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Paleogeomorphology of the Sub-Pennsylvanian Unconformity
on the Arbuckle Group (Cambrian-Lower Ordovician)

by

Jason R. Cansler

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by

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Abstract

The Sub-Pennsylvanian unconformity is the most important surface controlling the distribution of oil and gas in Kansas. Understanding the paleogeomorphology of the erosional surface, the influence of Precambrian topography, and the relationship of karst landform development to pre-existing structure and stratigraphy are important components to continued hydrocarbon exploration and production. The karst geomorphology of the Arbuckle Group rocks (Cambrian and Lower Ordovician) was examined at various scales, from regional mapping to core, over the southern extent of the Central Kansas uplift (Barton, Ellsworth, Rice and Stafford counties). Structure contour and interval isopach maps were produced to reconstruct the paleotopography using abundant well information where the well density in the studied counties exceeds 24 wells per km^2 (40 per $mile^2$). Major karst landform geometries were identified and landform development was related to the basement structure of the area. Arbuckle karst erosional features also show the influence of ground-water sapping processes. Scalloped-shaped escarpment edges and U-shaped stubby channels on the down-dip side of local highs are suggestive of slumping of Arbuckle carbonates by ground-water sapping. In contrast, up-dip scarp edges are relatively straight and form divides between drainage basins. Removal of slump blocks by continued weathering and fluvial processes is essential to maintain the effectiveness of ground-water sapping and consequent scarp retreat. Subsurface ground-water piracy appears to be an important process resulting in significant basin head widening. Differences in paleogeomorphic patterns can be attributed to structural and stratigraphic constraints that determine the relative effectiveness of ground water (sapping) processes.

The characterization of structural, karst and ground-water sapping controlled landforms was refined by constructing cross-sections and core examination. Integration of the core and well data provided the basis to delineate the stratigraphic controls on the morphology of the erosional surface and the distribution of reservoir facies. Data at a wide range of scales were used to develop a model of reservoir formation and distribution within the Arbuckle Group of Kansas, and genesis and geomorphology of large scale early Paleozoic karst terrains.

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1. INTRODUCTION

Rocks of the Arbuckle Group (Cambrian and Lower Ordovician) represent an important record of deposition on the North American continent and contain significant accumulations of hydrocarbons. The Arbuckle Group is the single most prolific petroleum-producing horizon in Kansas, accounting for nearly one-third of the 6.6 billion barrels produced to date.

Erosion of the Arbuckle, related to repeated karst development, heavily modified the relief associated with both pre-existing erosional, depositional, and structural patterns. Understanding the paleogeomorphology of the Arbuckle weathering surface, the possible influence of Precambrian topography, and the relationship of karst landform development to pre-existing structure and stratigraphy are important components to continued hydrocarbon exploration and production (Carr et al., 1995a).

This study examined the morphology of the Sub-Pennsylvanian erosional Arbuckle surface at a range of scales from regional mapping to core in a four county area over the southern extent of the Central Kansas uplift (Figure 1.1). The goals are to delineate the karst geomorphologic controls on Arbuckle petroleum production, and to investigate the genesis and geomorphology of large-scale Paleozoic karst terrains. With the description of how karst erosion influenced the Sub-Pennsylvanian surface, I hope to improve our understanding of reservoir formation and distribution within the

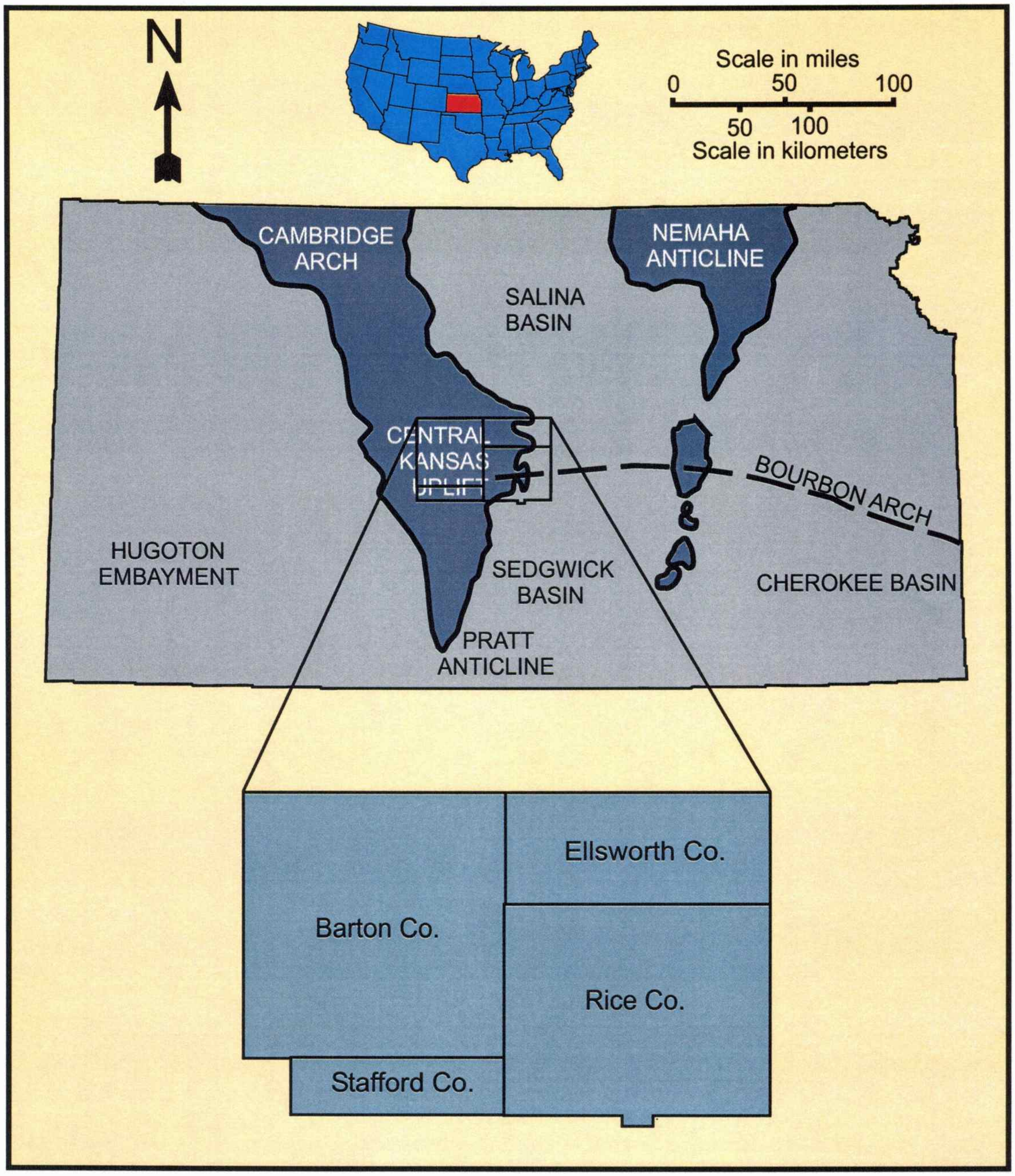

Figure 1.1: Location map of study area consisting of Barton, southern Ellsworth, Rice, and northern Stafford counties, Kansas in relation to major stuructural features. Modified from Merriam (1963).

Arbuckle Group in central Kansas. Many erosional processes were recognized on the Arbuckle surface at varying degrees of intensity. The interaction of pre-existing structural features, renewed tectonics, and variations in lithology of the Arbuckle Group resulted in a complex erosional surface characterized by ground water sapped plateaus and surface karst features.

Study Area

This study of the Arbuckle erosional surface encompasses the southern extent of the Central Kansas uplift, and includes Barton, Ellsworth, Rice and northern Stafford counties (Figure 1.1). The focus of this study is the area where Sub-Pennsylvanian erosion was greatest. Including the area where Middle Ordovician through Mississippian rocks are absent, and Arbuckle Group rocks subcrop beneath Pennsylvanian strata (Figure 1.2). The study area contains three of the six largest oil fields in Kansas (i.e. Chase-Silica, Trapp, and Kraft-Prusa fields). In the four counties encompassing the study area, an extensive subsurface database exists with over 28,500 wells. In some parts of the study area, drilling densities exceed 24 wells per square kilometer (40 per square mile).

Geologic Background

The Cambrian-Lower Ordovician Arbuckle Group dolomite is present in the subsurface over most of Kansas with the exception of local uplifts and Precambrian highs (Merriam, 1963). The Arbuckle Group rocks occur at

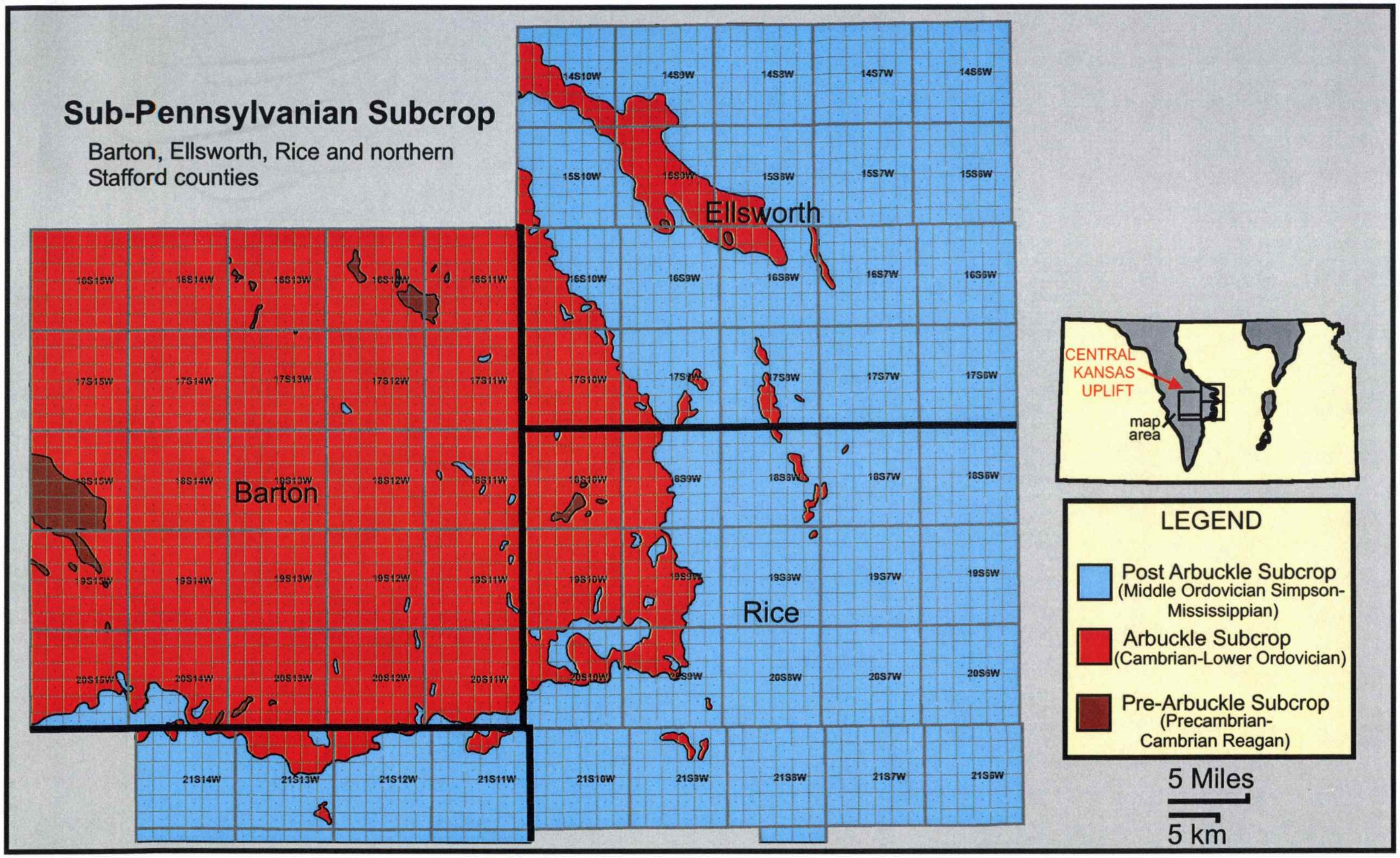

Figure 1.2: Sub-Pennsylvanian subcrop map of study area in Central Kansas. The study includes only the area where Pre-Pennsylvanian erosion was greatest, where Middle Ordovician through Mississippian strata were removed and Arbuckle strata subcrops beneath the Pennsylvanian.

depths ranging from approximately 500 feet (150 meters) in southeastern Kansas to more than 5000 feet (1500 meters) in southwestern Kansas (Cole, 1975). From north to south, Arbuckle rocks thicken to approximately 1390 feet (425 meters) in the southeastern corner of the state (Cole, 1975).

A sea-level fall marked the end of Arbuckle Group deposition and resulted in extensive subaerial exposure of platform carbonates. During the early Middle Ordovician, dissolution and karst development formed a regionally extensive karst system over most of the North American craton. This regional karst system has been labeled the Arbuckle-Ellenburger-Knox-Prairie du Chien-Beekmantown-St. George karst plain (Kerans, 1988). Extensive regional exposure was repeated at least one more time in the Late Mississippian to Early Pennsylvanian (Kluth and Coney, 1981). During repeated and extended periods of weathering, the exposed surface on the Arbuckle Group underwent a geomorphic evolution. Karstification, is a common geologic process that can significantly affect paleotopography and alter petrophysical properties through diagenesis (Hanford and Loucks, 1993).

The Arbuckle and equivalent reservoirs in the Midcontinent are generally considered to have reservoir qualities related to basement structural elements including fractures, regional uplifts, and minor horst and graben features (Franseen et al., 1995). The regional and stratigraphic extent of subaerial exposure and karstification in the Arbuckle was influenced by regional patterns of uplift and subsidence (Newell et al., 1987, Franseen et al., 1995). Reservoir qualities were modified by karst processes during prolonged and repeated subaerial exposure that began after Arbuckle deposition and continued in some areas until the Pennsylvanian (Franseen et al., 1995).

In Kansas, structure played a major role in the development of Arbuckle reservoirs on several different scales. On a regional scale, most hydrocarbon production within the Arbuckle occurs on two major structural uplifts. The two features that affect the Paleozoic rocks in Kansas are the northeast-southwest trending Nemaha uplift, and the group of structures trending northwest-southeast that include the Cambridge Arch, the Central Kansas uplift, and the Pratt Anticline (Newell et al., 1989). Throughout much of the Paleozoic, until the Permian, the Central Kansas uplift was a shelf area sinking and receiving sediments, but with a thinner sedimentary cover than the more rapidly subsiding Salina basin on the northeast and the Hugoton embayment of the Anadarko basin on the southwest (Walters, 1958). Locally, Arbuckle strata were uplifted and extensively eroded during Late Mississippian-Early Pennsylvanian deformation. Especially affected was the Central Kansas uplift, where Middle Pennsylvanian strata directly overlie Arbuckle strata, or where the Arbuckle has been completely removed and Middle Pennsylvanian rocks overlie the Precambrian basement (Franseen, 1994, Newell et al., 1987).

Stratigraphy

The Arbuckle Group consists of Upper Cambrian and Lower Ordovician deposits including the Eminence Dolomite, Gasconade Dolomite, Roubidoux Dolomite, Jefferson City Dolomite, and the Cotter Dolomite (Figure 1.3). "Arbuckle Group" is sometimes used for all rocks between the top of the Reagan Sandstone and the base of the Simpson Group (Zeller, 1968). Arbuckle rocks are part of the craton-wide Sauk Sequence, which is bounded, at its base and top, by major interregional unconformities (Figure 1.4; Sloss, 1963).

Merriam (1963) described the Arbuckle Group as consisting of mainly dolomite with scattered beds of sand and chert, and minor amounts of glauconite and pyrite. Arbuckle Group and equivalent-age rocks from Kansas and surrounding areas consist of platform deposits dominated by ramp-type subtidal to peritidal carbonates that have been extensively dolomitized. Major depositional facies of the Arbuckle Group in central Kansas consist of coarse-grained packstones/grainstones, fine-grained packstones/wackestones/mudstones, stromatolites-thrombolites, intraclastic conglomerate and breccia, and shale (Franseen, 1994).

Karst processes have been targeted as important in Arbuckle equivalent rocks (Ellenburger and Knox groups). However, the significance of karst formation and original depositional fabric is not well understood in the Arbuckle of Kansas. Karst processes have been documented to variously

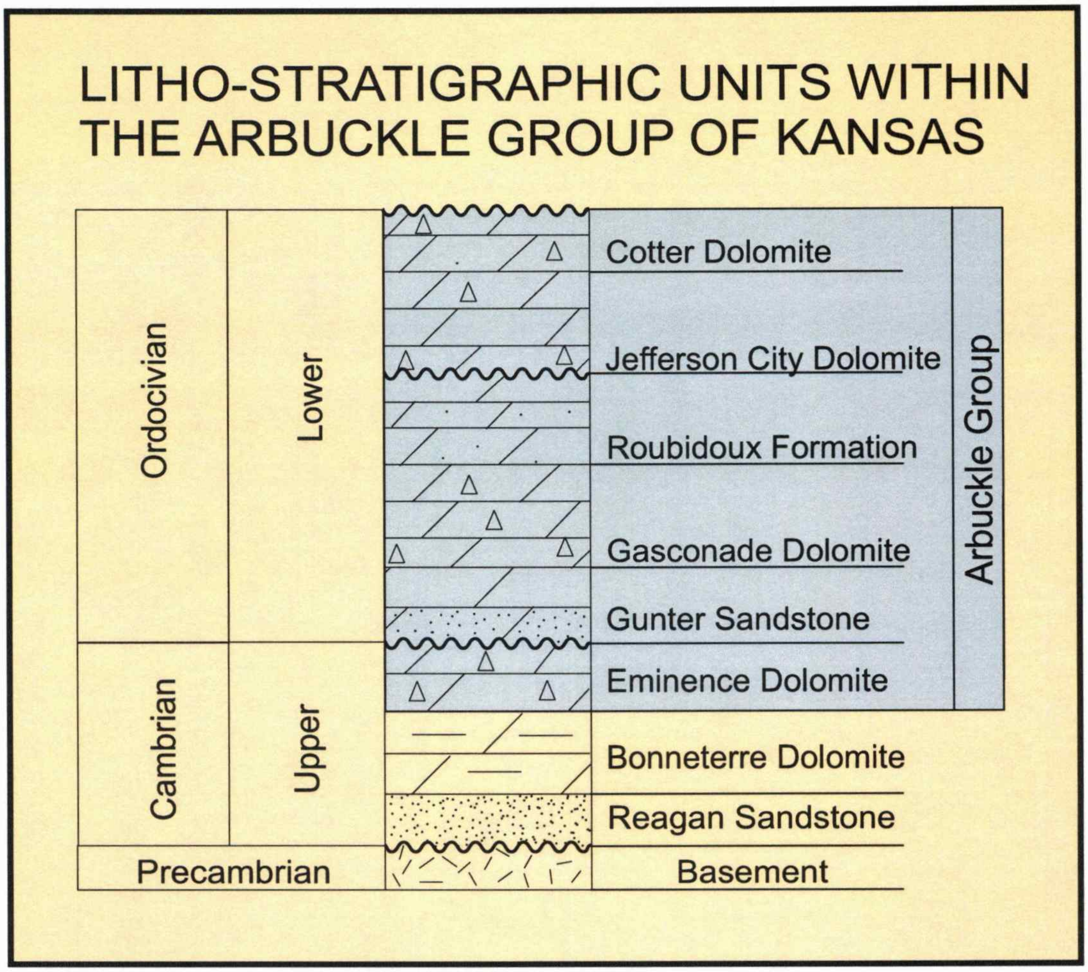

Figure 1.3: Stratigraphic column of Cambrian and Lower Ordovician units in Kansas.

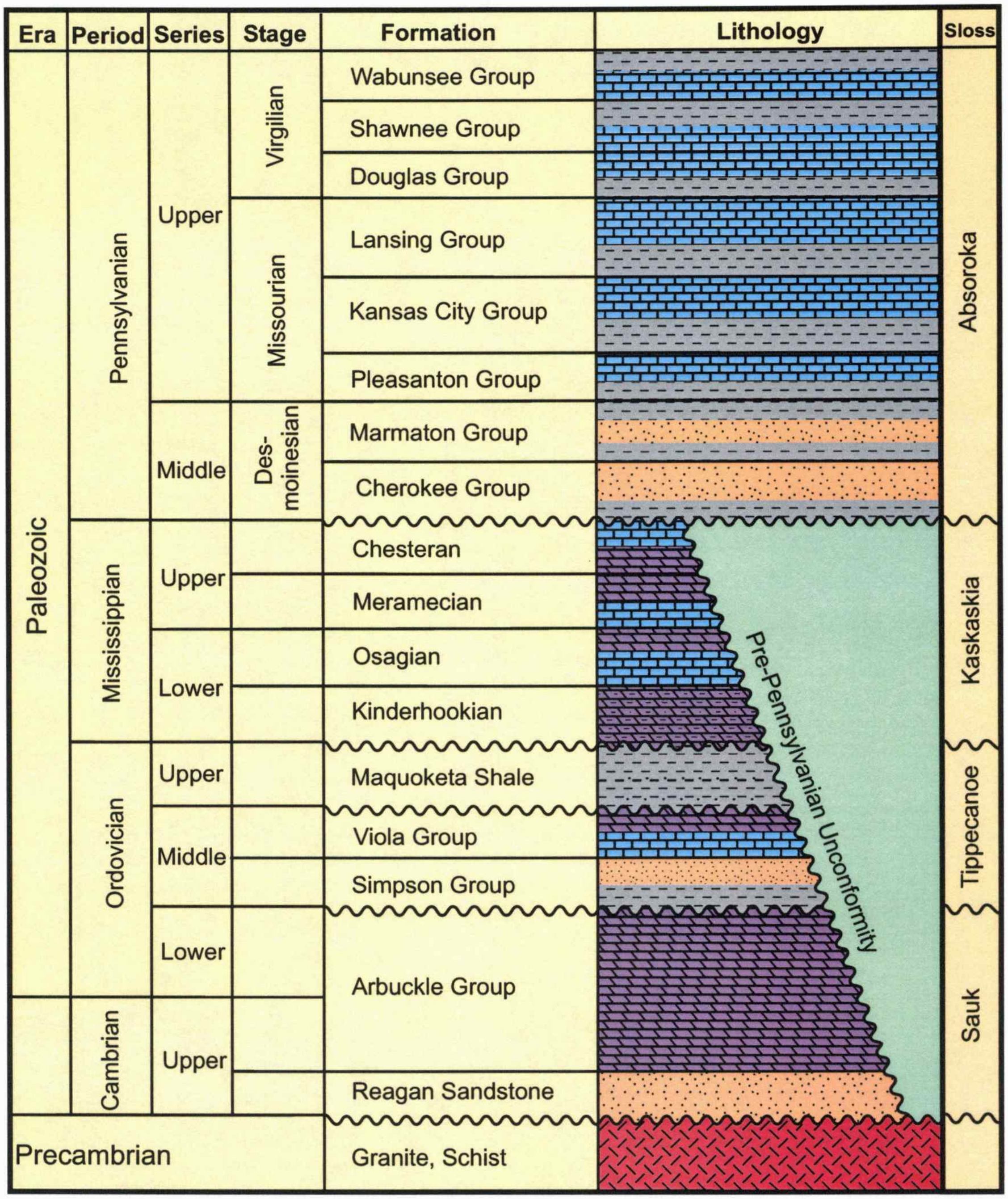

Figure 1.4: Stratigraphic column in central Kansas in relation to Sloss super-sequences. Over much of the Central Kansas uplift the lower Paleozoic rocks above the Arbuckle, and in some areas down to the Precambrian basement, have been removed by Late Mississippian to Early Pennsylvanian erosion.

enhance or destroy porosity in the Arbuckle carbonates (Franseen, 1994, Steinhauff, 1998). Based on examination of selected Arbuckle cores, Franseen (1994) concluded that a significant amount of porosity is controlled by depositional facies and dolomitization with only minor porosity related to late stage brecciation and fracturing that resulted from structural and karst controls.

Regional Structure

The region of the central Midcontinent has been called the "stable interior" of the North American continent (Bunker et al., 1988). However, the central Midcontinent is filled with evidence of tectonic activity (Bunker et al., 1988). Prominent uplift and subsidence occurred episodically throughout the Phanerozoic, separated by periods of gradual deformation (Newell et al., 1989).

Gravity and magnetics maps provide a useful display of aerial continuity of basement block patterns that allow interpretations of fault patterns, sense of displacement, and deformation of the overlying sedimentary rock sequence (Thompson et al., 1995). Gravity and magnetics maps of Kansas highlight the configuration of the basement (Figures 1.5 and 1.6). The gravity and magnetic data exhibit an overall northwesterly grain across the state, except for the strong northeasterly trend that cuts through the center of the state. This northeastern trend (outlined in red on Figures 1.5 and 1.6) represents the deep-seated boundaries of the Central North

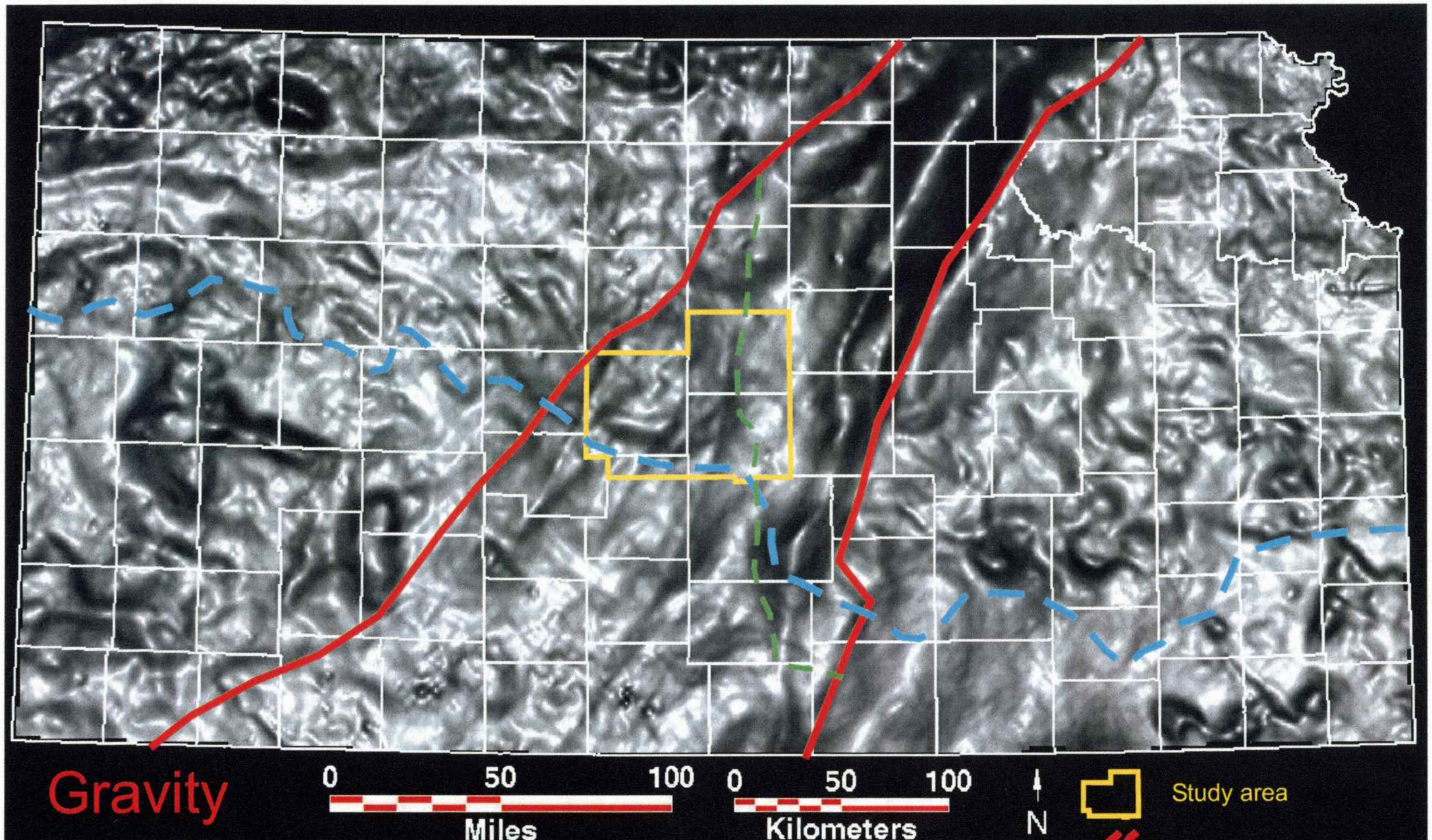

Figure 1.5: Gravity map of Kansas showing interpreted boundary of the of the Central North American Rift System (CNARS). Northwesterly grain of gravity features are cut by the CNARS (modified from http://www.kgs.ukans.edu/DPA/Plays/Grav/ksGravCnty.html, boundaries modified from Yarger, 1983).

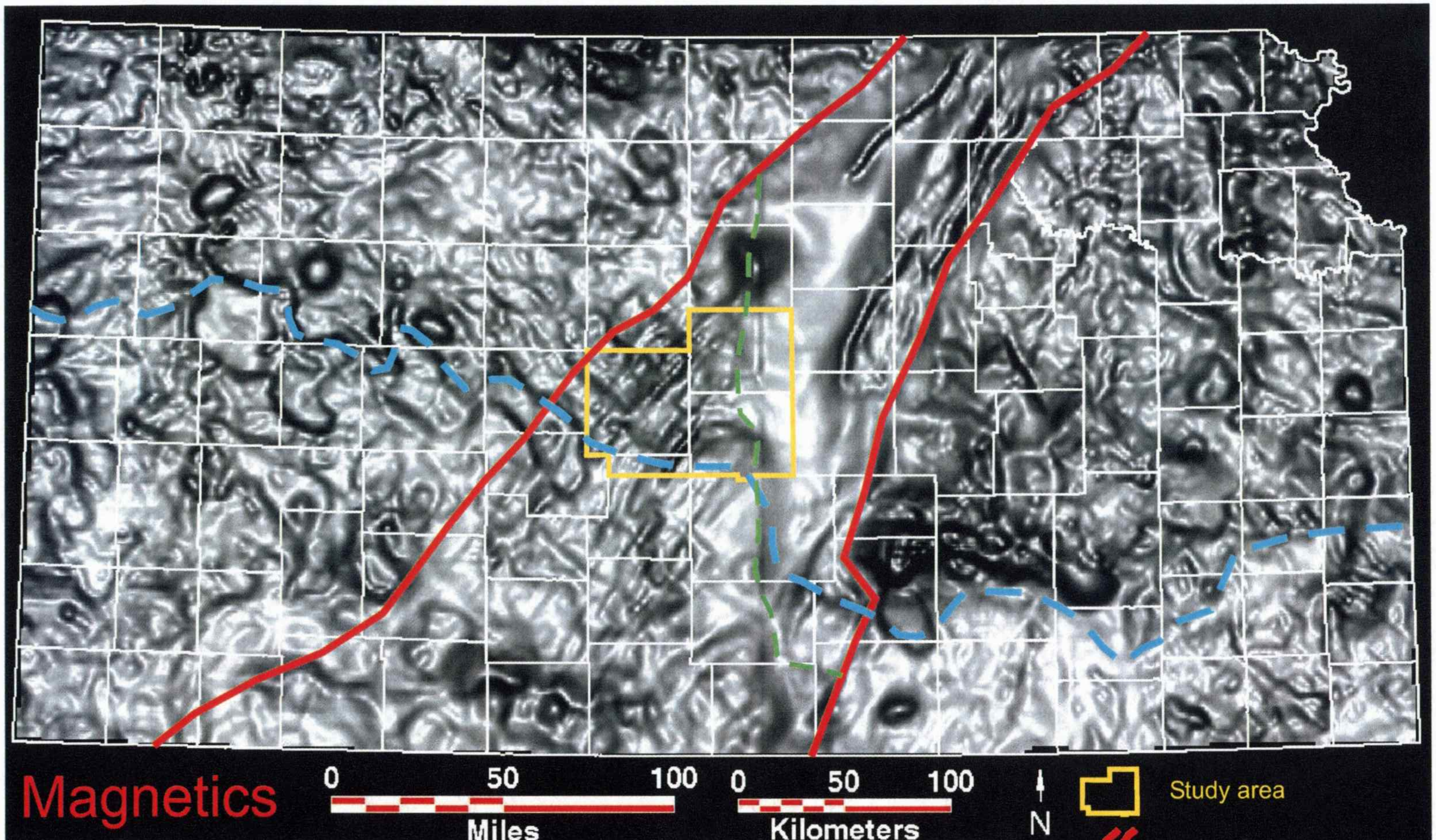

Figure 1.6: Magnetics map of Kansas showing interpreted boundary of the of the Central North American Rift System (CNARS). Northwesterly grain of magnetics features are cut by the CNARS (modified from http://www.kgs.ukans.edu/DPA/Plays/Mag/ksMagCnty.html, boundaries modified from Yarger, 1983).

American Rift System (CNARS; Yarger, 1983). Both the eastern and western boundaries of this Keweenawan system (1100 million years B.P.) are sharply defined, suggesting they may be fault bounded (Yarger, 1983). The CNARS represents a zone of weakness susceptible to reactivation during subsequent deformational events. One example the Humboldt fault, a post-Mississippian fault that borders the eastern side of the Nemaha Ridge, closely parallels the CNARS across the state (Yarger, 1983). The northwest-southeast trending lineaments along the Central Kansas uplift appear to be offset structures related to the Precambrian rift (Baars and Watney, 1991).

Dominant northeast-southwest and minor northwest-southeast gravity and magnetic trends are apparent in the western two-thirds of the study area. However, distinct gravity and magnetic trends are obscured in the eastern one-third of the study area by the presence of Keweenawan sedimentary rocks (Rice Formation, Yarger, 1983). A possible deep-seated paleoplate boundary, delineated by a sharp, high frequency boundary within the crust, may exist in the southern portion of the study area (Yarger, 1983).

Early Paleozoic geologic structures are difficult to recognize because their original geometry has been considerably altered by the more severe Late Mississippian-Early Pennsylvanian structural movements (Newell et al., 1987). However, a broad northwest-southeast trending Pre-Mississippian structural high is recognized (Figure 1.7). This feature is called the Central Kansas arch in south central Kansas; its northwest and southeast extensions

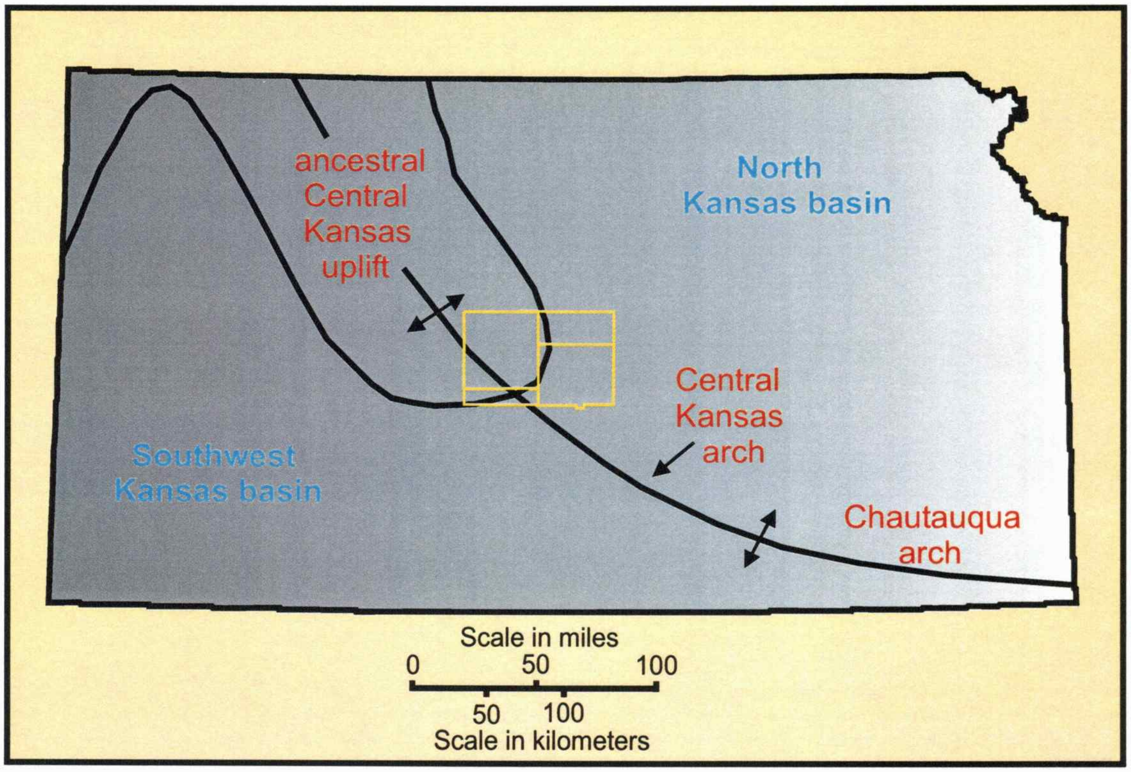

Figure 1.7: Pre-Mississippian-Post Ordovician structural features of Kansas. Modified from Merriam (1963).

are respectively called the ancestral Central Kansas uplift and the Chautauqua arch (Merriam, 1963).

Paleogeographic syntheses of various Phanerozoic intervals in North America indicate that intraplate tectonism can be correlated with episodes of orogenesis along the continental margins (Bunker et al., 1988). During the Middle and Late Mississippian, Midcontinent deformation was focused in the vicinity of the Central Kansas, Nemaha, and Ozark uplifts (Brown, 1995). Brown (1995) attributed this deformation in the Midcontinent to the shallow dipping subduction taking place beneath the eastern United States, while steeply dipping subduction took place offshore Texas and Louisiana. This tectonic configuration produced a transition zone in subduction geometry that focused the stresses associated with this period of deformation toward the Central Kansas, Nemaha, and Ozark uplifts (Brown, 1995).

Late Mississippian to Early Pennsylvanian deformation of the craton is related to the early deformational phases of the Ouachita orogeny (Kluth and Coney, 1981). The Ouachita orogeny has been interpreted to reflect the suturing of the North and South American continents. Major structural features in Kansas (Nemaha uplift, Central Kansas uplift) represent significant Late Mississippian to Early Pennsylvanian (pre-Desmoinesian) deformation associated with this plate convergence along the orogenic belt now defined as the Ouachita Mountains of Arkansas (Newell et al., 1989). By late Pennsylvanian time, suturing was taking place only in the Marathon region (southwestern Texas), and cratonic deformation had decreased in extent and spread southward into New Mexico and West Texas (Kluth and Coney, 1981). Movement on all major features in Kansas, particularly the Central Kansas uplift, had ceased after the Pennsylvanian except for minor tilting and compaction related "prairie style" deformation (Merriam and Forster, 1996).

Petroleum System

The Arbuckle Group and stratigraphically equivalent reservoirs have been some of the most prolific oil producers in the Mid-continent. Arbuckle strata account for nearly one third of the approximately 6.6 billion barrels of cumulative oil production in Kansas (Figure 1.8). In the early 1900's oil was found mostly by random wildcat drillers in Arbuckle reservoirs in the subsurface of southeastern Kansas and northeastern Oklahoma (Cardwell, 1977). Since then, thousands of wells have successfully encountered petroleum based on a drilling philosophy of penetrating only the very top of the thick Arbuckle sequence. In Central Kansas, drilling strategies focused on karstic porosity developed in the upper 200-300 feet (60-90 meters) subjacent to the Sub-Pennsylvanian unconformity. Recent studies highlight the importance of matrix porosity for fluid storage and indicate that reservoir quality porosity exists well below the unconformity (Franseen, 1994; Franseen et al., 1995, Steinhauff et al., 1998). If suitable trapping

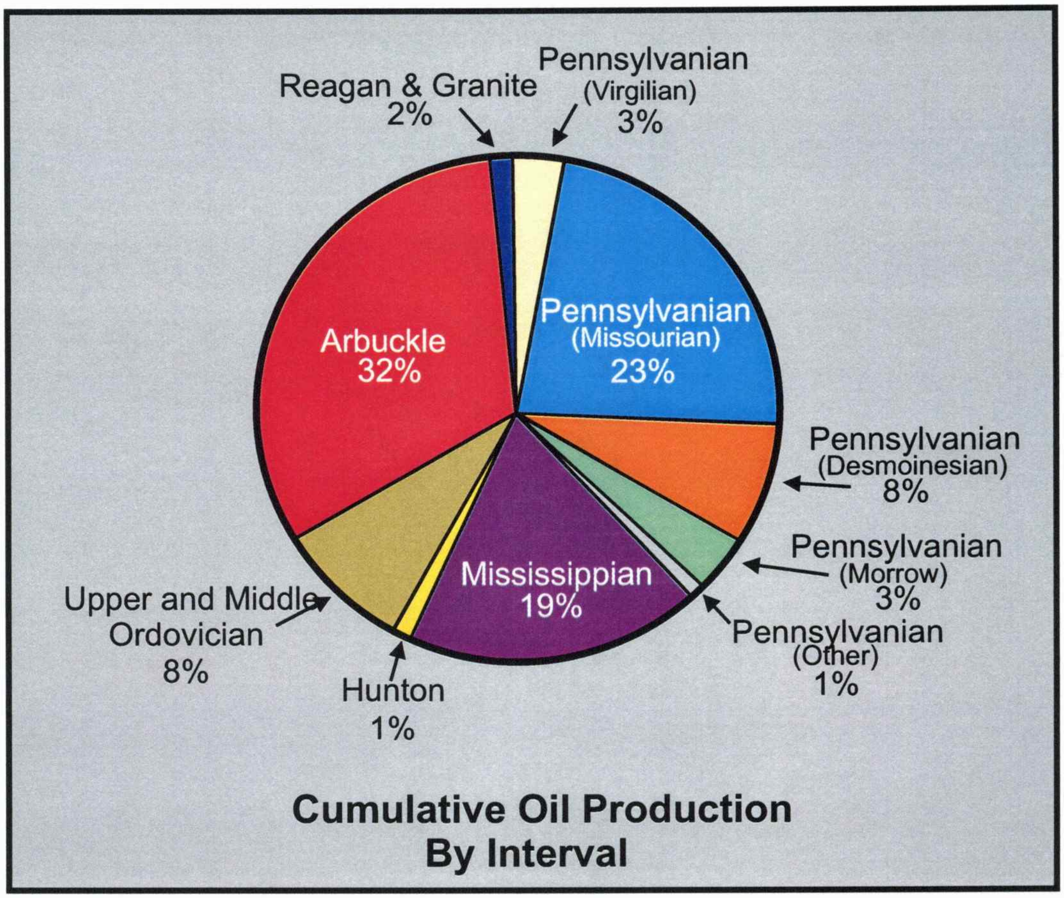

Figure 1.8: Cumulative oil production in Kansas by interval showing the importance of the Arbuckle Group on total production (modified from Carr et al., 1995b).

mechanisms exist, deeper horizons within the thick Arbuckle Group may also be productive.

For decades, Arbuckle reservoirs were discovered in many different stratigraphic horizons within the group. Some horizons proved to be more successful than others, but it was thought that all hold oil only when subjacent to the Sub-Pennsylvanian unconformity surface (Walters, 1958). As deeper horizons were discovered over the years the identity of the source for Kansas oils became more important. Some petroleum geologists proposed that the Arbuckle itself could be the source for the oil and gas in Kansas (Cardwell, 1977).

Cardwell (1977) employed oil-source correlations to determine the source potential of the Arbuckle. He concluded that the oils and rock volatiles were different, indicating the oils were not generated in these rocks. Other studies tested the thermal maturity of the Paleozoic strata in Kansas (Cardwell, 1977; Burruss and Hatch, 1989; Walton et al., 1995; and Wojcik et al., 1997). These studies indicate that Arbuckle Group rocks can generate oil, and probably have in the past, but the amounts were small and likely never migrated out of the rocks. The data in these studies argue that the Paleozoic section in Kansas is thermally immature, except for a narrow strip along the southern border approaching the Anadarko basin.

Long distance migration of oil and gas was proposed by Rich (1931) and expanded on by Walters (1958). Walters (1958), using a series of structure and isopach maps determined the horizontal component of migration through time. Considering the geologic history of the area, he concluded that oil and gas in central Kansas traps probably migrated long distances out of the Anadarko basin in Oklahoma. Burruss and Hatch (1989) also inferred long distance migration, however they took the problem one step further. They found that oils from the Kansas shelf area of the Anadarko basin are similar to the Anadarko basin itself, except that shelf oils have only traces of toluene and no detectable benzene. The relative abundance of toluene in the C_7 hydrocarbons systematically decreases with distance from the depocenter of the basin (Burruss and Hatch, 1989). Aromatic compounds are removed by water washing, and could have been lost by contact with greater amounts of formation water during long-distance migration (Burruss and Hatch, 1989).

Assuming that hydrocarbons in Arbuckle reservoirs in Kansas migrated long distances from Oklahoma, the question remains, which unit in the Anadarko basin is the source. Burruss and Hatch (1989) distinguished three genetic groups of petroleum in the Midcontinent. The gasoline paraffinicity and other genetic fingerprints of the Kansas oils match up most closely with oils derived from the Woodford Shale, which is one of North America's richest and most important source rocks.

Previous Reservoir Studies

Early studies of the Arbuckle Group reservoirs in Kansas focused on description and classification of the strata (McCracken, 1955; Jewett. 1951; Merriam, 1963; Zeller, 1968; Cole, 1975). Studies conducted by Walters (1946, 1953, 1958, 1991) concentrated on controls on the petroleum production from Arbuckle reservoirs on the Central Kansas uplift.
Loucks and Anderson (1985) described porosity development in the age equivalent Ellenburger Group in relation to depositional facies and diagenetic terrains. Kerans (1988, 1990) and Mazullo (1990) described various karst processes as related to reservoir heterogeneity and compartmentalization in the Ellenburger Group of West Texas. Kerans (1988) also provided a detailed model for paleokarst breccia development in the Ellenburger Group. The Arbuckle of Oklahoma has received a great deal of attention in both the surface exposures and subsurface cores. Lynch and Al-Shaieb (1991) constructed various models concerning the genesis of karstification in several Arbuckle cores from Oklahoma. These recent studies in the Ellenburger and Arbuckle group rocks have focused on internal karsts (i.e. caves), and reservoir development within the units. The geomorphologic expression of the karst processes at the exposure surface and its relationship to reservoir development has not received significant modern study.

Recently, the Arbuckle Group rocks have been receiving attention with respect to sedimentology and stratigraphy in order to gain an understanding of the microscopic to macroscopic reservoir properties. Franseen (1994) conducted a petrographic examination of two Arbuckle cores to evaluate the relationship between depositional facies and reservoir porosity. Steinhauff et al. (1998) described the importance of depositional facies, diagenesis, and karst processes on reservoir properties. Franseen (1994) and Steinhauff et al. (1998) concluded that depositional facies and dolomitization are important contributors to reservoir porosity, and that significant pay zones may be present well below the unconformity surface.

In order to understand reservoir performance, reservoir description is associated with a "volume scale" (Haldorsen and van Golf-Racht, 1992). The "microscopic scale" involves the study of grain and pore characteristics discernible in thin sections and core plugs. The "macroscopic scale" is associated with a core or electric log. This is the scale at which reservoir rock properties and vertical stacking patterns are determined. The "megascopic scale" reflects the internal architecture of the reservoir and the influence of hydraulic units and major barriers to fluid flow. The dimensions, shape, orientation and spatial distribution of megascopic features determine the severity of reservoir compartmentalization and have a strong effect on reservoir performance. Megascopic descriptions reflect the external geometry of the reservoir and large-scale internal features such as fracturing and solution joints. These megascopic features are major components in formation of reservoir compartments and recovery effectiveness, and cannot be easily described by vertical well bore data (i.e. core and logs). Understanding and evaluating the megascopic geometry and behavior of reservoirs is very difficult from macroscopic and microscopic data (Haldorsen and van Golf-Racht, 1992).

Carr et al. (1995) incorporated detailed structural mapping of the Arbuckle surface and seismic data to gain an understanding of the controls on the paleogeomorphology and distribution of reservoir quality on a megascopic scale of a single Arbuckle field. Other than the study provided by Carr (1995), there has been little work on the nature of karst development and its influence on reservoir quality in the Arbuckle of Kansas. This study will focus on understanding and evaluating geomorphologic expression of surface karst, and its influence on reservoir quality on a megascopic scale for the numerous Arbuckle reservoirs of the southern Central Kansas uplift.

Methodology

The objective of the study is to improve the understanding of the controls on the karst geomorphology of the erosion surface and how they relate to Arbuckle reservoirs on the megascopic scale. Reconstructing the Sub-Pennsylvanian Arbuckle surface was accomplished by assembling a series of structure and interval isopach maps using commercial mapping software (GeoGraphix Exploration System). In addition, maps were constructed on horizons above the Arbuckle erosional surface to remove any post-karst deformation. By downloading the Kansas Geological Survey well history database, these maps were built using over 22,000 wells, (18,000 wells contain Arbuckle tops data, Panel 1). The database was qualified by checking the accuracy of the information given, as well as the addition of well data in areas where greater detail is required. Various sources of random error were addressed to improve the database, such as incorrect well locations and formation tops. Over the entire study area, average drilling densities exceeded 20 wells per square mile (7.5 wells per square kilometer). Using a large database with dense data coverage provides excellent well control that can improve images of karst landforms that have been previously too small to map on a regional scale, and too large to recognize in a single core or well log.

County scale maps were generated to image regional erosional and structural features. The minimum curvature gridding method was applied to the data. Minimum curvature is a gridding technique that derives grid node values multiple times. The initial gridding pass averages the data to express a regional trend, then successive gridding iterations calculate additional grid values to reflect the influence of localized features. A grid spacing of 1320 feet (400 meters) was chosen to capture the regional grain of the area. This grid spacing allows imaging features with a minimum horizontal dimension of 2640 feet (800 meters). With a horizontal resolution of 2640 feet, a contour interval of 25 feet (7.5 meters) was sufficient to accurately represent the vertical relationships of the large-scale features. At this contour interval (25 feet), features with approximately 50 feet (15 meters) of vertical relief could be adequately resolved.

Selected areas were mapped in greater detail in order to image finer-scale erosional features. The minimum curvature gridding method was applied to the data and a grid spacing of 165 feet (50 meters) was chosen. In some areas wells are as close as 330 feet (100 meters), so choosing a well spacing of 165 feet ensures that each grid cell is represented by only one well. This grid spacing allows imaging features with a minimum horizontal dimension of 330 feet (100 meters). A contour interval of 5-10 feet (1.5-3.0 meters) provides a vertical resolution of 10 to 20 feet (3 to 6 meters).

To aid in the description and characterization of the geometries of these landforms, several cross-sections were constructed. These cross-sections provided the basis for determining the stratigraphic controls on the surface morphology, as well as recognizing karst features within the Arbuckle (e.g. caves).

In order to determine the Pre-Mississippian regional structural dip of Arbuckle strata, a "three point" approach was used. A series of triangular patterns created by three wells within a relatively small area that penetrate a sufficient section of the Arbuckle were used to calculate dips within the unit. Well logs were used to correlate shaley horizons beneath the Sub-Pennsylvanian Arbuckle surface. These shaley horizons were identified mainly from gamma ray logs, but the interpretations were supported with available neutron, density and resistivity logs. The control on the internal dip within the Arbuckle was limited by the paucity of wells that sufficiently penetrate the Arbuckle and were logged. In fact, of the 18,000 wells with Arbuckle tops data, less than seven percent penetrated the formation deeper than 100 feet (30 meters).

In order to describe the structural, burial-related, and karst features at a finer scale available Arbuckle core housed at the Kansas Geological Survey were examined. Core analysis provided detailed data on karst processes at the reservoir scale such as, dissolution cavities, solution-enlarged fractures, collapse breccias, and vugular porosity.

Basement structure is believed to control the development of an extensive joint system in the Arbuckle dolomites, with joint directions parallel to tectonic fault directions of basement rocks (Walters, 1958). Gravity and magnetics maps were used at both the state and county-scale to gain an understanding of the structural controls on the erosional surface. These maps provided a framework to understand the fracture-controlled solution in the Arbuckle, as well as the influence of basement tectonics on the karst geomorphology. Directions of interpreted lineaments from gravity and magnetics maps were plotted on rose diagrams for comparison with orientations of structural and erosional features.

Evaluating Post-Erosional Deformation

To gain an understanding of the paleogeomorphology of the Arbuckle surface it is necessary to evaluate and remove deformation that occurred after burial of the surface. It is important to determine if relief on the present Arbuckle structure represents an actual erosional surface, or has been extensively modified by post-erosional deformation. By generating structure and interval isopach maps using well-defined markers above the unconformity, one can evaluate and remove the effects of possible younger deformational events.

The regional structure on the Arbuckle Group rocks has a relatively high degree of relief in relation to other horizons in Kansas (Figure 1.9). There are many minor northwest-southeast and northeast-southwest trending antiform structures in the area. The 1700 foot subsea contour line roughly outlines the southeastern extent of the Central Kansas uplift. Structural patterns from the Arbuckle structure map can still be discerned on the base of the Kansas City Group structure map, however the structure is subdued (Figure 1.10). The interval isopach between the base of the Kansas City and the top of the Arbuckle Group displays the character of the Pre-Missourian sediment fill over the exposed Arbuckle rocks. The interval isopach thins over Arbuckle highs and thickens in the lows (Figure 1.11).

Local regions across the study area can be used to illustrate the decrease in structural relief due to Pre-Missourian deformation. In

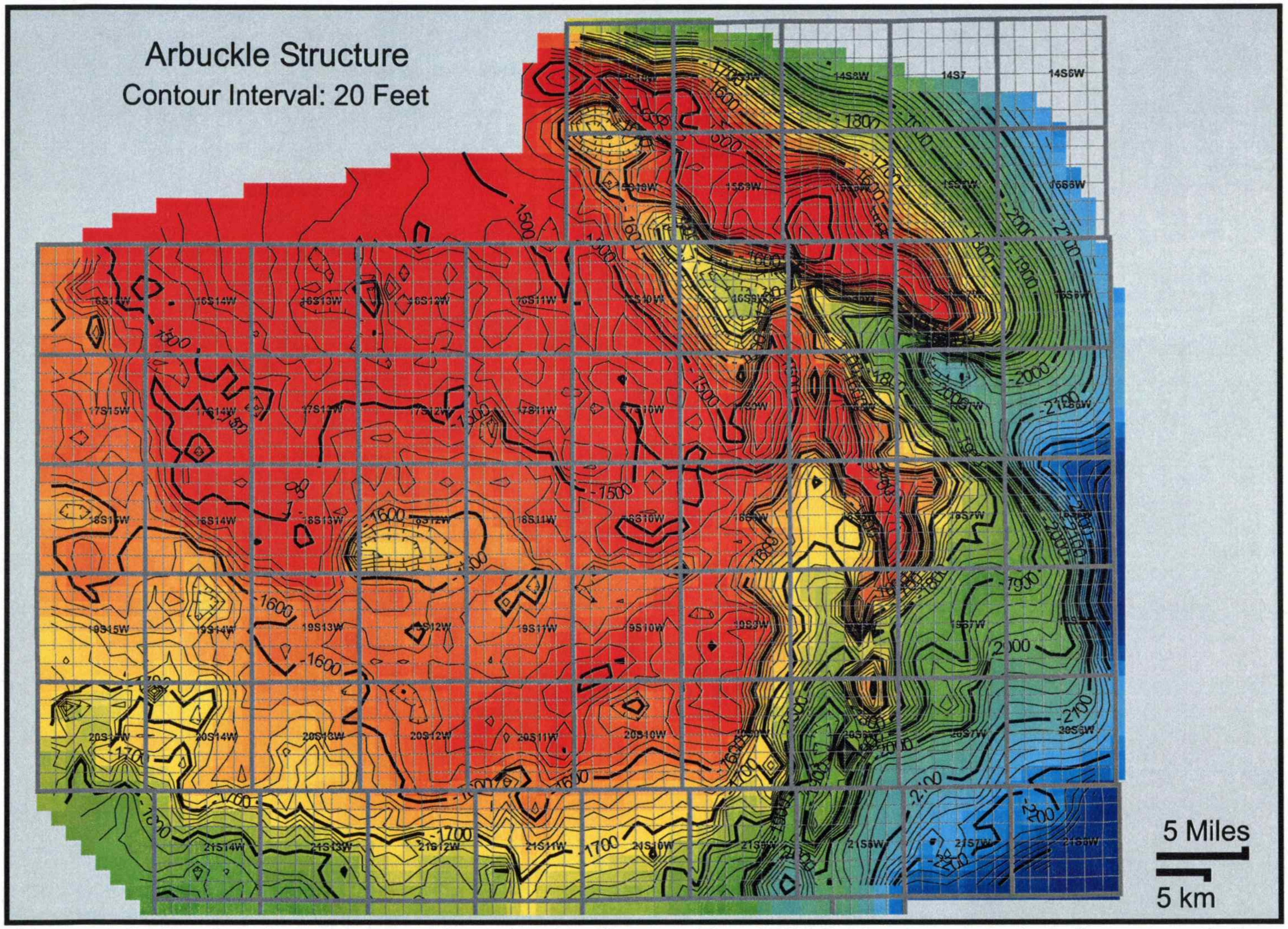

Figure 1.9: Regional structure on the Arbuckle Group. The 1700 foot subsea contour line essentially defines the southeast extent of the Central Kansas uplift.

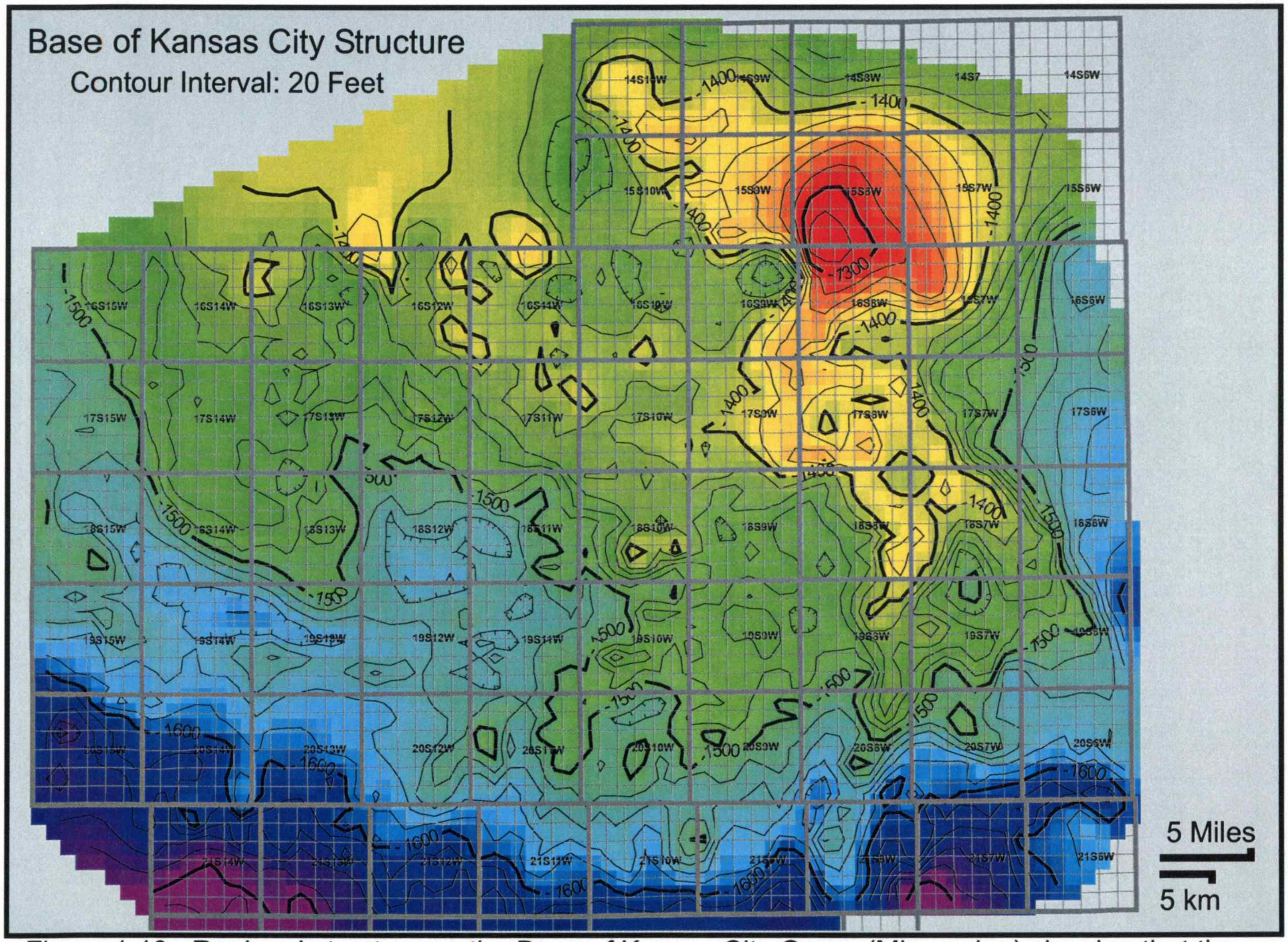

Figure 1.10: Regional structure on the Base of Kansas City Group (Missourian) showing that the structure evident at the Arbuckle (Figure 1.9) remains, but is subdued.

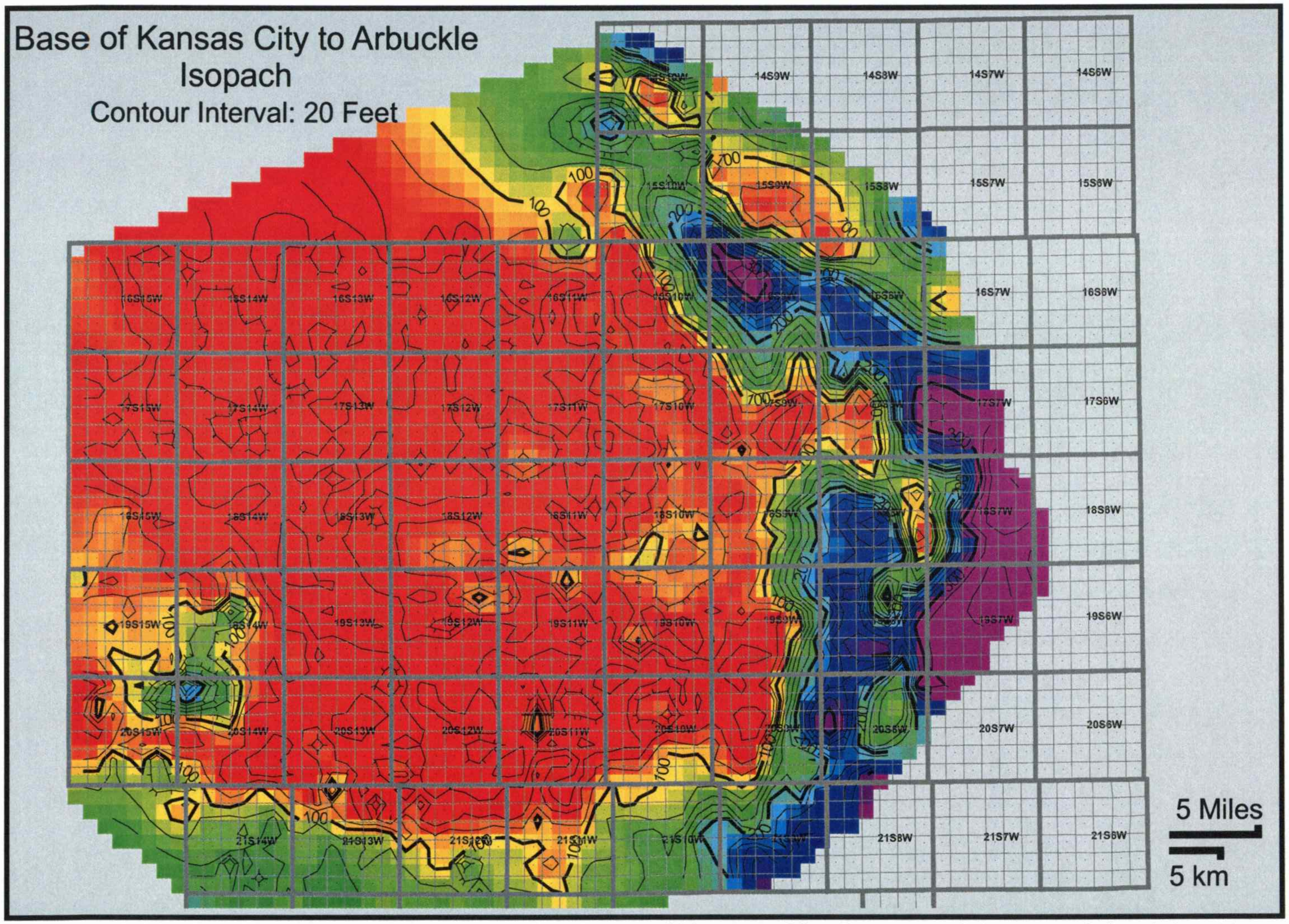

Figure 1.11: Regional isopach between the base of Kansas City Group and the top of the Arbuckle Group showing the influence of pre-existing structural features.

northwestern Barton County, a large southeast trending asymmetric antiform is evident at both the Arbuckle and base of Kansas City Group horizons (T18S-R13 and 14W). The southwest flank of this structure has over 160 feet of relief at the Arbuckle horizon, but has less than 120 at the base of Kansas City horizon. Over the same area, the interval isopach thins by over 40 feet. This relationship is also evident in townships 19S-14W and 20S-14W where the isopach significantly thickens in a regionally extensive Sub-Pennsylvanian Arbuckle low. The Arbuckle sinkhole in section 6-T20S-R14W, which has around 100 feet of relief at the Arbuckle horizon, experiences an 80 foot increase in isopach thickness relative to surrounding areas. Another regionally extensive Arbuckle low in the southern half of T18S-12W displays this same relationship. The Arbuckle surface has around 100 feet of relief in the area, however at the base of Kansas City level the relief is only 20 feet. The interval isopach between the base of Kansas City Group and Arbuckle experiences a thickening of around 20-40 feet suggesting that the Pre-Missourian sedimentation subdued inherited Arbuckle topography. In light of these specific examples, and the general decrease in structural relief over the study area, support the interpretation that the base of the Kansas City structure represents Late Mississippian to Early Pennsylvanian (Pre-Desmoinesian) deformation that has been subdued by Middle Pennsylvanian sedimentation.

Compared to the Arbuckle and base of Kansas City structure maps, the structure map on the Stone Corral Formation (Early Permian) shows only regional tilting with relatively subdued structural trends (Figure 1.12). The Stone Corral structure has a regional NNE-SSW strike, which is nearly perpendicular to the Pennsylvanian strike, and shows little evidence of the buried Central Kansas uplift. The regional trend on the Stone Corral structure map is probably related to much later tilting during the Laramide deformation.

The interval isopach between the Stone Corral and base of Kansas City was used to quantify and remove the effects of possible Post-Desmoinesian deformation (Figure 1.13). A regional trend was obtained by fitting an azimuth and dip magnitude to the isopach map. A representative dip direction trending S38°E was chosen in the direction of isopach thickening. Along that fitted line it was calculated that 300 feet of thickening occurred over approximately 25 miles, producing a regional dip magnitude of 0.13° to the S38°E.

The Ellsworth Anticline (northeast portion of Figures 1.10 and 1.11, T15S-R9W), a subsidiary feature of the Central Kansas uplift that may have been active after the Missourian (Merriam, 1963). The interval isopach between the Stone Corral and base of Kansas City does show a very subdued expression of the Ellsworth Anticline, which suggests that movement on this structure could have continued into the Middle and Late Pennsylvanian.

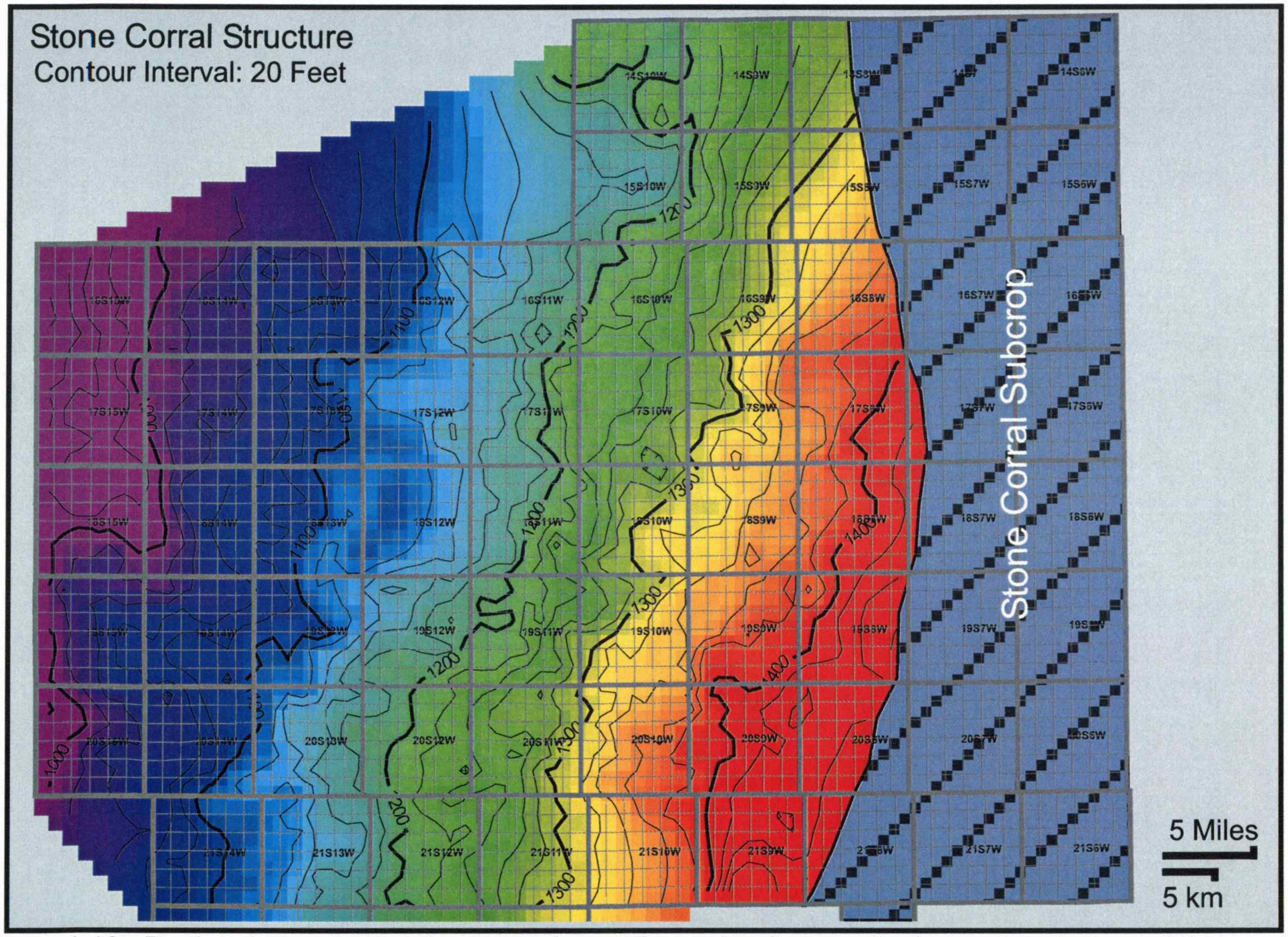

Figure 1.12: Regional structure on the Stone Corral Formation (Leonardian) showing dip toward the west. Structure is probably due to Laramide deformation that formed the Cretaceous Interior Seaway.

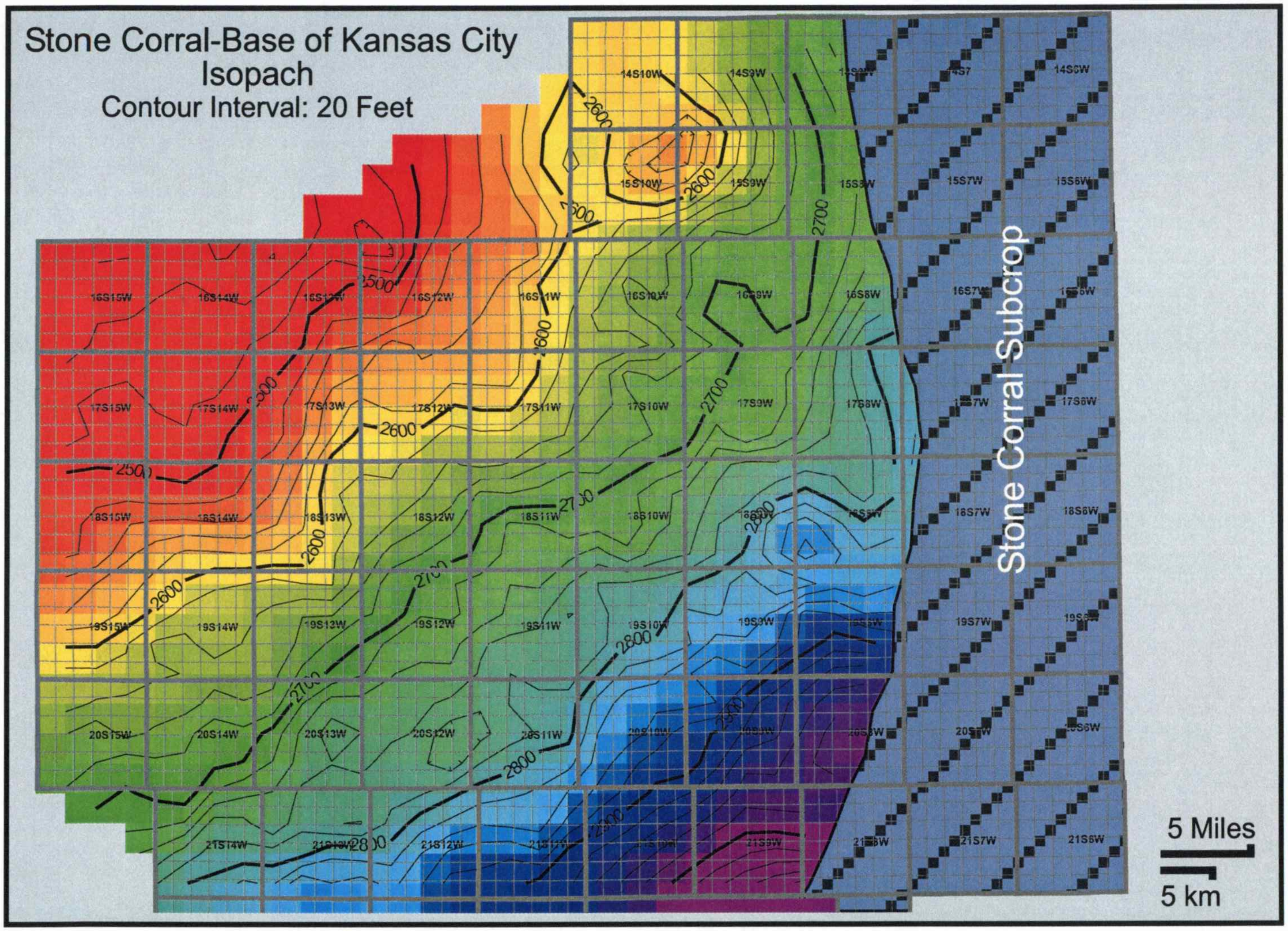

Figure 1.13: Regional interval isopach between Stone Corral Formation and base of Kansas City Group showing thickening toward the southeast.

In order to examine the effects of Post-Desmoinesian deformation, several dips within Arbuckle strata were calculated. This was accomplished by identifying and correlating horizons within the Arbuckle Group from at least three locations (wells) on a given structural block. Three criteria were used to identify and distinguish structural blocks. First, the wells needed to be in close proximity to one another. Second, the Arbuckle structural elevation needed to be relatively flat to one another. Finally, to identify a structural block there could be no intervening areas of significantly high or low Arbuckle structural elevations. Once the uncorrected dip directions and magnitudes were determined in local areas, the regional trend was then applied to these values. The regional trend was not applied to the Arbuckle strata on the Ellsworth Anticline due to the later and more complex deformational history. Figure 1.14 displays how dip direction and magnitude values were combined with the regional trend value to obtain a corrected Arbuckle paleo-dip by removing Pennsylvanian deformation. Representative uncorrected and corrected dips are listed in Table 1.1. The maximum change is only 0.3° and the average change is only 0.18°. In general, the dip correction does not appear show significant post-erosion deformation in the study area indicating that any post-Desmoinesian movement had very little effect on Arbuckle Sub-Pennsylvanian paleotopography.

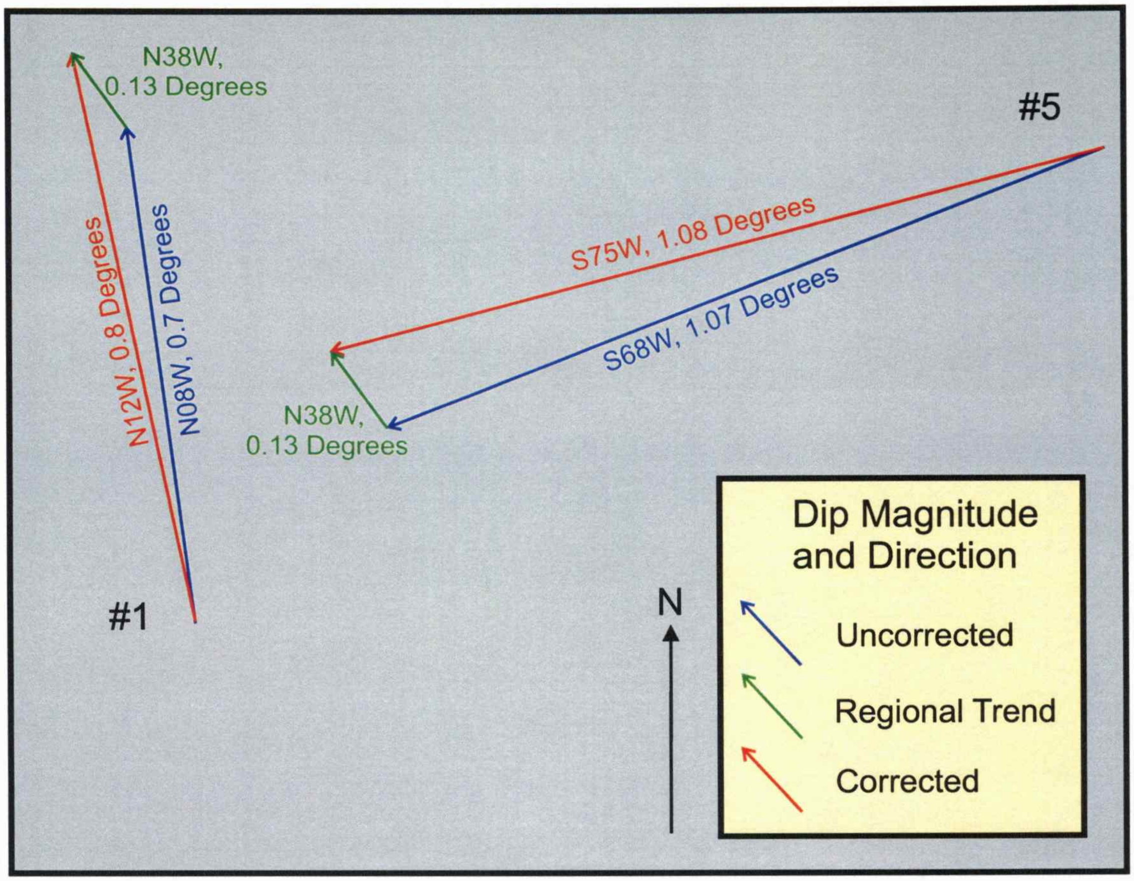

Figure 1.14:: Examples of using vector algebra to obtain Arbuckle Sub-Pennsylvanian dip by removing computed Post-Desmoinesian regional deformation.

		Uncorrected Dip		Corrected Dip	
	Location	Direction	Magnitude	Direction	Magnitude
1	(W2 SE) 32-19S-10W	N08°W	0.7°	N12°W	0.8°
2	(NE)31-19S-10W	N33°W	0.32°	N34°W	0.42°
3	(E2 SE) 32-19S-9W	N24°W	0.83°	N26°W	0.93°
4	(NW) 36-19S-10W	N29°W	0.23°	N36°W	0.36°
5	(S/2) 20-19S-9W	S68°W	1.07°	S75°W	1.08°
6	(NW SE) 20-19S-9W	N76°W	1.3°	N73°W	1.6°
7	(NE) 20-19S-9W	S69°W	0.2°	N88°W	0.23°
8	(SE SE NE) 4-18S-14W	S21°E	1.08°	S19°E	0.98°
9	(SE NE) 4-18S-14W	S5°E	1.3°	S3°E	1.24°
10	(W2 NE) 9-18S-14W	S40°E	0.88°	S41°E	0.71°

Table 1.1

2. ARBUCKLE EROSIONAL STYLES AND PROCESSES

Karst is the product of subaerial (terrestrial and coastal) exposure of carbonate rocks. Karst is recognized by features produced by dissolution, precipitation, erosion, sedimentation and collapse in a variety of surface and subsurface landforms (Esteban and Wilson, 1993). Sweeting (1973) described karst as a solution-controlled landform type, characterized by an exclusive surface morphology, subsurface drainage and collapse features. Karst features occur at a wide range of scales, from landforms and drainage patterns covering many square kilometers to cement and internal sediment textures observed in thin sections (Table 2.1).

The processes of landform evolution in terrains underlain by carbonate rocks are somewhat different from the fluvial processes that operate in terrains underlain by other kinds of rocks because of the importance of solutional weathering and the transport of both solution and clastic loads through subsurface drainage conduits (White and White, 1979).

Dolines

Closed depressions (dolines) are the most characteristic features of karst landscapes. Dolines have three components: (1) the bowl-like depression dissolved into the underlying bedrock, (2) a mantle of soil or other insoluble material draped over the bedrock basin, and (3) a drain connecting the depression to the conduit drainage system in the subsurface (White, 1990).

Karst Features

Megascopic Features (100-10,000 meters)
Karst Towers
Dolines
Poljes
Cockpits
Uvulas
Extensive Cave Networks
Blind and Half-Blind Valleys

Macroscopic Features (1cm- 100 meters)

Surface Karst	**Subsurface Karst**
All types of Karren	Caves
Kamenitzas	Non-selective dissolution voids
Lapies	Brecciated and fractured strata (in situ)
Terra Rosa	Collapse structures
Paleosols	Dissolution-enlarged fractures
Caliche (Calcrete)	Rubble and fissure fabrics
Lichen Structures	Sediment in non-depositional cavities
Boxwork structure	Breccia in irregular bodies
Non-sedimentary breccias	

Microscopic Features (1 micron - 1cm)
Eluviated soils in small pores
Etched carbonate cements
Reddened and micritized grains
Meniscus, pendant, and needle fiber vadose cement
Saddle dolomite

Table 2.1: Features commonly associated with karst. modified from James and Choquette (1988).

Dolines are closed hollows of small to moderate dimensions, that can be cone or bowl shaped with circular or elliptical plan (Sweeting, 1973). Each closed depression has an associated catchment area from which precipitation is captured and focused as internal runoff into the drain of the depression (White, 1990).

Jennings (1985) recognized five major classes of dolines (Figure 2.1A). The three main types observed in the Arbuckle carbonates of the study area are solution, collapse, and alluvial stream-sink dolines. The two types of dolines not recognized in the study area are the subsidence doline and subjacent collapse doline. Evidence against these two types of dolines lies in the strata above the Arbuckle unconformity. The interval isopach between the base of Kansas City Group and Arbuckle would demonstrate a thinning of Early Pennsylvanian fill over a subsidence doline. This relationship was not observed in the study area. In the case of a subjacent collapse doline, one would expect to see collapse breccia in the overlying Lansing-Kansas City strata. Solution dolines occur as water infiltrates into joints and fissures in the rocks initiating the chemical breakdown of the carbonates. As a result of the enlargement of the fissures by dissolution, a settling and lowering of the surface takes place, which is represented on the surface as a closed depression (Sweeting, 1973). Collapse dolines occur as the result of the breakdown of cavern roofs relatively near the surface. The most characteristic collapse dolines have steep-cliffed sides and an oval or

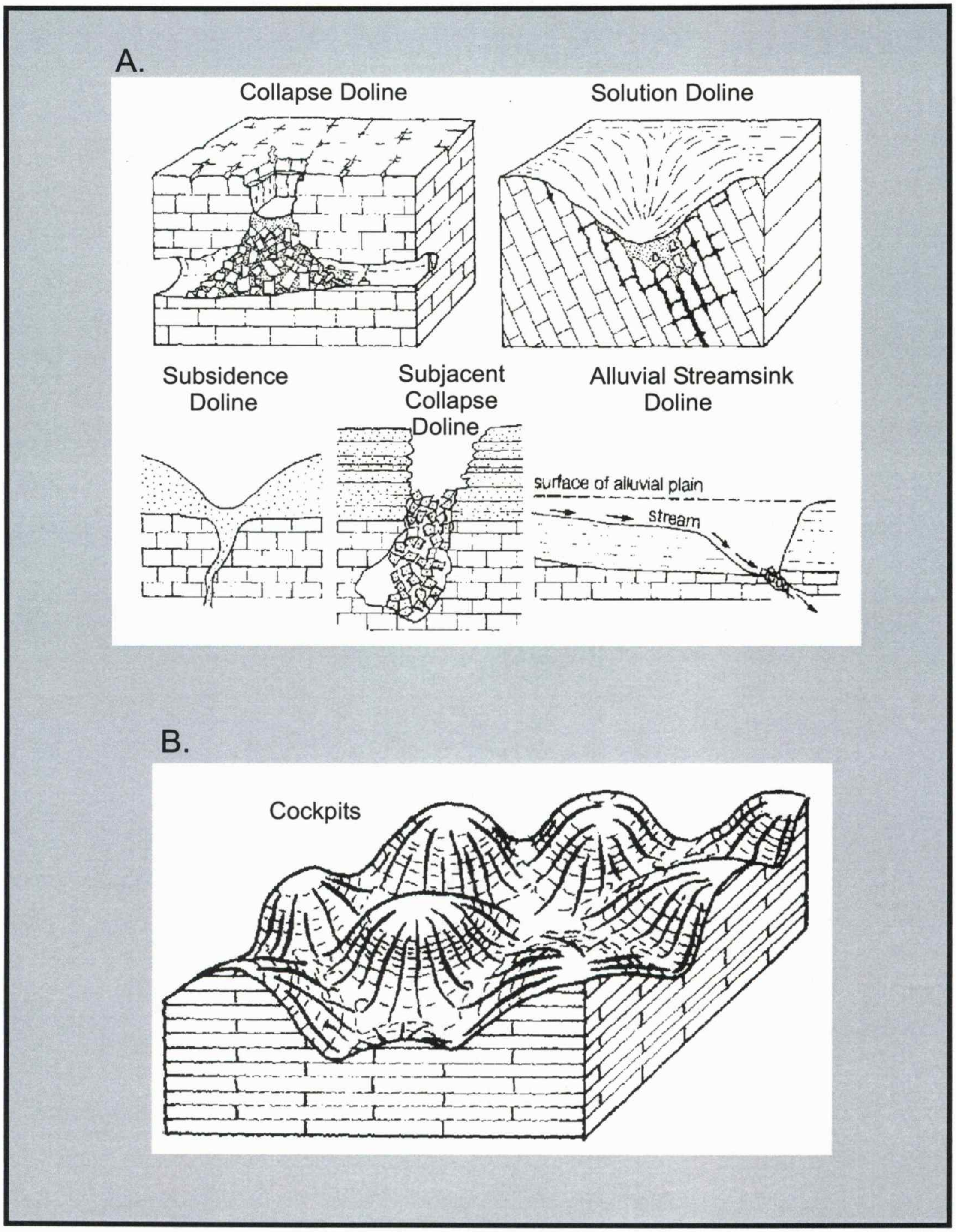

Figure 2.1: A. Schematic representation of the five types of dolines. Typical size ranges of Arbuckle dolines are from 10-60 feet deep (3-20 meters) and 1000-2000 feet (300-600 meters) in diameter. B. Schematic view of a cockpit karst terrain, modified from Jennings (1985).

irregularly shaped circular form (Sweeting, 1973). It is difficult to distinguish between solution and collapse dolines from map view because the two processes are common in most dolines (Bloom, 1991). A thick residual soil or alluvium may mantle an active karst landscape, and this surface material may be carried into a doline or ephemeral stream system. Frequently, alluvial stream-sink dolines develop in stream beds, which capture surface runoff and cause the stream to disappear, abandoning downstream segments of the channel except during periods of high stream flow (Bloom, 1991).

Dolines occur as individual sinkholes but are more often observed as a network of closed depressions pitting a landscape. There are two theories on the origin and distribution of large doline populations. The mutually independent random process model (MIRP) proposed by McConnell and Horn (1972) describes doline-forming processes as being spatially intermixed and random. In this model, efficient subsurface discharge results in depression enlargement as subsurface drainage accelerates, rather than initiation of secondary (daughter) dolines (Kemmerly, 1982).

The multigenerational diffusion and competition process model (MDCP), based on the collective works of several authors (LaValle, 1968; Ford, 1964; Drake and Ford 1972; Williams, 1972a, 1972b; and Palmquist, 1976, 1979) predicts the opposite effect following primary doline initiation (Figure 2.2, Kemmerly, 1982). As the primary depression is enlarged and the hydraulic gradient is increased, more runoff is diverted into the subsurface

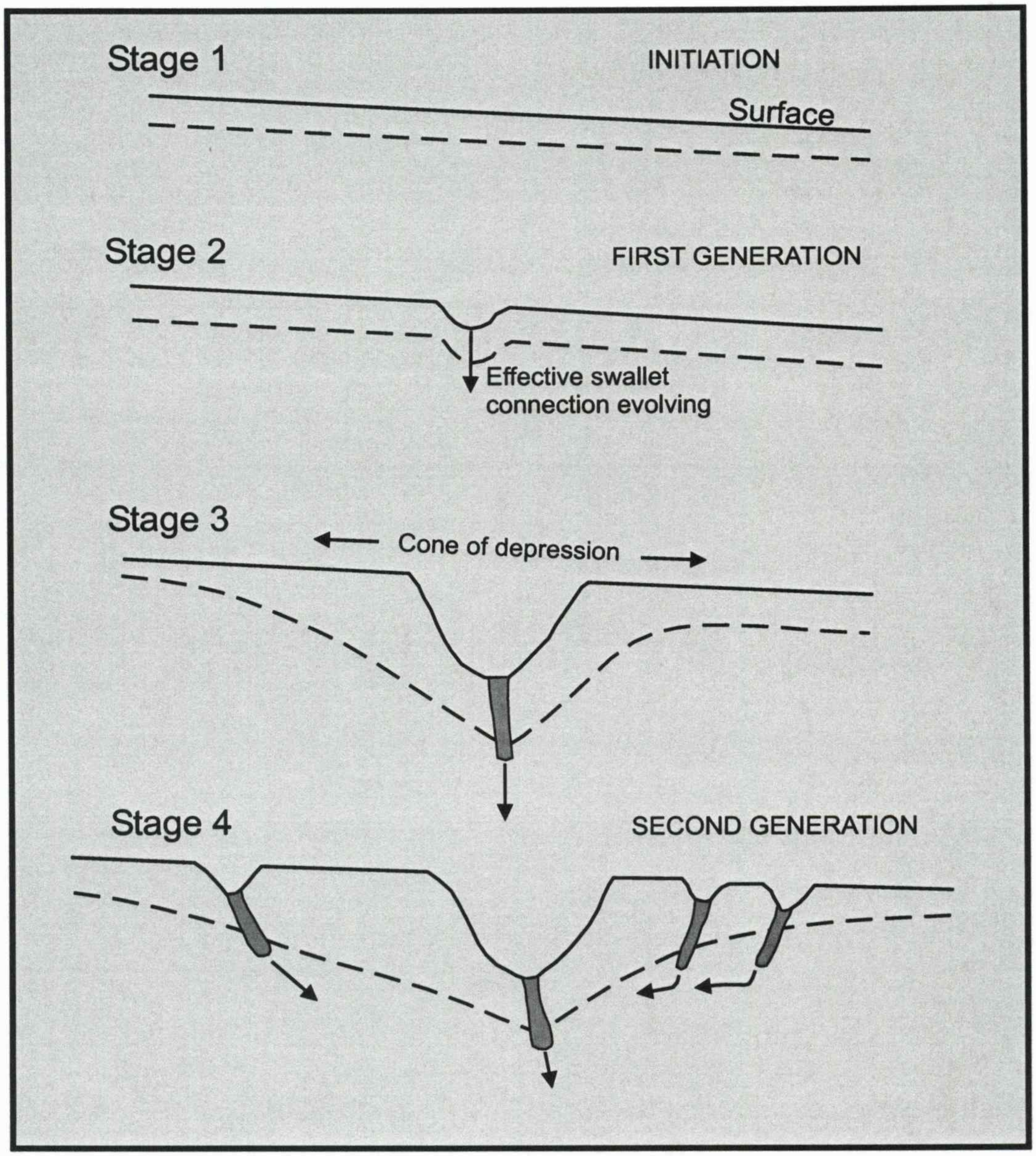

Figure 2.2: Generalized model of depression genesis showing how primary depressions trigger secondary depression initiation (Kemmerly, 1982).

along solution-widened joints around its perimeter. The increased ground-water recharge triggers the initiation of secondary dolines by removing much of the sediment filling solution-enlarged joints in the vicinity of the primary doline (Kemmerly, 1982). A regular spatial distribution of dolines supports the concept of geomorphic competition. Geomorphic competition is defined as the interaction of two or more dolines for catchment area and runoff and the effect of each on the enlargement of the other. If geomorphic competition exists between two dolines, one doline should enlarge at the expense of any adjacent depression doline (Kemmerly, 1982).

Cockpits

Cockpit karst terrains are visually dominated by the residual hills that occur between a system of closed depressions (Figure 2.1B). Cockpits do not usually have surface outlets, and therefore must have subsurface outlets, which are often near the center of the depression (Sweeting, 1973). Williams (1972a) believed that in cockpit karst landscapes, the depressions behave as small river basins, characterized by intermittent and centripetally directed flow down poorly developed gulley-like channels. This suggests that karst cockpits are the product of superficial chemical erosion rather than collapse. The topographic divides of the residual hills in cockpit karst terrains were found by Williams (1972a) to be polygonal in shape.

Polygonal Karst

Karst regions are often treated as chaotic landscapes of randomly oriented collapse and solution features. Williams (1972a), in his analysis of the karsts of New Guinea, concluded: (1) that all karsts are to some extent aligned or directed; (2) the general land slope, which corresponds closely to tectonic dip, is the most consistent influence on the orientation of the depressions; and (3) master joints often coincide with and likely cause the orientation of many of the depressions.

A growth model for polygonal karst was proposed that visualizes scattered small depressions on an uplifted surface expanding and capturing smaller neighbors until the entire surface is occupied by adjoining polygonal depressions (Williams, 1972a). In this growth model the starting point is considered to be an uplifted horizontal or gently sloping surface of carbonate strata with low relief. The uplifted block is fissured by a system of shear and tension joints (Figure 2.3A). The rock may possess primary porosity, but secondary permeability by way of fissures becomes more important as chemical weathering continues. Runoff becomes increasingly more directed as developing stream-sinks attract greater amounts of water. Small depressions acting as local stream-sinks are initiated at sites of maximum fracturing, where the intersection of several master joints encourages vertical drainage and corrosion (Figure 2.3B). When sections of major joint planes between the established basins are enlarged, a second generation of

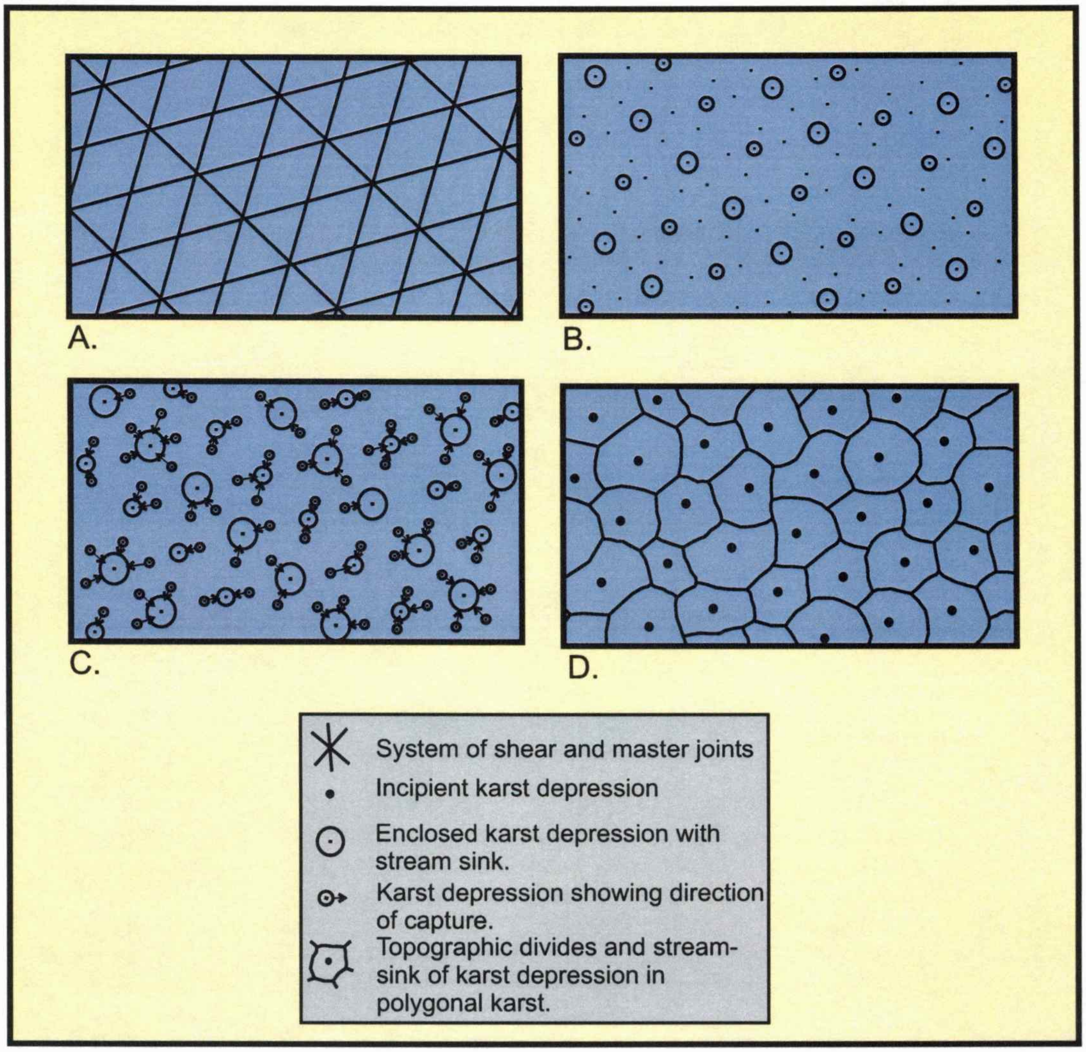

Figure 2.3: Growth model of the evolution of polygonal karsts (Williams, 1972a). The starting point in this model is a horizontal surface that is fissured with a system of shear and tension joints (A.). Runoff is collected at sites where master joints intersect, initiating stream sinks and karst depressions (B.). Later, a second generation of depressions are initiated at slightly less favorable sites (C.). Eventually the uplifted surface is completely pitted with depressions, the mutual divides of which form the cellular network of polygonal karst (D.).

depressions are incised, at slightly less favorable sites that require more time to establish vertical circulation (Figure 2.3C). Eventually the initial uplifted surface is completely pitted with depressions, the mutual divides of which form the cellular network of polygonal karst (Figure 2.3D, Williams, 1972a).

In polygonal karst, depressions are the dynamic centers of the system, conditioning the form of the hills. The boundaries of the depressions are largely stabilized by competition, and growth of the depression is also limited by the permeability of the karstified rock. Once a cellular polygonal karst is established, its geometry undergoes only minor modification through time, unless altered by an important environmental factor (Williams, 1972a).

Examples of Arbuckle Dolines

Description

Karst features of the Arbuckle erosional surface display a range of morphologies including closed depressions surrounded by pinnacle-like highs that are interpreted as dolines and cockpits in a polygonal karst terrain. Other Arbuckle erosional features form characteristic drainage patterns attributed to ground-water sapping processes. Arbuckle paleotopography is dominated by the surface expression of karst weathering. Internal karst features such as collapse breccia associated with large-scale cavern development are also recognized. However, compared to the Ellenburger Group of West Texas, caves in the Arbuckle Group of Kansas do not appear to be abundant, and do not have a major influence on reservoir development.

To date there is little information on the nature of the Arbuckle erosional surface in Kansas beyond evidence of extensive stratigraphic truncation and core-scale solution-enhanced fracture networks (Franseen et al., 1995). Detailed regional and local mapping of the erosional Arbuckle surface using abundant well data provides a basis for imaging features of this buried karst surface that are larger than a single well (megascopic scale).

In the study area, differential dissolution of Arbuckle carbonates produced a characteristic karst surface on many different scales, with positive landforms and closed depression features. The most characteristic feature of the Sub-Pennsylvanian Arbuckle surface is the extensive populations of dolines, cockpit karst and sapped drainages.

In the study area, individual dolines can be circular or elliptical in plan view (Figures 2.4 and 2.5). Dolines on the Arbuckle surface can be as deep as 250 feet (75 meters) and encompass an area as wide as a mile (1.6 kilometers). More typically, dolines are 10-60 feet deep (3-20 meters) and have a diameter ranging from 1000-2000 feet (300-600 meters). The Arbuckle karst surface is probably pitted with a large number of smaller dolines that were either too small in area to delineate from well spacing, or did not exceed a depth of five feet (the smallest contour interval used). In some areas, it appears that dolines are not just isolated depressions but they coalesce to form compound dolines (Figure 2.5, Sections 13-15 T17S-R14W and Sections 18 and 19 T17S-R13W).

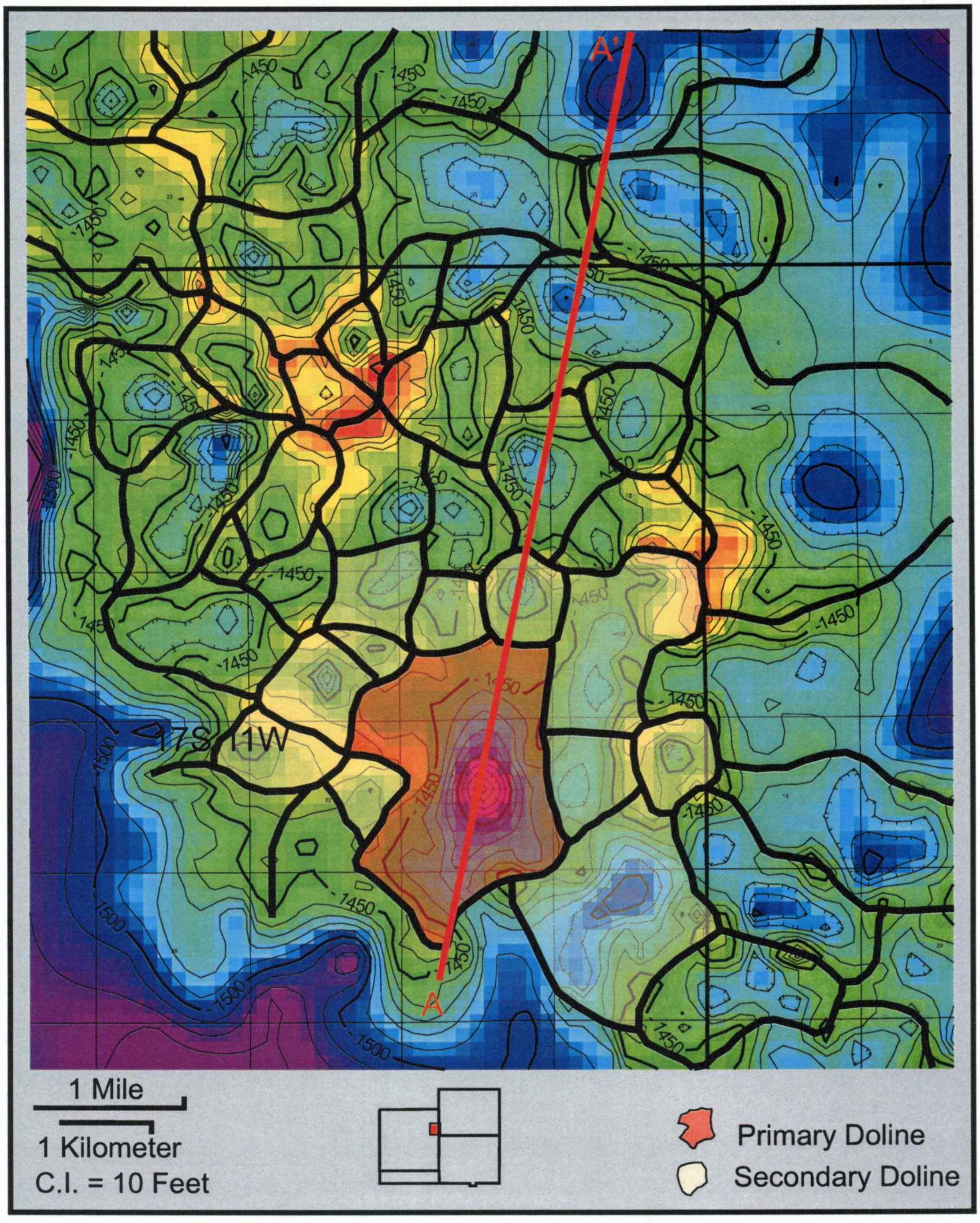

Figure 2.4: Arbuckle structure overlain with paleotopographic divides. Notice the polygonal nature of the network and the spatial relationship between the primary and secondary dolines. Profile A-A' shown on Figure 2.6.

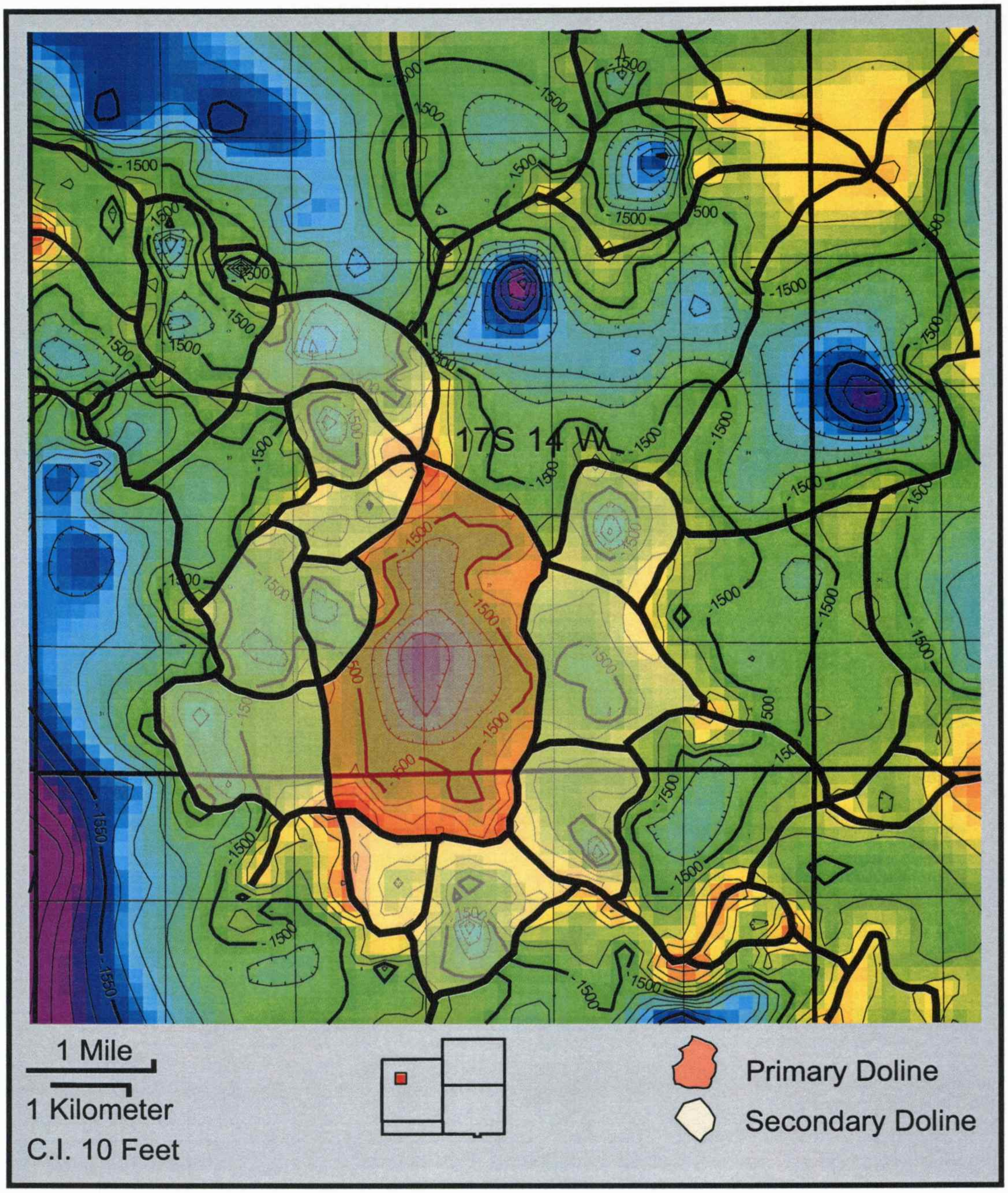

Figure 2.5: Arbuckle structure overlain with paleotopographic divides. Notice the polygonal nature of the network and the spatial relationship between the primary and secondary dolines.

Large dolines (roughly larger than 3000 feet in diameter and deeper than 30 feet) appear to have a fairly regular distribution. In some areas, these large dolines are surrounded by a number of smaller dolines (less than 3000 feet in diameter). Profile A-A", through Figure 2.4, displays the relationship of two large dolines and the associated smaller dolines (Figure 2.6). The major axes of the dolines in Figures 2.4 and 2.5 had a dominant northwest-southeast trend, as well as some minor north-south and northeast-southwest trends (Figure 2.7). The major axis orientation was measured parallel to the dominant trend of the largest closed contour associated with the doline. The dolines in the area condition the form of the landscape. The polygonal shape of the paleotopographic divides of these residual hills and dolines resembles a honeycomb network.

Figure 2.8 displays a stratigraphic cross-section across a doline in section 20-T18S-R10W (location of cross-section shown on Figure 2.9). The basal Pennsylvanian (Pre-Missourian) sediments significantly thicken into the doline observed in the Feist #9 well. It appears that the sandy horizons within the Pre-Missourian fill that are observed in the Feist #1, Feist #9 and Schultz #1 pinch out against Arbuckle rocks to the north and south

Interpretation

The Arbuckle surface is pitted with hundreds of dolines in the study area. Dolines can be formed by many variations of karst solution and collapse processes. Subsidence dolines can occur in mantled karst settings

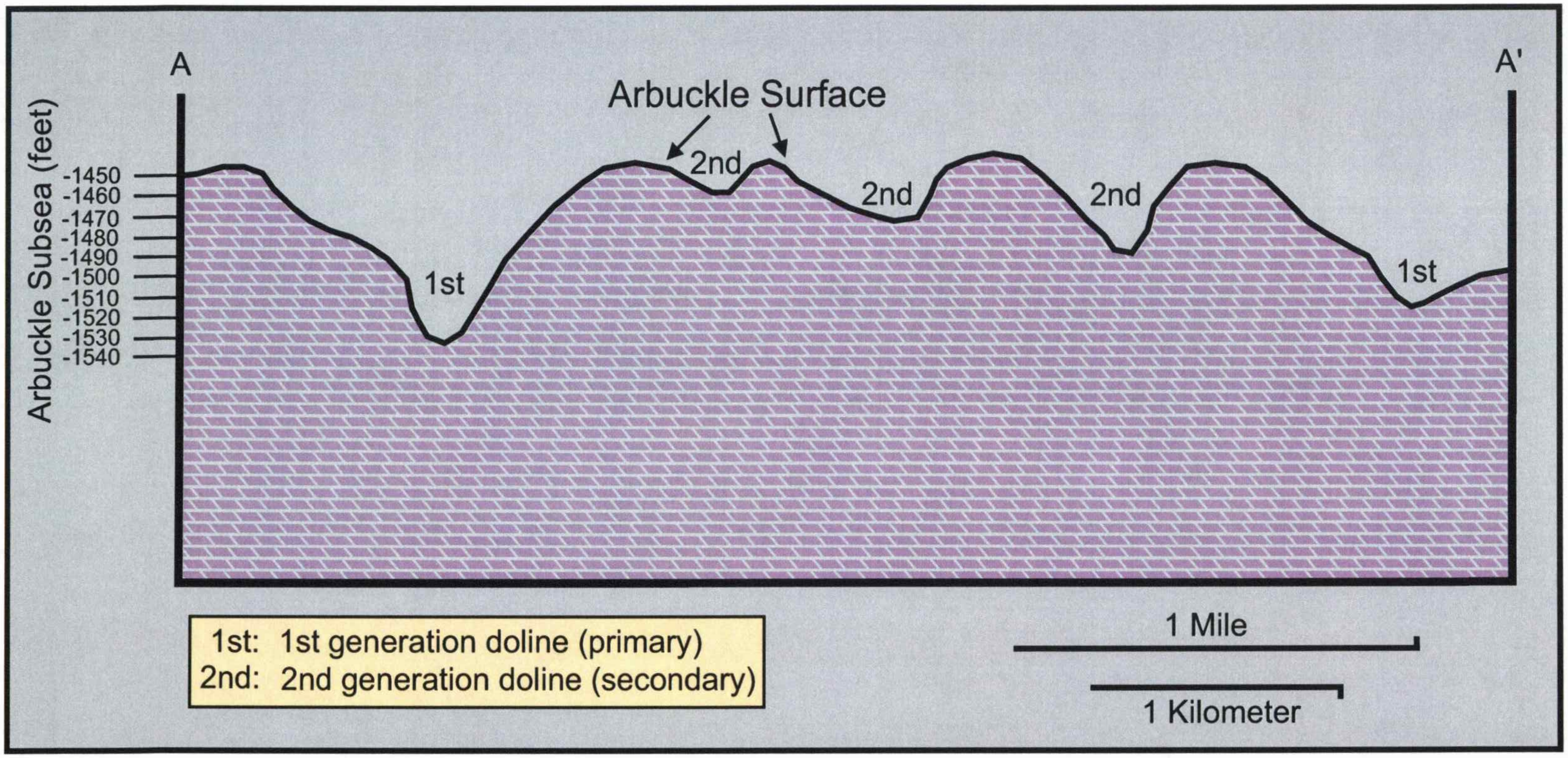

Figure 2.6: Profile across series of dolines in T17S-R11W showing the relationship between primary and secondary dolines in cross-section. Location of profile shown on Figure 2.4.

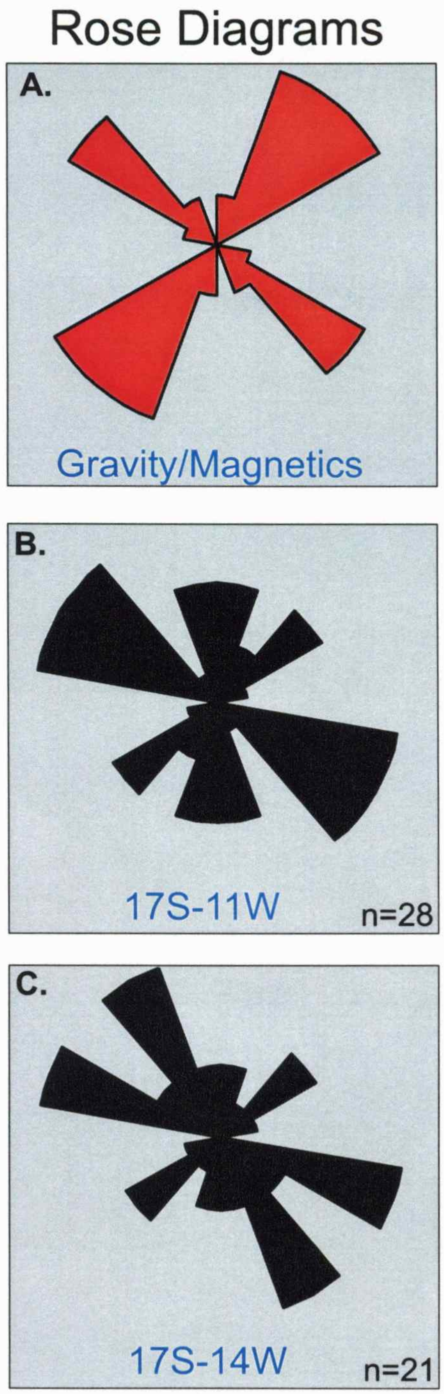

Figure 2.7: Rose Diagrams of: A. Interpreted Gravity/Magnetics lineaments, from Figure 8 (modified from Kruger, 1996), B. Doline major axis orientation in 17S-11W, and C. Doline major axis orientation in 17S-14 W.

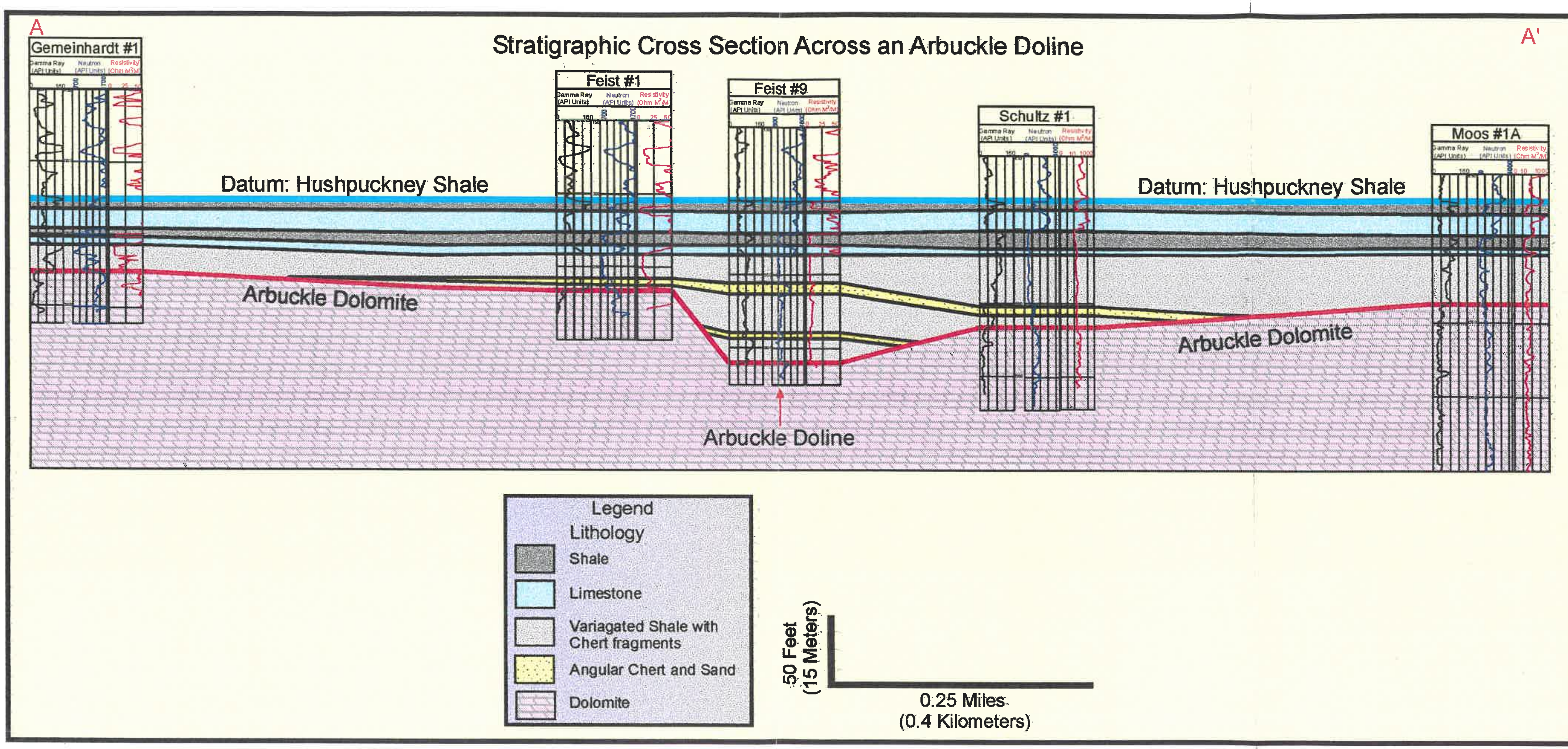

Figure 2.8: Stratigraphic cross-section across an Arbuckle doline in section 20-T18S-R10W. Notice the increase in basal Pennsylvanian (Pre-Missourian) fill. Locatiion shown on Figure 2.9.

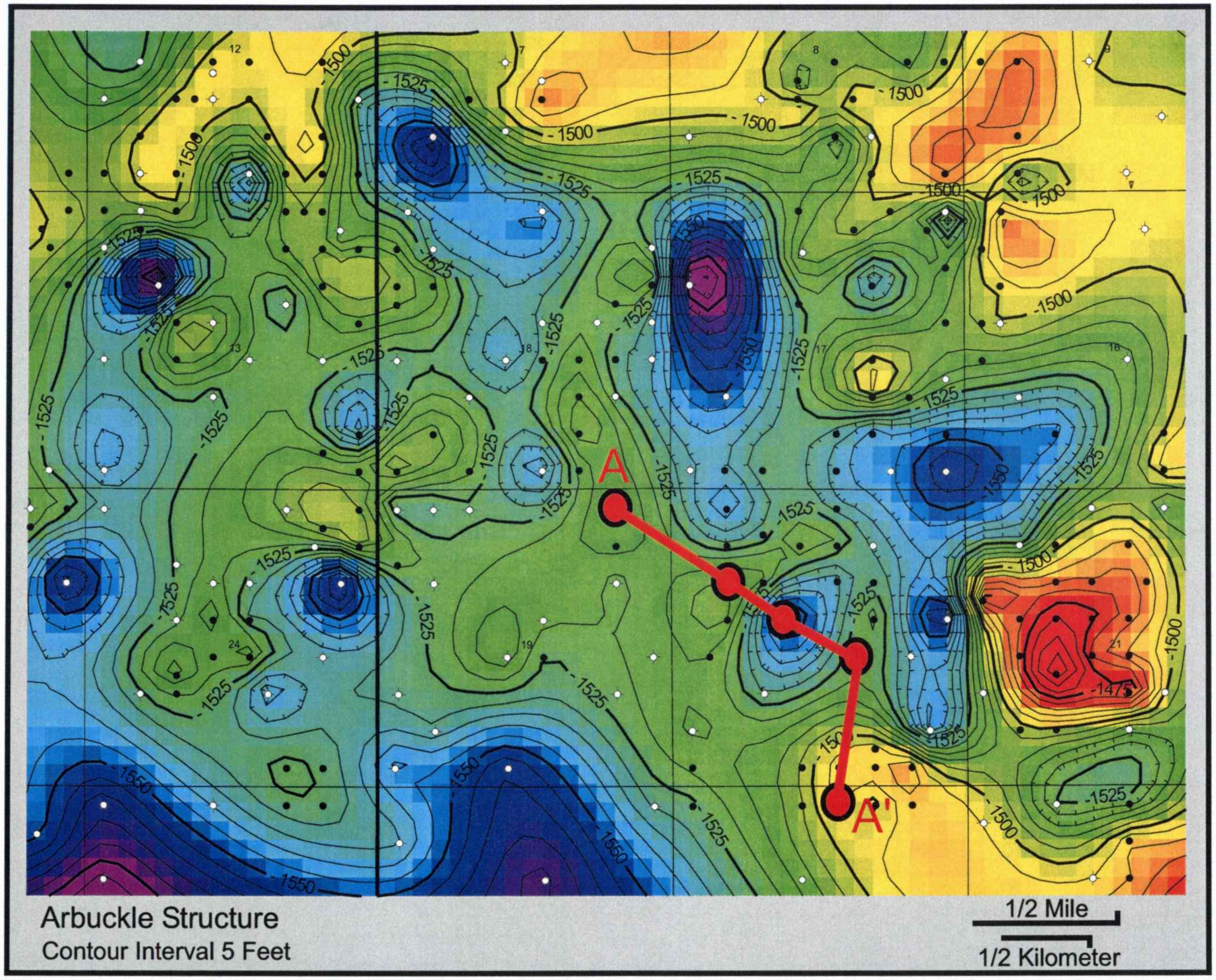

Figure 2.9: Location of cross section A-A" across a doline. Cross section shown on Figure 2.8.

with the overlying sediment settling into the dissolved carbonate strata. In this case the surface expression of the doline would be in the overlying non-carbonate rock, producing the typical doline morphology on the base of Kansas City horizon. This relationship is not observed in the study area. Subjacent collapse dolines occur after burial of a karst erosional surface. It is very difficult to distinguish between the major process involved in doline formation in map view, however a subjacent collapse doline would show some collapse brecciation in the overlying Lansing-Kansas City Group strata. In addition to a closed depression on the Arbuckle surface, a subjacent collapse doline would produce a sag on the base of Kansas City Group structure. Arbuckle dolines in the study area have very little expression on the base of Kansas City structure map indicating the dolines did not form from post-burial collapse. The morphology of the dolines in the study area and the character of the overlying strata suggest that the dolines were formed primarily as standard collapse and solution dolines, with some alluvial stream sink doline development. Cross-section A-A' displays the thickening of Pre-Missourian sediment fill into the doline indicating that it was, in fact, a Pre-Desmoinesian Arbuckle feature on an active Sub-Pennsylvanian karst surface (Figure 2.8).

The populations of dolines in the study area appear to have a relatively consistent orientation, which is most likely due to a degree of structural control. Structural control of karst features such as dolines is defined as the degree of alignment between regional joints and depression major-axis orientations. Structural control was tested by interpreting joint trends from major lineaments on gravity and magnetic maps (Figure 2.10) and relating lineament orientations to the orientations of depressions in selected areas. The general trend of both the depression axes and the basement lineaments have a strong northwest-southeast trend, as well as a northeast-southwest trend Figure 2.7).

In addition to structural control, a regular spatial distribution supports the concept of geomorphic competition and an implied area of primary depression influence (Kemmerly, 1982). Following primary doline initiation, secondary depressions were initiated due to the increased hydraulic gradient in the area (Figure 2.2). Profile A-A" highlights this relationship. The large dolines representing first generation depressions are surrounded by the smaller secondary dolines (Figure 2.6). Structural control and geomorphic competition appear to be responsible for the regular spatial distribution of the large dolines, as well as the clusters of smaller secondary dolines surrounding each of major depression (Figure 2.4 and 2.5).

The influence of Arbuckle stratigraphy on the spatial distribution and morphology of dolines is unclear. The lack of adequate core coverage and the difficulty in detailed stratigraphic analysis from log data in the Arbuckle precludes a definitive understanding of the stratigraphic controls. However, it appears that the paleogeomorphology of the Arbuckle erosional surface

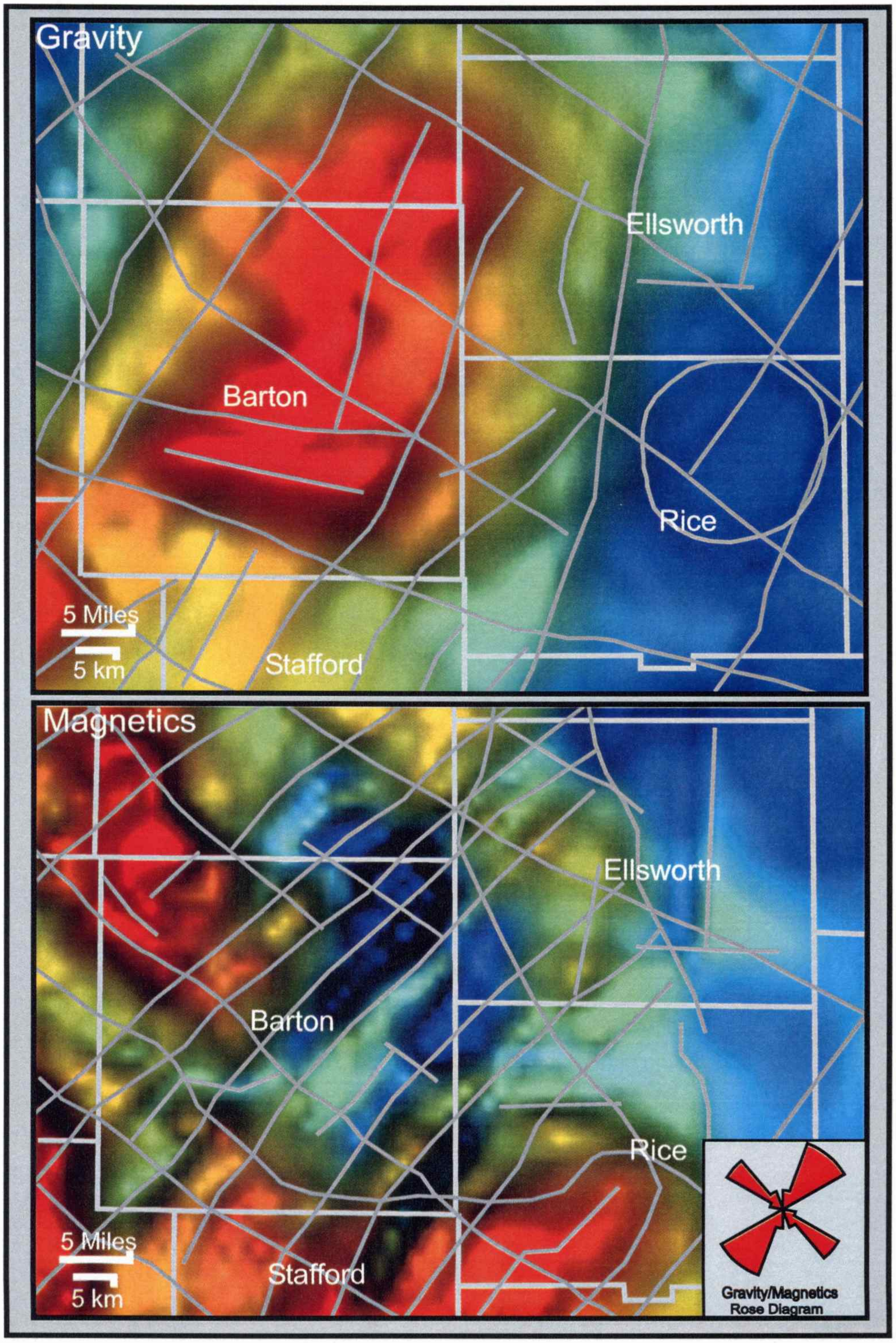

Figure 2.10: Gravity and magnetics maps showing major structural lineaments (lineaments modified from Kruger, 1996).

reflects the relative lateral and vertical permeability within the formation. This suggests that Arbuckle depositional stratigraphy might exhibit some control on the location and pattern of dolines.

Dolines completely pit the Arbuckle landscape of the Central Kansas uplift. When delimited on the basis of their topographic divides, the Arbuckle dolines form a cellular network that can be termed polygonal karst (Williams, 1972a, Figure 2.4 and 2.5). The size of Arbuckle polygonal cells vary considerably, but the boundaries of the closed depressions have been stabilized by competition (Williams, 1972a). Each polygonal cell would have been a solution depression that drained internally. In Williams (1972a) model of polygonal karst, there is very little chaos that is normally ascribed to karst landscapes. The overall relief in these areas is relatively low (less than 150 feet), however, when viewed three dimensionally with vertical exaggeration, the residual hills of this polygonal karstic network resembles a cockpit karst terrain (Figure 2.11 and 2.12).

Ground Water Sapping Discussion

Modern geomorphological theory has stressed the role of running water, especially of streams, in the development of erosional landscapes. However, there are several ways in which valleys and slopes can be cut out from below rather than incised from above. Some processes where erosion is concentrated at the base of a slope are: sea-cliffs attacked by waves or eroded at the waterline by intertidal organisms, or valley walls undercut by

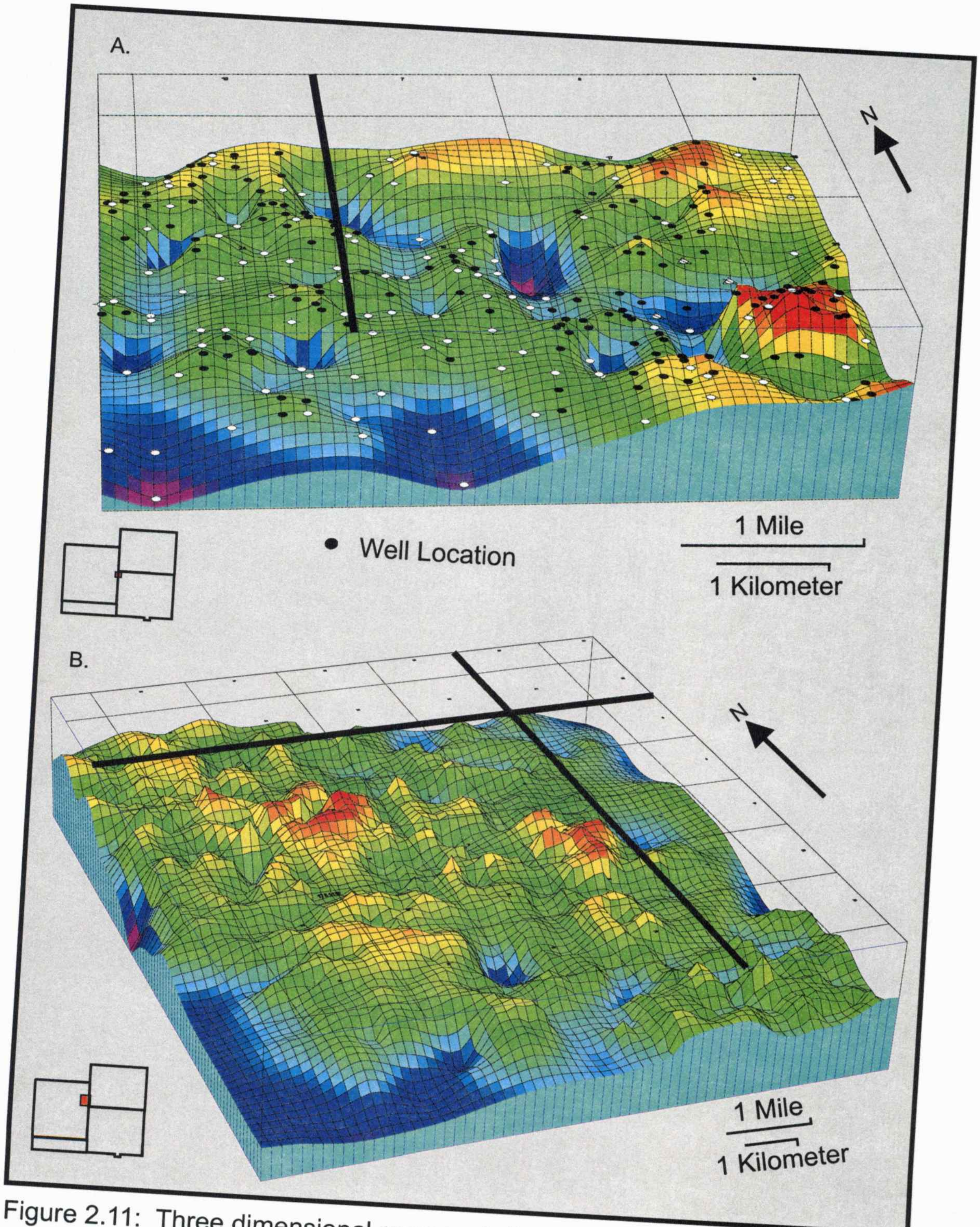

Figure 2.11: Three dimensional representation of Arbuckle structure maps in A. 18S-10W and B. 17S-11W. Notice the cockpit karst nature of the Arbuckle surface. Vertical exaggeration 10X.

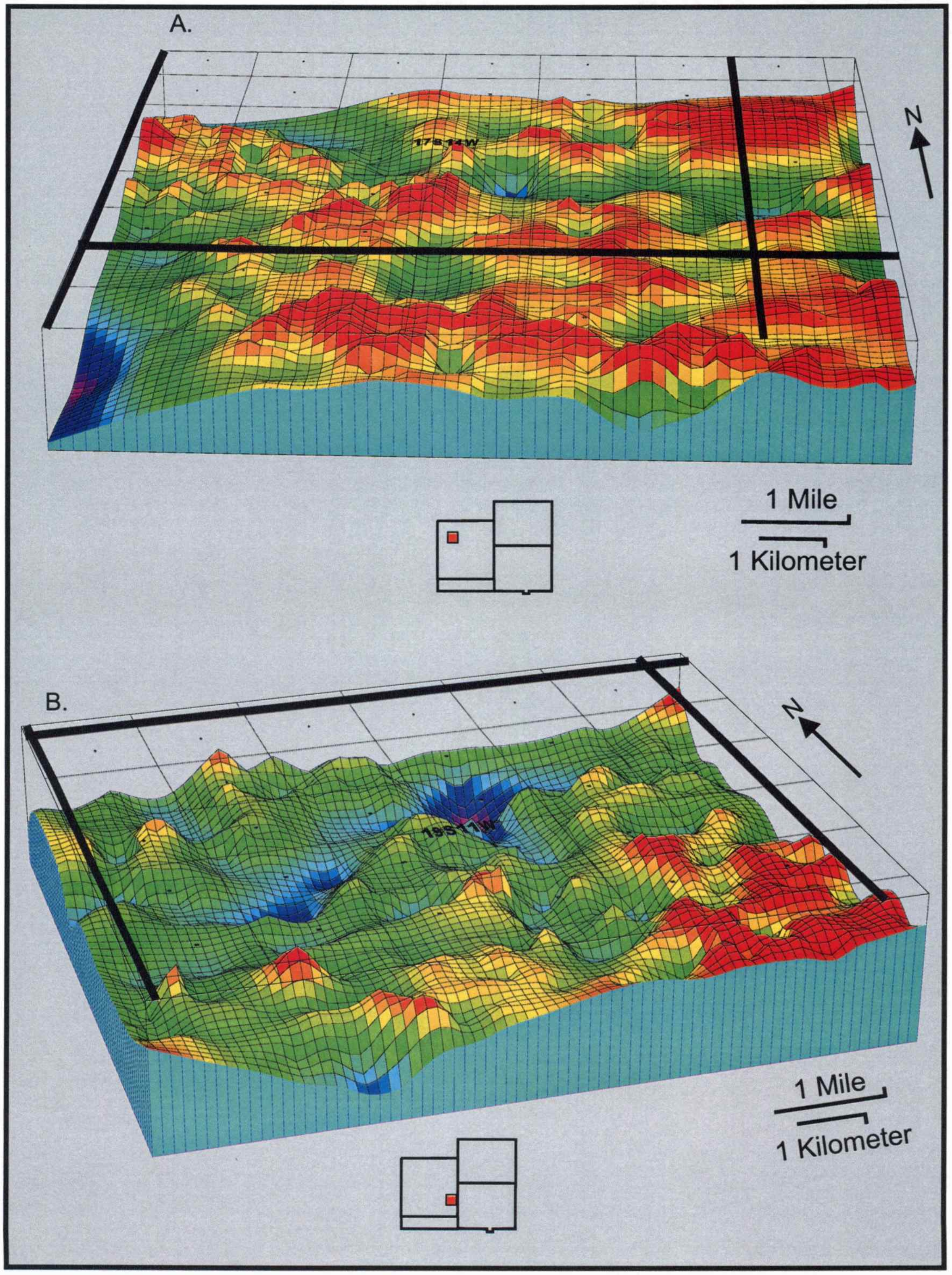

Figure 2.12: Three dimensional representation of Arbuckle structure maps in A. 17S-14W and B. 19S-11W. Notice the cockpit karst nature of the Arbuckle surface. Vertical exaggeration 10X.

glaciers. Erosion at the base of slopes can also be attributed to the combined effects of seepage weathering, seepage erosion, and ground-water sapping (Higgins and Oskerkamp, 1990).

Ground-water sapping is the process that causes entrainment of soil or rock when ground-water flows through and emerges from a porous medium at a free slope surface (Luo, et al., 1997). Subsurface flow discharges from the ground surface where topography is intersected by the water table. Topography, structure and stratigraphy, and the recharge rate and size of the flow system determine the spatial distribution of the seepage zone (Dunne, 1990). Ground water emerging from the seepage zone leads to shear stress loss of the basal support and failure of the overlying rock producing a retreat in the valley heads and side walls (Luo, et al., 1997; Laity and Malin, 1985). Higgins (1990) distinguishes between "seepage erosion," "seepage weathering," and "sapping." Seepage erosion results from entrainment and transport of loose grains by effluent flow in seeps and springs. Seepage weathering is defined as the group of processes that are concentrated at sites of seepage moisture. These chemical and mechanical weathering processes intensify the breakdown of rock materials, preparing them for removal by erosional agents. Where the disaggregated material is carried away from a spring-head or from the base of a slope, the undermined area fails and the slope retreats. This undermining is called sapping (Higgins and Oskerkamp, 1990).

Sapping is an erosional process that produces unique landforms. Sapped drainage systems differ from their fluvial counterparts in morphology, pattern, spatial evolution of the network, rate of erosion and degree of structural control (Laity and Malin, 1985). A comparison between the characteristics of runoff-dominated versus sapping-dominated systems is presented in Table 2.2. Characteristic requirements for ground-water sapping include a permeable aquifer, a rechargeable ground-water system, a free face at which subsurface water can emerge, and a means of transporting material from the scarp surface (Luo, et al., 1997).

To understand the landform evolution of any surface it is important to be aware of the interactions between the lithology, structure, stratigraphy, hydrology, and climate. Ground-water emerging from a spring line would enhance chemical weathering, thereby increasing the porosity of the seepage zone, reducing the local rock tensile strength, and rendering the weathering zone more susceptible to erosional undercutting of adjacent slopes (Baker, et al., 1990). Heterogeneity of the rock, as well as, jointing, faulting and folding accelerate the undermining of slopes. Once the process is initiated it is self-enhancing, because the ground-water flow lines converge on the spring which increases the flow (Baker, et al., 1990). The rate of headward erosion is accelerated the farther a spring head retreats because it generates a greater flow convergence. This headward growth may intersect other zones that are susceptible to sapping which may result in a network of tributaries.

Parameter	Runoff-Dominated	Sapping-Dominated
Basin shape	Very Elongate	Lightbulb shaped
Head termination	Tapered, gradual	Theatre, abrupt
Channel trend	Uniform	Variable
Pattern	Parallel	Dendritic
Junction angle	Low (40-50 deg.)	Higher (55-65 deg.)
Downstream tributaries	Frequent	Rare
Relief	Low	High
Drainage density	High	Low
Drainage symmetry	Symmetrical	Asymmetrical
Cross-section shape	V-Shape	U-shape, steep wall flat floor
Valley width	Widens downstream	Relatively constant
Tributary length	Relatively long	Short stubby tributary
Structural control	Less strong	Strong
Basin area/canyon area	Very high	Low

Table 2.2: Comparison of geomorphic characteristics of sapping and fluvial channels in the Colorado Plateau and Hawaii (from Luo et al., 1997).

Thus, sapping of theater headed valleys that develops in an area of jointing or faulting will develop a pattern aligned with those structures (Laity and Malin, 1985). However, sapping will be organized by the hydraulic controls on the ground-water flow (Baker, et al., 1990). Dunne (1980) proposed a general model of drainage extension by sapping processes (Figure 2.13).

Climatic conditions have an influence on the effectiveness of ground-water sapping and cliff retreat; however, the optimal conditions are not clearly defined (Higgins and Oskerkamp, 1990). Many geomorphological studies that investigate ground-water sapped landscapes report that modern seepage rates have been greatly reduced or the morphological processes involved in sculpting the landscape have ceased altogether (Luo, et al, 1997; Laity and Malin, 1985, Oskerkamp, 1990, Higgins, 1990). This precludes observation of the cliff retreat at its full strength and the analysis of how the climatic conditions affected the system (Higgins and Oskerkamp, 1990). The characteristic requirements for ground-water sapping include both ground-water system recharge and fluvial processes to transport material released from the scarp face (Luo et al., 1997). Both of these requirements are directly dependent on precipitation. It is generally understood that the presence of precipitation is necessary, but it is unclear if the important variable is total precipitation, seasonality, or intensity (Higgins and Oskerkamp, 1990).

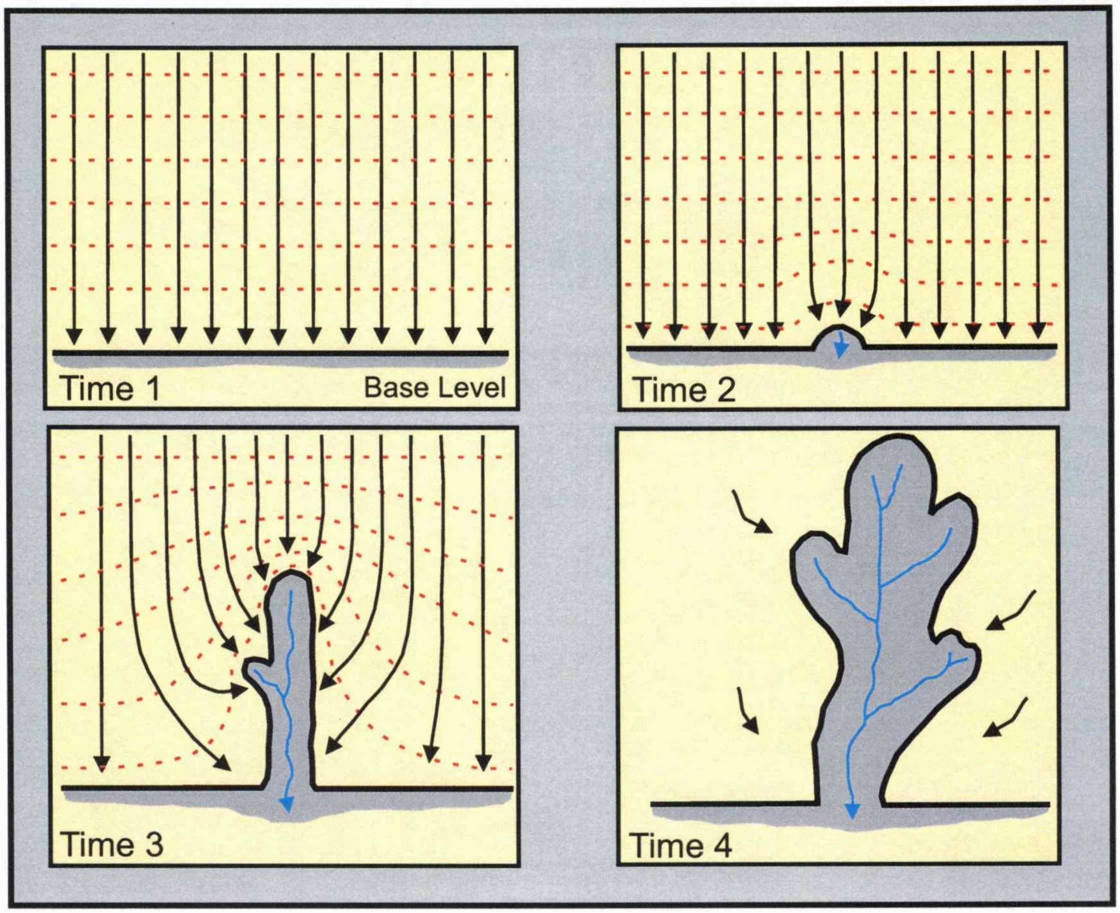

Figure 2.13: A general model of drainage extension by sapping processes (after Dunne, 1980). Ground-water flows through the strata towards base level (Time 1) encounters an irregularity (Time 2; an outcropping joint or erosional notch) that causes ground-water to converge at this point. The increased flow enhances local weathering and initiates the sapping processes, causing headward migration of the valley (Time 3). Tributaries grow as ground-water, emerging along valley sidewalls, exploits zones of susceptibility, usually joint planes. The rate of lateral weathering approaches that of headward retreat as the drainage area of the spring head declines (Time 4; modified from Laity and Malin, 1985).

Recently, many studies have focused on the role of ground-water sapping to explain canyon evolution and valley drainage networks on Mars and along the edge of marine shelf margins (Sharp and Malin, 1975, Laity and Malin, 1985, Paull et.al., 1990, Robb, 1984). In the Glen Canyon region of the Colorado Plateau, Laity and Malin (1985) recognized two populations of valleys formed with distinctly different features. The first group exhibits theater heads: longitudinal profiles with high, steep discontinuities and commonly asymmetric, structurally controlled patterns. The second group is characterized by tapered terminations; a relatively smooth, concave-up profile, and a more arborescent network. The valleys formed under the same lithologic, stratigraphic, and climatic conditions. Differences were attributed to structural constraints, primarily bed dip, that determine the relative effectiveness of overland-flow and ground water (sapping) processes in valley development (Laity and Malin, 1985).

Depressions and escarpments of the Western Desert of Egypt were used to develop a numerical model that integrated fluvial and sapping processes into a landform evolution system (Luo et al. 1997). Scallop-shaped escarpment edges and stubby-looking channels that cut into the plateau units are suggestive of slumping of the limestones by ground-water sapping at the limestone-shale interface, removal of slump blocks by weathering and fluvial erosion, and consequent scarp retreat. Sapping landforms developed preferentially along fractures associated with the El

Rufuf Pass fault system, due to the increased hydraulic conductivities and greater ground-water discharge.

Examples of Ground-Water Sapping Processes

Description Arbuckle Plateaus

A northeast-southwest trending Arbuckle plateau-like feature located in T19S-R10W, is roughly outlined by the -1500 foot contour (Figure 2.14). Only the center 3 square miles (7.7 square kilometers) of Feature 1 is displayed. In its entirety, Feature 1 is about 5.5 miles in length and 1.75 miles in width (14 km by 4.5 km). The orientation of Feature 1 corresponds to major gravity and magnetic lineations in the area, however it does not correspond exactly to the basement structure.

The northwest side of Feature 1 is characterized by an undulating boundary with numerous reentrants. The plateau is bounded on the south and east sides by relatively distinct and linear boundaries. The center of the plateau is interrupted by two dolines that are oriented parallel to the main axis of the feature and one that is not. The northeast arm of the feature appears to be offset to the north by a little less than one mile (1.6 kilometers). A cross section across Feature 1 displays the correlation of Arbuckle beds (Figure 2.15). A fault is indicated by the relatively dramatic drop in Arbuckle horizons between the #2 Neeland and the #2 Schartz wells. The fault appears to be Sub-Pennsylvanian in age due to the increase in basal Pennsylvanian fill observed at the #2 Schartz. It is possible that the southern border of this

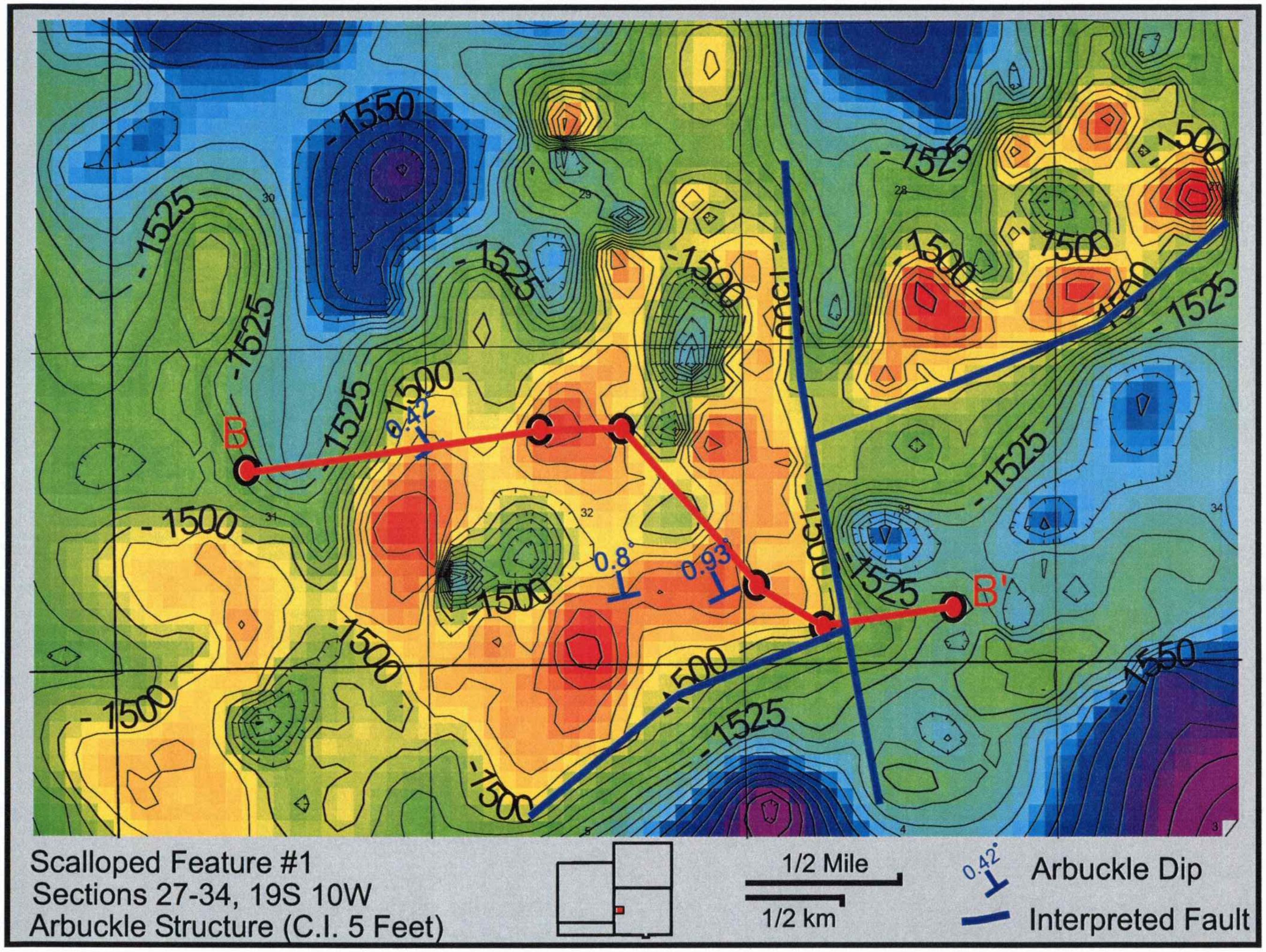

Figure 2.14: Scalloped feature #1 showing the undulating northwest side of the Arbuckle plateau and the relatively linear (fault-bounded) southeast side. Location of cross-section B-B' shown on Figure 2.15.

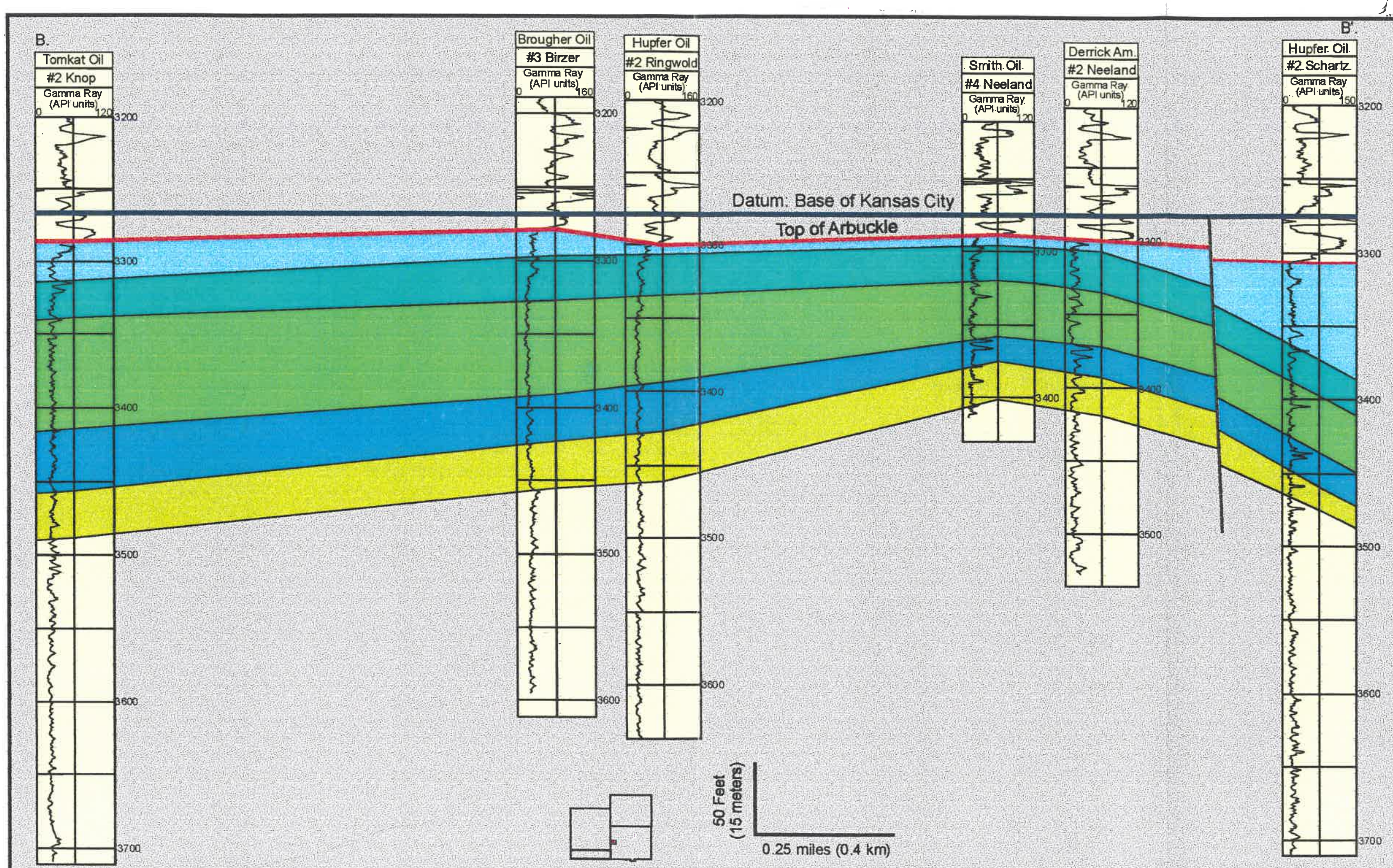

Figure 2.15: Cross Section across sapped feature in 19S-10W showing Arbuckle bed dip. Dips were determined by correlating horizons within the Arbuckle strata. Notice the fault between the #2 Neeland and the #2 Shartz, evidenced by the offset in Arbuckle horizons and the increased basal Pennsylvanian fill.

feature is characterized by only a steep slope and no fault is present. However, the morphology of the feature in map view and the offset of the northeast arm, the relatively dramatic increase in dip relative to surrounding areas, as well as the offset in the horizons within the Arbuckle suggest a fault origin.

A series of polygons created by combinations of three wells were used to calculate dips of stratigraphic horizons within the Arbuckle strata. The control on the internal dip within the Arbuckle was limited by the availability of wells that sufficiently penetrate the Arbuckle and were logged. However, three Arbuckle dip measurements were made on Feature 1. The dip between the #5 Ringwold (NE NE of 32-T19S-R10W), #2 Ringwold (NE SE SE of 32-T19S-R10W), and the #4 Neeland (NW SW SW of 33-T19S-R10W) trends N26°W with a magnitude of 0.93°. The dip between the #5 Ringwold (NE NE of 32-19S-10W), #2 Ringwold (NE SE SE of 32-T19S-R10W), and the #1 Mitchell (SE SE SW of 32-T19S-R10W) trends N12°W with a magnitude of 0.8°. The dip between the #3 Birzer (E/2 NW of 32-T19S-R10W), and the #2R Deuser (SE SW of 31-19S-10W), and the # 3 D Knop (NE NW NW of 31-T19S-R10W) trends N34°W with a magnitude of 0.42°. In general, Feature 1 appears to have a structural dip of less than 1° to the north-northwest.

Another similar northeast-southwest trending feature in Sections 22-27 T18S-R10W is roughly outlined by the -1510 contour (Figure 2.16). Feature

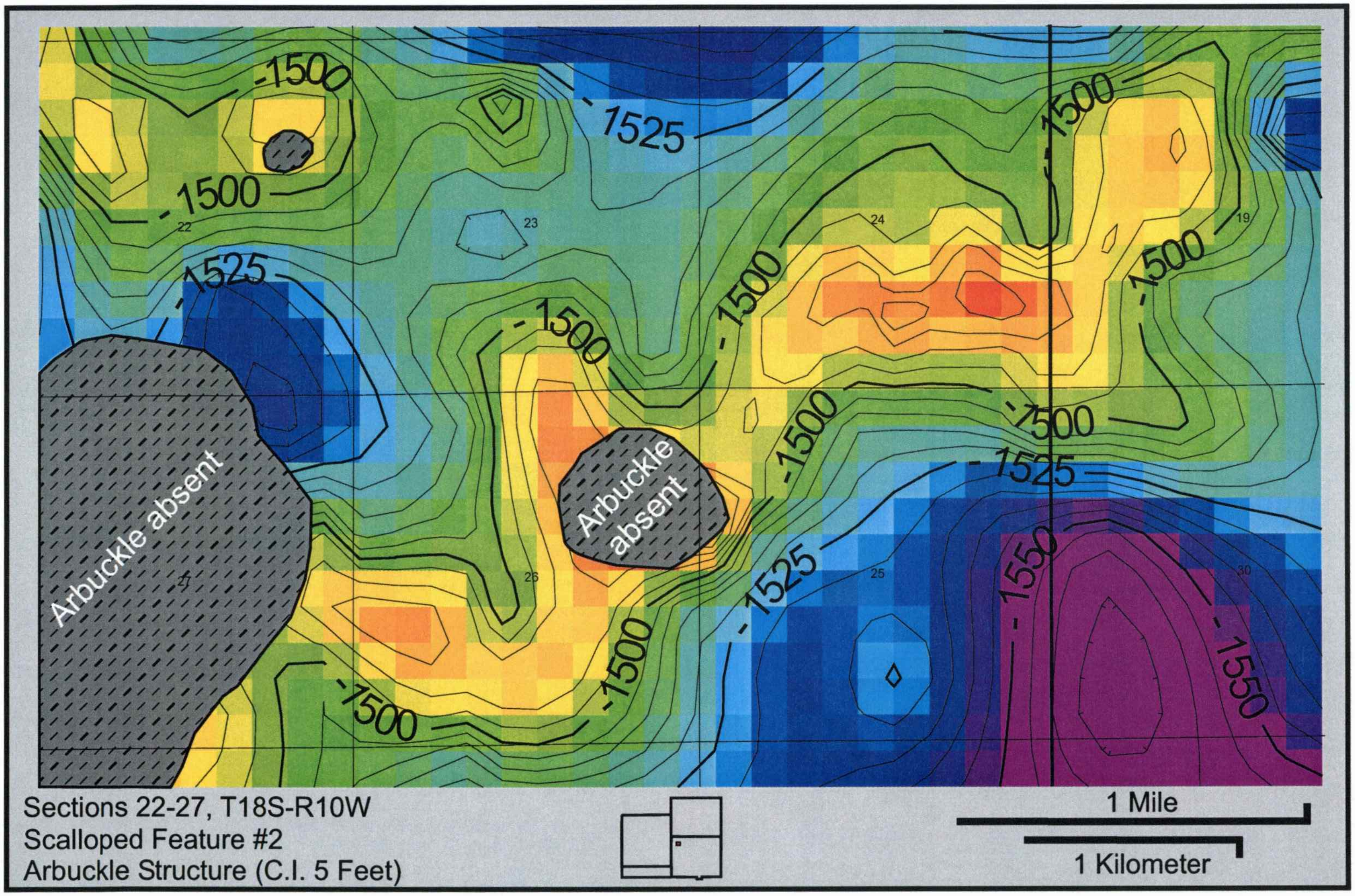

Figure 2.16: Scalloped feature #2. Notice the relatively straight and linear southeastern boundary and the more scalloped northwestern edge. Arbuckle is absent locally in areas with greatest uplift and erosion.

2 is characterized by a relatively linear boundary on the southeast side, and an undulating northwest boundary. Arbuckle strata were stripped from the crests of local uplifts where the Precambrian basement subcrops beneath Pennsylvanian sediments. No Arbuckle dip directions were generated on this feature due to shallow penetration of the Arbuckle, and limited log availability. However, the structure on the Precambrian surface indicates a northwest dip of 2-4°.

Another segmented west/northwest-east/southeast trending plateau-like feature in T18S-R14W exhibits a similar morphology to the Feature 1 and 2 (Figure 2.17). Feature 3 has relatively distinct linear boundaries to the north and northwest. The south and southeast boundaries have a series of light-bulb shaped reentrants into the feature. Three Arbuckle dips were generated on this feature. The dip between the #9 Frieb (NW SE NW 4-T18S-R14W), #11 Monroe (SW NE SE 4-T18S-R14W), and the #8 Riedel (SE NE 4-T18S-R14W) trends S19°E with a magnitude of 0.98°. The dip between the #9 Frieb (NW SE NW 4-T18S-R14W), #10 Monroe (NE NE SE 4-T18S-R14W), and the #11 Monroe (SW NE SE 4-T18S-R14W) trends S03°E with a magnitude of 1.24°. The dip between the #4 Whiteman (NE NW NE 9-T18S-R14W), the #1 Whiteman (SW SW NE 9-T18S-R14W), and the #2 Whiteman (SE SW NE 9-T18S-R14W) trends S41°E with a magnitude of 0.71°. In general, Arbuckle strata in Feature 3 dips to the south-southeast at less than one degree.

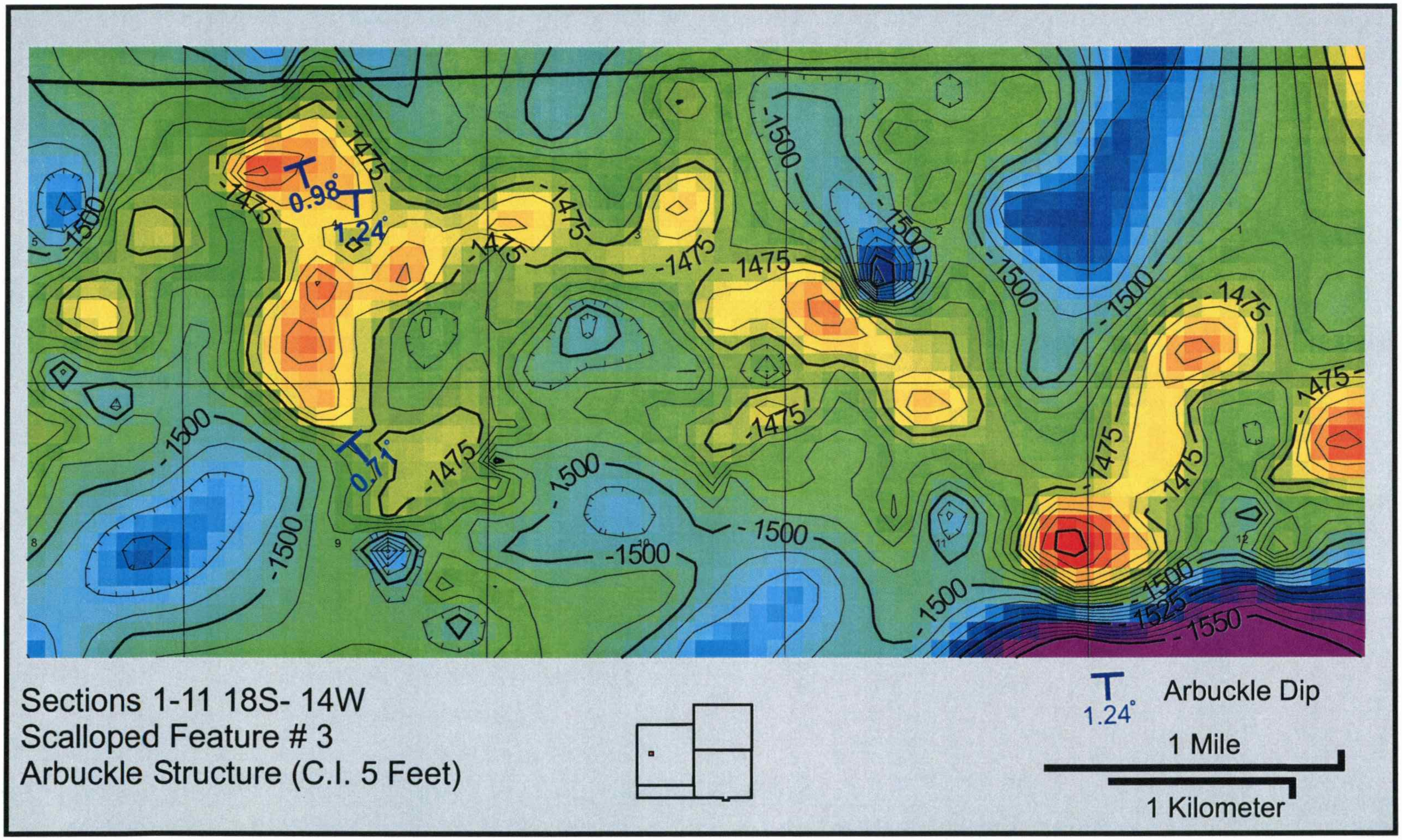

Figure 2.17: Scalloped feature in T18S-R14W. Notice the relatively straight northern boundary relative to the more undulating southern boundary.

Interpretation

Ground-water sapping processes were initiated as exposed joints on the plateau concentrated surface runoff, and in some cases enlarged to form channels (Figure 2.18). Precipitation was rapidly diverted into the ground-water system and flowed down bedding planes. Sapping occurs locally at sites where ground-water emerges from the Arbuckle just above lithologic discontinuities (e.g. intraformational shale layers). Ground-water emerging from these seepage springs slowly removed material that provides basal support for the cliffs and slopes (Laity and Malin, 1985). Slope failure occurred as the scarp was undermined allowing debris to accumulate at the base of the slope. It is speculated that slump blocks and debris that accumulated at the base of Arbuckle plateaus underwent continued mechanical and chemical weathering. Continued scarp retreat depended on fluvial processes effectively removing the talus.

Figures 2.14, 2.16, and 2.17 show three examples of ground-water sapped plateaus. The structures in figures 2.12 and 2.14 the Arbuckle dips at very low angles (0.3-1.5 degrees) to the northwest, and in figure 2.17 the strata dips to the south-southeast. The fault-bounded boundaries of these features are relatively uniform, whereas the down-dip sides have a more scalloped nature. Ground-water likely emerged above internal Arbuckle shale layers on the down-dip sides of these features initiating sapping processes. The sapping process produced theatre-headed valley terminations on the

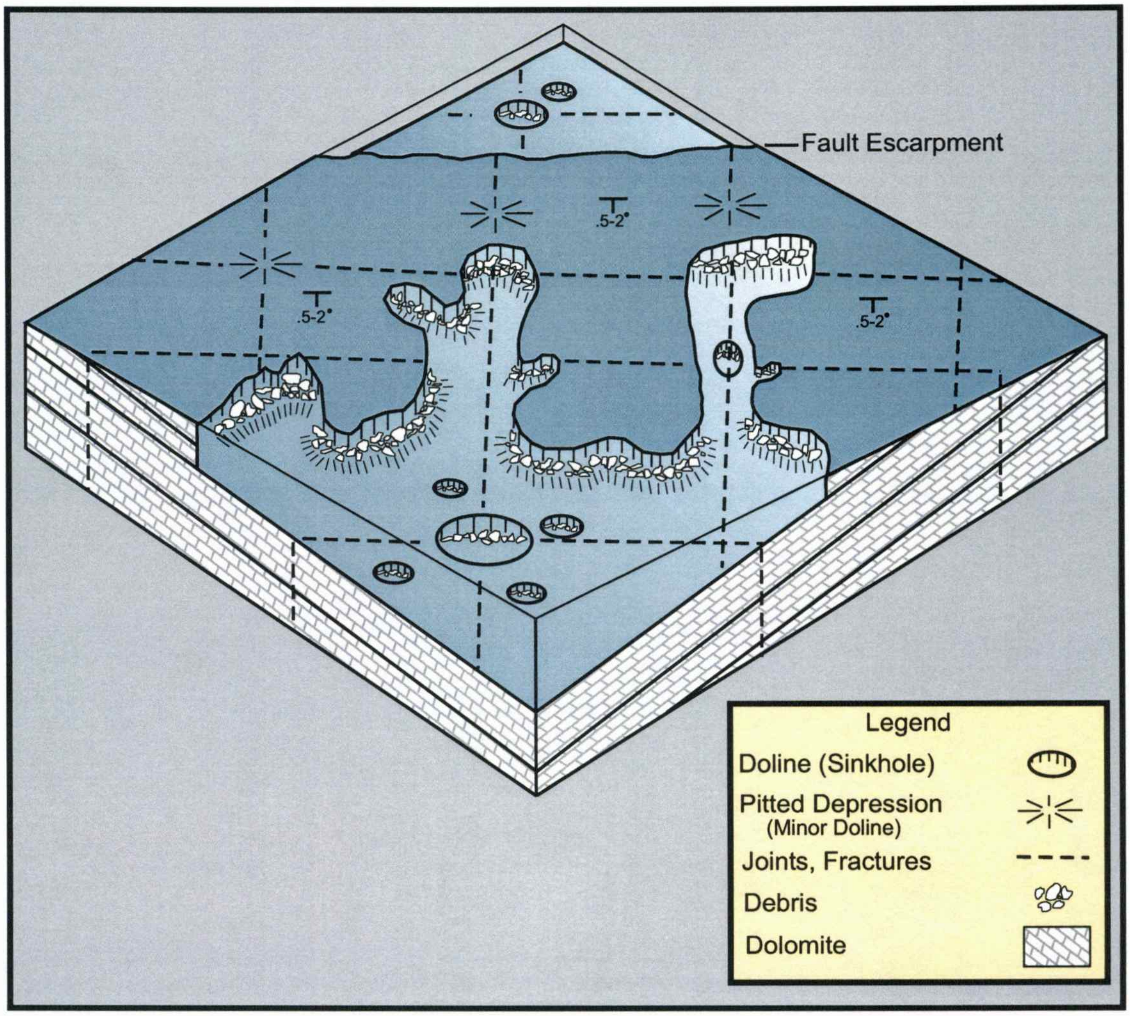

Figure 2.18: Conceptual diagram showing evolution of a ground-water "sapped" drainage network in relation to structural control (joints, fractures) and Arbuckle bed dip. Valley becoming more mature from left to right.

north side giving this feature a scalloped appearance on the down-dip side. The lack of sapping on the up-dip faulted side of the features preserved the relatively straight edge observed on Arbuckle plateaus.

Description Arbuckle Valley Networks

Ground-water sapping in combination with other karst processes formed distinctive drainage systems on the Arbuckle erosion surface (Figures 2.19 and 2.20). The Arbuckle drainage systems were delineated by their drainage divides and interpreted flow directions of surface runoff were plotted. Watershed 1 has a large number of upstream tributaries that are focused into the large alluvial stream-sink doline in section 24-T19S-R10W (Figure 2.19). The head terminations of Watershed 1 tributaries are relatively abrupt, and in some cases light-bulb shaped (22-T19S-R10W and 29-T19S-R9W). The main axis of the drainage system is oriented northwest and connects with a larger drainage system that flows to the southwest.

Watershed 2 has a relatively constant valley width with a number of short stubby upstream tributaries and alluvial stream-sinks. A longitudinal profile (B-B') through the main channel in Watershed 2 displays a sharp head termination, with a relatively steep wall (Figure 2.21A). Profile C-C' displays the relatively flat floor and U-shape of the drainage system (Figure 2.21B). The main axis of this drainage is to the northwest, but is diverted to the northeast by a scalloped shaped Arbuckle high in sections 5 and 6-T19S-R9W.

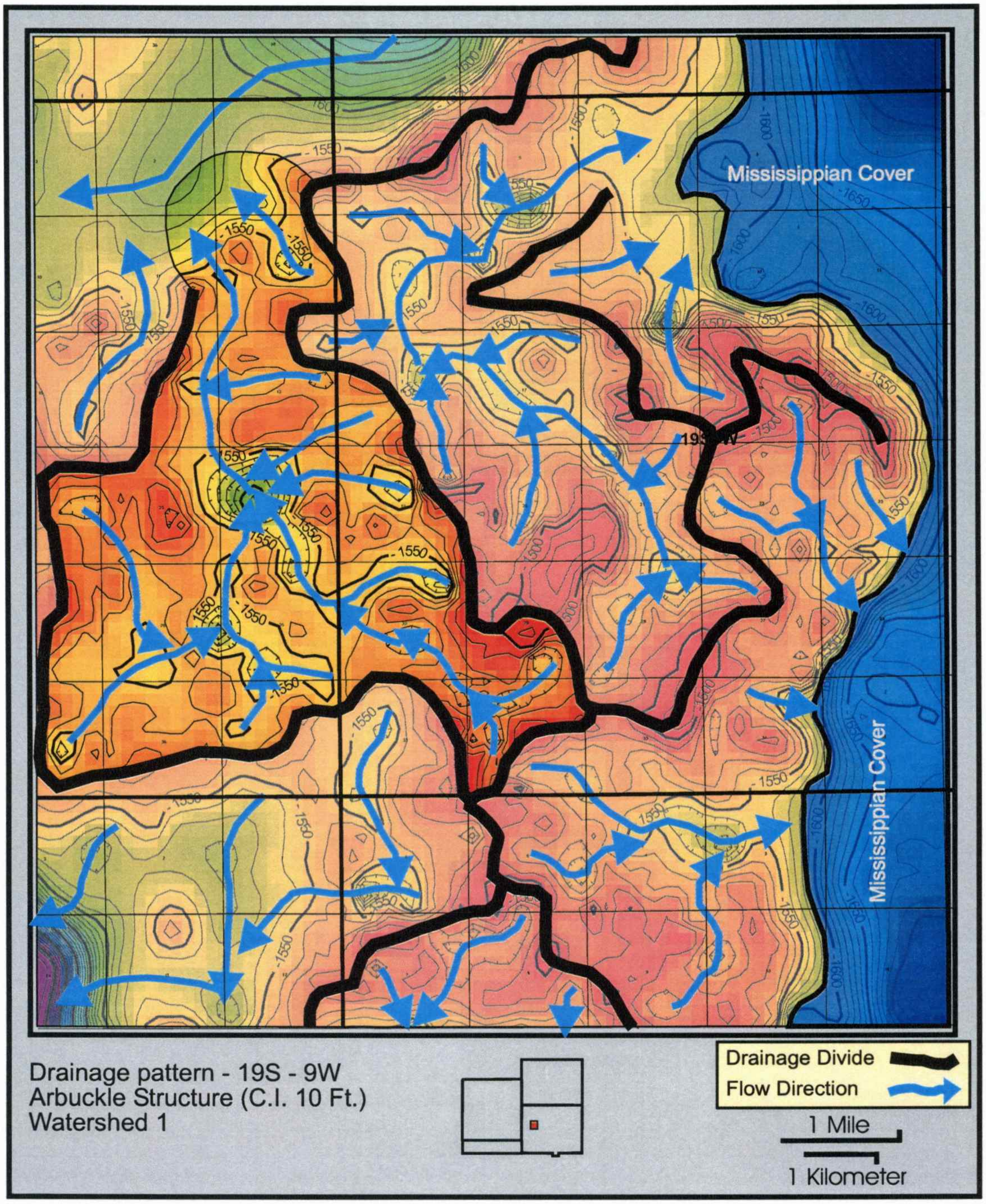

Figure 2.19: Two watersheds delineated on the basis of their topographic divides. Interpreted surface drainage patterns illustrated with blue arrows. Watershed 1 in brighter colors.

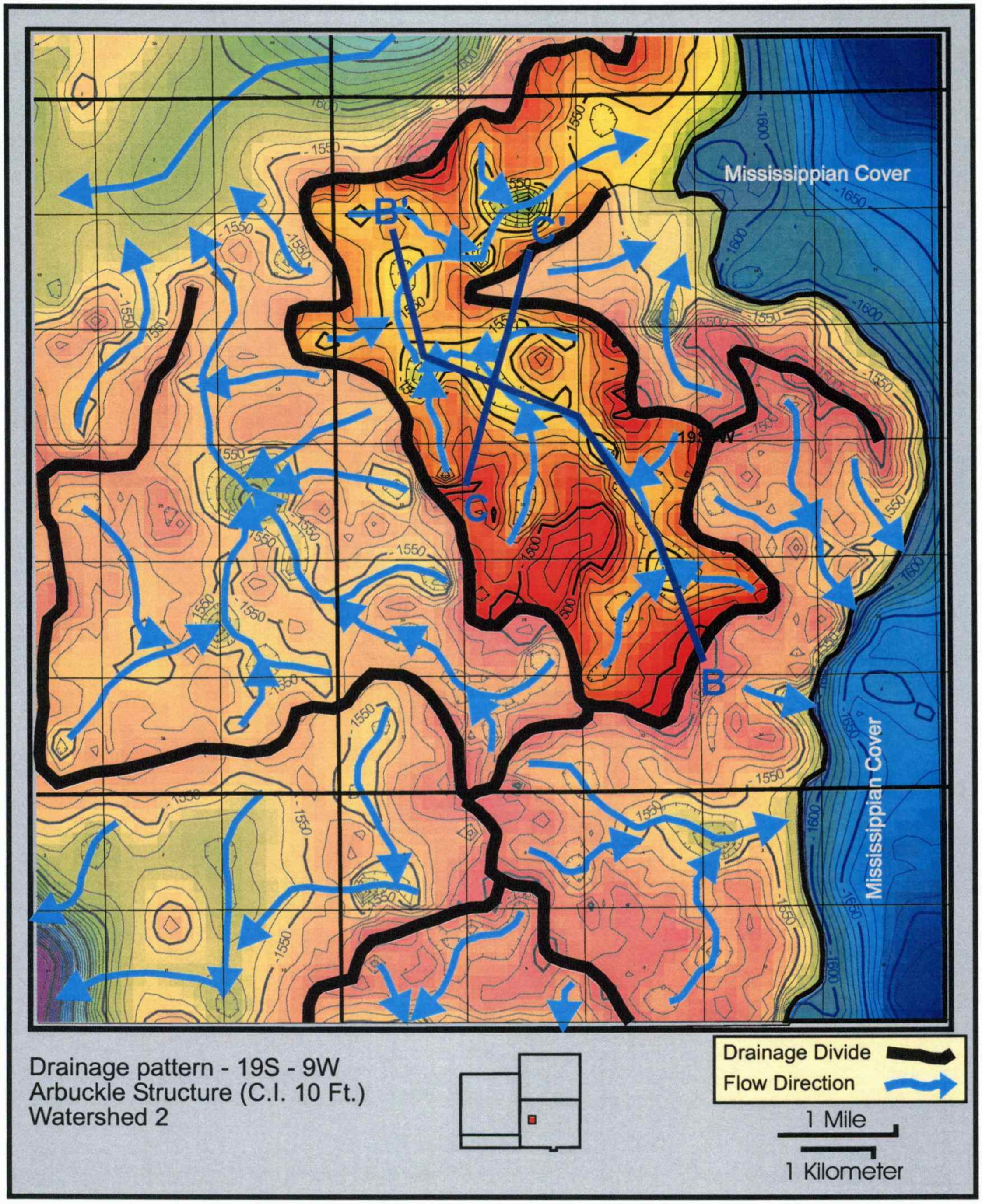

Figure 2.20: Two watersheds delineated on the basis of their topographic divides. Interpreted surface drainage patterns illustrated with blue arrows. Watershed 2 in brighter color. Profiles C-C' and D-D' are shown on Figure 2.21.

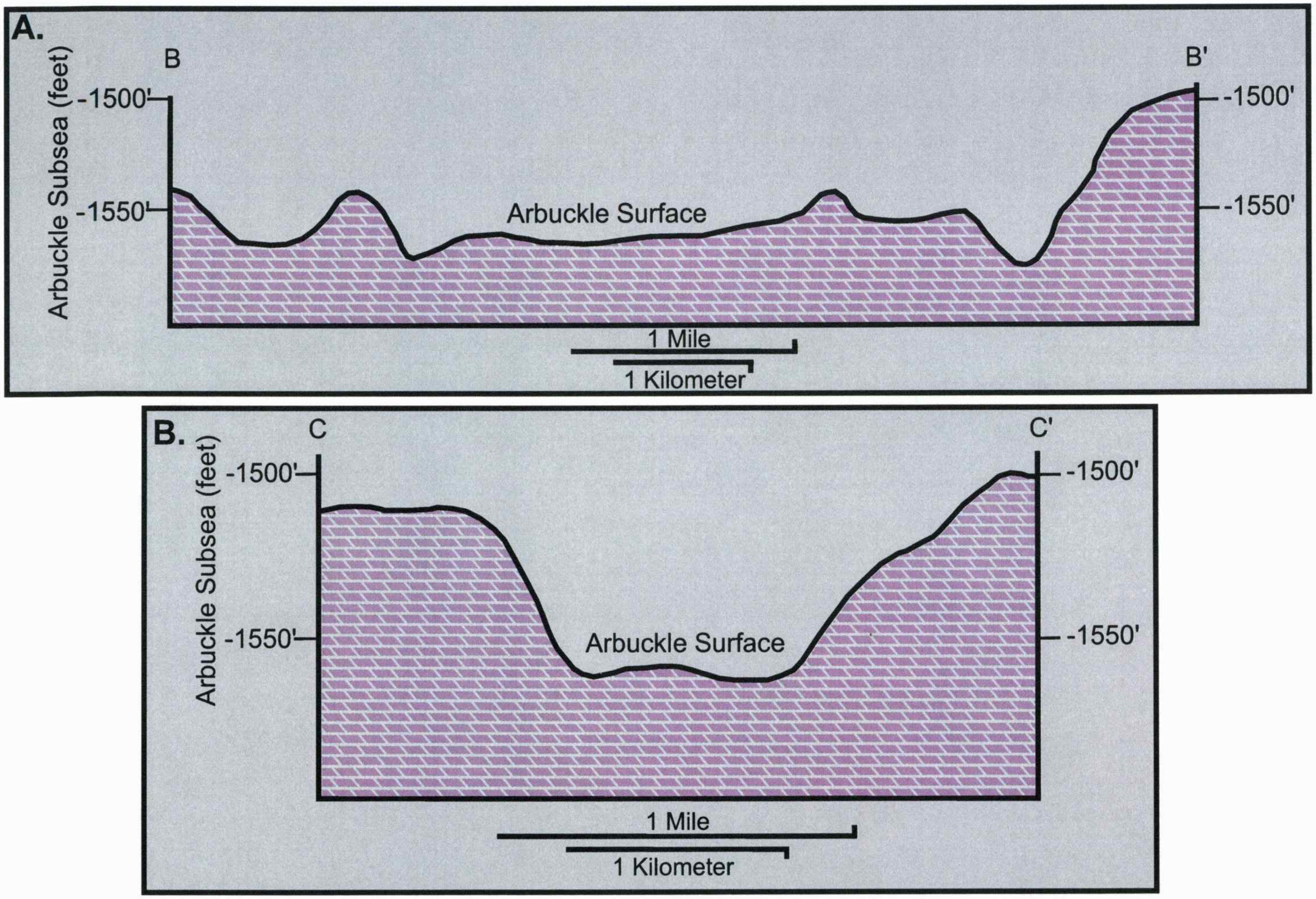

Figure 2.21: A.Longitudinal profile across drainage in T19S-R9W. B. Cross-section of drainage in T19S-R9W. Location of profiles shown on Figure 2.20. Vertical Exaggeration = 50X.

Interpretation

It appears that valleys on the Arbuckle surface formed by the combination of karst and ground-water sapping processes with secondary run-off and mass wasting processes. Figures 2.19 and 2.20 display two watersheds with interpreted flow paths. Watershed 1 (Figure 2.19) drains to the north and connects with larger system. As the underground drainage system evolved and enlarged, surface drainage is disrupted, and low-order tributary streams are pirated into the subsurface. This is evident in Watershed 1 by the paucity of downstream tributaries beyond the large stream-sink doline in section 24-T19S-R10W. Alluvial stream-sink dolines formed along the axes of the drainage network and captured surface flow (Figure 2.22).

Watershed 2 (Figure 2.20) exhibits a sapped valley at a mature stage. As headward migration continued to a mature stage the drainage basins interact, resulting in light-bulb shaped areas in up-dip parts of drainage basins (Laity and Malin, 1985). As the valley back-sapped the positive features, it loses area of ground-water recharge. At the mature stage, as local topography is degraded, sapping will decrease while the relative influence of surface runoff and mass-wasting processes will increase. It appears that dolines were developed at sites where runoff was collected beneath steep headwalls (NE corner of section 28-T19S-R9W, Figure 2.20 and 2.21A). White and White (1979) noted that there are basins from which

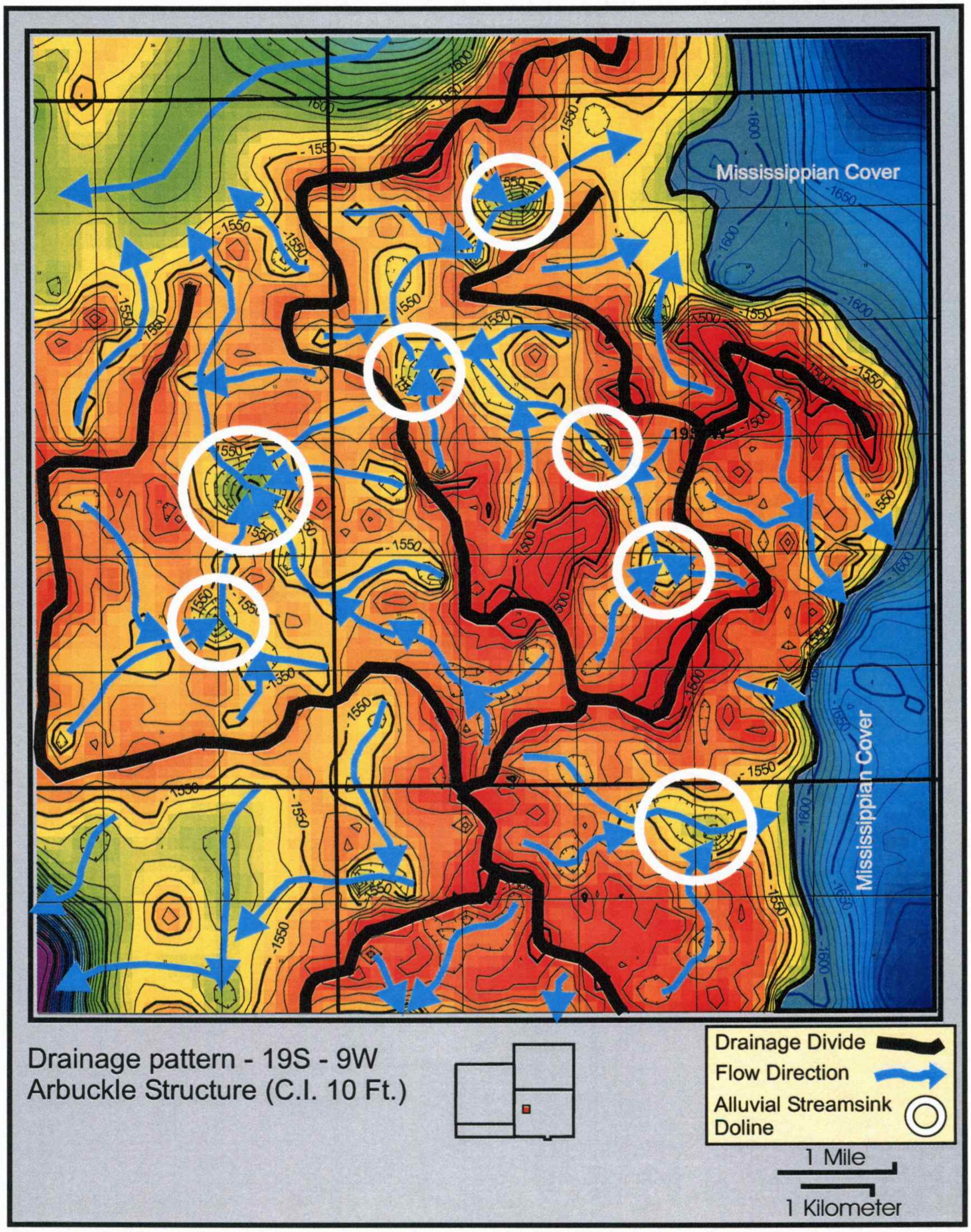

Figure 2.22: Arbuckle structure map in T19S-R9W showing alluvial streamsink dolines. Notice how these dolines occur down the axis of the drainage and capture surface flow.

the only exit of runoff is by underground routes. In such basins, all sediment load derived from erosion and slope retreat must be carried through this underground drainage system. It is inferred that sediment blockage is one of the factors that can inhibit development of competent underground channels, forcing flood flows at least to remain in their surface channels, thus maintaining the fluvial pattern.

Just as in karst erosion in the area, regional and local structural elements have an important role in ground-water sapping processes. The spatial relations of the regional joint pattern exert considerable control on the orientations of the drainages. Most of the drainages in the area follow a northwest-southeast or northeast-southwest trend, aligned closely with interpreted gravity and magnetics lineaments. The relative constancy of orientation of tributary valleys suggests structural control. Tributaries are likely located at sites where secondary joints collected run-off and were subsequently widened to form channels. Where faulting is recognized there is an alignment of drainages.

Cave Occurrence

Reservoir compartmentalization generated by regionally extensive karst modification can have a major impact on reservoir productivity. Formation of regionally extensive cave networks in the Ellenburger carbonates of West Texas produced a complex system of vertical and lateral flow barriers. In order to understand the heterogeneity of the Ellenburger reservoirs, Kerans (1988) developed a karst-controlled model of cave development. The cave networks developed between 100 to 300 feet (30 to 90 meters) from the top of the exposed Ellenburger surface. Kerans (1988) segmented the cave system vertically into three karst facies, 1) cave-roof-dolomites (fracture and mosaic breccias), 2) laterally persistent cave-fill (siliciclastic-matrix-supported and carbonate-matrix-supported breccias), and 3) lower collapse facies (chaotic clast-supported breccias).

Identifying cave development in the Arbuckle using Kerans (1988) model could possibly explain anomalous features observed in Arbuckle logs and core, and might improve characterization of reservoirs in the study area.

Arbuckle Caves

Five wells with significant penetration of the Arbuckle across T19S-R10W (location shown in Figure 2.23) were correlated using gamma ray, neutron, resistivity, and density logs (Figure 2.24). The base of the Kansas City Group was chosen as the datum. The top of the Arbuckle was picked and correlated based on the extreme shift in the gamma ray, neutron, and resistivity logs. Below the Arbuckle surface, there are hundreds of feet of dolomites represented by a relatively "clean" log character on the gamma ray curve, as well as a distinct separation between the neutron-density logs. The Arbuckle dolomite has many characteristic intraformational shale layers, which are identified from pronounced spikes on the gamma ray curve. These shale horizons can be correlated from log to log to gain an understanding of

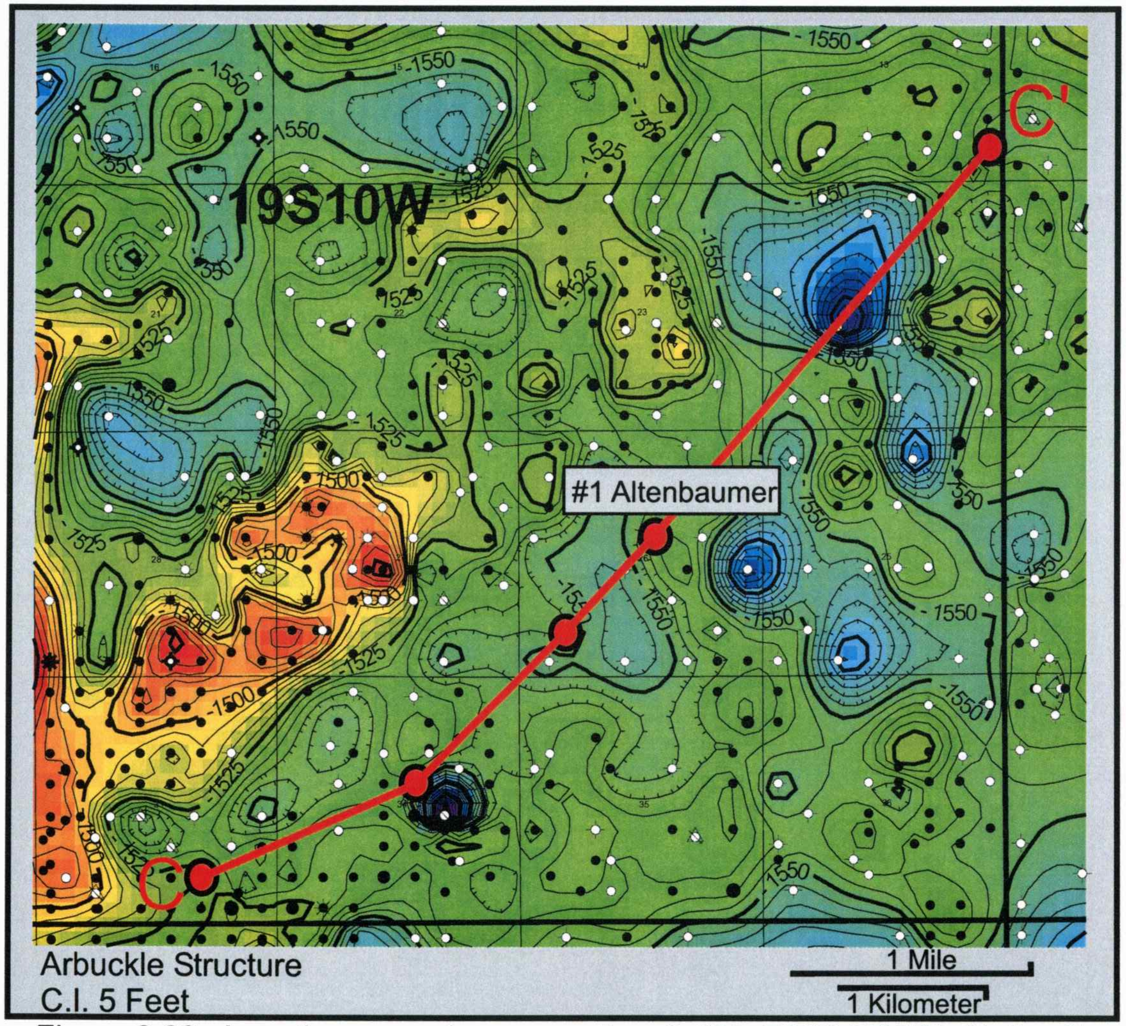

Figure 2.23: Location map of cross-section C-C' in T19S-R10W. Notice the lack of surface expression from the anomalous subsurface feature in the #1 Altenbaumer.

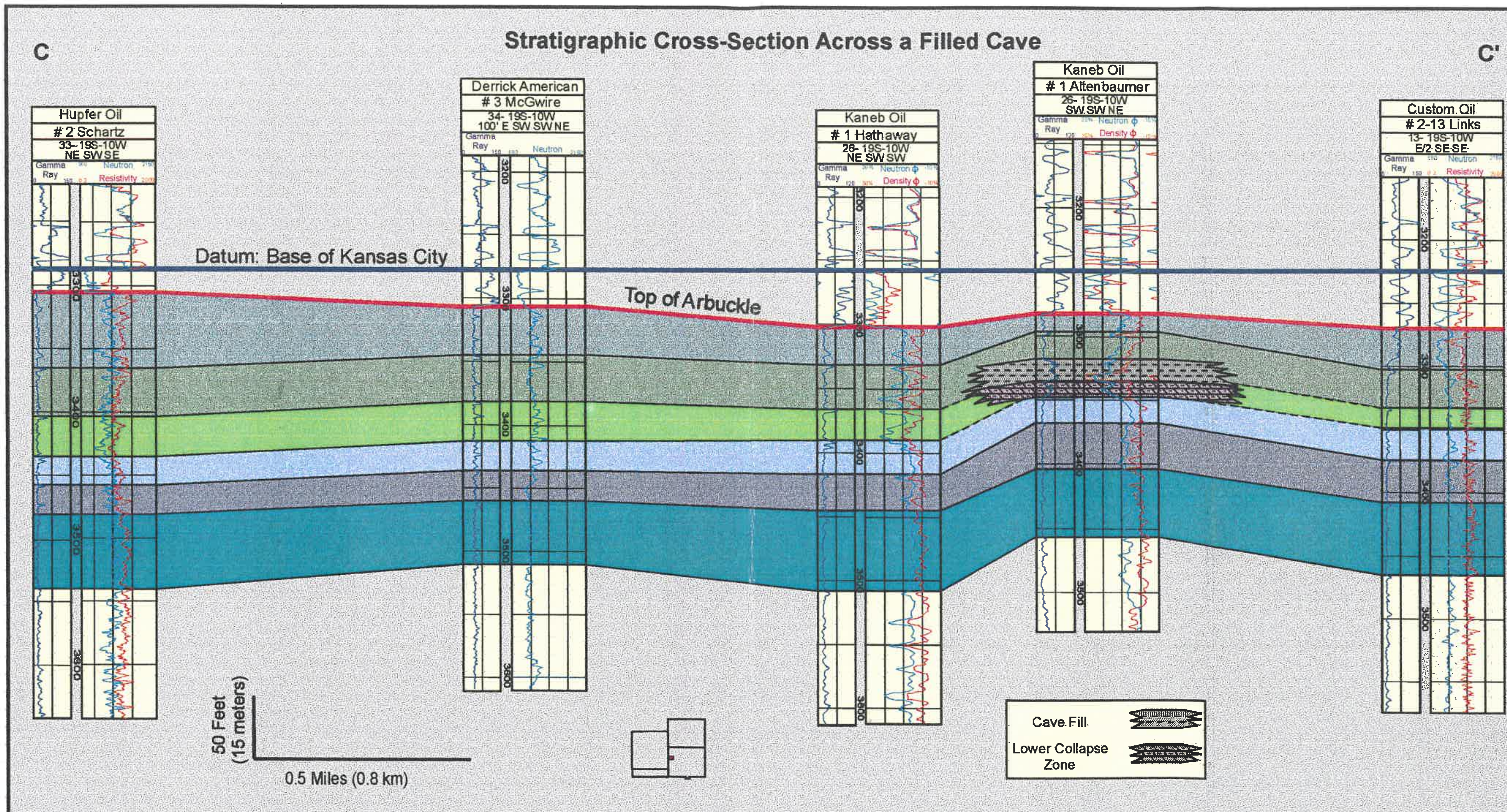

Figure 2.24: Cross-section in T19S-R10W showing correlations of Arbuckle strata and anomalous zone in the #1 Altenbaumer. Location of cross-section shown on Figure 2.23.

the Arbuckle dip, as well as the continuity of the Arbuckle strata. Shale layers were correlated in the log cross-section in T19S-R10W, however an anomalous horizon was identified from log response. The correlation of shale horizons was disrupted in the #1 Altenbaumer (26-T19S-R10W) by a 20 foot (6 meters) thick section of "dirty" gamma ray log character (i.e. elevated gamma ray count). The anomalous horizon in the #1 Altenbaumer was also evidenced by the shift in the neutron and density logs. The combined log character of these three curves suggests a 20-foot (6 meters) thick section of shale, which is only recognized in the #1 Altenbaumer well (Figure 2.24). Below the anomalous horizon there is a 10-12 (3-4 meters) foot zone with a slightly cleaner log signature. Above and below the anomalous zone in the #1 Altenbaumer, the log signature is relatively "clean," which is typical of the Arbuckle dolomite.

Interpretation

Based on examination of available well logs and the distribution of known hydrocarbon production, cave formation in the Arbuckle Group of Kansas does not appear to be as extensive as age equivalent strata elsewhere in the Midcontinent (e.g., Ellenburger Group of West Texas). However, rare cave sequences were recognized in log cross-sections (e.g., Figure 2.24). Cross section C-C' shows correlations within the Arbuckle strata based on thin shale horizons chosen as key marker beds. The anomalous shaly horizon 20 feet from the top of the Arbuckle in the #1

Altenbaumer is interpreted to be cave fill. Below the anomalous cave fill zone there is an interval (10-12 feet thick) that is represented on the gamma ray curve as slightly cleaner, which is interpreted to be a lower collapse breccia zone (Kerans, 1988). Arbuckle horizons can be correlated above and below the interpreted cave zone. The cave sequence in the #1 Altenbaumer was not recognized in adjacent wells indicating that it is laterally restricted. The collapsed cave in the #1 Altenbaumer has no apparent correlation on the Sub-Pennsylvanian surface.

It is possible that many more cave systems exist within the Arbuckle Group. Collapse zones and cave networks would be difficult to recognize in Arbuckle strata from logs alone if the caves collapsed before they were filled with siliciclastic material. In addition, the majority of wells drilled to date did not penetrate a significant section of the thick dolomites. However, concentration of hydrocarbon reservoirs at the top of the Arbuckle and the absence of known deeper production suggests that karst processes differed between the coeval Arbuckle carbonates of Kansas and the Ellenburger carbonates of West Texas. It is possible that Arbuckle caves are more laterally restricted, which would make them more difficult to recognize. Significant Late Mississippian to Early Pennsylvanian tectonism appears to have developed extensive fracturing and local dip in the Arbuckle rocks. The structural influence on the Arbuckle may have precluded the development of extensive cave networks, while enhancing surface karst features.

Arbuckle Core

Karst processes influence Arbuckle paleogeomorpholgy and reservoir performance at many different scales. Karst processes observable at the core scale have been documented to variously create and destroy porosity in Arbuckle carbonates (Franseen, 1994). Very few Arbuckle core are available in the study area, however two cores were examined to illustrate the micro and macroscopic scale erosional features in the Arbuckle.

Description

The Edwards Oil #3 Groth (23-T17S-R9W) core consists of horizontally bedded dolomite (Figure 2.25). The #3 Groth core begins about 5 feet (1.5 meters) below the unconformity as identified from the well log. The core is characterized by dozens of small vugs that range in size from a millimeter to over a centimeter. Vugs are concentrated along bedding planes or randomly oriented through out the matrix. The #3 Groth core also contains a number of randomly oriented open and filled fractures. Widths of the fractures vary from a hairline to 7 millimeters.

The core from the Shell #1 E.E. Tobias (6-T19S-R9W) actually cored across the Sub-Pennsylvanian unconformity surface (Figure 2.26). This core contains 14 inches (35 centimeters) of basal Pennsylvanian shale and Arbuckle dolomite. The shale that rests on the unconformity consists of greenish-gray to black shale with circumgranular cracking around individual grains. The top 8 inches (20 centimeters) of carbonate consist of numerous

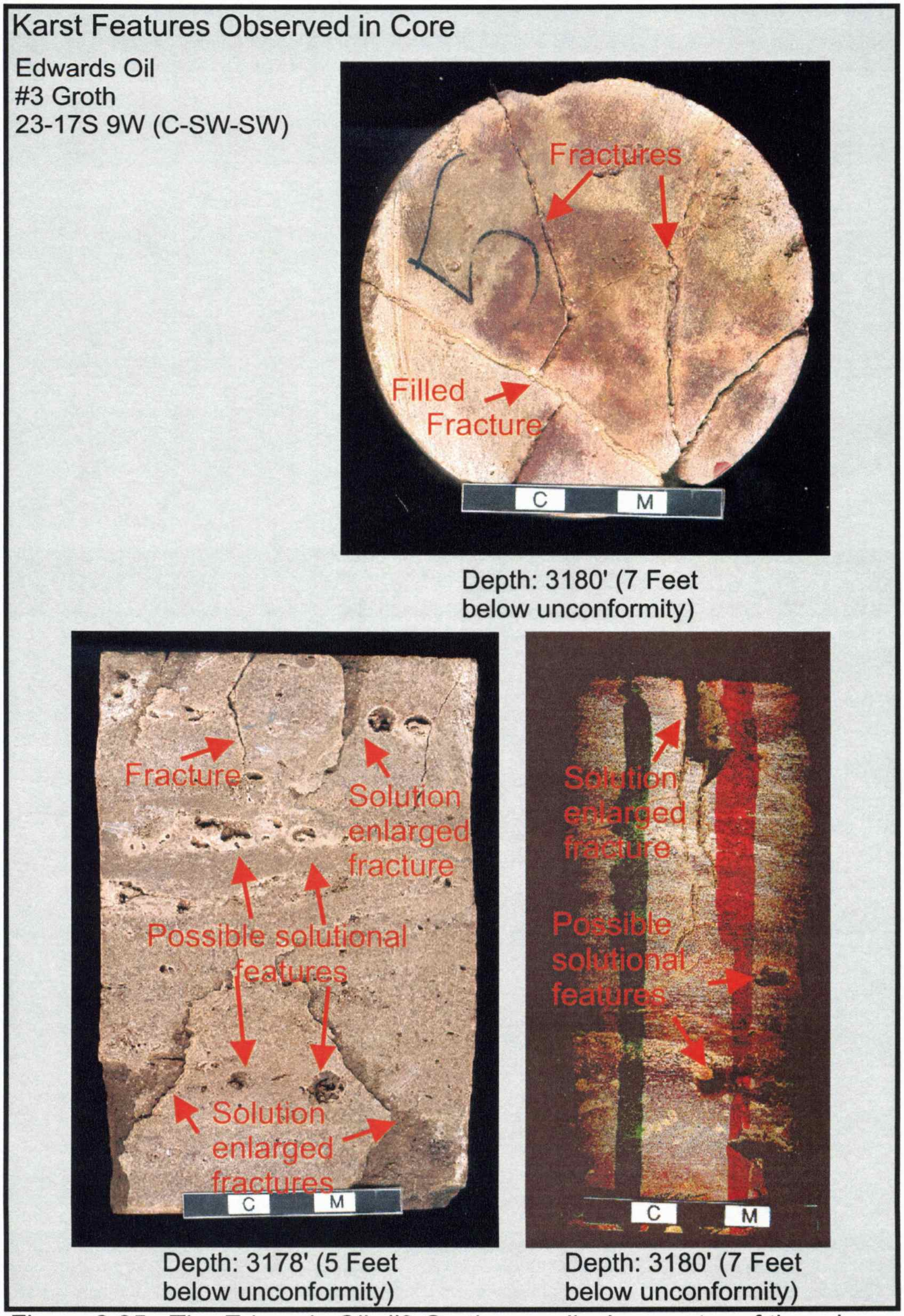

Figure 2.25: The Edwards Oil, #3 Groth core displays some of the micro- and macroscopic karst solutional features.

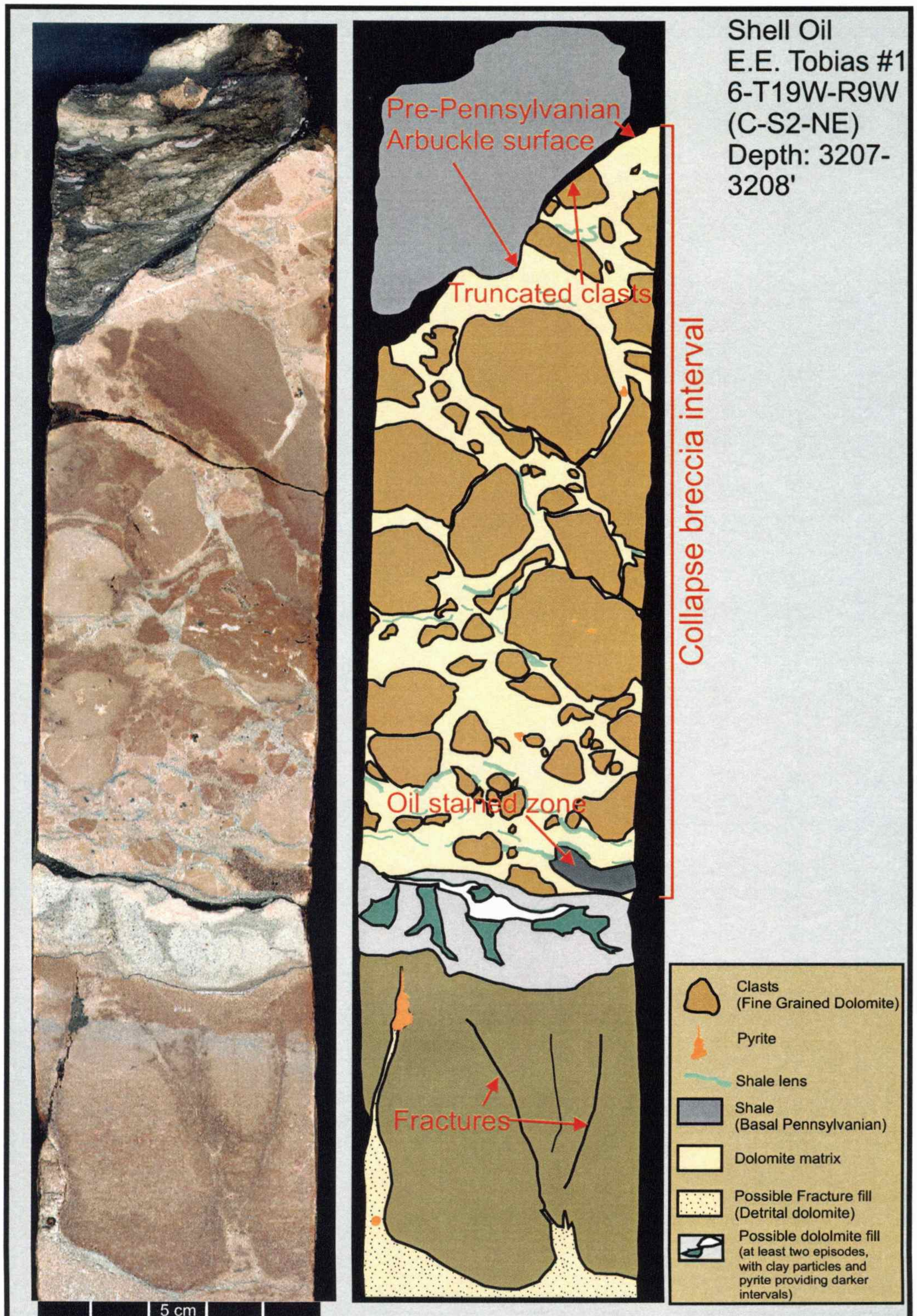

Figure 2.26: The #1 E.E. Tobias core displays the nature of the Pre-Pennsylvanian unconformity surface and the associated micro- and macroscopic karst features.

rounded to subrounded dolomite clasts in a relatively coarse dolomite matrix. Laminations within the clasts illustrate a random orientation. Clast size ranges from a few millimeters to 3 centimeters. Some of the clasts are truncated at the unconformity surface. This section of the core has multiple green to gray shale lenses that range in size from 1-2 millimeters thick and 5-15 millimeters long. Near the bottom of this section, about 8 inches (20 centimeters) from the top of the Arbuckle, there is a small oil stained zone (about 2 centimeters long). Below this zone there is a two centimeter thick gray and white zone of coarse grained dolomite. Tiny green clay particles (>1mm) and pyrite are also present. The bottom 4 inches (10 centimeters) of the core consists of a relatively finer grained dolomite with several vertical fractures. Fractures are filled with detrital dolomite and clay, and near the top of one fracture, there is an occurrence of pyrite.

Interpretation

Development of brecciation, fracturing and dissolution related to the post-Arbuckle unconformity is variable. The unconformity both created and destroyed porosity (Steinhauff et al, 1998). Figure 2.25 shows the character of fracturing and solution features that enhanced porosity in an Arbuckle core. The large number of vugs present in the #3 Groth core may or may not be related to the Sub-Pennsylvanian exposure event. The concentration of vugs along bedding planes suggests the possibility that these might be related earlier dissolution of evaporite nodules. However, the proximity to the unconformity surface and the presence of solution enlarged fractures suggest the possibility that vugs are related to Late Mississippian-Early Pennsylvanian karst dissolution.

Figure 2.26 shows a 14 inch (35 centimeter) section of Arbuckle core across the Sub-Pennsylvanian unconformity. The circumgranular cracking around grains in the basal Pennsylvanian shale on top of the unconformity provides evidence of subaerial exposure and soil forming processes. The top 8 inches (20 centimeters) of Arbuckle consists of randomly oriented dolomite clasts. This zone is interpreted to be a gravity driven clast supported chaotic collapse breccia. The truncation of Arbuckle clasts at the unconformity surface indicate the formation of the breccia was Sub-Pennsylvanian. In this zone karstification essentially occluded porosity. There are dozens of tiny shale lenses within the Arbuckle breccia that have the same character of the overlying Pennsylvanian shale suggesting shale infilling from the exposure surface. It appears that at least two zones of detrital dolomite fill are present in the core. One horizontal fill occurs near the bottom and is represented by light gray and white dolomite with clay particles and pyrite, and vertical fills within fractures consisting of coarse grained dolomite and clay. This suggests that there might have been more than one episode of dissolution, sediment transport and collapse in this core.

Discussion of Arbuckle Erosional Styles and Processes

The Sub-Pennsylvanian erosional surface on the top of the Arbuckle Group in central Kansas is an excellent example of karst processes that heavily modified topographic relief associated with pre-existing erosional, depositional and structural patterns. The Late Mississippian-Early Pennsylvanian deformation produced a regional uplift of the basement on the Central Kansas uplift. Local blocks were differentially affected, producing minor horst and graben features. Associated with this deformation, the exposed terrain was cut by a regional pattern of joints and fractures. The joints and fractures, oriented in preferred directions along zones of basement weaknesses, localized and directed surface and subsurface runoff. It appears that uplifted plateaus were attacked by a combination of karst dissolution, mass wasting, and fluvial processes. It seems unlikely that the Sub-Pennsylvanian morphology of Arbuckle plateaus is a product of only one erosional process. Karst or fluvial processes alone cannot sufficiently explain the geomorphic relationships in the study area. Settings dominated by ground water sapping processes are generally characterized by high relief and show evidence of effective fluvial processes. Admittedly, the overall relief in the study area is relatively low and there is little clear evidence of extensive fluvial processes. However, Arbuckle plateaus exhibit a characteristic morphology that is consistent with ground-water sapping processes in combination with karst and fluvial erosion. The interplay of

Arbuckle stratigraphy and structure, as well as karst, ground-water, and fluvial erosional processes all appear to be important components to the evolution of the Arbuckle surface.

Many erosional processes are recognized on the Arbuckle surface at varying degrees of intensity. It is speculated that a karst geomorphologic sequence can be recognized, beginning with the initial uplift and associated fracturing of the Arbuckle carbonates. At an early stage, it appears that some plateaus composed of relatively large structural blocks were sculpted by ground-water sapping processes, producing scallop shaped escarpments on the down-dip side of the features. Slumping of Arbuckle carbonates produced characteristic valleys as mechanical breakdown and fluvial processes became important mechanisms shaping the sapped features and drainage networks. At a mature stage, plateaus were degraded and began to lose ground-water recharge area, reducing the influence of ground-water sapping processes. As increasingly competent underground drainage networks were developed, karst solution and collapse became an important erosion process. As karst erosion intensified, sapped plateaus and drainage systems began to break up into isolated dolines and residual hills, occluding the original sapped morphology. At this point, a characteristic polygonal karst morphology is superimposed on the surface. The Arbuckle surface was completely pitted with multi-generational dolines, the residual hills of which resembled a cockpit karst landscape.

Many factors contributed to the final morphology of the Sub-Pennsylvanian Arbuckle surface. The influence of ground-water sapping processes were variable depending on surface area of uplifted plateaus and the competition for rechargeable ground-water. Variations in structural controls and fracturing of Arbuckle strata were also important factors determining the relative influence of karst and ground-water sapping processes. The extent and intensity of Arbuckle fracturing likely influenced the development of underground drainage, which in turn accelerated karst solution and collapse. It is possible that variations in lithology exhibited a degree of influence on the evolution of the Arbuckle surface. The absence of competent shale layers or ground-water flow barriers precluded the development a perched water table. The absence of barriers that directed ground-water flow down regional dip hindered the ground-water sapping processes, while karst processes were accelerated.

The Sub-Pennsylvanian Arbuckle carbonates were subjected to extensive and prolonged weathering. The interaction of pre-existing structural features, renewed tectonics, and variations in lithology of the Arbuckle Group resulted in a complex erosional surface characterized by extensive sapped plateaus and drainage networks and surface karst features.

3. EVALUATING PRECAMBRIAN STRUCTURAL CONTROLS ON THE ARBUCKLE SURFACE

In addition to the gravity and magnetics data (Figure 2.10), the structure of the Precambrian basement and its influence on the Sub-Pennsylvanian Arbuckle erosion surface was evaluated by mapping basement penetrations in the region. The general correspondence of many Phanerozoic structures to Precambrian basement features, as indicated by gravity and magnetic data, suggests that deformation during the Late Mississippian-Early Pennsylvanian may represent reactivation of zones of weakness related to earlier structures. Many local Arbuckle highs have been interpreted as corresponding to buried Precambrian topography (Walters, 1958).

The correspondence of Sub-Pennsylvanian Arbuckle topography with Precambrian basement structural features was evaluated by overlying the structure contour map on the top of the Arbuckle as a color-shaded grid over the structure contours of the top of the Precambrian surface (Figures 3.1 and 3.2). In addition, interpreted lineaments from gravity and magnetics maps were overlain on the Arbuckle structure map to illustrate the general relationship of the erosional surface to basement structural elements (Figures 3.3 and 3.4). Several positive relationships can be recognized between interpreted lineaments and the Arbuckle surface, both locally and regionally.

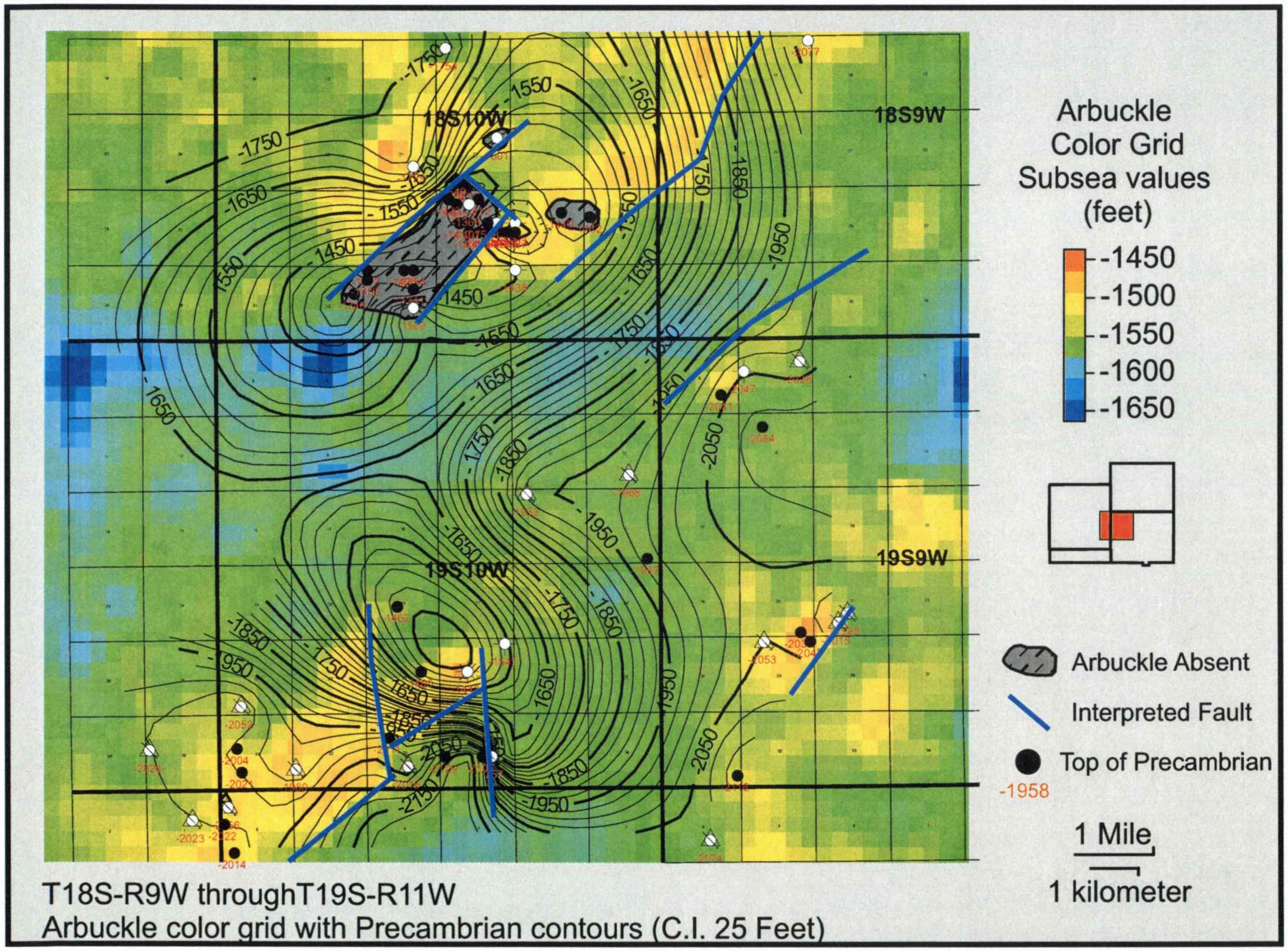

Figure 3.1: Arbuckle color grid and Precambrian contours illustrating relationship of Pre-Pennsylvanian Arbuckle surface to basement.

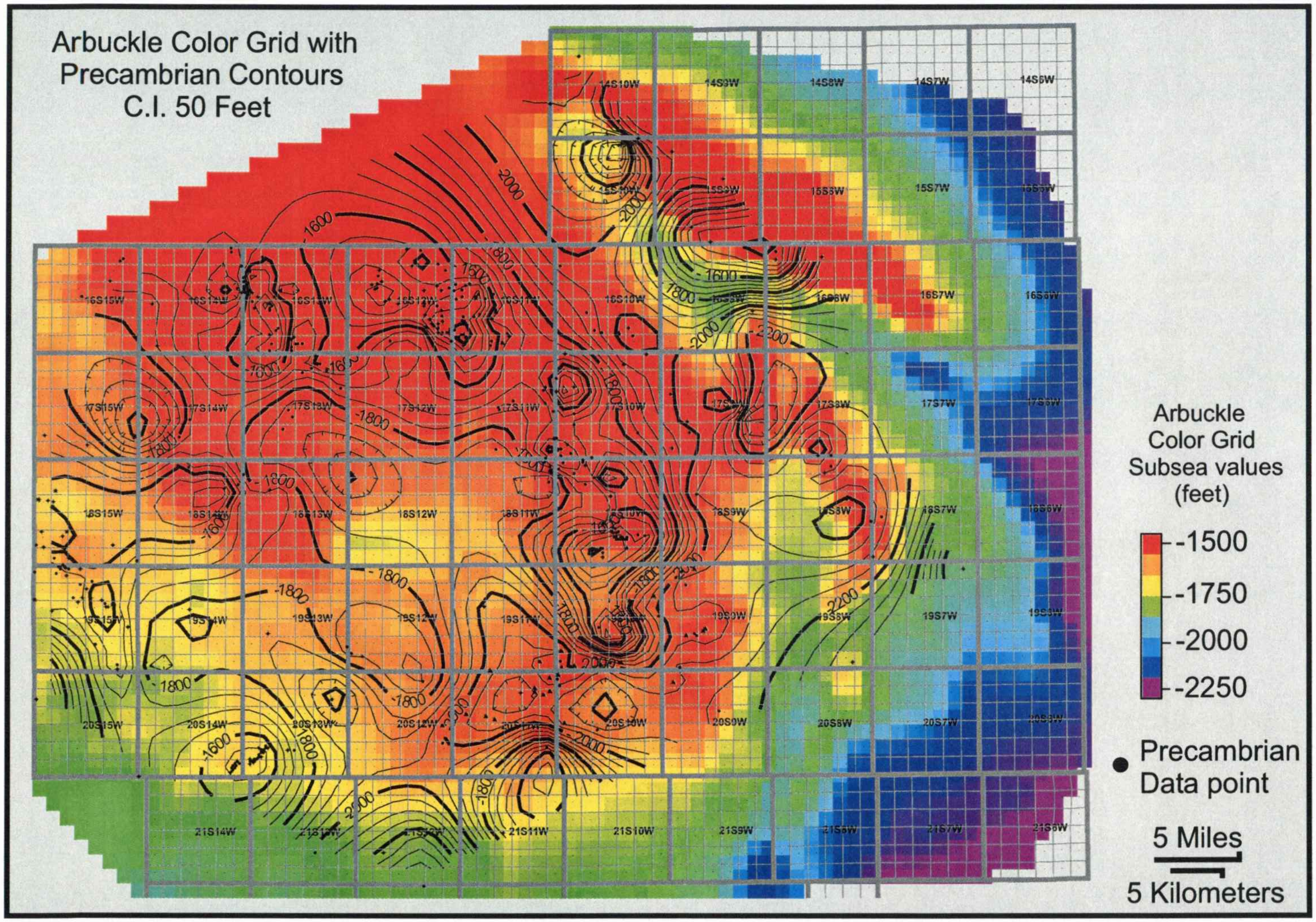

Figure 3.2: Arbuckle color grid with Precambrian contours illustrating the regional relationship of Pre-Pennsylvanian Arbuckle surface to the top of basement structure contour.

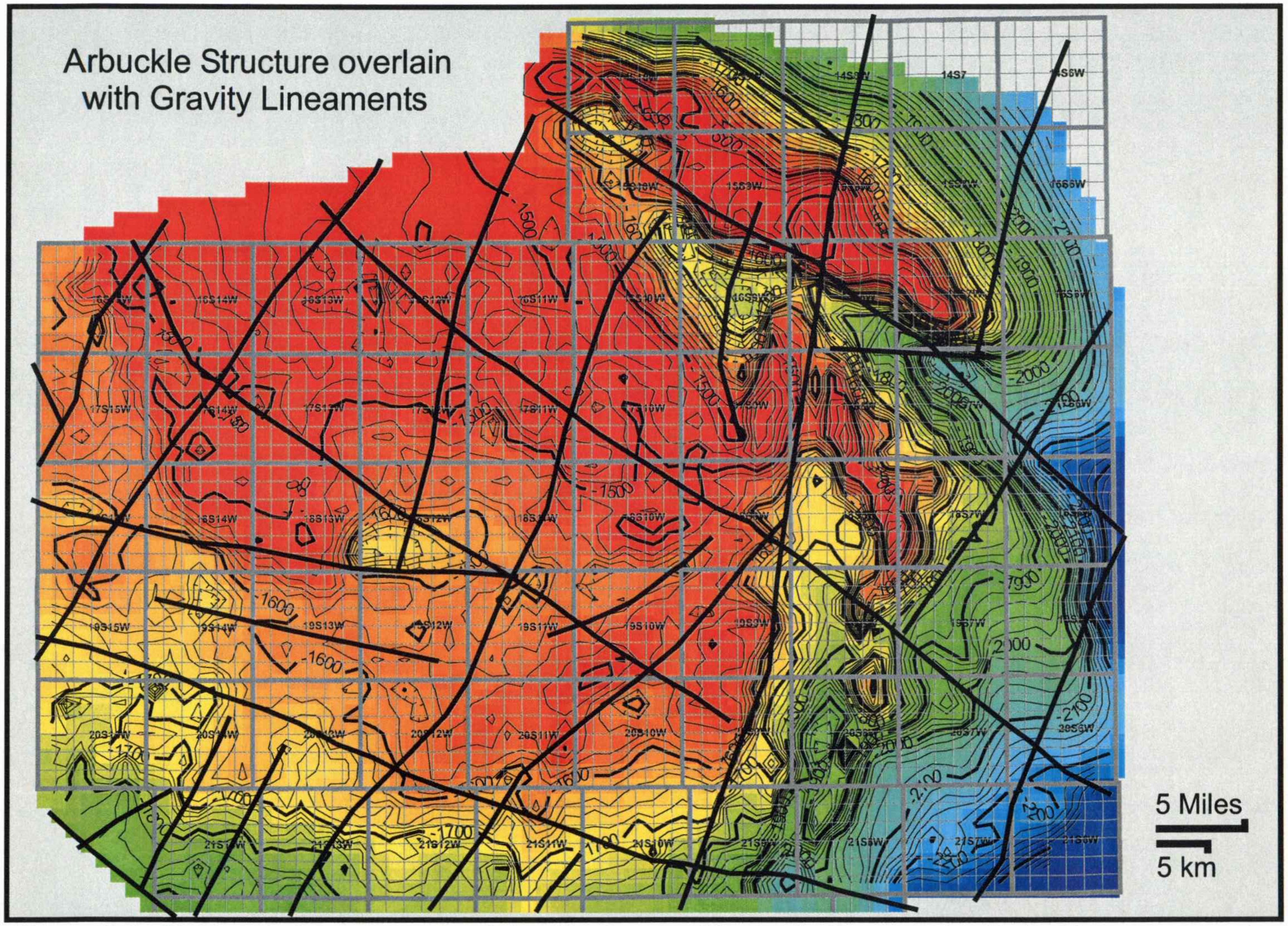

Figure 3.3: Regional structure on the Arbuckle Group with gravity lineaments. Notice how some major features on the Arbuckle surface correspond to gravity lineaments.

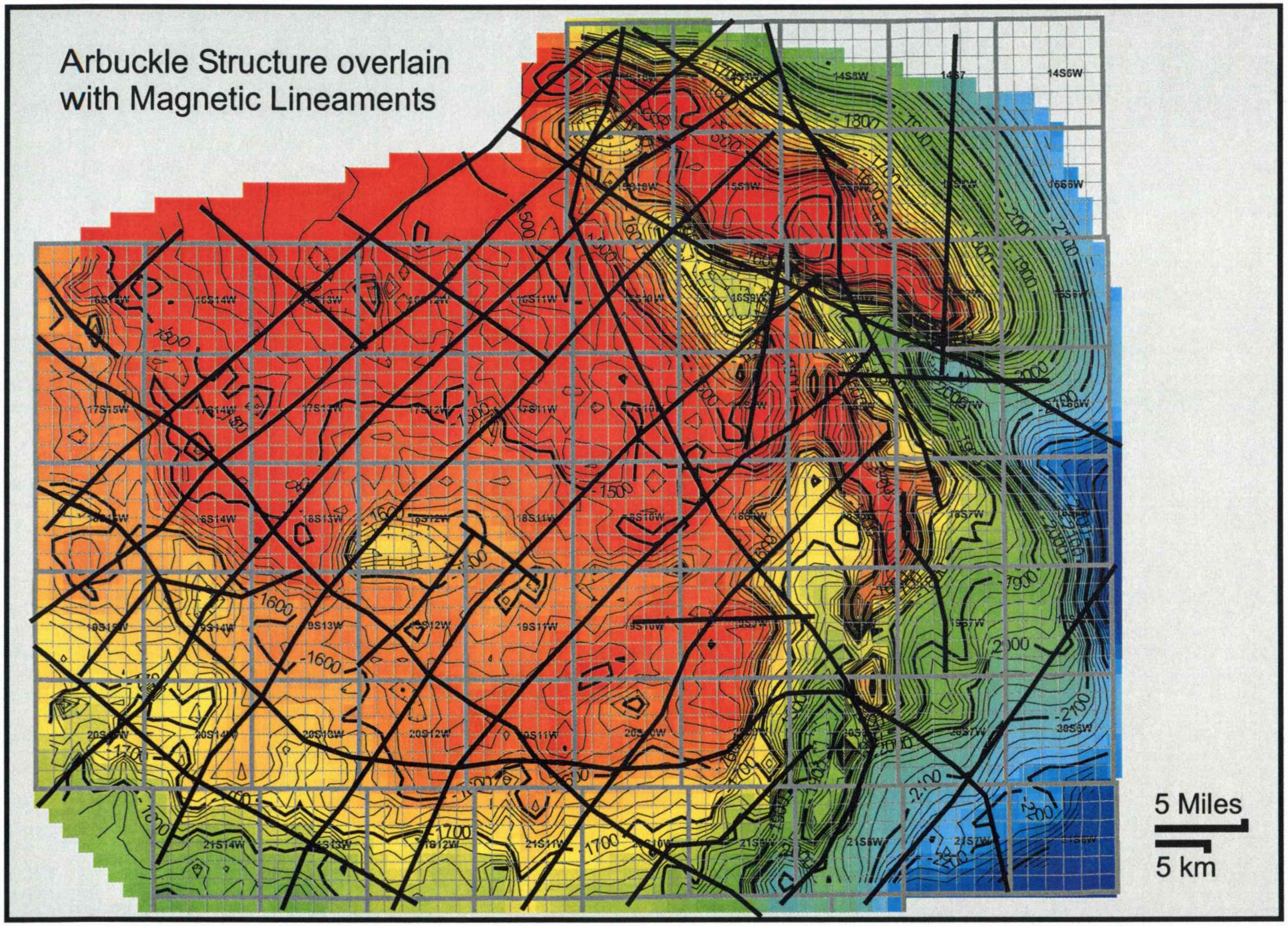

Figure 3.4: Regional structure on the Arbuckle Group with magnetic lineaments. Notice how some major features on the Arbuckle surface correspond to magnetic lineaments.

The Arbuckle high in the southwestern portion of the map corresponds to a major gravity and magnetic lineament in the area, but it does not exactly mimic basement topography (Figure 3.1). The northeast portion of the feature is coincident with a Precambrian high (-1450' subsea), but the basement drops dramatically towards the southwest and southeast (<-2050' subsea). The Sub-Pennsylvanian Arbuckle surface does not reflect the magnitude and exact orientation of the Precambrian structure.

The structural position of the basement does appear to have some reflection on the Arbuckle surface to the north. In the northern part of T19S-R10W a major drainage on the Arbuckle surface is bounded on both the north and south sides by distinct linear boundaries. The boundaries of the Arbuckle drainage correspond to a sag in the basement (Figure 3.1). On a local scale, Arbuckle rocks were completely removed in areas where uplift and erosion were greatest. The basement high in the southern half of T18S-R10W trends parallel to the two Arbuckle plateaus to the northwest and southeast. The increased number of Precambrian data points highlight the variability of the structure on the basement in this area. The 1500 foot contour outlines a northeast-southwest antiform feature on the Precambrian surface, but there appears to be several locations where the basement changes dramatically suggesting significant faulting in the area. The north and south limbs of this structure are relatively linear, which supports the fault-bounded interpretation. The northeast-southwest trending Arbuckle high in

T18S-R10W corresponds to the distinct southern boundary of the Precambrian antiform and its distinct linear southern boundary. The dramatic drop in the basement on the northeast edge of the feature suggests fault termination. The northeast termination of the basement feature corresponds to a doline on the Arbuckle surface, suggesting a direct relationship between basement faulting Arbuckle doline generation (Figure 3.1 and Figure 2.16).

The influence of basement structure is more apparent when viewed on a regional scale. The Arbuckle color grid was overlain on the Precambrian structural contour lines over the entire study area to highlight the regional relationships (Figure 3.2). The Precambrian surface is rarely reached in Kansas, however in the southern part of the Central Kansas uplift 406 tests penetrated the basement. Precambrian data points tend to cluster around basement highs giving the structure map the irregular appearance of a series of isolated hills. However, data coverage was sufficient to highlight some regional trends on the Central Kansas uplift. The main axis of the uplift is coincident on both the basement and Sub-Pennsylvanian Arbuckle surfaces (Figure 3.2). In addition, local basement highs in T16S-R13W and T16S-R11W are coincident with regional positive Arbuckle features. The Ellsworth anticline, a subsidiary feature of the Central Kansas uplift, displays the positive correlation of the basement structure and Arbuckle surface. In addition, the Ellsworth anticline is also bounded on the northeast and southwest sides by interpreted gravity and magnetics lineaments (Figures 3.3

and 3.4). In addition to positive correlation of several Arbuckle and basement highs in the area, the relatively large Arbuckle low in T18S-R12W is represented by a significant low on the basement structure.

While limited data on the Precambrian surface precludes detailed structural mapping and correlation to the Arbuckle surface, some conclusions can be drawn. The structural elements in the Arbuckle of the Central Kansas such as: regional uplifts and lineaments, and local uplifts and faults are represented on the Precambrian structure. Basement structure, when recognized has a significant influence on alignment of karst and drainage features on the Arbuckle erosion surface. However, the Sub-Pennsylvanian surface does not perfectly mimic the basement structure. The decreased relief on the Arbuckle erosional surface compared to the Precambrian surface is interpreted as a product of both depositional onlap of Cambrian and Lower Ordovician sediment on pre-existing Precambrian topography, and differential movement and subsequent erosion of Arbuckle sediments across reactivated basement structures. Depositional onlap of early Paleozoic sediments on Precambrian topography, and differential erosion of the Arbuckle related to reactivation has been described from the Kraft-Prusa and Otis-Albert Fields (Walters, 1946; Miller, 1968). The varying influence imposed by basement structure on the Arbuckle erosional surface is an important consideration for understanding the genesis of the erosional surface and the distribution of the hydrocarbon reservoirs.

4. CORRELATING ARBUCKLE PALEOGEOMORPHOLOGY TO HYRDROCARBON PRODUCTION

Many factors control the distribution of hydrocarbons in Arbuckle reservoirs of Central Kansas. Oil and gas is found in Arbuckle Group rocks in a variety of structural and stratigraphic traps. Structural position affected the location of reservoirs both locally and regionally. In Central Kansas, potential Arbuckle reservoir rocks underwent varying degrees of modification from subaerial exposure. This erosional modification enhanced and destroyed reservoir qualities at the micro to macroscopic scale (i.e. pore to core), as well as at the megascopic scale (i.e. interwell to field). At the megascopic scale, two different styles of erosional terrains were identified on the Sub-Pennsylvanian Arbuckle surface, a polygonal karst terrain (cockpit karst) and plateau-like erosional features (ground-water sapping). The two types of erosional terrains are end members and numerous intermediate examples exist. However, differences in oil productivity were recognized between cockpit terrains and plateau regions.

To examine general relationships between production and paleogeomorphic style on the Arbuckle surface, it is necessary to understand current limitations in data quality. Historical records of production are not widely available until the late 1960's, so production prior to that date is pooled together into one cumulative total for each field. This limits analysis to average annual and cumulative production, and average and total number of producing wells over the entire field. Production information showing average cumulative per well is posted for Arbuckle fields in selected areas (Figure 4.1, 4.2, and 4.3).

The size and shape of the fields vary significantly as well as the cumulative production per well. Relatively small, irregularly shaped fields occur in mature polygonal karst landscapes on the Arbuckle surface (southern half of Figure 4.1, T17S-R14W in Figure 4.2, and T17S-R11W in Figure 4.3). These Arbuckle fields have relatively low cumulative production per well. Typical ranges of production in these areas are between 50,000 and 100,000 barrels of oil per well. The Kraft-Prusa field is one of the largest fields in Kansas, however cumulative production per well is below 45,000 barrels of oil (Figure 4.3). Based on the geomorphology of the Arbuckle erosion surface, the Kraft-Prusa Field appears to be an excellent example of a reservoir developed over an area dominated by a polygonal karst morphology.

Fields that occur on ground-water sapped plateaus show significantly higher per well cumulative recovery of hydrocarbons. The sapped feature in the northern part of T18S-R14W, which is the Boyd Field, has per well cumulative production of over 213,000 barrels (Figure 4.2). The Boyd Field is an elongate feature oriented northwest-southeast, with an undulating southern boundary. Another large sapped feature in the northern part of Figure 4.1 is the Bloomer Field. The Bloomer Field is oval shaped, relatively

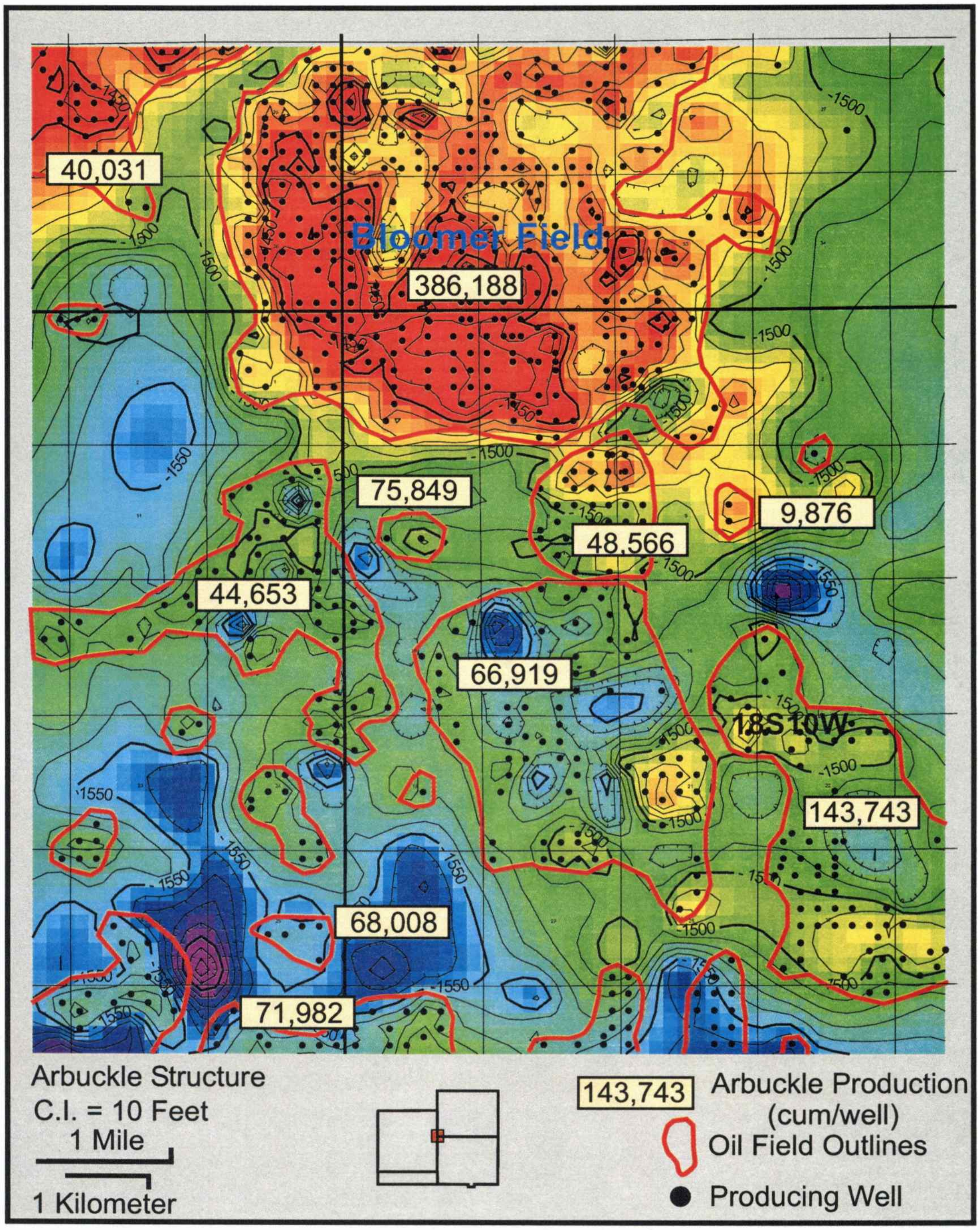

Figure 4.1: Arbuckle structure with oil field outlines and producing wells in T18S-R10W. The Bloomer Field is a large reservoir that was developed by ground-water sapping processes. In the field, cumulative average recovery per well exceeds 385,000 barrels of oil.

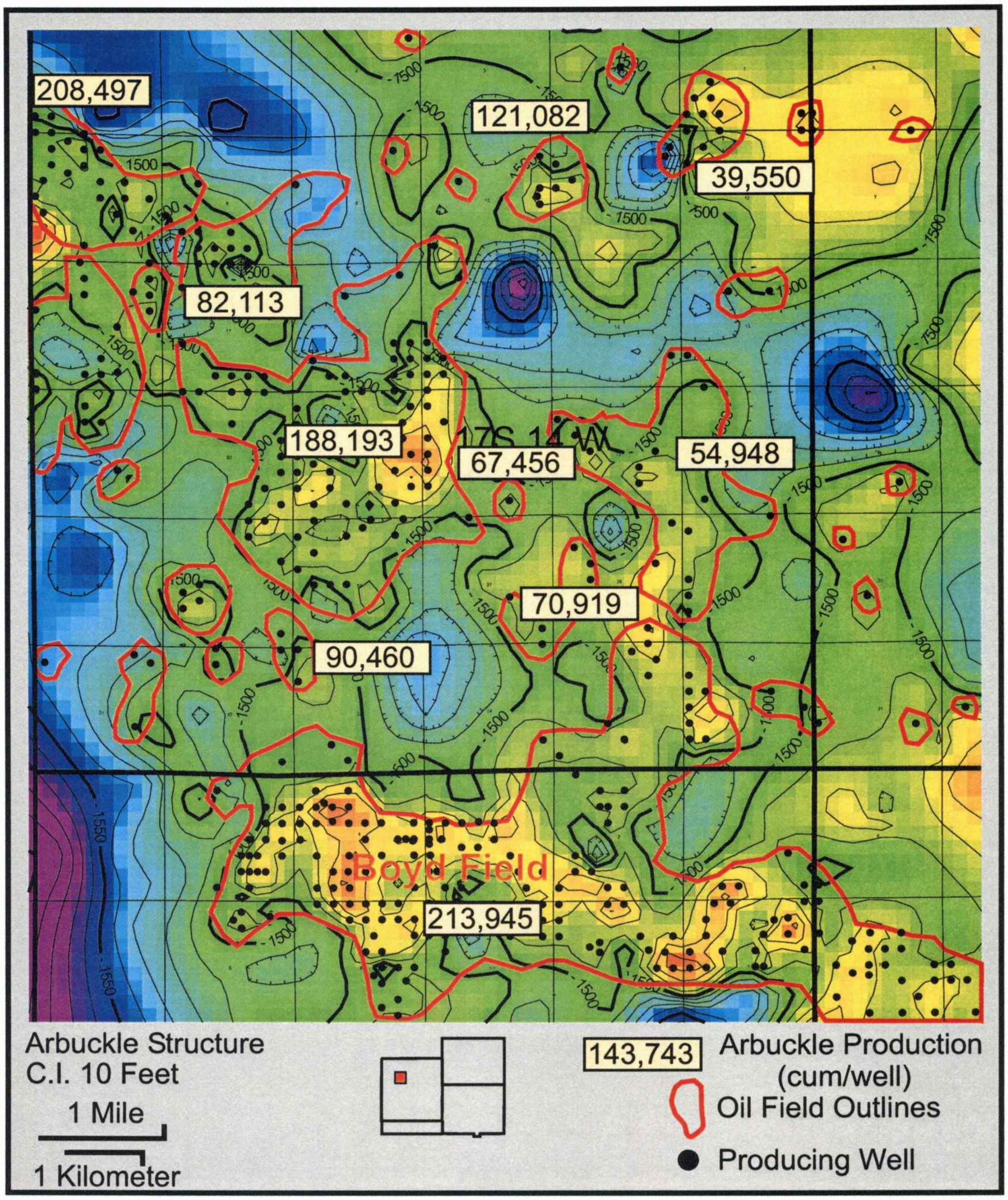

Figure 4.2: Arbuckle structure with oil field outlines and producing wells in T17S-R14W. The Boyd Field is an elongate reservoir developed primarily by ground-water sapping processes. In the field, cumulative average recovery per well exceeds 210,000 barrels of oil.

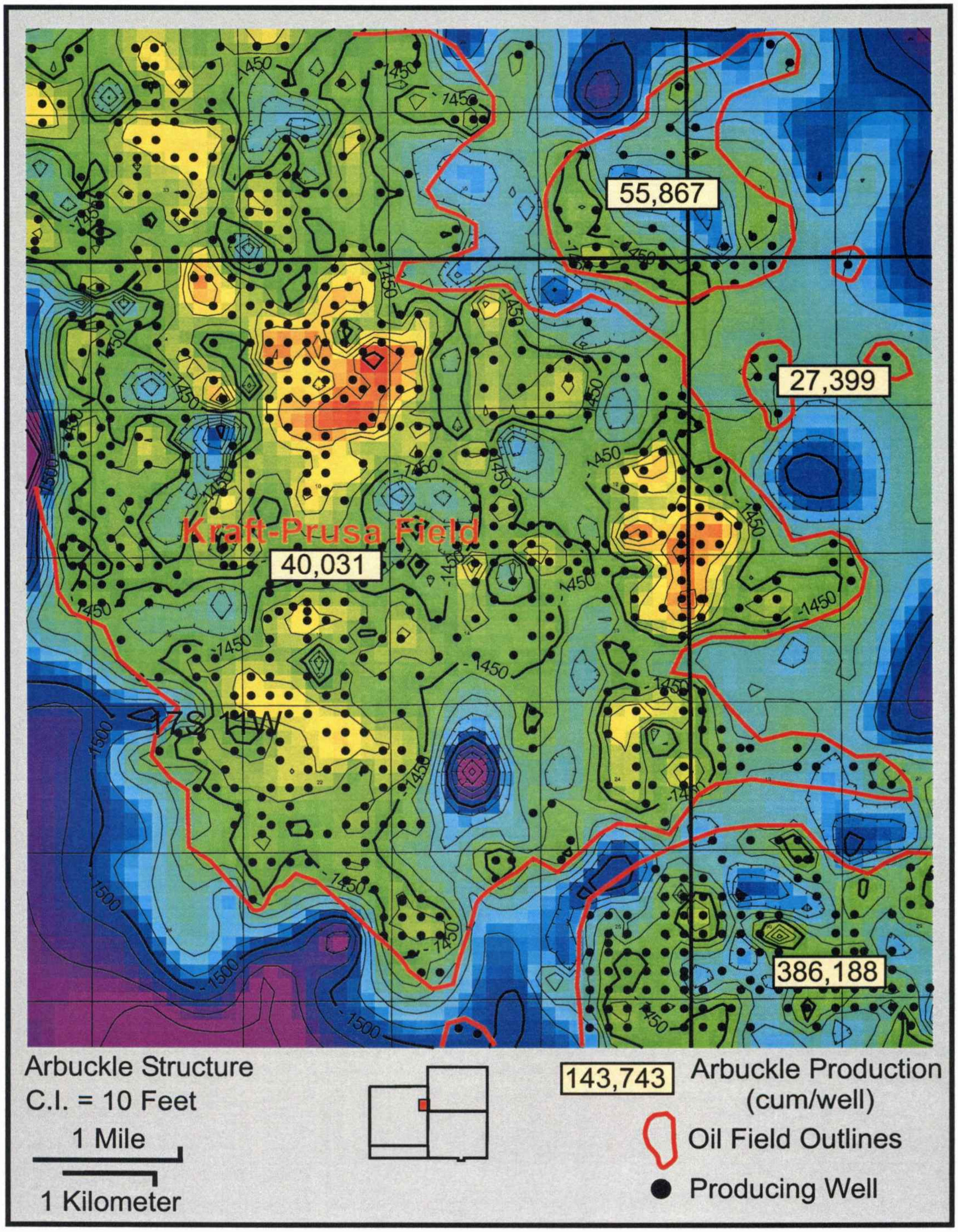

Figure 4.3: Arbuckle structure with oil field outlines and producing wells in T17S-R11W. The Kraft-Prusa Field is a very large reservoir developed over an area dominated by polygonal karst. In the field cumulative average recovery per well is just over 40,000 barrels of oil.

flat-topped feature with an average production of over 386,000 barrels of oil per well.

Initial analysis of drill stem test data from relatively recent (1960 - present) infill wells from the Kraft-Prusa and Chase-Silica fields highlight other production differences in the two types of geomorphic terrains. In general, infill wells located in areas dominated by polygonal karst (i.e. Kraft-Prusa) experienced relatively high final shut in pressures (1000-1200 psi). Infill wells located on sapped plateaus (Chase-Silica) were characterized by significantly lower final shut in pressures (250-750 psi). One possible explanation for this might relate to the stratigraphic controls on reservoir development. Ground water sapped plateaus are interpreted to have intra-formational shale layers or permeability barriers within the Arbuckle strata, responsible for directing ground water flow down-dip. The same ground water flow barriers could also be responsible for reducing vertical permeability and aquifer support. The permeability barriers reduce the influence of a strong bottom water drive. The cockpit terrains characteristic of Arbuckle reservoirs formed by vertical ground water movement show strong pressure support from a bottom water drive.

While intermediate examples exist, the average cumulative hydrocarbon recovery per well is significantly lower in Arbuckle reservoirs characterized by polygonal karst relative to Arbuckle reservoirs formed by ground-water sapping processes. Differences in reservoir performance can be attributed to numerous factors. Possible explanations include differences in lateral reservoir continuity at the megascopic scale relative to vertical continuity, as well as decreased lateral sweeping of hydrocarbons due to increased coning from a strong bottom water drive. Due to processes of formation, heavily karsted terrains might be expected to have less lateral drainage than the areas dominated by ground-water sapping processes.

The Central Kansas uplift is one of the most densely drilled provinces in the world, however additional targets may exist. Small undiscovered reservoirs, one to five wells, may exist in polygonal karst landscapes. Smaller features, such as residual hills in a cockpit terrain, may be best located with 3-D seismic imaging. Some of the interdoline areas that are local Arbuckle highs may contain commercial amounts of hydrocarbons. Independent oil and gas companies have had success to the north locating these small fields with 3-D seismic surveys (i.e. Ellis and Rooks counties). Some mature fields that are located on sapped plateaus may also hold bypassed oil. The down-dip, scalloped-side of these sapped features may have extensional opportunities that could be located and exploited. The cumulative per well oil recovery might be increased by application of horizontal drilling in Arbuckle reservoirs with low horizontal reservoir continuity. Deeper production may also exist within the Arbuckle. If competent permeability barriers from cave collapse exist at depth and reservoir quality strata can be located, additional hydrocarbon accumulations may be found. Additional targets may also exist deep within the Arbuckle section with reservoir development related to depositional and diagenetic controls rather than the standard karst and unconformity trap model (Franseen, 1995, 1999; and Stienhauff et al., 1998).

5. CONCLUSIONS

When examining the Sub-Pennsylvanian Arbuckle erosional surface it is necessary to determine if present day structure accurately represents paleotopography. Structure and interval isopach maps of the Arbuckle surface and several well defined horizons above the unconformity indicate that most of the southern Central Kansas uplift has not been significantly altered by Middle Pennsylvanian (Desmoinesian) or younger deformation. However, the Ellsworth Anticline, a subsidiary feature of the Central Kansas uplift, did experience some post-Desmoinesian deformation. The Ellsworth Anticline is a major structural feature at the Arbuckle horizon, but is devoid of Arbuckle petroleum production.

Two different erosional terrains were recognized on the Sub-Pennsylvanian surface. Karst landforms and extensive populations of dolines are widely distributed across the study area. Dolines varied in size and shape, but had a relatively consistent spatial pattern. Structural control and geomorphic competition was responsible for the regular distribution of the large primary dolines, and smaller secondary dolines that surrounded them. Consistent orientations and spatial pattern of these karst features (dolines) is attributed to a high degree of structural control. The dolines, when delimited on the basis of their topographic divides, form a cellular network termed polygonal karst. A broad class of Arbuckle reservoirs is confined to the interdoline highs of the polygonal karst.

The second group of geomorphic features recognized in the study area were the ground-water sapped plateaus and drainage systems. Ground-water sapping processes produced scalloped-shaped down-dip escarpments on the Arbuckle surface. The dip of the Arbuckle beds controlled direction of ground-water flow, which controlled sites where ground-water sapping processes are initiated and the up-dip direction of headward migration of valleys. Fluvial processes were essential to maintain effectiveness of ground-water sapping by removing talus.

Late Mississippian-Early Pennsylvanian deformation produced regional uplifts and many local horst and graben features that subsequently underwent varying degrees of erosion. Exposed plateaus were attacked by subaerial karst erosion as well as shaped by ground-water sapping processes. It appears that the Arbuckle surface on the Central Kansas uplift contains erosional surfaces at varying stages of maturity. At an early stage, these plateaus exhibit characteristics of ground-water sapping. Further erosion degrades these features into a multi-generational complex of dolines. At the mature stage the Arbuckle surface is completely pitted with dolines and the surface resembles a cockpit karst terrain.

Reservoir development associated with karst modification of the Sub-Pennsylvanian Arbuckle Group carbonates appears to depart from models developed for age-equivalent strata in West Texas. Karst development and reservoir compartmentalization in the Ellenburger of West Texas resulted from subaerial exposure induced from a pronounced drop in eustatic sea level (Kerans, 1988). The lack of tectonic induced fracture systems and structural dip in the Ellenburger Group encouraged extensive cave development in the massive carbonates. Collapse structures associated with cave development and karst modification in the Ellenburger produced lateral and vertical heterogeneity, which greatly influenced petroleum exploration and production strategies. However, Arbuckle exposure in Central Kansas resulted from regional Late Mississippian-Early Pennsylvanian deformation and uplift as well as an extended sea level low stand. Arbuckle carbonates contain an extensive system of joints and fractures, and horst and graben structures related to the Late Mississippian-Early Pennsylvanian deformation. Fracture pattern and intensity, and local structural dip controlled the location of some surface karst features, while development of extensive cave networks and associated collapse features were hindered in the Arbuckle strata.

Basement structure is variously reflected on the Sub-Pennsylvanian Arbuckle surface. In some areas, local Arbuckle highs correspond to basement structures, but in other areas basement trends are disguised by Arbuckle paleotopography. However, regional northwest-southeast and northeast-southwest structural trends are apparent at both the Arbuckle and basement horizons. The structural trends appear to have a strong influence on the orientation, intensity and style of erosional features on the Arbuckle erosional surface. It is possible to gain an understanding of local dip direction and structural trends within the Arbuckle by the geometry and expression of karst and sapped landforms on the erosional surface.

Petroleum production has been on the decline in this area for decades, however opportunities exist to increase reserves through discovery of small interdoline reservoirs, extension of existing reservoirs and infill drilling. Understanding the nature of the erosional surface can help guide seismic interpretations and horizontal drilling when looking for local Arbuckle highs and residual hills in an interdoline setting. Some larger fields may contain bypassed oil on down-dip scalloped sides of ground-water sapped Arbuckle plateaus.

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