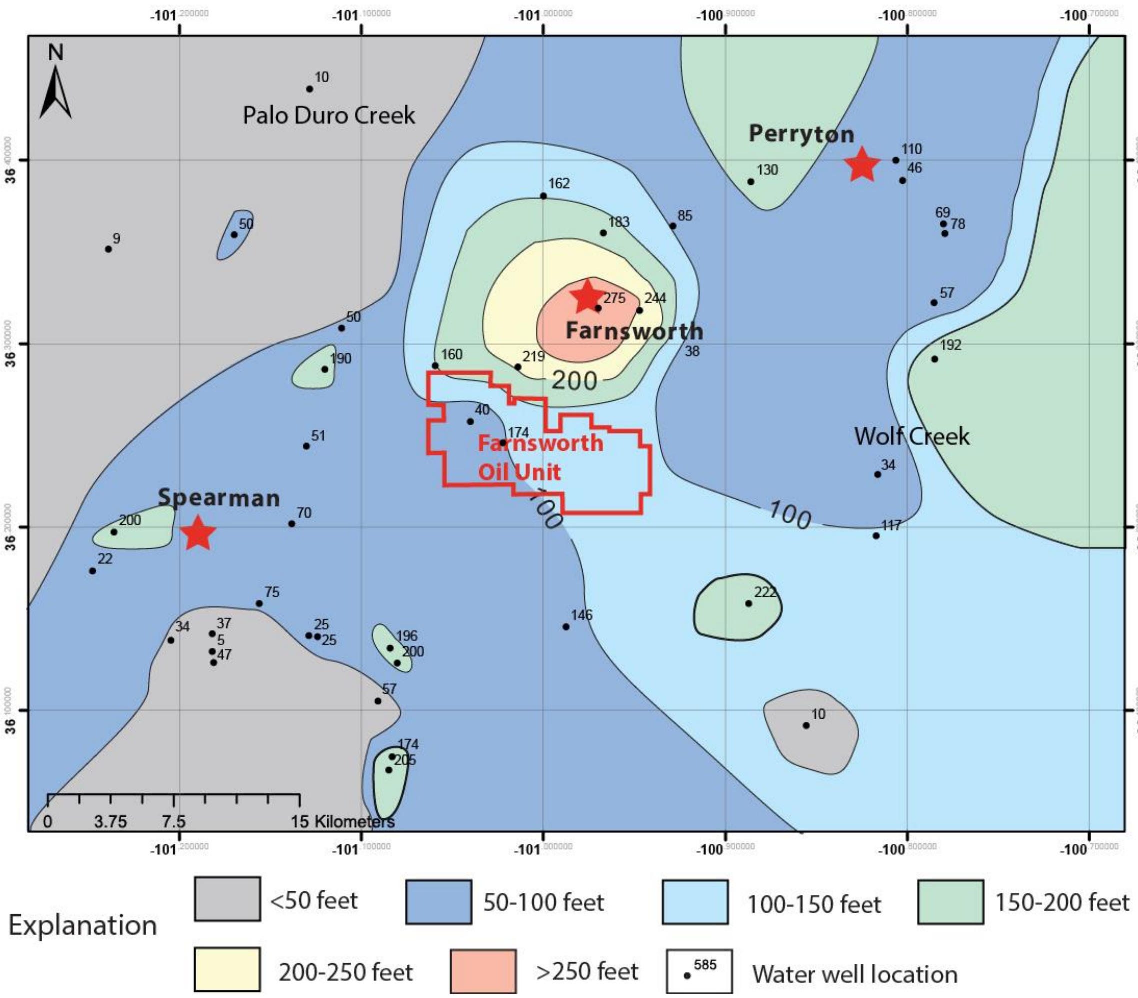

Fig. 16. Isopach map of the caliche caprock. Contour interval = 50 ft.

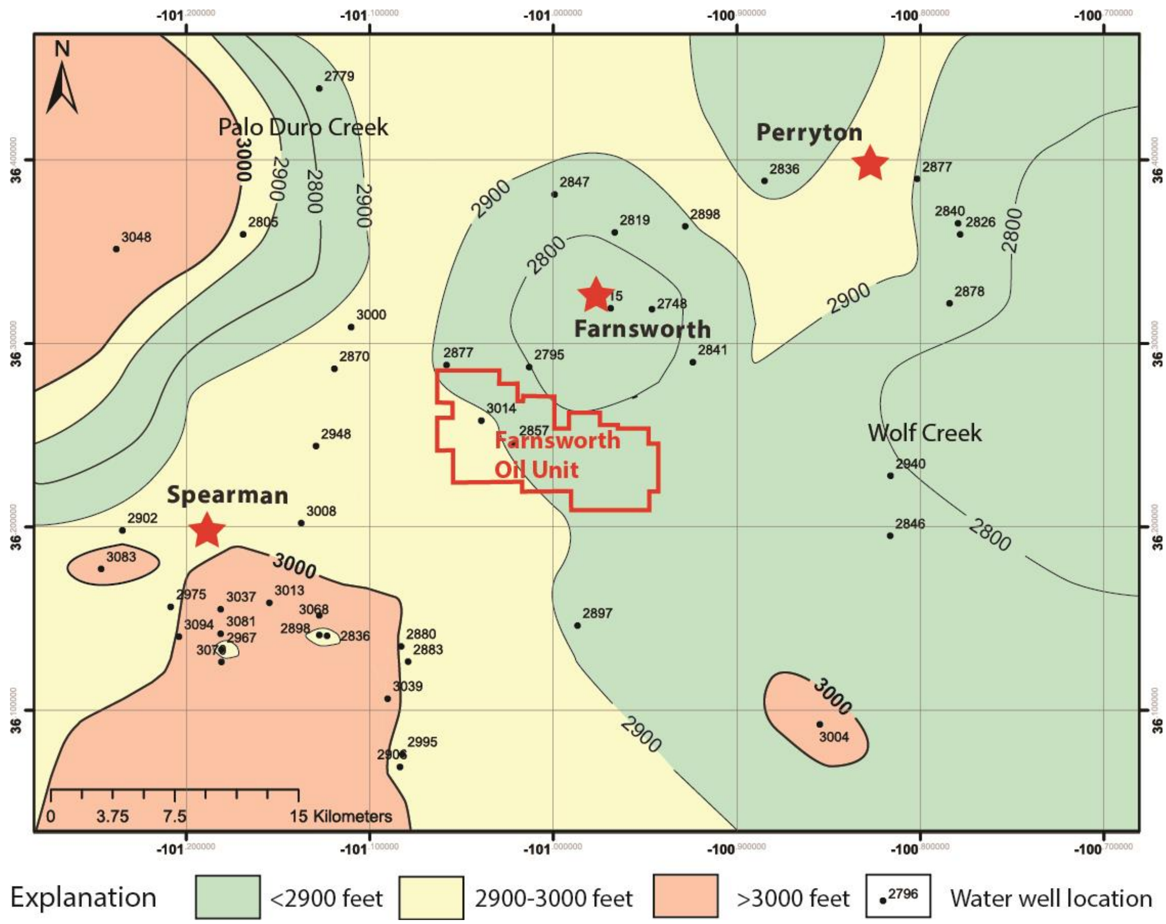

Fig. 17. Structural contour map of the top of the Ogallala Formation. Contour interval = 100 ft.

Topography is characterized regionally by a gentle slope of about 0.06 degree toward the northeast containing relief of about 70 m (~210 ft) (Fig. 18). This area of gentle slope defines the elevated plain containing the Farnsworth Oil Unit. The plain is deeply dissected northwest of the oil unit by Palo Duro Creek and east of the oil unit by a dendritic stream system containing Wolf Creek. The plain is held up by the caprock succession, whereas the Ogallala Formation is exposed in the dissected terrain.

Based on the topographic map and field observations, there are no major faults or folds in the study area. However, some localized folds and rotational slumps were observed along the edges of some valleys in the study area. Figure 19, for example, shows a dipping chert layer overlain by Quaternary fill along Palo Duro Creek. Nearby, the chert caprock is gently folded along the valley margin, with strata dipping gently toward the axis of the valley. Similar structures were also observed locally along Wolf Creek. These structures appear to have formed by localized slumping and flow of poorly consolidated Ogallala sand along the steep slopes of modern stream valleys. No evidence for similar structures was found in the subsurface below the plain containing the Farnsworth Oil Unit.

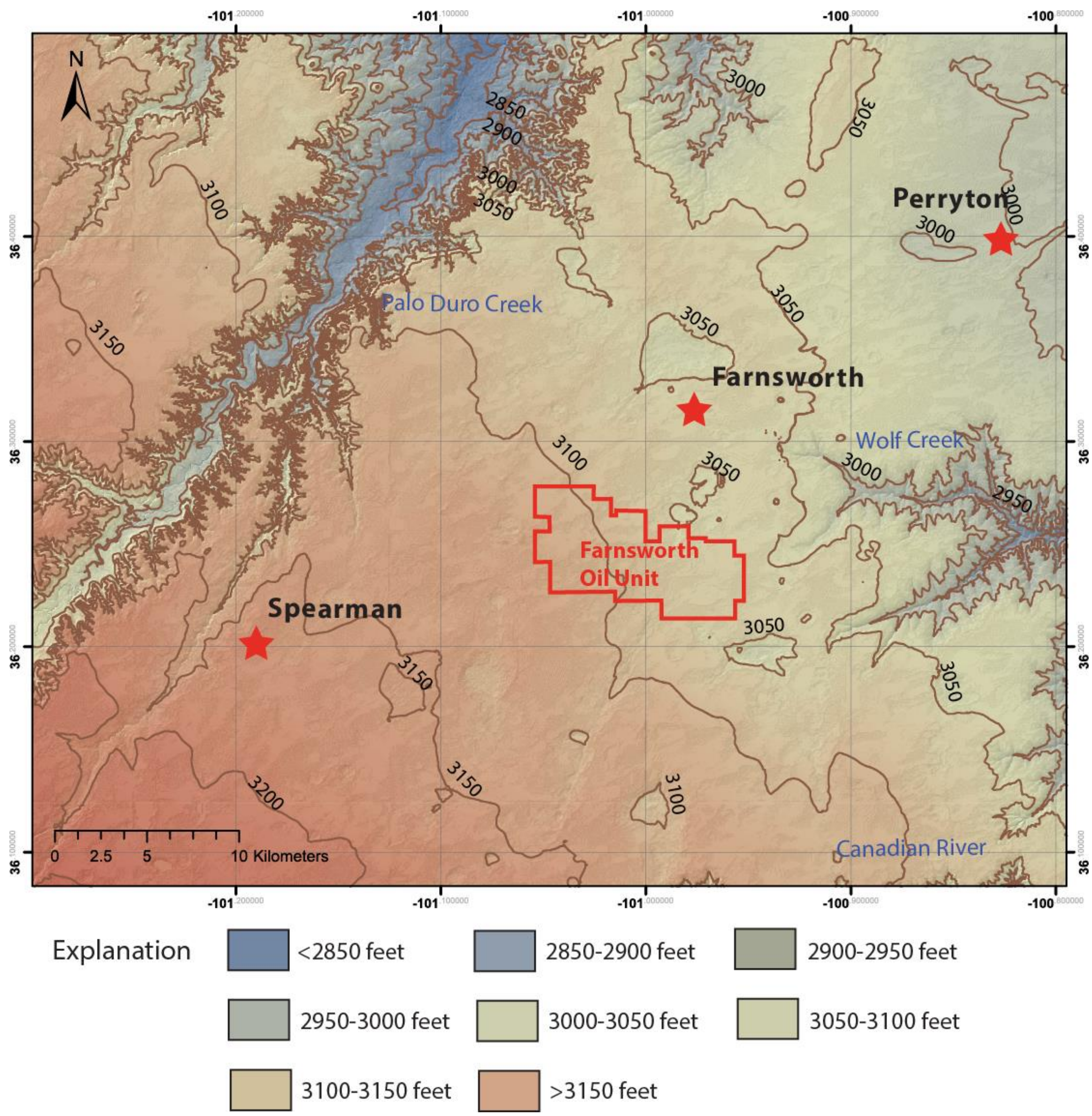

Fig. 18. Hill-shade map showing topography of the Farnsworth area. Contour interval = 50 ft.

Fig. 19. Dipping chert layer along Palo Duro Creek.

IV.4. Fracture analysis

Outcrops and Landsat Thematic Mapper (TM) images in Google Earth reveal that numerous joints crop out in the field area and form significant fracture pavements on bedding plane exposures in the Ogallala Formation and in the chert caprock (Fig. 20). In vertical section, the joints are typically curvilinear and effectively strata-bound, cutting well-cemented, indurated sandstone and caprock, terminating either at bedding contacts or within the adjacent friable sandstone (Figs. 6, 8A). On bedding planes, the exposed joints are weathered and host vegetation. Indeed, it is the vegetation that has colonized the fractures rather than the fractures themselves that define the joint pathways in satellite imagery (Fig. 20A).

The satellite imagery reveals that fracture networks consist of well-developed systematic joints and cross joints (Fig. 20B). Systematic joints are strongly aligned and have average length that typically exceeds 60 m. Average length of the joints is hard to calculate due to the incomplete exposure of the long fractures. Systematic joint length typically exceeds the dimensions of the exposures. Cross-joints tend to terminate at systematic joints, and so cross-joint length is effectively equal to systematic joint spacing.

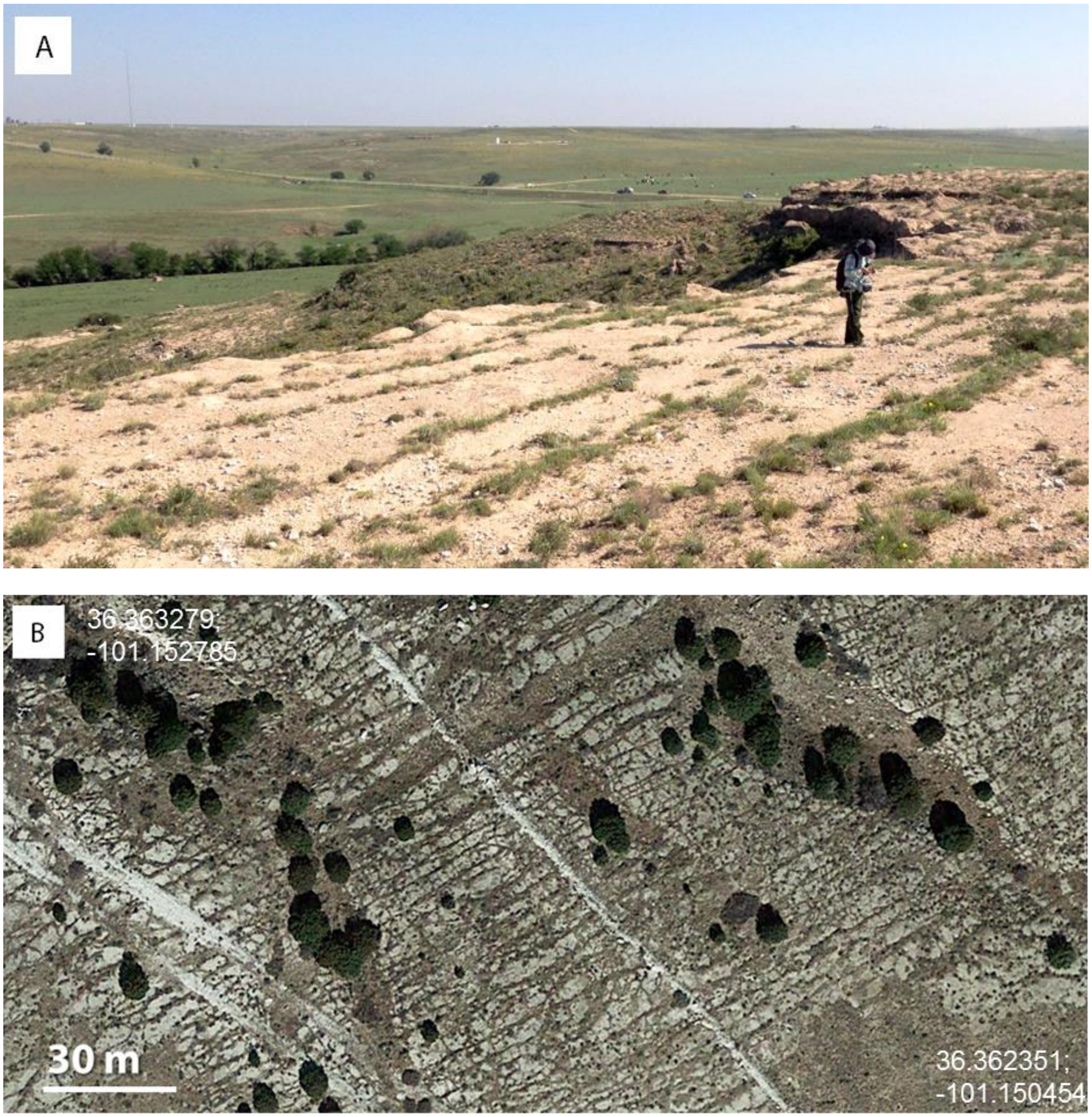

Fig. 20. Exposures of joint networks in the field area. A). Outcrop image showing bedding plane exposure of joints marked by vegetation in the Ogallala Formation along Wolf Creek. B) Satellite image showing well-developed joints in the siliceous caprock along Palo Duro Creek.

Data collected from 21 outcrop bedding plane exposures using Google Earth resulted in more than 1,700 azimuth measurements. Two main joint systems are apparent in rose diagrams (Fig. 21). In the Wolf Creek area, two suborthogonal joint networks are well exposed in the Ogallala Formation. Joint System 1 is the dominant (i.e., most abundant) joint set striking southeast with a vector mean azimuth of 115° and a subordinate joint set striking northeast with a vector mean azimuth of 31°. System 2 joints, by contrast, contain a dominant set striking northeast with a vector mean azimuth of 67° and a subordinate set striking southeast at 146°. Cross-cutting relationships among outcrops are highly inconsistent, with systematic joints in one system belonging to the dominant joint set in one outcrop and to the subordinate set in another. In addition to distinctive regional joint systems, non-systematic joints that follow topography and are thus probably related to hillslope stresses also are developed in places.

Northwest of the Farnsworth Oil Unit along Palo Duro Creek, extensive fracture pavements are developed atop the siliceous caprock and are dominated by System 2 joints. System 2 in this area contains a well-developed systematic joint set striking northeast accompanied by SE-striking cross joints abutting the systematic joints. The vector mean azimuth of the systematic joints in System 2 is 67°, and the cross joints strike with a vector mean azimuth of 146°; these azimuths are identical to System 2 in the Wolf Creek area.

Spacing data from 1,288 joints were collected using the measurement tool in Google Earth. Cumulative probability plots of spacing data indicate that joint spacing in the study area is highly organized and follows log-normal spacing rules (Fig. 22). Mean, log-normal mean (geometric mean), and the limits of the log-normal standard deviation of joint spacing are shown in Table 2. For the Ogallala Formation sandstone along Wolf Creek, the general spacing of the System 1 joints are 2.0 m of southeast mode and 1.9 m of northeast mode. Joint System 2 contains the general spacing of 1.7 m at northeast mode and 1.8 m at southeast mode. For the chert caprock along the Palo Duro Creek area, the general spacing of the System 2 joints is 3.3 m in the northeast mode and 3.4 m in the southeast mode.

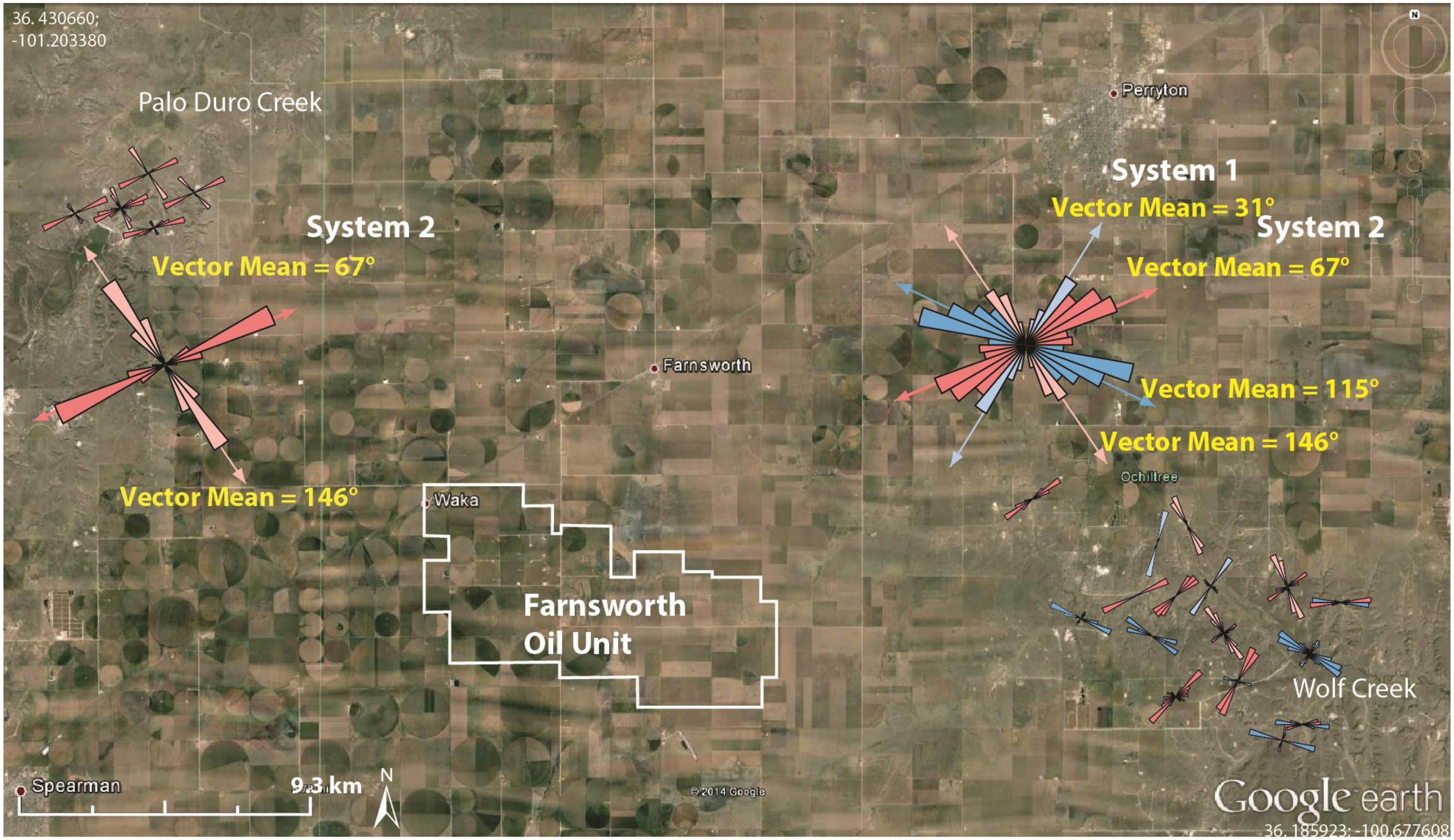

Fig. 21. Rose diagram showing joint systems and joint orientation in the study area.

Table 2. Analysis of joint properties and statistical distributions.

Lithology	System	Strike	Number of readings	Distribution	Mean of joint spacing (m)	Log-normal Mean (m)	Limits of the standard deviation (m)
Ogallala Formation	System 1	115°	345	Log-normal	2.2	2.0	(1.3, 3.0)
	System 1	31°	123	Log-normal	2.2	1.9	(1.2, 3.1)
	System 2	67°	288	Log-normal	1.8	1.7	(1.1, 2.6)
	System 2	146°	191	Log-normal	2.0	1.8	(1.2, 2.7)
Chert Caprock	System 2	67°	187	Log-normal	3.5	3.3	(2.3, 4.8)
	System 2	146°	154	Log-normal	3.6	3.4	(2.4, 5.0)

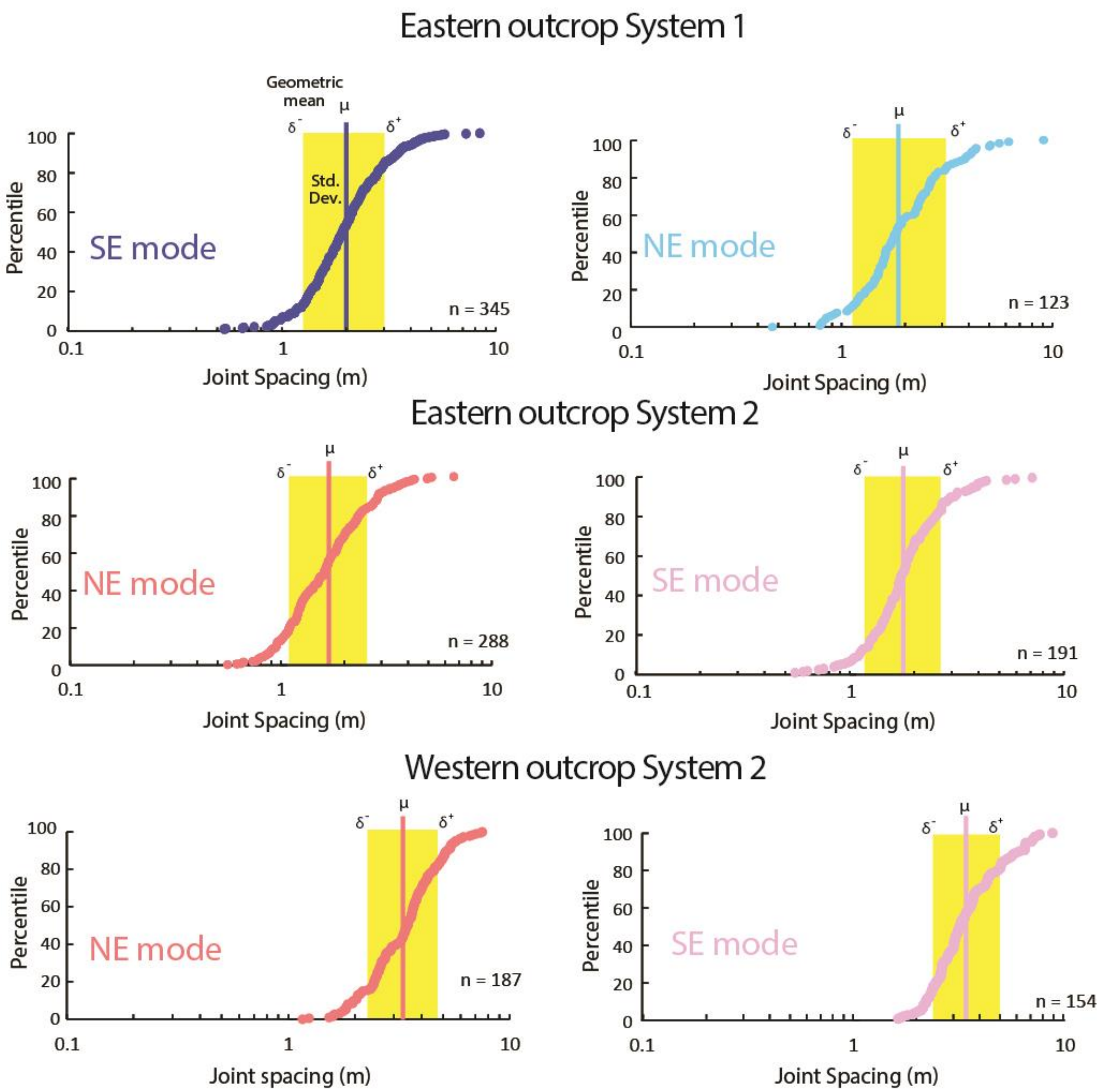

Fig. 22. Percentile plots showing the log-normal distribution of joint spacing in the study area.

CHAPTER V

DISCUSSION

V.1. Origin of the fractures in Farnsworth Oil Unit

Cross-cutting relationships of the two joint systems among outcrops are highly inconsistent along the Wolf Creek. No bedding plane exposures are found in the Ogallala Formation along Palo Duro Creek. Accordingly, it is unclear whether the sandstone beds host joints of both systems as is the case in the eastern outcrop area. However, the absence of System 1 joints in the chert caprock suggests that System 1 joints may have formed earlier than System 2 joints. The inconclusive abutting relationships in the Ogallalla Formation suggest that aquifer strata have experienced a complex breaking history and that the poorly consolidated sandstone was a poor propagator of stress in comparison to the brittle chert caprock.

Orientation analysis and spacing analysis indicate that joint networks in the study area are well organized. Also, the jagged shape of the probability curves reveals that the dataset from the Palo Duro Creek area is not as well organized as that from the Wolf Creek area. Different level of organization and average spacing in both outcrops may related to the geomechanics of different caprock types. The systematic joints indicate the orientation of regional tectonic stresses. Joints are tensile fractures that strike parallel to the maximum horizontal compressive stress and perpendicular to the minimum horizontal compressive stress. Accordingly, the dominant joint set of System 1 (i.e. southeast mode joints) may be related to maximum horizontal compressive stresses that were oriented NW- SE. Similarly, the dominant joint set of System 2 (i.e. northeast mode joints) formed due to a NE-SW maximum horizontal compressive stress. The subordinate joint sets may be related to local stress release. This interpretation appears to be consistent with the active stress regime according to the World Stress Map (Heidbach et al., 2008). The World Stress Map reveals that joint orientation in the Farnsworth area is consistent with the modern lithospheric stress in the western Texas Panhandle as determined by hydraulic fracturing. The two joint systems may also be the fracture conjugate pair formed by NE-SW tectonic stress (Fig. 23).

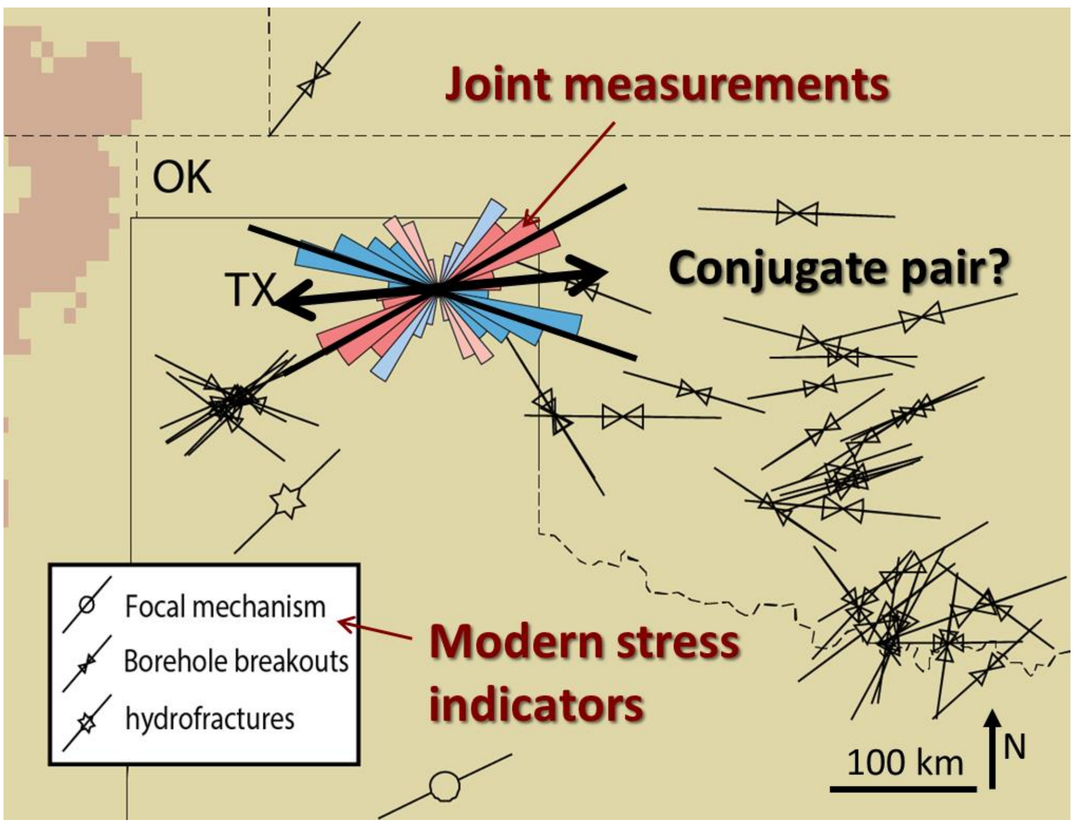

Fig. 23. Stress map showing the present-day stress in the Texas Panhandle area (modified from Heidbach et al., 2008).

V.2. Conceptual models

Damen et al. (2006) concluded that the risks of geological CO_2 storage can be divided into two classes: 1) infrastructural risk related to wells, pipelines, and processing facilities, and 2) geological risk related to reservoir and seal integrity (CO_2 and CH_4 leakage, seismicity, ground movement and displacement of brine). In the Farnsworth Oil Unit, geologic risk associated with CO_2 injection in the upper Morrow appears minimal because numerous sealing strata exist in the subsurface. Moreover, the Permian evaporites form a widespread seal that protects the High Plains Aquifer from any potential leakage associated with CO_2-enhanced oil recovery. Accordingly, the greatest risks are associated with infrastructure, and even this risk is low because the surface and production casing strings intervene between the wellbore and the USDW of the High Plains Aquifer (i.e., the Ogallala Formation).

The High Plains Aquifer in the Farnsworth Oil Unit is composed of very fine- to medium-grained sand and sandstone. The indurated sandstone lithofacies contains more cement than the less resistant massive and argillaceous sandstone lithofacies, and so limits fluid flux in the aquifer. Above the aquifer is a thick section of caliche and chert that would further buffer any seepage of CO_2 and CH_4. Numerous joints, including well-developed systematic joints and cross joints, were observed in the indurated sandstone lithofacies of the Ogallala Formation and in the siliceous caprock. Vegetation along the surface joint traces demonstrates that the fractures are important conduits for water and may therefore also control the exchange of gas between the aquifer and the atmosphere.

Joint aperture highly impacts fluid transmissivity. According to numerous studies (e.g., Ortega et al. 2006; Guerriero et al., 2010; Hooker et al., 2013), joint aperture typically has a power-law population distribution. This distribution suggests that gases like CO_2 and CH_4 will not leak equally through all joints. In fact, it is typical for the vast majority of flow to occur along a small percentage of fractures in jointed formations (e.g., Pashin et al., 2004, 2008). Where gas flows through a fracture of uniform aperture, it will ideally form a line-source plume (Fig. 24). Alternatively, where joint aperture is nonuniform, point-source plumes may emanate from segments of joints where aperture is increased. Therefore, even though numerous fractures occur in near-surface formations in the Farnsworth area, few fractures may form significant CO_2 and CH_4 migration pathways. Thus, if gas is moving through joints in the Ogallala Formation and the chert caprock, only few of fractures will support flow, and of those only parts of fractures may have significant aperture, perhaps either along localized joint segments or at joint intersections. In addition, the effects of fractures may be obscured by diffusion as gas migrates upward through the caliche section and soil profile. The validity of these hypotheses will be tested when surface monitoring equipment and UAVs are deployed at the Farnsworth Oil Unit.

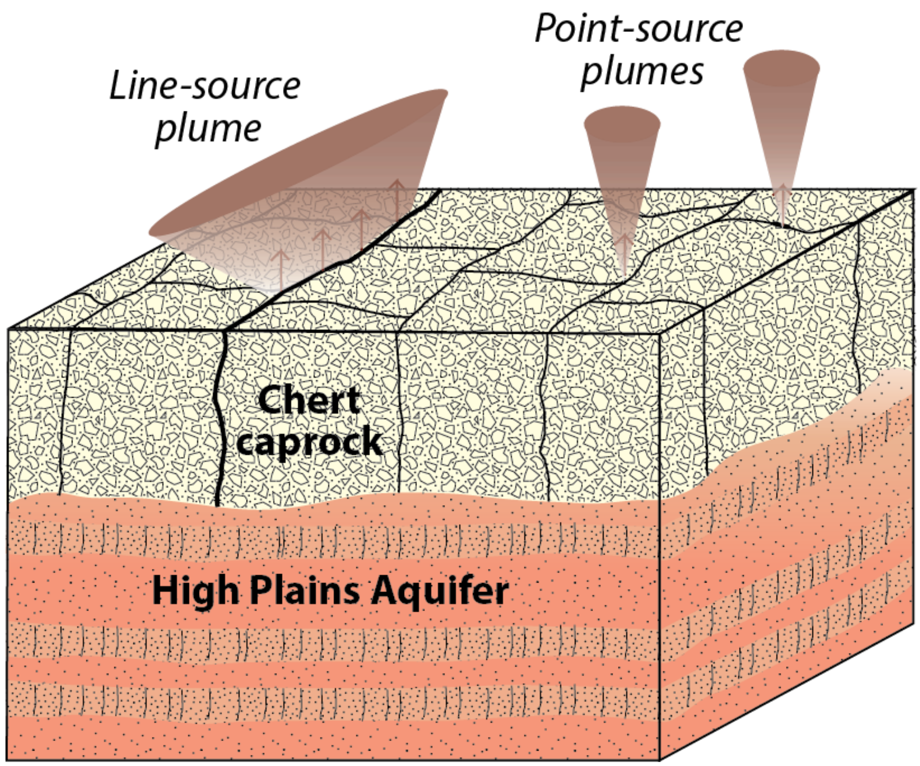

Fig. 24. Conceptual model of CO_2 movement through fractures.

Because the risk of reservoir leakage to the surface is very low in the Farnsworth Oil Unit, the CO_2 and CH_4 that the surface and airborne monitors detect may largely be the product of near-surface processes, such as microbial processes and reactions between carbonate and water (e.g., Klusman, 2005; McIntyre et al., 2008) (Fig. 25). CO_2 and CH_4 can be generated in soil and aquifers via microbial acetate fermentation. CH_4 also can be generated via microbial CO_2 reduction, which is a process that can consume fugitive CO_2. Another possibility is that CO_2 may be generated by calcite dissolution driven by meteoric recharge and groundwater movement, which may obscure the effects of natural fracturing in the shallow subsurface. Dissolved CO_2 in water also may generate carbonic acid, which will in turn be buffered by reaction with carbonate in the Ogallala Formation and the caliche section. Dissolution processes appear to be operating today, as evidenced by development of residual loam atop the caliche section (Fig. 7D).

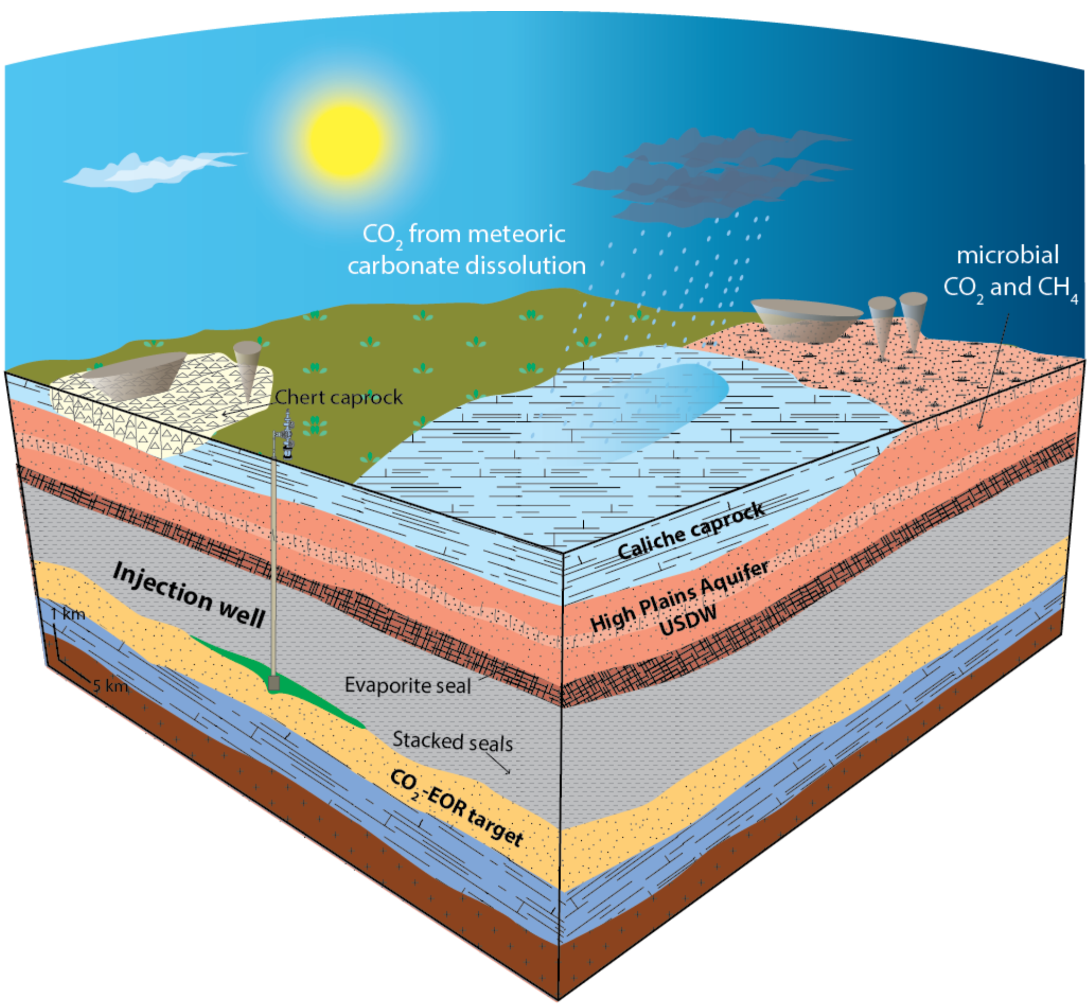

Fig. 25. Conceptual model showing CO_2 and CH_4 exchange among the aquifer, caprock, and atmosphere.

V.3. Design of UAV flight pattern

Based on the results of this research, surface and airborne monitoring programs should take fracture architecture into consideration to maximize the probability of detection of major CO_2 and CH_4 fluxes emanating from the land surface. Flight paths should ideally be oblique to systematic and cross-fracture orientations to increase the likelihood of fracture-related plume detection (Fig. 26). Future research will focus on field deployment of surface and UAV monitoring technology. During deployment the design UAV flight paths should not only consider the geologic architecture but also numerous other variables, such as, wind direction, wind velocity, flight altitude, and flight duration. After determining the actual CO_2 and CH_4 flux patterns in the Farnsworth Oil Unit, the results of surface and airborne monitoring will be used to adjust the geologic models, optimize surface sensor placement, and optimize UAV flight patterns.

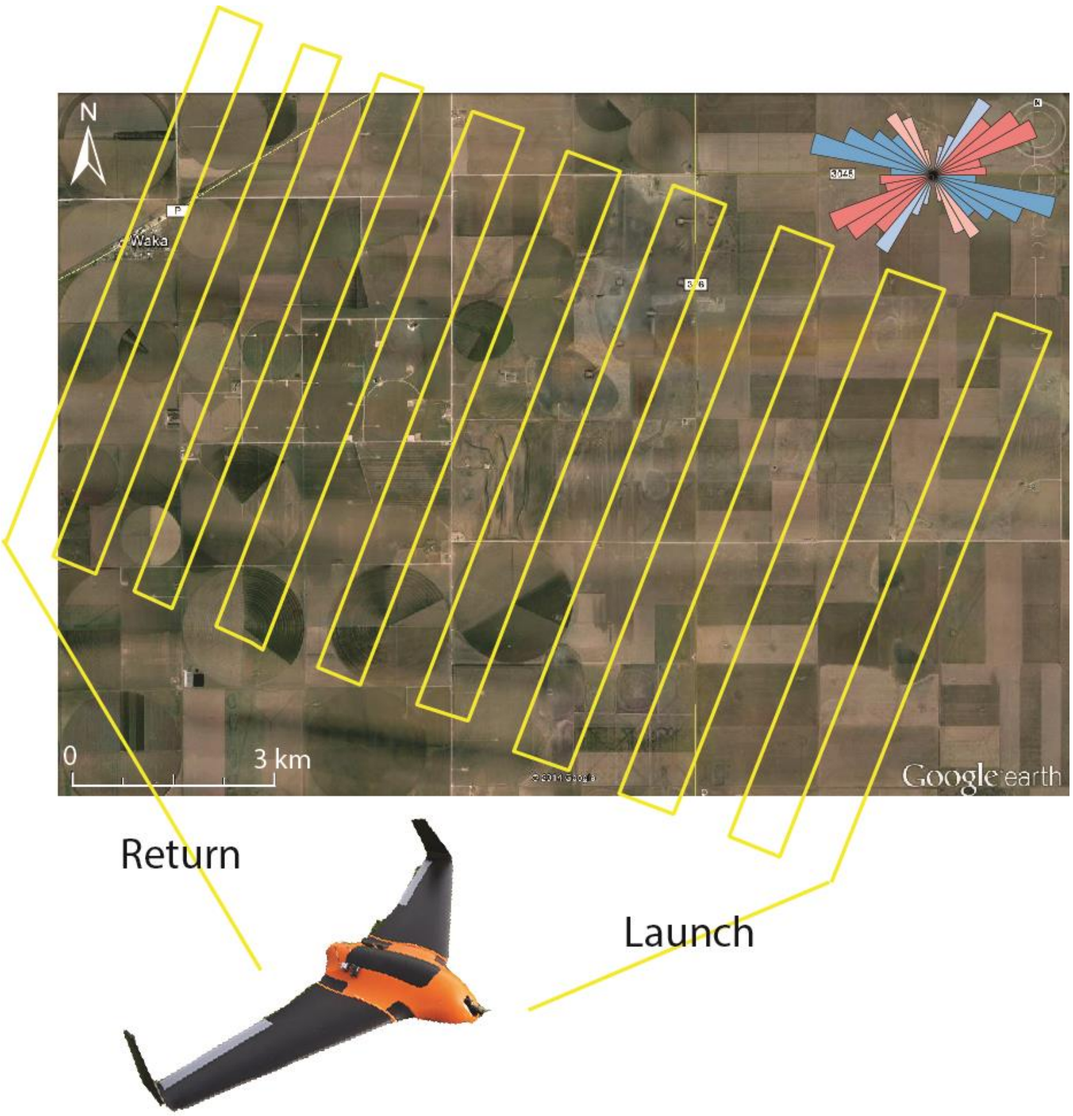

Fig. 26. Idealized aerial sampling pattern for terrains where orthogonal joint networks may influence the flux of gas into the atmosphere.

CHAPTER VI

CONCLUSIONS

The High Plains Aquifer of the northeastern Texas Panhandle includes sandstone of the Ogallala Formation and Quaternary strata that include sand, clay, chert, and caliche. The High Plains Aquifer disconformably overlies Permian and Triassic redbeds and is dominated by weakly to moderately indurated sandstone in the Miocene-Pliocene Ogallala Formation. Three lithofacies were identified in the Ogallala Formation, including the massive sandstone lithofacies, the argillaceous sandstone lithofacies, and the indurated sandstone lithofacies. Ogallala strata are overlain by Quaternary strata that include a siliceous caprock west of the Farnsworth Oil unit and a thick (~25 m) section of caliche east of the oil unit.

Field study of near surface strata reveals that indurated sandstone and a chert caprock strata contain numerous joints that provide crucial insight into aquifer architecture and subsurface flow pathways. The joint networks consist of well-developed systematic joints and cross-joints. Systematic joints are strongly aligned and are commonly longer than 60 m. Cross-joints tend to terminate at systematic joints and so joint length is typically equal to systematic joint spacing. The fractures are liner to curvilinear in plan view. In vertical section, the joints are typically curvilinear and strata-bound, cutting indurated strata and terminating within friable sandstone.

Analysis of joint indicates that that strike of the systematic joints varies among beds and regionally. Two distinctive joint systems were identified in the study area. The older system was observed in outcrops east of the oil unit and has vector mean azimuths of 115° and 31°. The younger system was observed throughout the study area, with joints having vector mean azimuths of 67° and 146°. Joint spacing follows a log-normal statistical scaling rule. In the west of the Farnsworth Oil unit, the general spacing of the older system joints are 2.0 m of SE mode and 1.9 m of NE mode. Joints of younger system contain the general spacing of 1.7 m at NE mode and 1.8 m at SE mode. In the west of the oil unit, the general spacing of the younger system joints is 3.3 m in the NE mode and 3.4 m in the SE mode. These fractures appear to be the product of regional tectonic stress and may have a significant effect on flow in the High Plains Aquifer system, as well as near-surface gas flux.

The risk of leakage from CO_2-enhanced oil recovery operations at Farnsworth is low, and multiple potential natural sources of CO_2 and CH_4 have been identified in near-surface formations. These near-surface sources are predicted to dominate shallow subsurface and atmospheric gas flux. CO_2 and CH_4 that the surface and airborne monitors detect may largely be the product of near-surface processes instead of gas from underground injection activities.

Design of UAV flight paths should be oblique to fractures in a way that maximizes the likelihood of CO_2 and CH_4 flux from of systematic joints and cross joints. Future research will focus on field deployment of surface and UAV monitoring technology, the results of surface and airborne monitoring will be used to adjust the geologic models, optimize surface sensor placement, and optimize UAV flight patterns.

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