UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

GEOLOGIC STUDY OF THE KARSTED ARBUCKLE BROWN ZONE AND ITS RELATION TO PETROLEUM PRODUCTION IN THE HEALDTON FIELD, CARTER COUNTY, OKLAHOMA

A THESIS

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ABSTRACT

The Arbuckle Group has a gross thickness in excess of 10,000 feet in the southern Oklahoma aulacogen . The Healdton field, located within the southern Oklahoma aulacogen, has produced over 12 million barrels of oil from the upper Arbuckle. Cumulative production records attribute approximately 95% of all Arbuckle production within the Healdton field to the Brown zone. The thesis problem is to determine why the Brown zone is the most prolific hydrocarbon producer within an 8,000 to 10,000 foot carbonate section and how to explore for areas with similar reservoir development.

The Brown zone in the Healdton field underwent extensive replacement dolomitization, while the overlying Wade and Bray zones retained their original limestone depositional fabric. A stratigraphic variation exists between the Healdton field and the Shell Chase #1-28 well, approximately 2 miles to the north. The stratigraphic equivalent of the Brown zone in the Chase well is a black carbonate mud, indicating it was deposited in a deeper and quieter water environment than that of the Healdton field. An isopach thinning was found over the Healdton field between the top of the Bray and the top of the Brown zone, indicating paleotopography played an important role in the development of the initial facies, and subsequent dolomitization.

The Brown zone has major karst development, but the Wade and Bray do not. No karst was observed in the stratigraphic equivalent of the Brown zone in the Shell Chase well either. Karst development is closely tied to dolomitization. The Brown

zone had opportunities for both meteoric and deep burial karst development. Some studies cite lack of faunal evidence in support of a pre-Simpson shallow burial karst, however geochemical studies cite evidence of higher temperatures indicating deep burial karst. Baroque dolomite, usually an indicator of hydrothermal fluids, was found throughout the Brown zone core examined in this study. Combined evidence suggest that the majority of the karst development in the Brown zone occurred during deep burial and exposure to basinal fluids.

The sequence of events for the development of the Brown zone dolomite are proposed as follows: (1) replacement dolomitization soon after deposition, (2) subsidence and exposure to basinal fluids, (3) deep burial karst development, (4) uplift of the Healdton field structure in the Morrowan, (5) collapse of dolomitic karsted reservoir, (6) subsequent deposition of pore rimming baroque dolomite, and (7) hydrocarbon migration.

Dolomitization is the key to Arbuckle reservoir development. It served as the conduit for all subsequent diagenetic fluids. Dolomitization also serves to significantly increase the fracture potential, thereby increasing the fracture network during tectonic movement.

Geologic Study of the Karsted Arbuckle Brown Zone and Its Relation to Petroleum Production in the Healdton Field, Carter County, Oklahoma

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Chapter I Introduction

The aims of this study were to (1) provide insight into the reservoir development of the upper Arbuckle Brown zone and (2) based upon a megascopic study of the Healdton field, test techniques to predict reservoir development of the upper Arbuckle Brown zone in prospective areas. These aims were accomplished by (1) distinguishing the prolific Brown zone from the rest of the upper Arbuckle Group, (Wade and Bray zones, Figure 1, Gatewood 1978), through the study of lithology by whole core examination, (2) determining what elements were necessary to facilitate the development of the Brown zone's porosity and permeability (such as paleotopography and facies development), (3) determining the significance of the timing of the porosity and karst development from related studies, and (4) the comparison of the reservoirs and trapping mechanisms in other fields in Oklahoma. This study also provides a methodology for interpreting karst development from core data, relating well log response to karst breccias, evaluating multiple mechanisms for karst development, and for comparing the prolific Brown zone to the overlying limestone members with respect to karst development and fracturing.

A. Definitions of Karst

The past few years have been replete with articles pertaining to karst development in the Mid-Continent (Read and Richmond, 1993, Waddell, Forgotson, and Liu, 1993, Matthews and Al Shaieb, 1993, Lynch 1990, Mescher, Schultz, et al 1993, Kerans, 1989, Carpenter and Evans, 1993). In a recent discussion of karst development in the

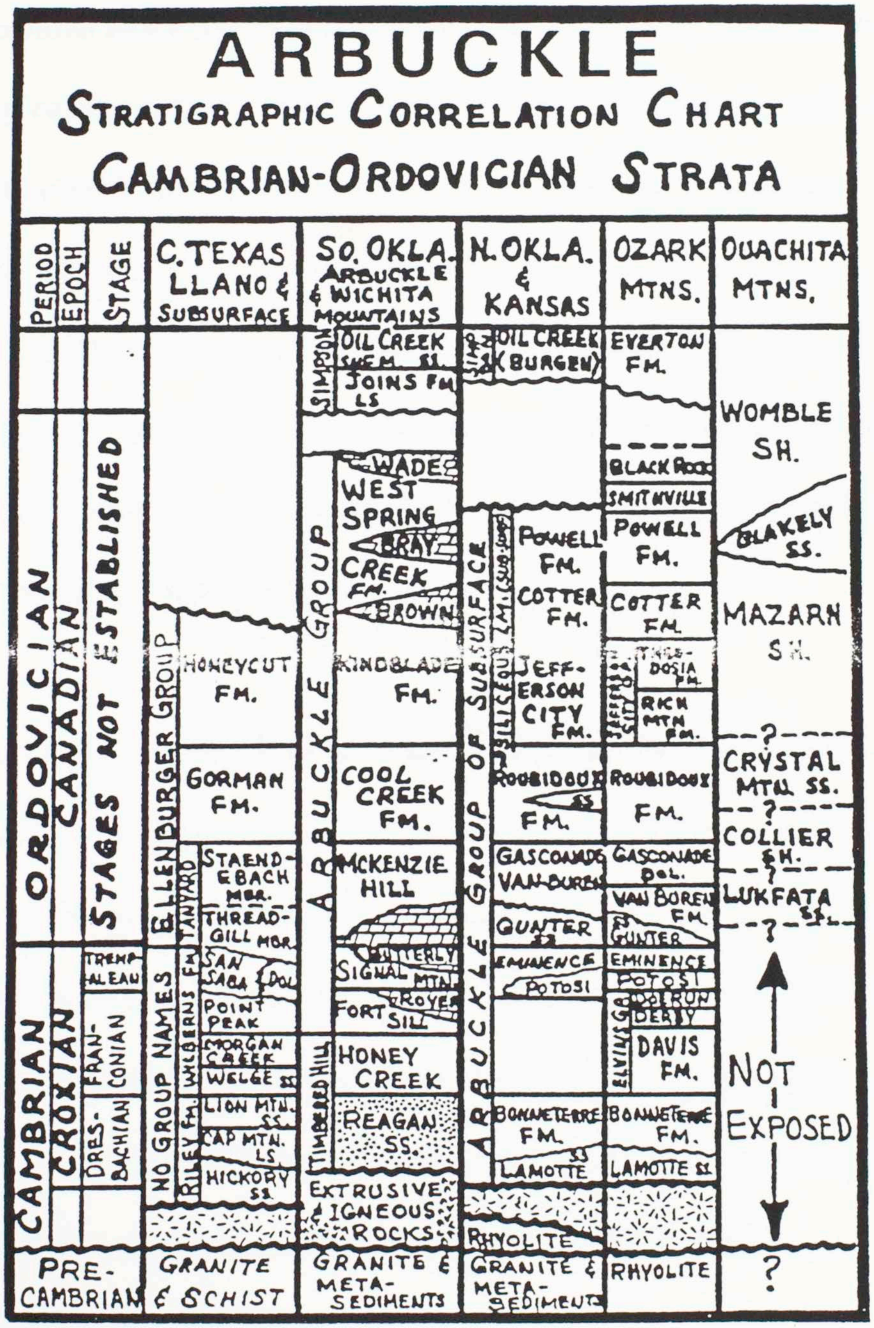


Figure 1. Stratigraphic Column of Southern Oklahoma, (Gatewood, 1978).

Mid-Continent, many perspectives have been taken on how the term karst is actually applied. Esteban and Klappa (1983) define karst as "***a diagenetic facies, an overprint in subaerially exposed carbonate bodies, produced and controlled by dissolution and migration of calcium carbonate in meteoric waters, occurring in a wide variety and climatic and tectonic settings, and generating a recognizable landscape".*** Others encompass the term karst to include not only near surface dissolution by meteoric waters, but that of hydrothermal fluids, also. Dzulynski (1976) defines hydrothermal karst as "***a system of caverns produced by hot waters of any origin and the associated deformational and mineralogical features that are consequent upon the passage of aggressive hydrothermal solutions***".

In a similar study of dolostones on Baffin Island Nova Scotia, Ford (1982,1981) proposed both types of dissolution to have occurred over a period of time within the same rock unit. The lithology, time period, and structural setting were similar to that of the Brown Zone deposited in the Southern Oklahoma Aulacogen. Therefore, this study will distinguish **subaerially exposed carbonates or near surface dissolution** as "***meteoric karst***", and **deep burial dissolution due to basinal fluids leaching rocks within the subsurface at temperatures higher than recognized surface temperatures** as "***hydrothermal karst***".

B. Methods of Study

Over 2000 feet of core and 150 thin sections from four wells were provided by the **ARCO Research Center** in Plano, Texas. An additional 500 feet of core was logged at the **Oklahoma Geological Survey Core and Sample Library** in Norman, Oklahoma. Stratigraphic sections from the cores in the Healdton field that were examined included the Wade, Bray, and Brown zones, and the upper Cool Creek Formation. Thin sections made from surface samples obtained from the **Dolese Overbrook Quarry** were examined. Cross sections were constructed to show the vertical and lateral distribution of dolomite in the upper Arbuckle. Lithologic logs were plotted next to geophysical logs to determine recognizable karst features. The sum of these components were considered in relating petroleum production to pore type, fracturing, and the timing of tectonic and karst events.

C. Previous Studies of Upper Arbuckle Strata and the Healdton Field Area

Billy Kirk Reed (1957) described the geology below the Pre-Atokan unconformity in Carter and Love Counties. This milestone study roughly mapped the structure of both the Healdton field (Figure 2), three years before the true Brown Zone development began in the Healdton Field in 1960, and the Cottonwood Creek field, thirty years before its discovery in 1987 (Read and Richmond, 1993). Reed's work will be discussed in detail in later chapters. Reed foresaw the need for further Arbuckle exploration in his thesis area.

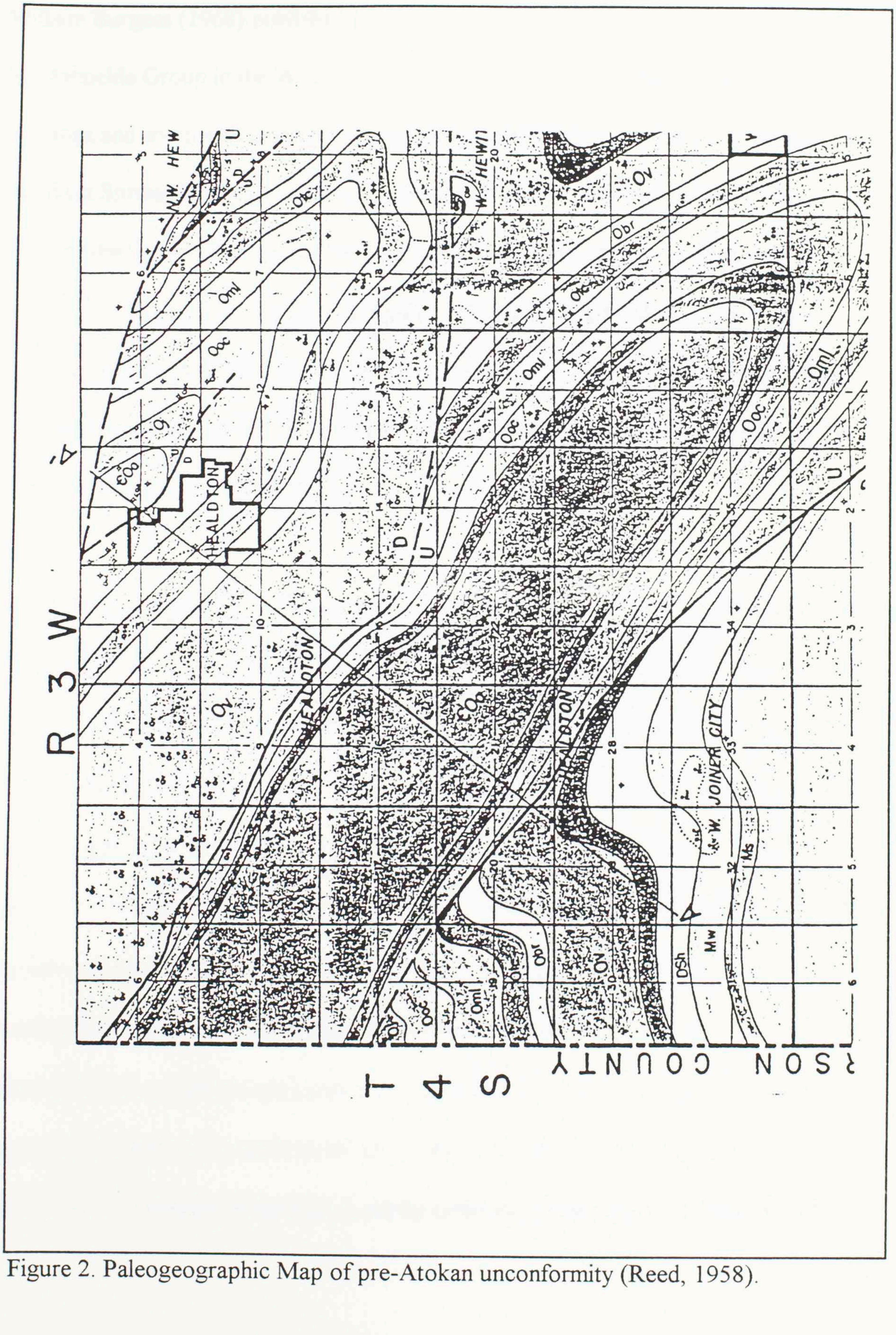


Figure 2. Paleogeographic Map of pre-Atokan unconformity (Reed, 1958).

William Burgess (1968) published his doctorate on "Carbonate Paleoenvironments in the Arbuckle Group in the West Spring Creek". In this broad study he examined outcrops and some well cuttings to determine the paleo-depositional environments of the West Spring Creek in southern Oklahoma (Figure 3). Burgess identified the orthochemical, allochemical, and terrigenous rocks and diagenetic style for each area sampled. He mapped the above components using percentage maps. Through his mapping Burgess identified four general environments: lagoonal, supratidal, intertidal and subtidal (1968). The West Spring Creek in the Healdton area is interpreted to be in the supratidal complex (Figure 3).

The first paper discussing in detail Arbuckle production from the Brown Zone in the Healdton Field was Jack Latham's (1968) description of production from the Wade, Bray, and the Brown Zones. Latham was the well site and exploration geologist for the majority of the Arbuckle wells drilled in the Healdton field by the Sinclair Oil and Gas Company. He described production from the Wade and Bray zones as being secondary to that of the primary Arbuckle reservoir, the Brown Zone dolomite which he interpreted as a thick porous dolomite in his "upper Kindblade". The trapping mechanism for the field is a pre-Pennsylvanian anticlinal fold with 1500 feet of closure in a northwest-southeast trend limited to the north by a major down-to-the-north normal fault, and to the south by an up- to-the-south reverse fault (Latham 1968, Figure 4). The interior of the field is cut by numerous small faults, dividing the field

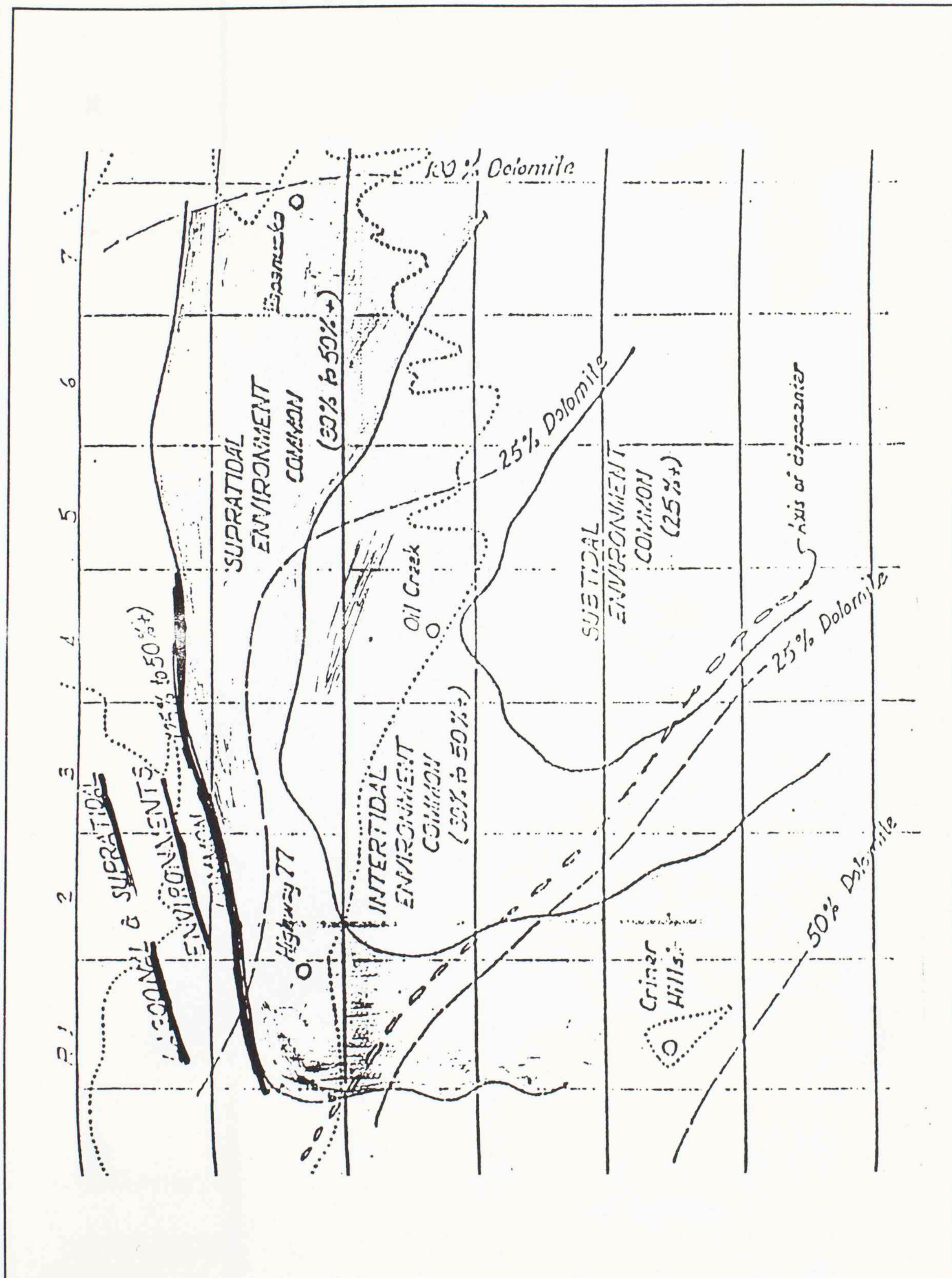


Figure 3. Paleoenvironmental and Dolomitic Percentage Map of the West Spring Creek, T1S-T6S, R1W-R7E (Burgess, 1968).

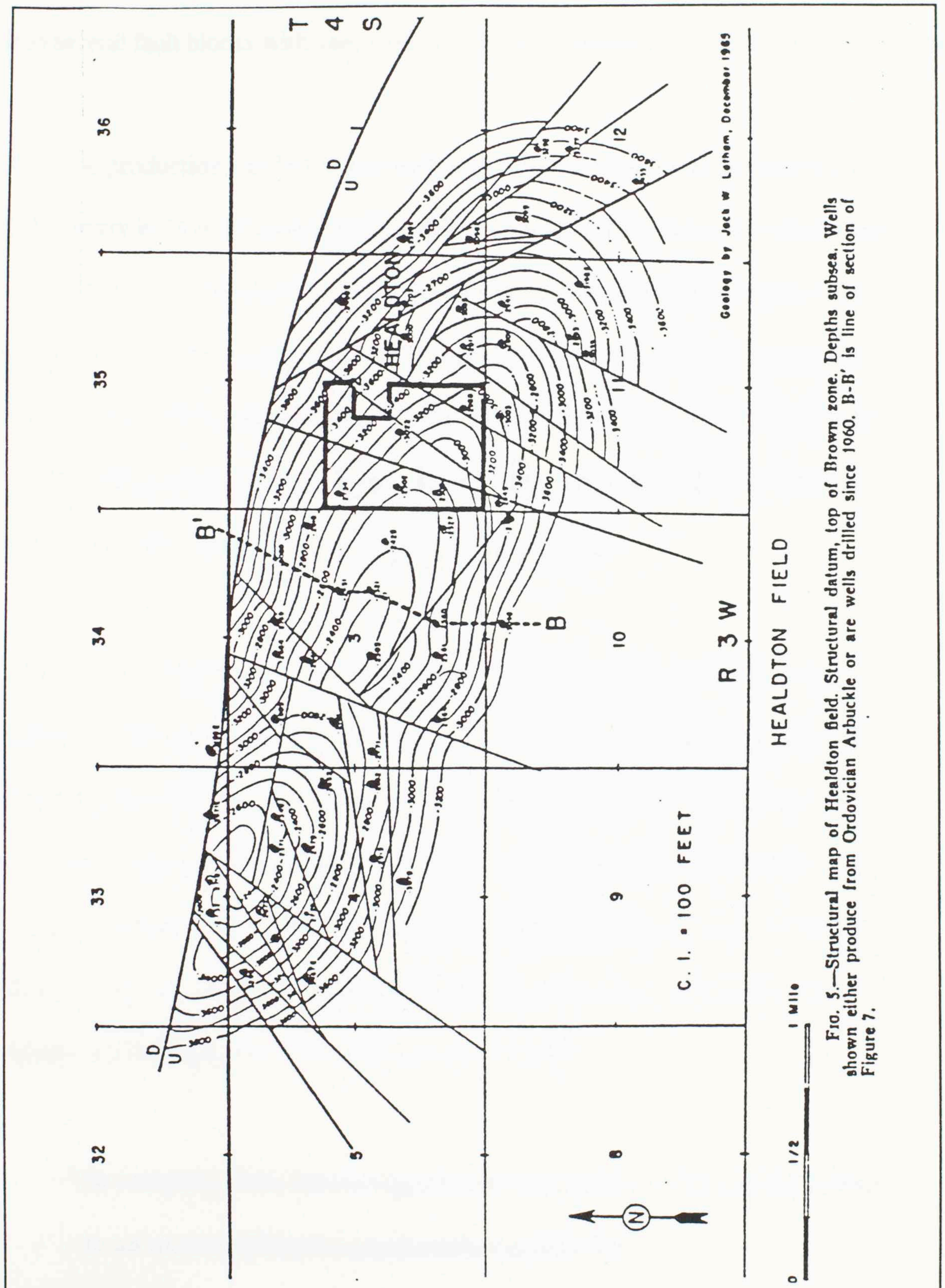


Figure 4. Structural Map of the top of the Brown zone in the Healdton Field, T4S-R3W, Carter County, Oklahoma. (Latham, 1968)

into several fault blocks with one common oil-water contact in the Arbuckle Brown Zone.

Arbuckle production was first discovered in the West Spring Creek by the Pure Oil #31 Lowery in 1924. Three additional wells were drilled but it was not until the late 1950's (Latham, 1968) that renewed interest lead to subsequent drilling. The Wade and Bray zones were productive from low permeability and generally poor quality reservoirs. In 1960, the Myrtle Brown well was completed flowing **336 BOPD** and **150 MCF/D** on a 12/64 choke from a thick porous dolomite. Latham named the Brown Zone after the lease on which this well was drilled.

Latham (1968) described the West Spring Creek (Wade and Bray Zones) as two dolomite zones, separated by more massive homogenous limestones, and theorized the dolomitization to be of a surface origin, due to the shallow water depositional environment. He records the upper 500-600 feet of the Brown Zone as fine to coarsely crystalline dolomite with well formed rhombs commonly found and porosity types that include vuggy, intergranular, cavernous, pinpoint, and fracture. Latham describes the intensity of the "fracturing" of the dolomite by stating:

> **"So complete is the fracturing that the rock bears a striking resemblance to an unconsolidated intra-formational breccia."**

This statement is important as it is perhaps the first observation in the Healdton Field of chaotic breccias caused by karst development. Latham observed many bit drops during the drilling of the Brown Zone in the Healdton Field (pers com, 1991). He also states the rocks above and below the Brown Zone are much less fractured and of poorer reservoir quality.

Goldhammer and Elmore (1983) described tempestites (storm deposits) in the Kindblade Formation in the Arbuckle Mountains. They recorded two types of tempestites occurring in crude cycles: proximal and distal, in which the distal deposits are overlain by the proximal and ooid grainstones. Their work will be discussed in detail in Chapter II.

Chris Tenney (1984 MS thesis) described the depositional facies and environment of the Kindblade Formation in the Arbuckle Mountain outcrops. Tenney identified 7 facies in the Kindblade: (A) sponge algal boundstone to wackestone, (B)wackestone with grain supported lenses, (C) lithoclastic grainstone to packstone,(D) wavy bedded mudstone, (E) flat pebble conglomerate (F) oolitic grainstone, and (TR) a truncated erosional surface (Figure 5). Tenney interpreted the formation as a series of normal shallow water sedimentation and storm deposits, as did Goldhammer and Elmore.

Transition from the subtidal lower Kindblade to the primarily upper intertidal upper Kindblade is interpreted by Tenney as (1) transgression after deposition of the Cool Creek followed by (2) regression during upper Kindblade time. Tenney constructed a Facies Relationship Diagram (FRD) for probability of these facies occurring at random

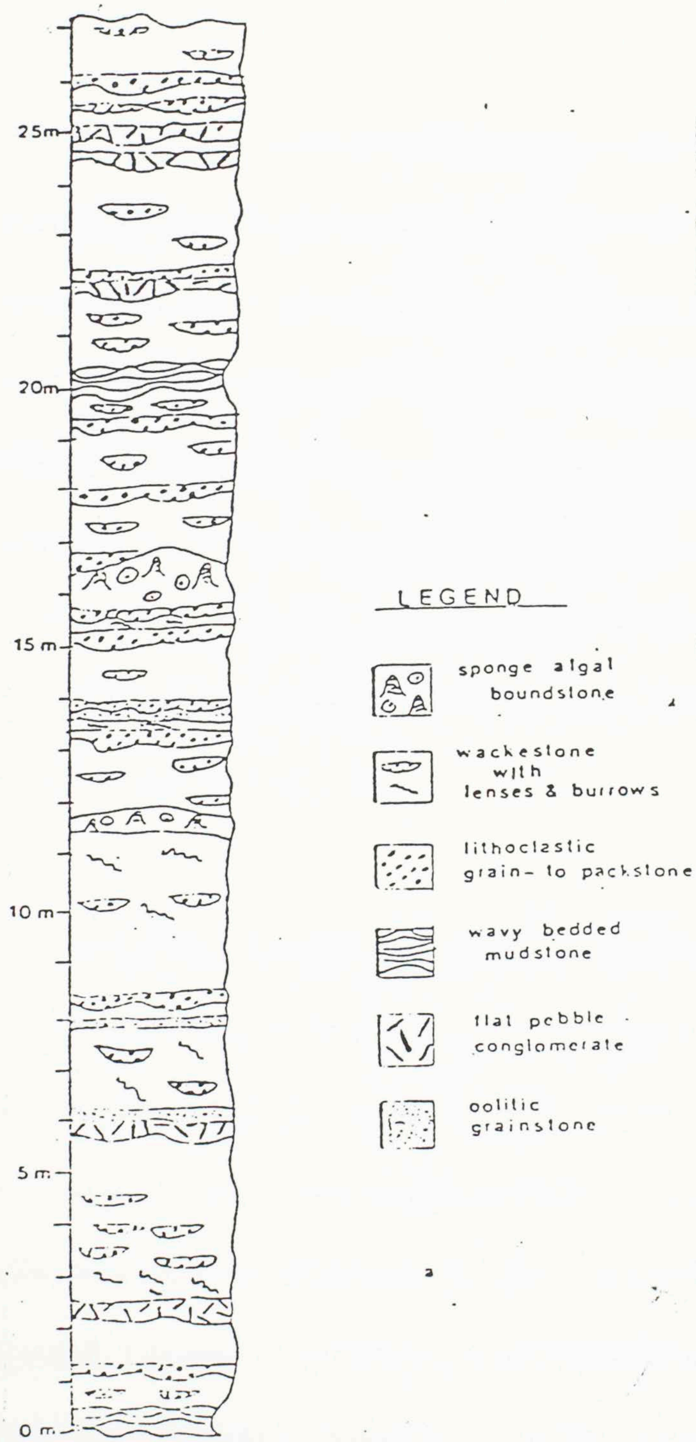
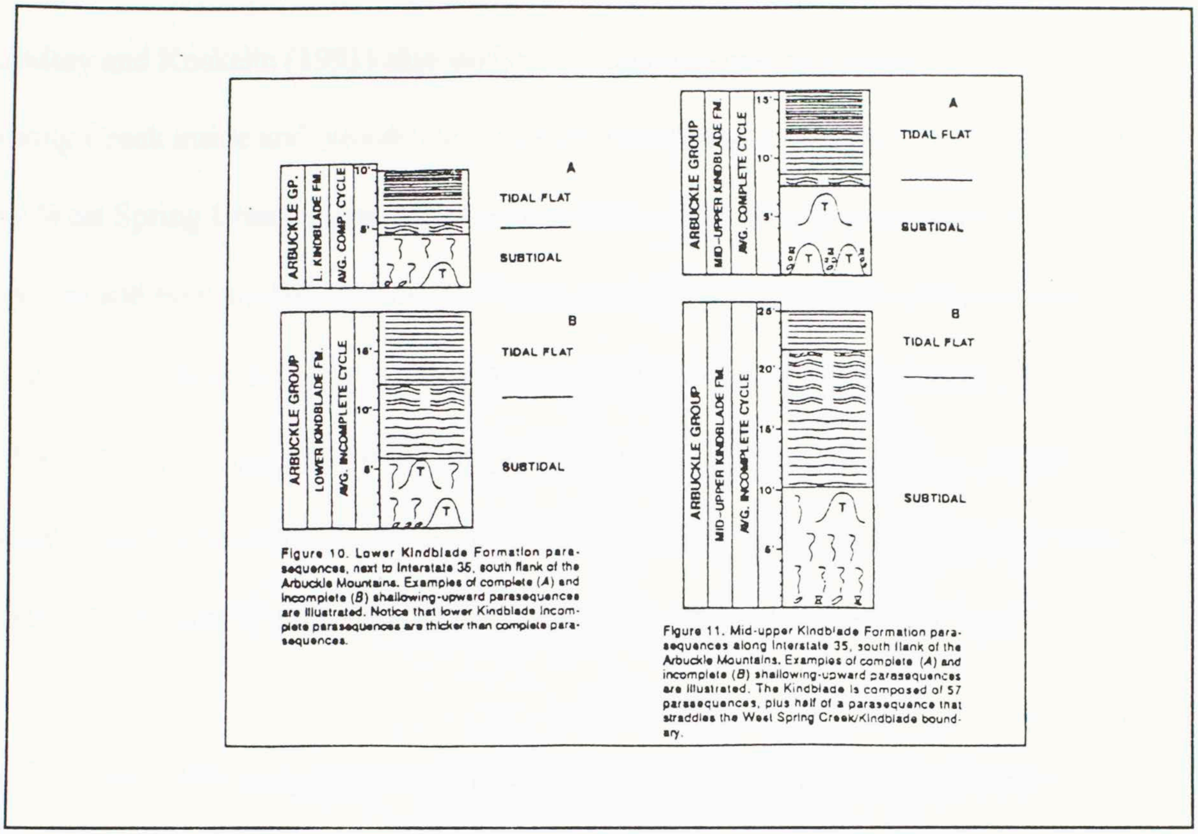


Figure 5. Lithologic Facies of the Kindblade. (Tenney, 1984)

versus an expected sequence. He interpreted his results as statistically significant, thus documenting the abundant, fining upward storm deposits in the upper Kindblade.

Charles Kerans (1989) related the effects of karst development to reservoir quality and heterogeneity in the Ellenburger (Arbuckle equivalent) in West Texas. His study shows the relationship of karst breccias to porosity, permeability, electric log signatures, paleocave reconstruction and petroleum production. The Healdton study in this thesis uses terminology based upon Kerans study and attempts to relate petroleum production to karst development in the Healdton field in a similar manner. However, a major difference in the two environments is that no recognizable unconformities are found in the upper Arbuckle in the Healdton area (Fay, 1989). Kerans' work will be referenced in greater detail in Chapters IV and VI.

Lindsay and Koskelin (1991) studied the Kindblade along I-35 on the south flank of the Arbuckle Mountains. They divided the Kindblade into lower and upper-middle sections. One of the main purposes of their study of the Kindblade was to compare complete and incomplete sequences found in the shallow marine facies (Lindsay and Koskelin 1991). Incomplete sequences contained more near shore and shoreline facies than complete sequences which contained more tidal flat and embayment facies (Figure 6). Overall, they characterize the Kindblade as deposited in a shallow marine, shallowing upward environment.



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(Lindsey and Koskelin, 1991)

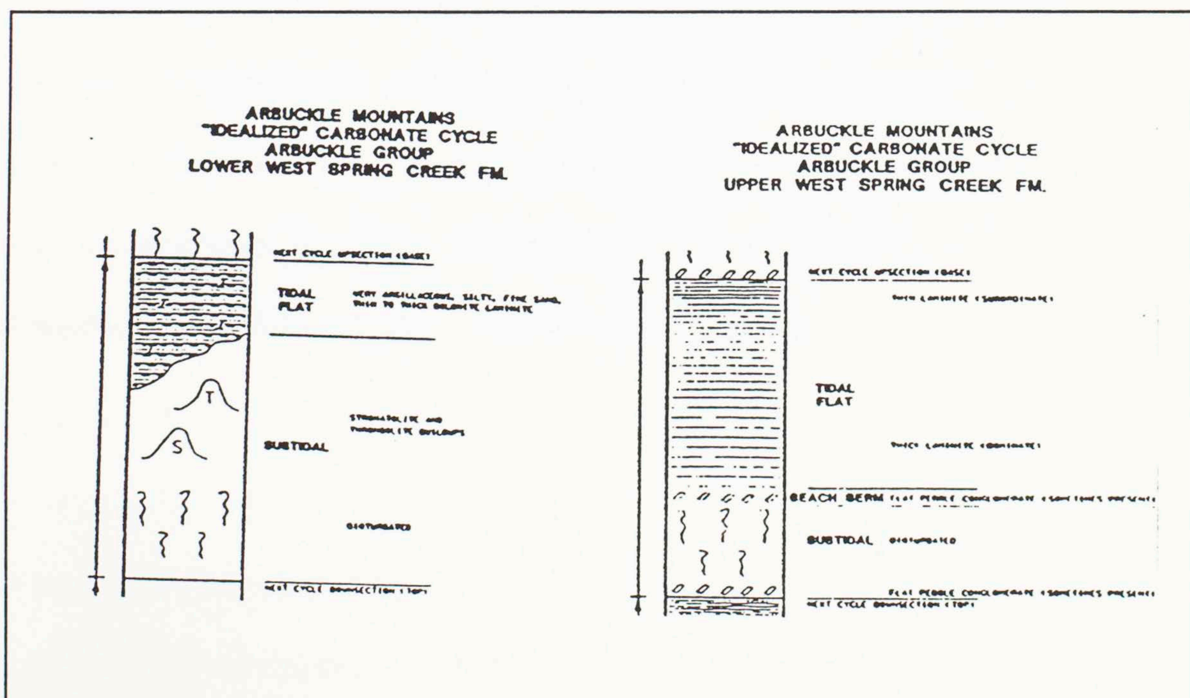

Figure 7. Cycles in the lower and upper West Spring Creek.
(Lindsey and Koskelin, 1991)

Lindsay and Koskelin (1991) also studied the depositional environments in the West Spring Creek inside and outside the Southern Oklahoma Aulacogen. They interpreted the West Spring Creek to contain fourth and fifth order depositional cycles based on outcrop and core studies (Figure 7). These cycles were correlated to Milankovitch cycles produced by a change in the tilt of the Earth's axis every 40,000 years (Milankovitch, 1941). This cyclic tilting of the earth's axis is theorized to control glacial eustasy, the rise and fall of relative sea level. Dolomitization of the West Spring Creek on local paleotopographic highs could have been related to these cycles.

Mark Lynch (1990) recorded an inventory of paleokarstic features from selected cores throughout the State of Oklahoma. He described the petrology of paleokarst features and presented a model for the genesis, diagenesis and timing of certain Arbuckle reservoirs. Lynch examined two cores from the Healdton field, one of which was examined by this author. Lynch's study, which provides the most petrographic detail of cores with karst development in the Arbuckle throughout Oklahoma, will be discussed in Chapter 5, Karst Development of the Arbuckle Brown Zone.

Chapter II Paleogeography and Depositional Environments

A. Regional Paleogeography

During the deposition of the Arbuckle, the North American paleo-continent was between the latitudes of approximately twenty degrees north and thirty degrees south (Ross, 1976, Figure 8). This lies within the same tropical latitudes where modern carbonate deposition is occurring today (Bathhurst, 1975). An isopach map of the Cambro-Ordovician strata over the North American paleo-continent shows thicknesses ranging from 1000 to 3000 feet, except for the Southern Oklahoma Aulacogen (Ross 1976, Figure 9) where Arbuckle sediments are more than 8000 feet thick. Ross (1976) interprets the West Texas Ellenburger as a restricted shelf carbonate, and the Arbuckle in the Southern Oklahoma Aulacogen as an open shelf carbonate (Figure 10).

B. Depositional Environments

1. West Spring Creek Formation

Burgess (1968) identified the West Spring Creek as having four general environments: (1) lagoonal, (2) lagoonal-supratidal complex, (3) intertidal, and (4) subtidal (Figure 3). He stated that the Arbuckle Mountain area was a shallow water regime and that all environments were near shore. His percentage maps showed that the Healdton area was probably in the supratidal-lagoonal complex. The West Spring Creek has also

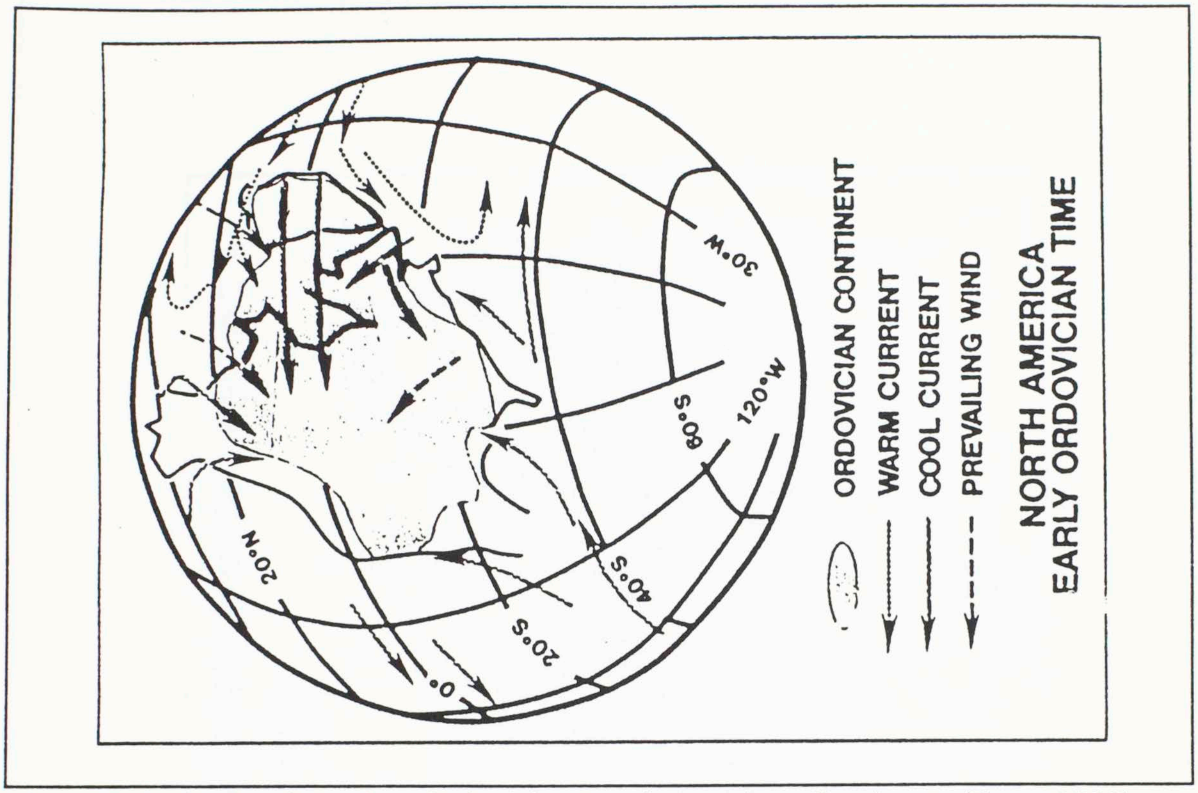

Figure 8. Latitude of Cambro-Ordovician North American Continent. (Ross, 1982)

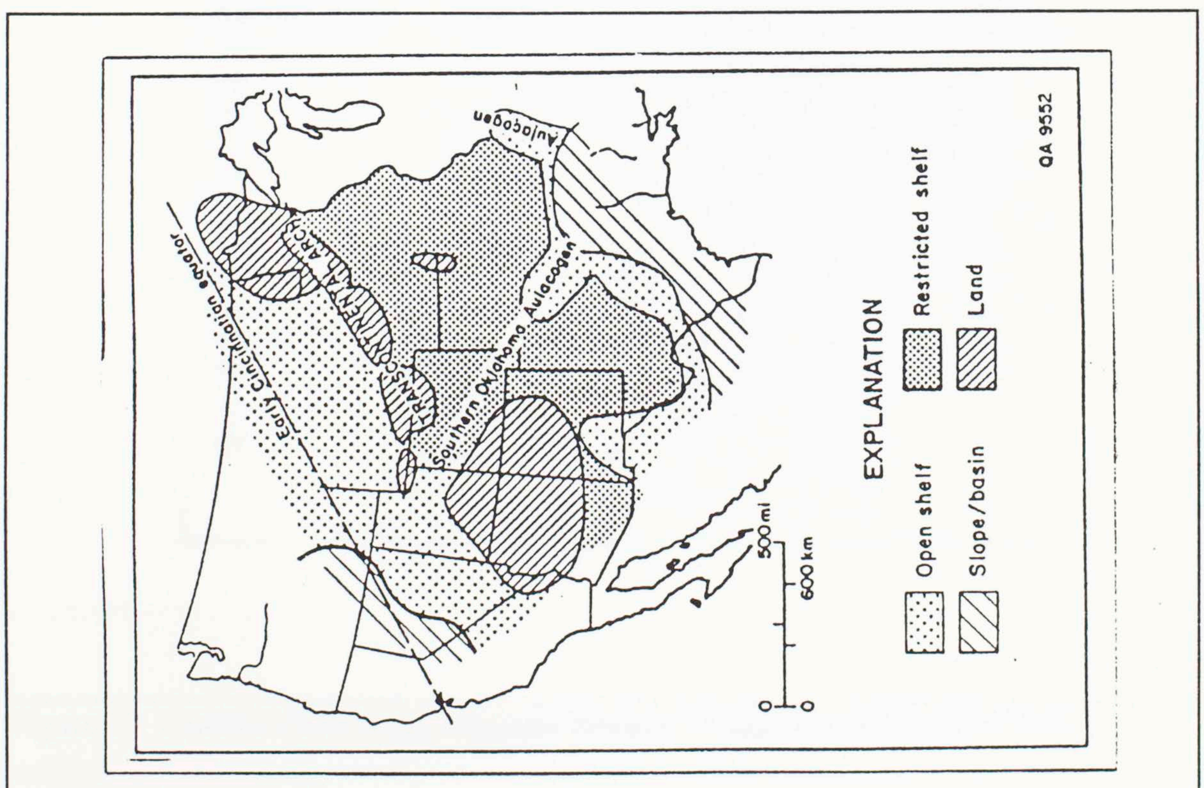

Figure 9. Cambro-Ordovician Facies Distribution. (Ross, 1982)

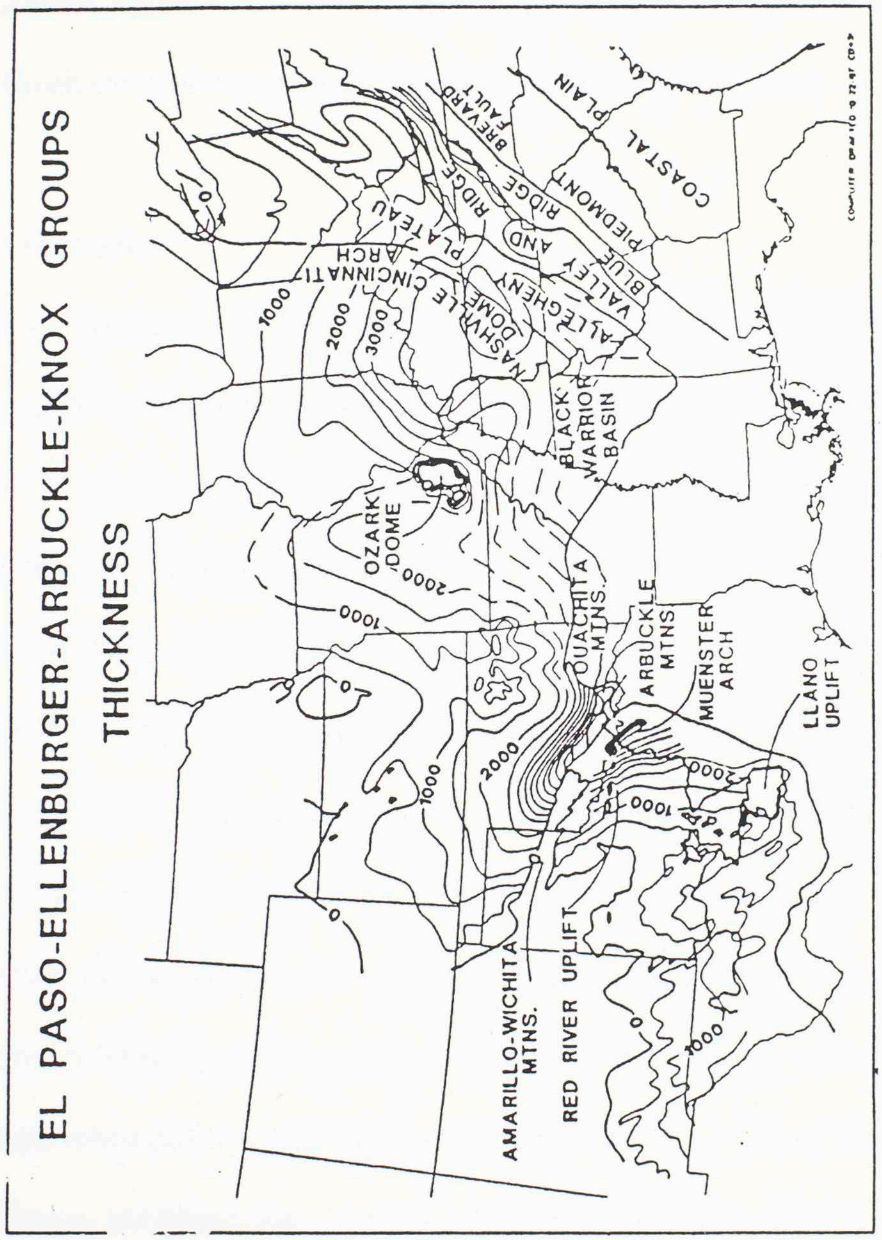

Figure 10. Cambro-Ordovician Regional Isopach. (Lindsey and Koskelin, 1991)

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been described by Fay (1989) and Lindsay and Koskelin (1991). Lindsay and Koskelin's (1991) divided the West Spring Creek into subtidal and tidal flat facies. The Southern Oklahoma Aulacogen is dominated by shallow marine sediments in the lower West Spring Creek and tidal flat deposits in the upper West Spring Creek.

2. Kindblade Formation

Goldhammer and Elmore (1983) described the Kindblade Formation as a shallow marine epicontinental carbonate sequence containing numerous storm deposits (more than most other Arbuckle Formations). Both proximal and distal storm deposits are recorded with distal deposits being more abundant in number and aggregate thickness. **Distal deposits** are **fining upward sequences that overlie an eroded hardground or firmground**. The distal sequence grades upward from a lag lithoclastic grainstone through a laminated peloidal grainstone and into a mudstone. The lithoclasts at the base of the sequence are bored, well rounded, discoid in shape, and consist of mudstone, peloidal packstone, and an oolitic grainstone. Cement-filled shelter voids occur within the lithoclastic grainstone. The peloidal grainstone contain ripple cross laminations, plane laminations, and hummocky cross stratification. The mudstone is sparsely fossiliferous and bioturbated with burrows that are either dolomitized or infilled with lithoclastic grainstone.

Proximal deposits are interbedded coarse lithoclastic flat pebble conglomerates and ooid grainstones that overlie mudstones. These two types of deposits occur in crude cycles in which the distal deposits are overlain by proximal tempestites and ooid grainstones. Goldhammer and Elmore's (1983) interpretation is a shallowing upward progradational sequence. From their survey, abundant tempestites (one every 7.75 inches) indicate that hundreds of storm induced events occurred in the Kindblade Formation.

In summary, the ***depositional environment below*** and ***equivalent to*** the ***Brown Zone*** (lower West Spring Creek, Fay, 1989) is composed of ***an epicontinental shallow marine shallowing upward carbonate sequence***. The upper Kindblade has been described by Tenney (1984) and Goldhammer and Elmore (1983) to be composed of an upper intertidal shallowing upward progradational sequence with numerous recurring tempestites (storm deposits). Lindsay and Koskelin (1991) have similarly described the lower West Spring Creek in the Southern Oklahoma Aulacogen as being deposited as a shallowing upward shallow marine sequence composed of crude and often abrupt cycles with a dominant subtidal component in the lower portion of the sequence, and a tidal flat facies in the upper portion of the sequence.

Chapter III Criner Hills Overbrook Quarry: A Surface Analog to the Brown Zone Reservoir in the Healdton Field

A. Surface Study of the Dolese Overbrook Quarry

The Dolese Overbrook Quarry is located in the Criner Hills, T5S-R1W. Huaibo Liu, Kelvin Cates, and the author examined different aspects of the quarry. Cates sampled the quarry for a paleomagnetic investigation, Liu examined the quarry for a related co-authored paper pertaining to the original depositional environments, and I recorded the physical aspects of the karsted portion of the quarry.

The Overbrook Quarry has been mapped as West Spring Creek-Kindblade undifferentiated (Frederickson 1957, Figure 11). The West Spring Creek in this area was interpreted by Burgess (1968) to have been deposited in a supratidal or lagoonal-supratidal complex. He further describes it as a diagenetic terrain that is highly susceptible to dolomitization with anhydrite and algal stromatolite structures. The limestone portion of the quarry is mined for aggregate; the dolomite is not mined owing to its inability to pass the necessary freeze-thaw tests. A large cave is reported to have been found in the more dolomitic area of the quarry but was subsequently destroyed by mining. However, cave entrances still exist in the quarry today, although talus is piled against them to prevent entrance and potential accidents inside the caves.

B. Paleomagnetic Study

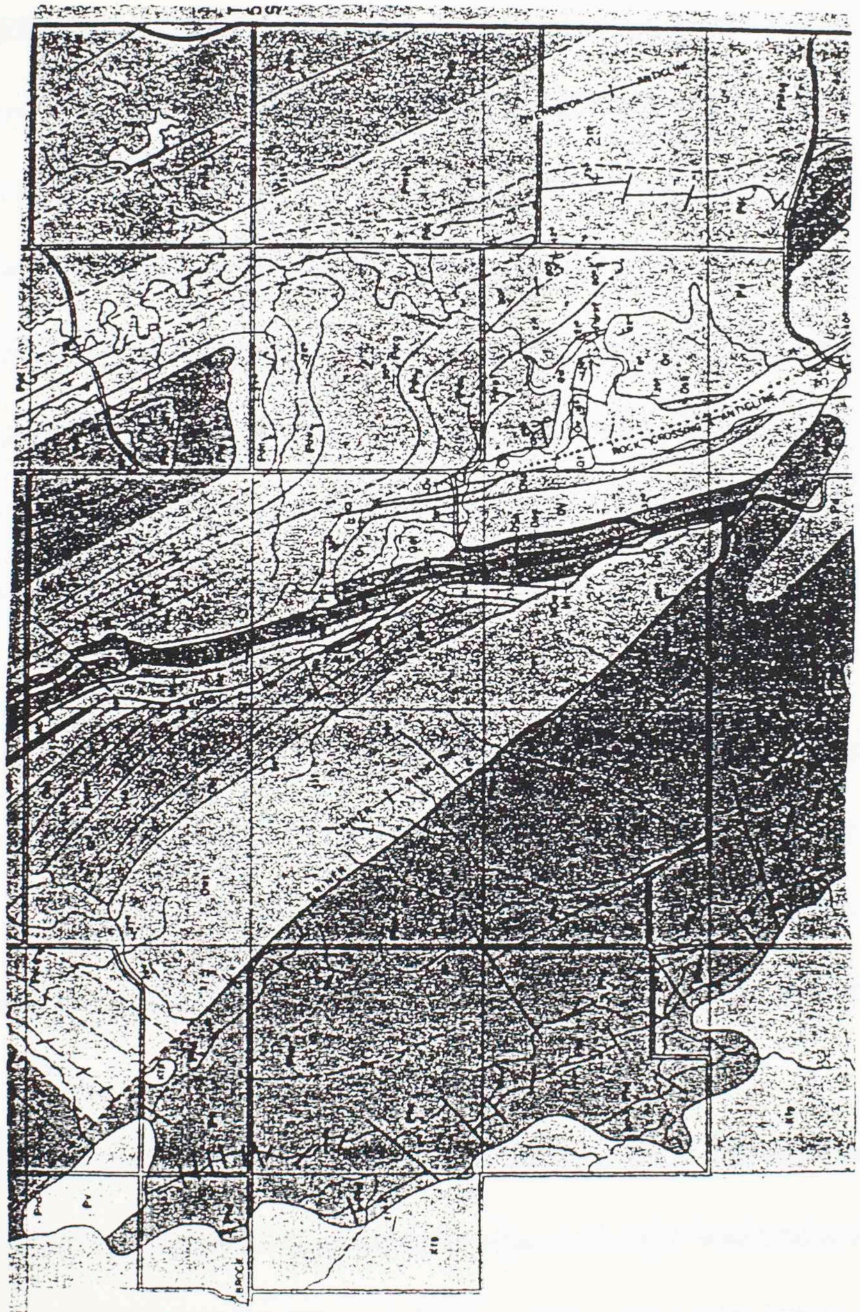


Figure 11. Geologic Map of the Dolese Overbrook Quarry, T5S-R1W, Carter County, Oklahoma. (Frederickson, 1957)

Crackle, mosaic, and chaotic breccias occur in descending succession along the cliff walls in the more dolomitic portion of the quarry (Figure 12a,b,c,d). These breccia have been related to paleocave reconstruction by Kerans (1989) in his work on the West Texas Ellenburger. The crackle breccia is related to the upper cave roof, the mosaic breccia related to the lower cave roof and cave floor, and the chaotic breccia related to the infill of cavern void space (Kerans, 1989). [More detail is given on this subject in Chapter 8, Karst Development of the upper Arbuckle Brown Zone]. In the area where the chaotic breccias were found intact with internal fill (Figure 13), core plugs were taken for thin section examination and paleomagnetic readings. An attempt was made to use paleomagnetic data to interpret the age of the karst development in the Overbrook Quarry.

Magnetite was not found in the samples at the Overbrook Quarry. The magnetic mineral (possibly goethite) found in the samples had a CRT below 200 degrees Fahrenheit, and would not provide a reliable measurement of the paleomagnetic direction at the time the mineral was precipitated. Therefore, results were inconclusive.

The age of karst development in the upper Arbuckle Kindblade was determined by Elmore and Crawford (1989) from speleothems that contained alternating layers of calcite and magnetite. These samples of Arbuckle speleothems were taken from Bally Quarry north of the Wichita Mountains.

Figure 12(a). Fracture or Crackle Breccia in the West Spring Creek-Kindblade undifferentiated from the Dolese Overbrook Quarry, T5S-R1E, Carter and Love Counties, Oklahoma. (Scale approximately 3.5' x 4' wide)

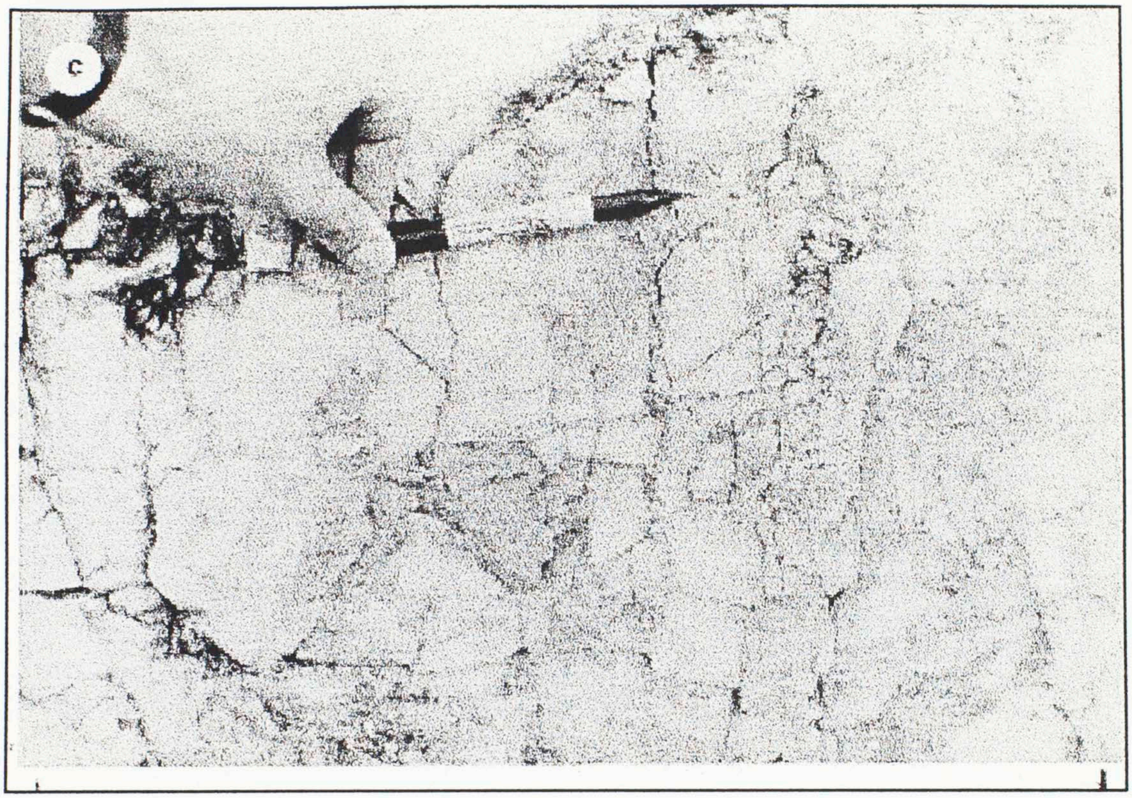


Figure 12(b). Mosaic Breccia in the West Spring Creek-Kindblade undifferentiated from the Dolese Overbrook Quarry, T5S-R1E, Carter and Love Counties, Oklahoma.

Figure 12(c). Cavernous opening in the West Spring Creek-Kindblade undifferentiated from the Dolese Overbrook Quarry, T5S-R1E, Carter and Love Counties, Oklahoma. (Cavern opening approximately 2-1/2' x 3' wide)

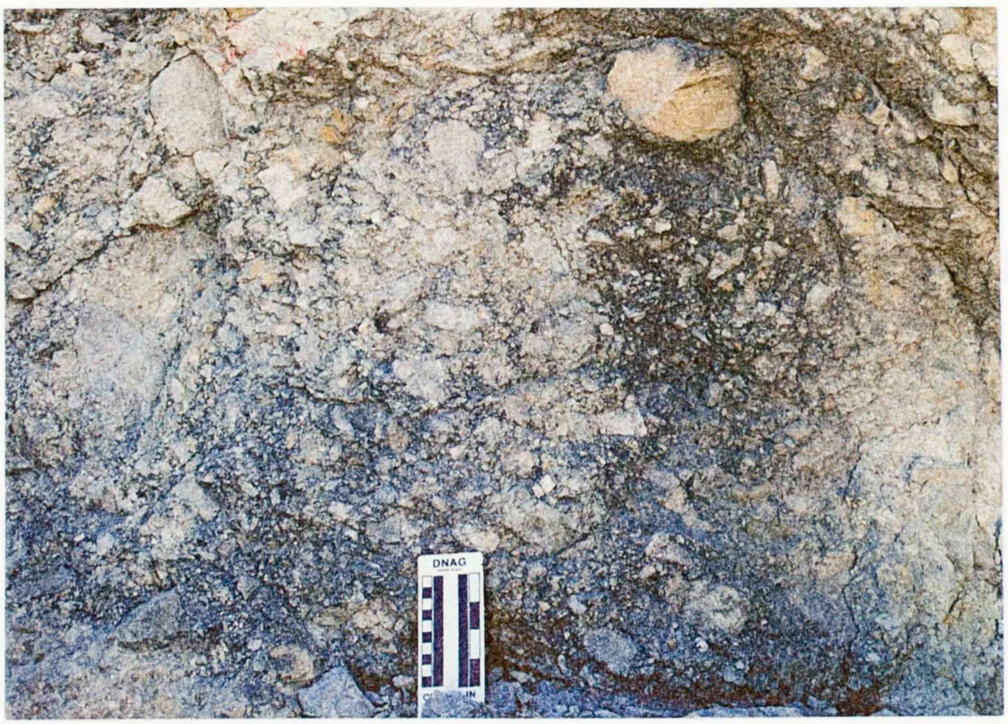


Figure 13. Chaotic Breccia infill in the West Spring Creek-Kindblade undifferentiated, from the Dolese Overbrook Quarry, T5S-R1E, Carter and Love Counties, Oklahoma.

The orientation of the earth's magnetic field varies through geologic time (polar wandering, Irving and Irving, 1982). The orientation of the earth's magnetic field was preserved in authigenic magnetite at the time of magnetite precipitation on the speleothems (Elmore and Crawford, 1989). The magnetite in the Bally Quarry has a sufficiently high CRT (critical roughening temperature) to preserve the paleomagnetic direction at the time of magnetite precipitation. Elmore and Crawford's (1989) interpretation that karst development was younger than Late Pennsylvanian (Figure 14) was confirmed by the finding of Permian vertebrates at the same site. This technique could be applied to the Arbuckle Brown zone if samples are retrieved that possess a sufficiently high CRT.

C. The Overbrook Quarry as an Aquifer

The area where the quarry is located was also used as a water supply for the adjacent Brock oil field. Shallow subsurface waters from the West Spring Creek-Kindblade undifferentiated formations in the Overbrook Quarry area were collected from the natural springs and runoffs and used for the adjacent Brock oil field waterflood (Robert O. Fay, pers com 1991). This observation is interpreted to indicate that an extensive aquifer exists today in the same area that had initial karst development millions of years ago. It also shows the susceptibility of this lithologic unit to karst development.

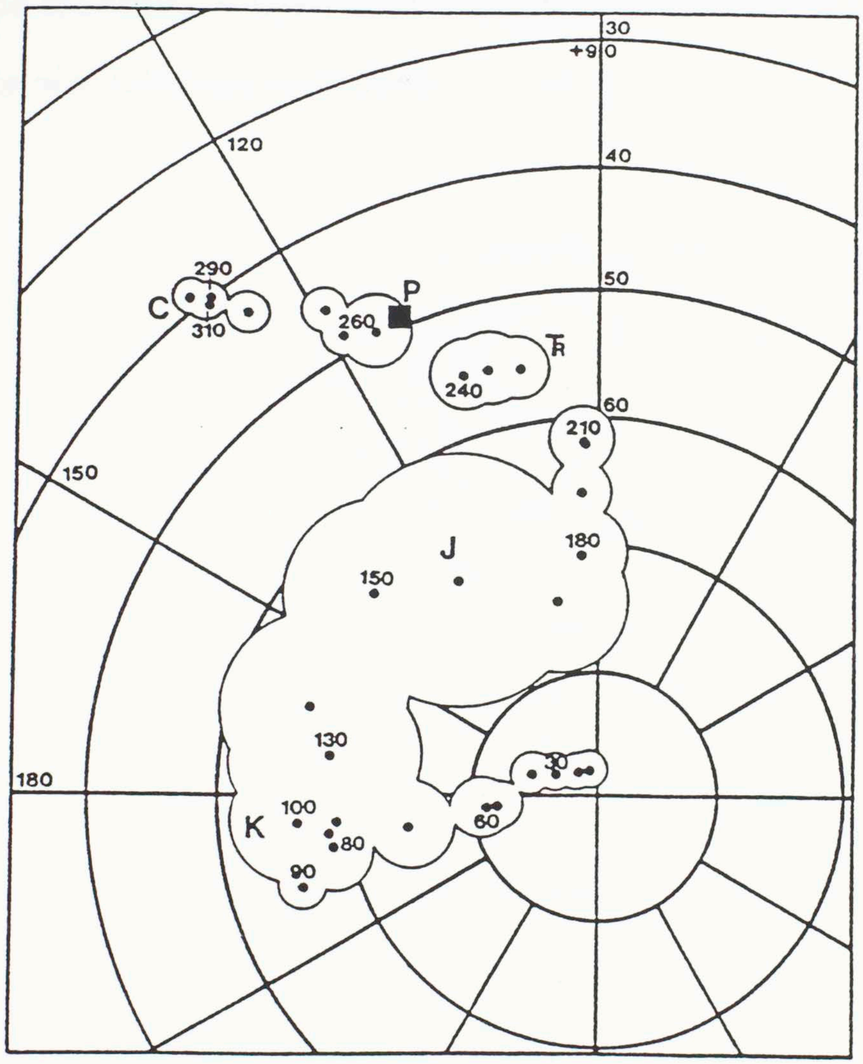


Fig. 5. Apparent Polar Wander Path (APWP) for stable North America [after Irving and Irving, 1982] with the apparent pole position (square) for the dark speleothems. The pole position suggests acquisition of remanence in the Permian. Circles around the 10-Ma poles of the APWP correspond to the standard errors.

Figure 14. Apparent Polar Wander Path (APWP) corresponding to formation of dark speleothems during the Permian. (Elmore and Crawford, 1990).

The Arbuckle anticline in the Overbrook Quarry is breached at the West Spring Creek-Kindblade level, similar to the structure of Cottonwood Creek. Observations of this surface model of a karsted Arbuckle reservoir provides a powerful analog for the interpretation of its subsurface counterparts.

Chapter IV Lithologic Descriptions and Depositional Facies Based on Core Examination

A. Core Study of the Upper Arbuckle in the Healdton Field

The Healdton Field, located in T4S-R3W, Carter County, (Plate I) , Oklahoma produces oil from the karsted Arbuckle Brown Zone reservoir. Cores were examined from the Wade, Bray, and Brown zones of the lower Ordovician upper Arbuckle from four wells in the Healdton Field (denoted by arrows on Plate 1). Thin sections were also examined to observe the relationship between pore size, porosity type, and petroleum production. The Brown zone, which is considered the stratigraphic equivalent of the lower West Spring Creek (Fay 1989), is the most prolific Arbuckle reservoir in the Healdton field. The Brown zone has produced a conservative estimate of 85-90% of the total oil from the upper Arbuckle in the Healdton field.

Dolomitization and karst development are the two major attributes that distinguish the reservoir quality in the Brown zone from the Wade and Bray zones. The Brown zone contains crackle, mosaic, and chaotic breccias and related porosity types (fracture, cavernous, vugular, and breccia) in addition to dolomitic porosity. In contrast, the cores examined in the Wade and Bray zones exhibit predominantly original depositional fabric with comparatively little diagenetic alteration. Although the Wade and the Bray zones produce from local porous zones, and some thin karst-like breccias in the Healdton field, their cumulative production is relatively minor compared to the Brown zone.

B. The Wade Zone

The Wade Zone core was taken from the Voorhees #1, in T4S-R3W Section 1. The Wade Zone is upper West Spring Creek (the upper most formation of the Arbuckle Group) and was deposited in a shallow water environment (Burgess 1968, Lindsay and Koskelin, 1991). Six dominant lithofacies were observed in the Wade zone from the Voorhees #1, in T4S-R3W, Section 1, and are described in Table 1:

Table 1. Lithofacies of theWade Zone

Lithofacies	Description
A	gray/green thinly laminated limestone mud with small fractures, some soft sediment deformation, caliche, some medium bedded lime mudstone layers
B	gray, thinly laminated dolomudstone containing sparse anhydrite nodules/concretions (locally interbedded with mottled mudstones)
C	light tan/brown mottled dolomicrite and lime mudstones
D	(2"-4") blue white anhydrite nodules
E	thin bedded fossil grainstones, packstones (mostly crinoids, ooids)
F	flat pebble conglomerates

These lithofacies are comparable to the depositional facies defined by Lindsay and Koskelin (1991). They divided the upper West Spring Creek into three depositional facies: tidal flat (thick and thin laminated mudstones), beach berm (flat pebble conglomerates), and bioturbated subtidal (mottled muds). Burgess (1963) had similarly defined facies as subtidal, intertidal, and supratidal.

The Wade zone in the Voorhees well primarily consisted of lime mudstones and dolomudstones exhibiting primary depositional fabric (Figure 15). Karst development does not occur in the Wade zone except for some possible microkarst.

C. Bray Zone Core Descriptions

1. **J.C. Voorhees, Section 1, 4S-3W, Carter County, OK**

The Bray zone core from the J.C. Voorhees well was predominantly lime mudstone and dolomudstone. It also contained possible algal laminates and stromatolites, karst breccias, and more abundant occurrences of flat pebble conglomerates than the Wade Zone (Figure 16). The karst development in the Bray Zone from the Voorhees core is interpreted to be minor compared to that examined in Brown zone cores, and local occurrences are attributed to proximity to younger fault cuts seen in the core (although not all karst development is seen in proximity of the faults within the core).

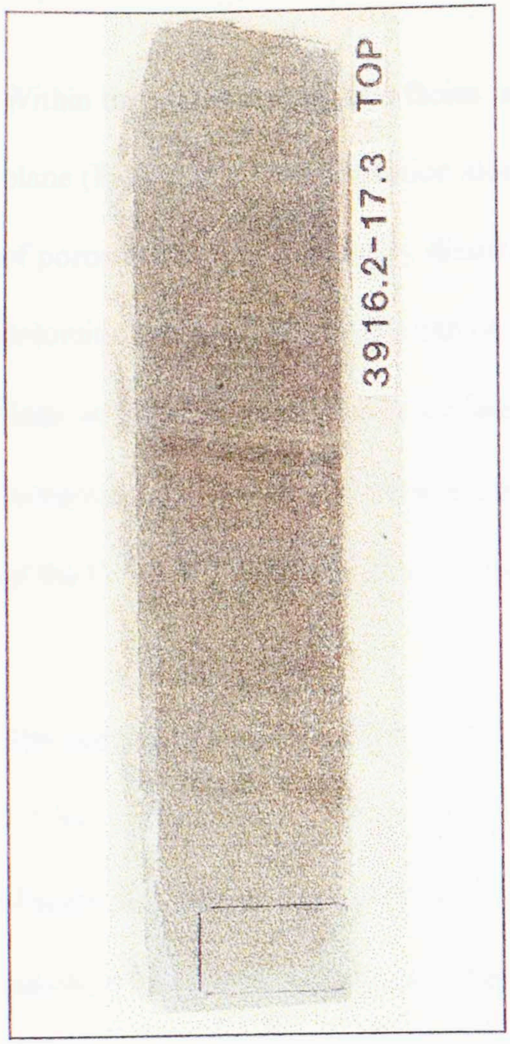
2. Geneva Bray #1, Section 2, 4S-3W, Carter County, OK

Greater than 99% of the rocks within the Bray Zone exhibited original depositional fabric. The Bray zone is composed of limestone muds with some dolomudstones, thin bedded grainstone/packstones, stromatolites and flat pebble conglomerates. Table 2 contains the major facies observed in the Bray Zone in the Geneva Bray well:

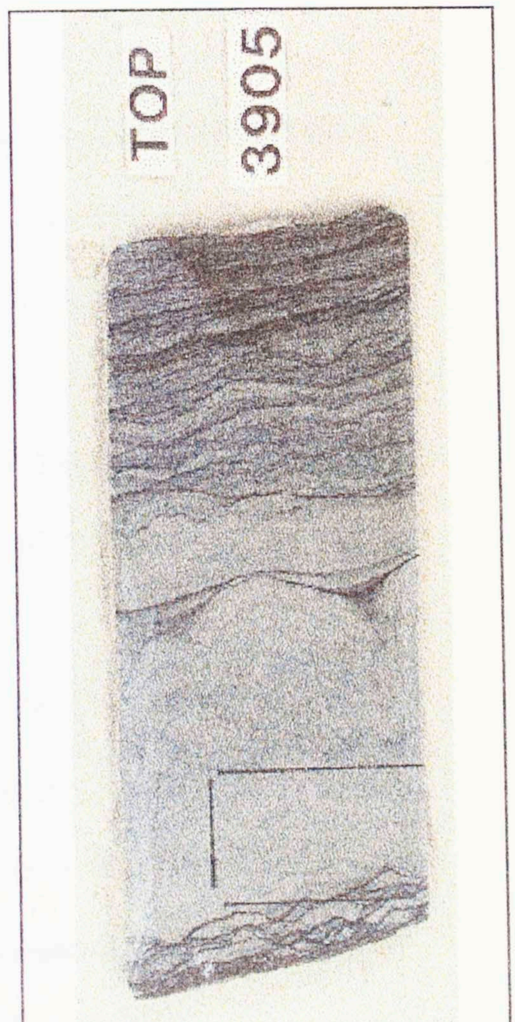
Table 2. Lithofacies of the Bray Zone

Lithofacies	Description
A	dark gray to green, brown to light tan, mottled limestone muds, bioturbated, few chert nodules
B	thin bedded fossiliferous packstone and grainstones, ooids, trilobites, and gastropod fragments
C	gray to dark gray green, thin to medium thick bedded laminated limestone and dolomudstones
D	gray green algal stromatolites (boundstones), dolomitic, stylolites
E	flat pebble conglomerates

Like the Wade, the Bray Zone is also composed of shallow water carbonate deposits (Figure 17). However, the Bray Zone contains more laminated and mottled mudstones than the Wade Zone, possibly due to a deeper and lower energy environment. Lindsay and Koskelin (1991) also found greater subtidal influence in the lower West Spring Creek than in the upper West Spring Creek.



Tan to grey laminated mudstone. Depostional fabric and texture are primarily intact.



Grey stromatolite interbedded between thin dark mudstone layers.

Figure 17. Lithofacies of the Geneva Bray core, T4S-R3W, Section 2, Carter County, Oklahoma. ***(Core courtesy of ARCO Research Center).***

Within the algal stromatolites facies, stylolites develop roughly parallel to the bedding plane (Figure 18). Dolomitization along the stylolites can develop porosity. This type of porosity can be enhanced by dissolution. Examples of stylolites with similar dolomitic and karst diagenesis can be seen in a similar lithofacies found in the Brown Zone in the HAU #5-3 (discussed later in this chapter). Olson (1984) has also recognized a close relation between stromatolites and karst development in his study of the Cambro-Ordovician strata in Baffin Island (Figure19).

The only significant indication of karst development is found between 3797.0-3798.5, 1.5 feet of karst lithology out of approximately 500 feet of core from the Bray Zone (Figure 20). The author has interpreted this type of karst as a solution pipe, lacking the sequence of crackle, mosaic, and chaotic breccias. The pipe walls are intact without significant fracturing. The interior resembles a pipe that has been dissolved out of the rock, with chaotic breccia and karst fill sediments re-deposited.

The interval of the Bray zone that produces in the Geneva Bray (3430-3530) well was not available for examination. The (3430-3530) interval shows a higher SP response and could indicate a different lithology than the examined core (Figure 21). The Geneva Bray's IP was 190 BOPD and 250 MCF/D. The cumulative production from this zone in the Bray well was 102,447 BO. The Brown zone was wet.

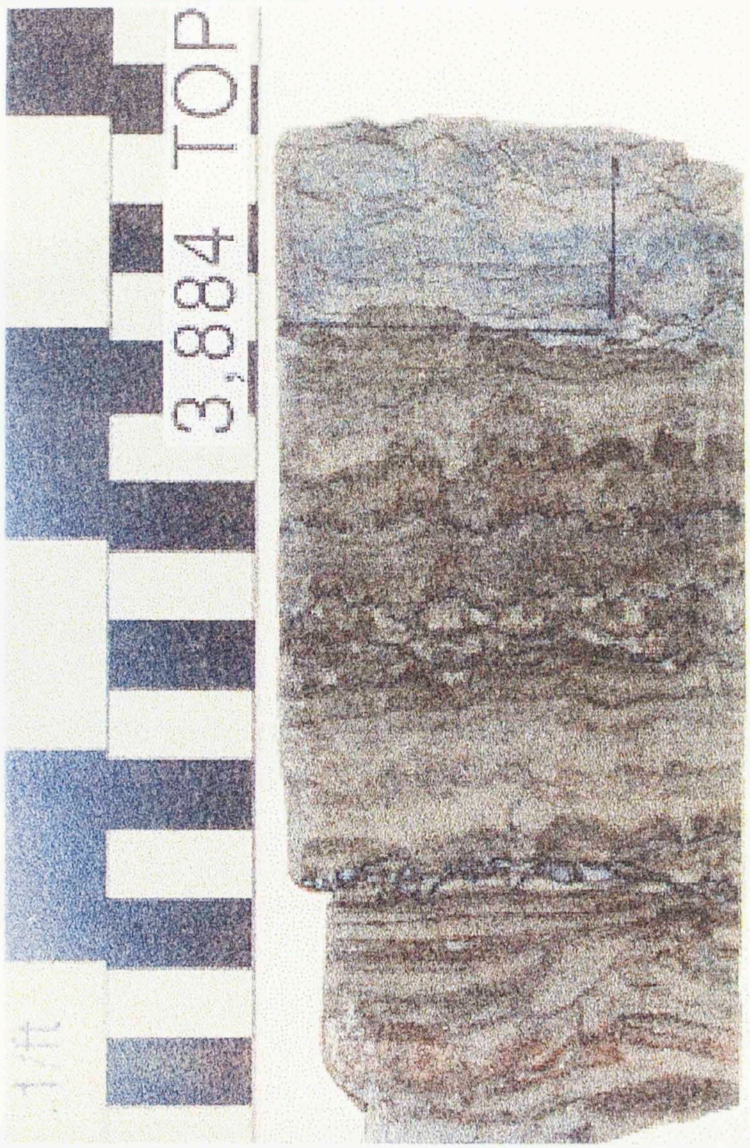


Figure 18. Stylolite Development along the Bedding Plane of Algal Stromatolites, from Bray zone, Geneva Bray core, T4S-R3W, Section 2, Carter County, Oklahoma . ***(Core courtesy of ARCO Research Center)***

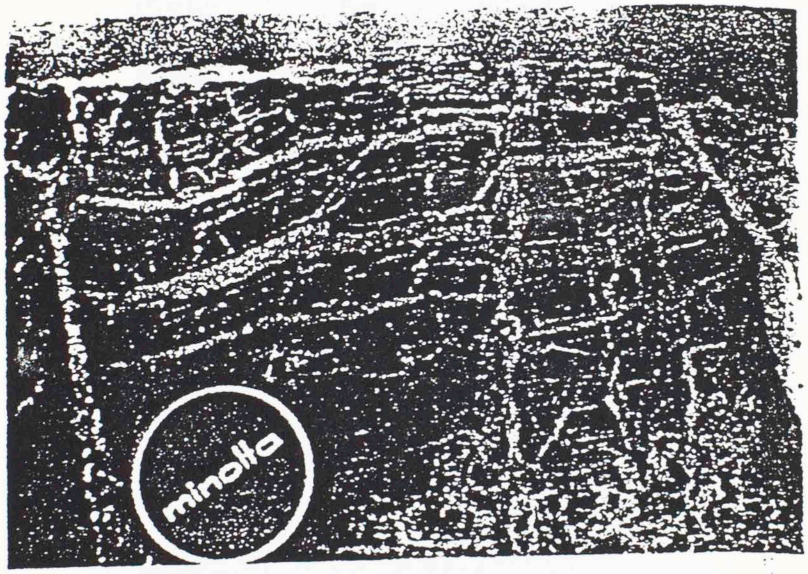


FIG. 3. Regularly laminated algal dolostone interbedded with dololutite in the Society Cliffs Formation; modified by crackle breccia and sparry dolomite veining.

Figure 19. Regularly laminated algal dolostone interbedded with with dololutite in the Society Cliffs Formation; modified by crackle breccia and sparry dolomite veining. (Olson, 1984)

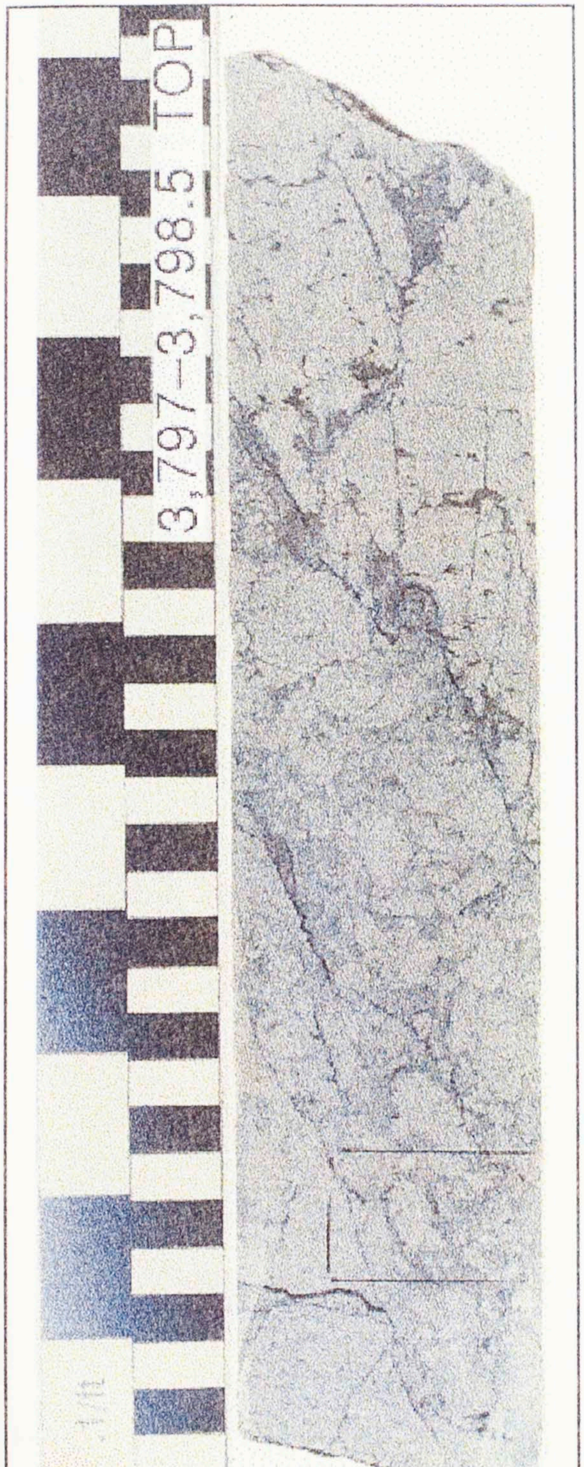


Figure 20. Solution Pipe from Bray zone (3797-3798) from Bray zone, Geneva Bray core, T4S-R3W, Section 2, Carter County, Oklahoma. ***(Core courtesy of ARCO Research Center)***

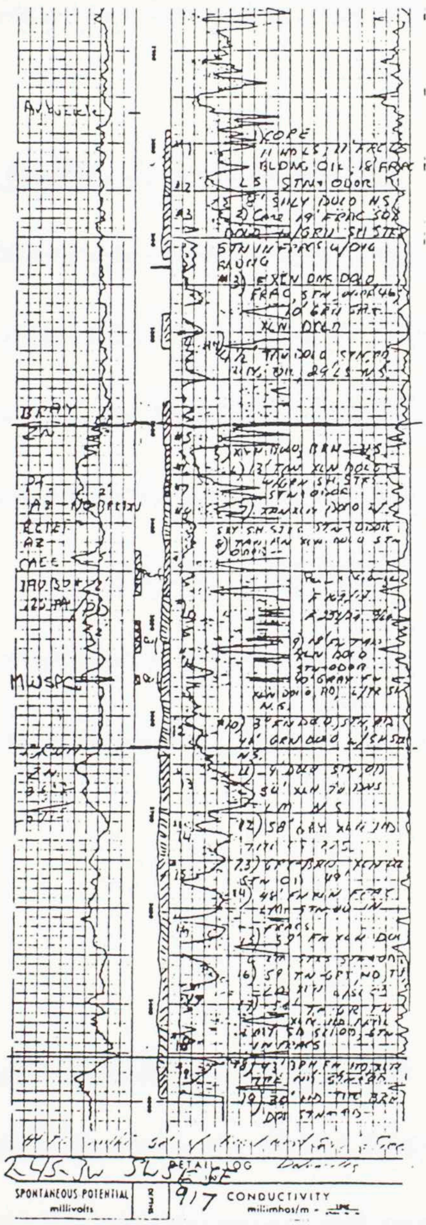


Figure 21. SP-Induction log showing the productive Bray zone interval, (3430-3530), Geneva Bray #1, T4S-R3W, Section 2, Carter County, Oklahoma.

The lack of karst development in the Bray Zone in the Geneva Bray well is attributed to the preservation of the original depositional fabric; primarily carbonate mud rich strata that would have inhibited the flow of karst forming waters.

3. HAU #5-3, Section 4, 4S-3W, Carter County, OK

The lower portion of the Bray Zone contains minor occurrences of crackle, mosaic, and chaotic breccias. The base of the lower Bray zone and the top of the Brown zone were based on well log correlations (Figure 22). The (3797-3798.5) interval is the only occurrence of significant amounts of breccia in the lower portion of the Bray zone within the cores examined. This karst-like breccia in the lower Bray zone suggests karst development occurred at least as late as post-Bray zone deposition. It is important to note that an unconformity is unknown in this part of the section.

C. The Brown Zone

1. HAU #5-3, Section 4, 4S-3W, Carter County, OK

In contrast to the Wade and Bray zones, the Brown Zone underwent extensive dolomitization that created a pre-existing porous and permeable conduit system for the flow of karst developing waters. The extensive dolomitization and karst development of the Brown zone, could be related to the subtle differences in depositional facies between the upper and lower West Spring Creek (Lindsay and Koskelin 1991), and resulted in the Brown zone possessing its prolific production and reservoir qualities.

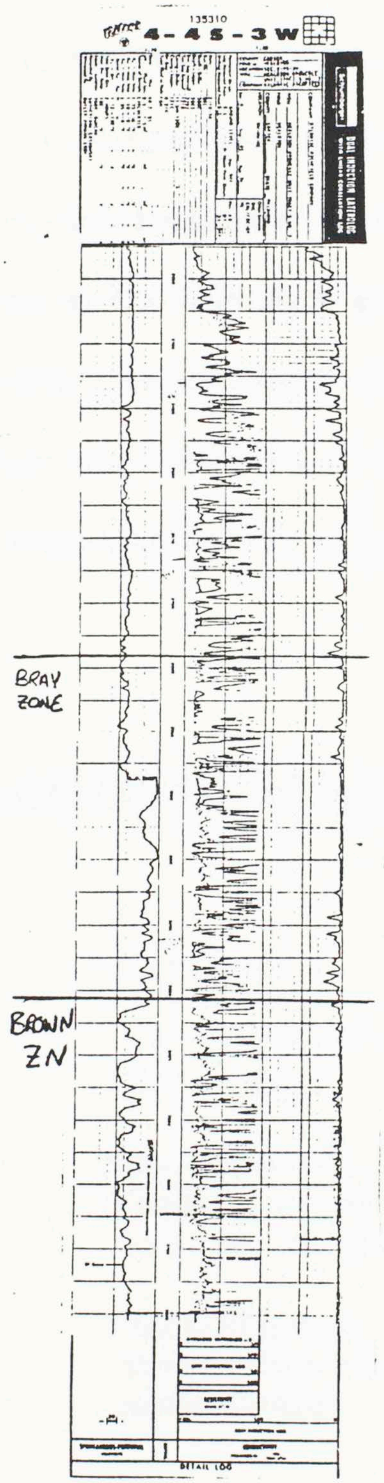


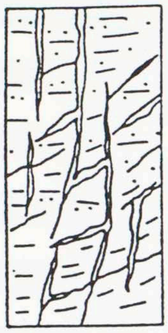
Figure 22. GR-DIL log showing the top of the Bray zone as determined by well log characterisitics, HAU #5-3 well, T4S-R3W, Section 4, Carter County, Oklahoma.

The Brown Zone core was taken from the HAU #5-3 located in T4S-R3W Section 4. The cored interval (3660-4270) covers the lower Bray Zone and all of the productive Brown Zone. The Brown Zone originally contained similar depositional facies as found in the Wade and the Bray zones, but the majority of the strata has been heavily dolomitized and brecciated (Plate 3). The following facies terminology used to describe the Brown zone is partially based upon Keran's (1989) study of the West Texas Ellenburger, where a major unconformity exists at the top of the section studied. Table 3 describes the facies observed in the Brown zone, from the HAU #5-3, T4S-R3W, Section 4:

Table 3. Lithofacies of the Brown Zone

Lithofacies	Description
Crackle breccia	Network of fractures, strata is still intact, little to no loose clasts
Mosaic breccia	Grid of individual clasts: some clasts partially rotated, rock is heavily fractured
Chaotic breccia	Two types: clast supported and matrix supported
Vuggy	Dolomitized strata that tends to be primary fabric selective dolomudstone porous and permeable facies
Green silty karst fill	Green silty micrite, high neutron log response

The vuggy dolomite may have been the dominant early porosity system, formed by uplift before a depositional hiatus occurred. This fabric has the highest porosity and permeability visible in core and thin section, (possibly the highest pore volume over the entire productive Healdton area excluding large cavern development). This fabric is probably relict algal structures that have been dolomitized (Huiabo Liu, pers com, 1991). Kerans (1989) has related karst breccias to paleocave reconstruction in his West Texas Ellenburger study (Figure 23). The crackle or fracture breccia is a relict of a cave roof. The mosaic breccia can represent both the cave roof and the cave floor. The chaotic breccias are distinguished by whether they are clast supported or matrix supported. The clast supported is the lower collapse zone, i.e. the cave floor (Kerans 1989). The matrix supported chaotic breccia represents the upper collapse zone, the top of the internal cave talus. As the cavern enlarges, the weight of the overburden causes the roof to fail and collapse. This collapse adds to previous fractures and has the most impact on the cave roof and floors. The mosaic breccia usually has the highest visible porosity and permeability value (Figure 24, 24a). The clast supported chaotic breccia can have good porosity, but the matrix supported usually has low porosity and low to nil permeability. The green silty karst fill is interpreted as cavern flood deposition. As the cavern floods periodically, the silts are deposited as light and dark bandings with soft sediment deformation. The varve-like bandings and soft sediment deformation indicate the time interval between deposition of each layer was relatively short (Figure 25).



FRACTURE BRECCIA

Fabric dense fracture network defines clasts; no significant rotation of clasts

Clasts incipient clasts composed of single host dolomite type; highly angular outline

Cements minor to pervasive saddle dolomite with rare anhydrite and calcite

Internal Sediment rare geopetal dolomicrite and fine siliciclastics

Porosity 1-15%

MOSAIC BRECCIA

Fabric fitted, clast-supported, discrete clasts displaying minor rotation

Clasts angular to slightly rounded, monomict dolomite of host lithology; usually 5-10 cm

Cements common saddle dolomite rim cement, rare anhydrite, calcite, and quartz

Internal Sediment geopetal dolomicrite and fine-grained siliciclastics

Porosity 2-20%

CHAOTIC BRECCIA, SILICICLASTIC MATRIX-SUPPORTED

Fabric randomly oriented clasts in massive, upward-fining or upward-coarsening units 10-200 cm thick

Clasts angular to rounded dolomite derived from various facies, chert, sandstone, and shale fragments; 1-50 cm

Matrix mixture of shale, very fine to medium-grained siliciclastic sand, and minor dolomicrite and glauconite

Cements minor dolomite cement in shale matrix

Internal Sediment none

Porosity 1-3%

CHAOTIC BRECCIA-CARBONATE CLAST-SUPPORTED

Fabric randomly oriented clasts in massive units tens of cm to several m thick

Clasts angular to rounded dolomite and rare chert fragments from a variety of depositional facies juxtaposed; 5-50 cm

Cements well-developed saddle dolomite rims with rare anhydrite, calcite, quartz, pyrite, marcasite

Internal Sediment geopetal dolomicrite with rare, fine-grained siliciclastics typically perched on clasts, but can fill intraclast space completely as a sieve-fill matrix

Porosity 1-15%

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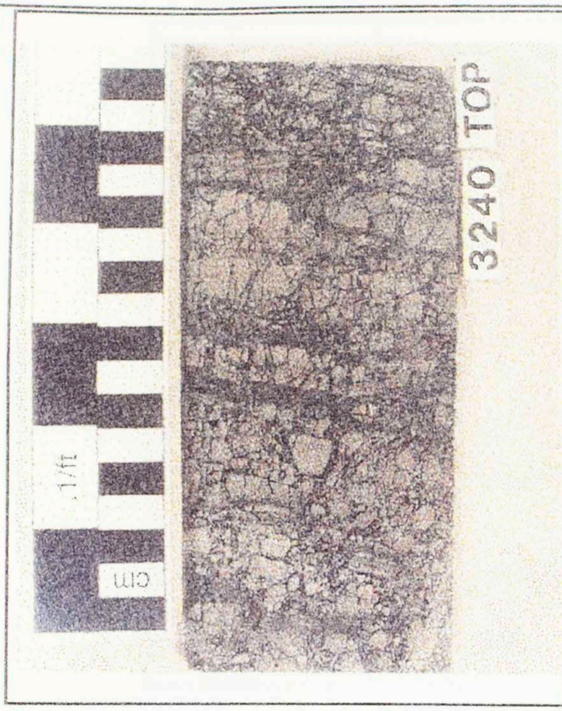
Figure 23. Karst Breccia Terminology from West Texas Ellenburger study, from (Kerans, 1989)

Mosaic Breccia.



Chaotic Breccia.

Vuggy Dolmite.

Figure 24. Lithofacies of the Brown zone, HAU #5-3well, T4S-R3W, Section 4, Carter County, Oklahoma.

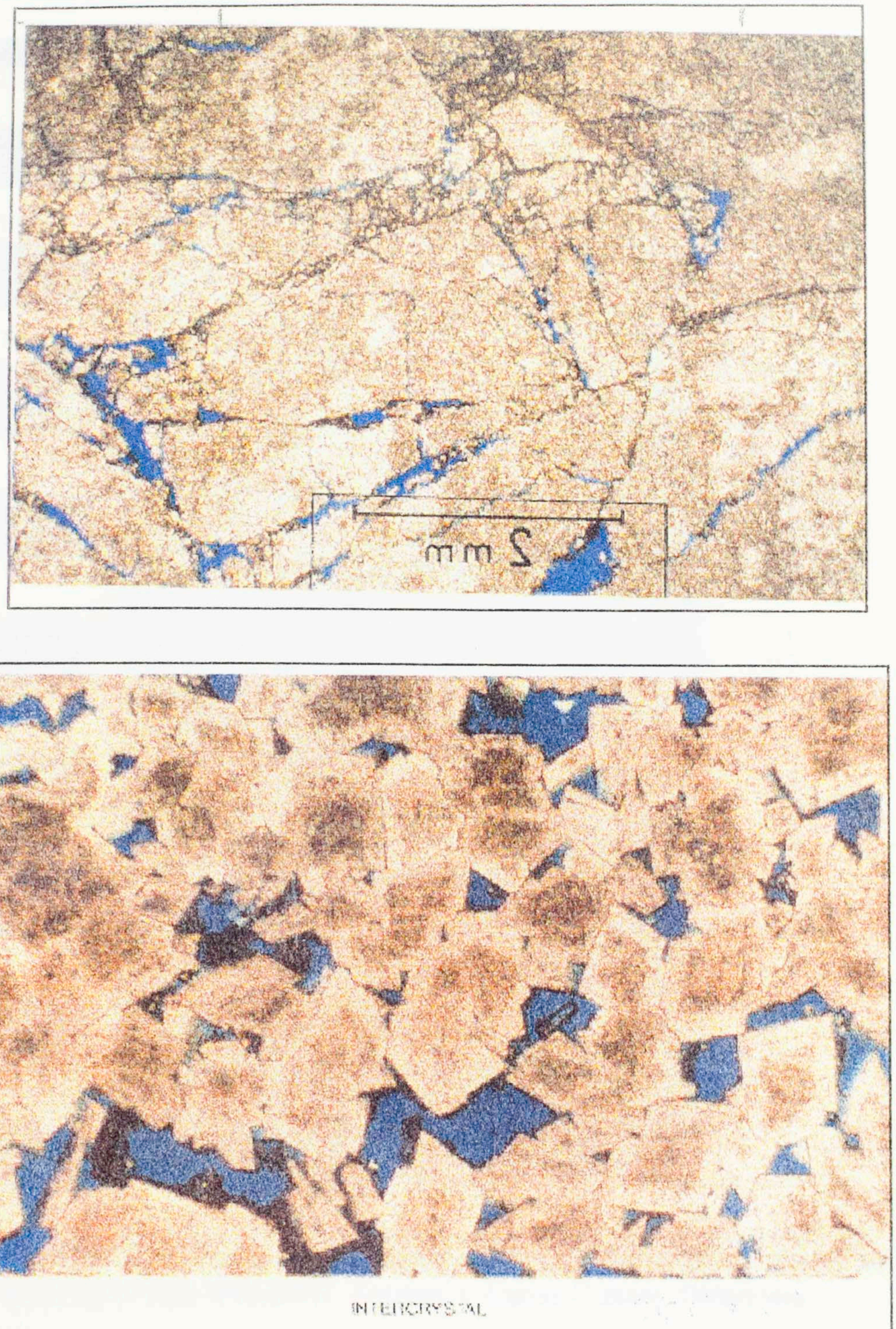
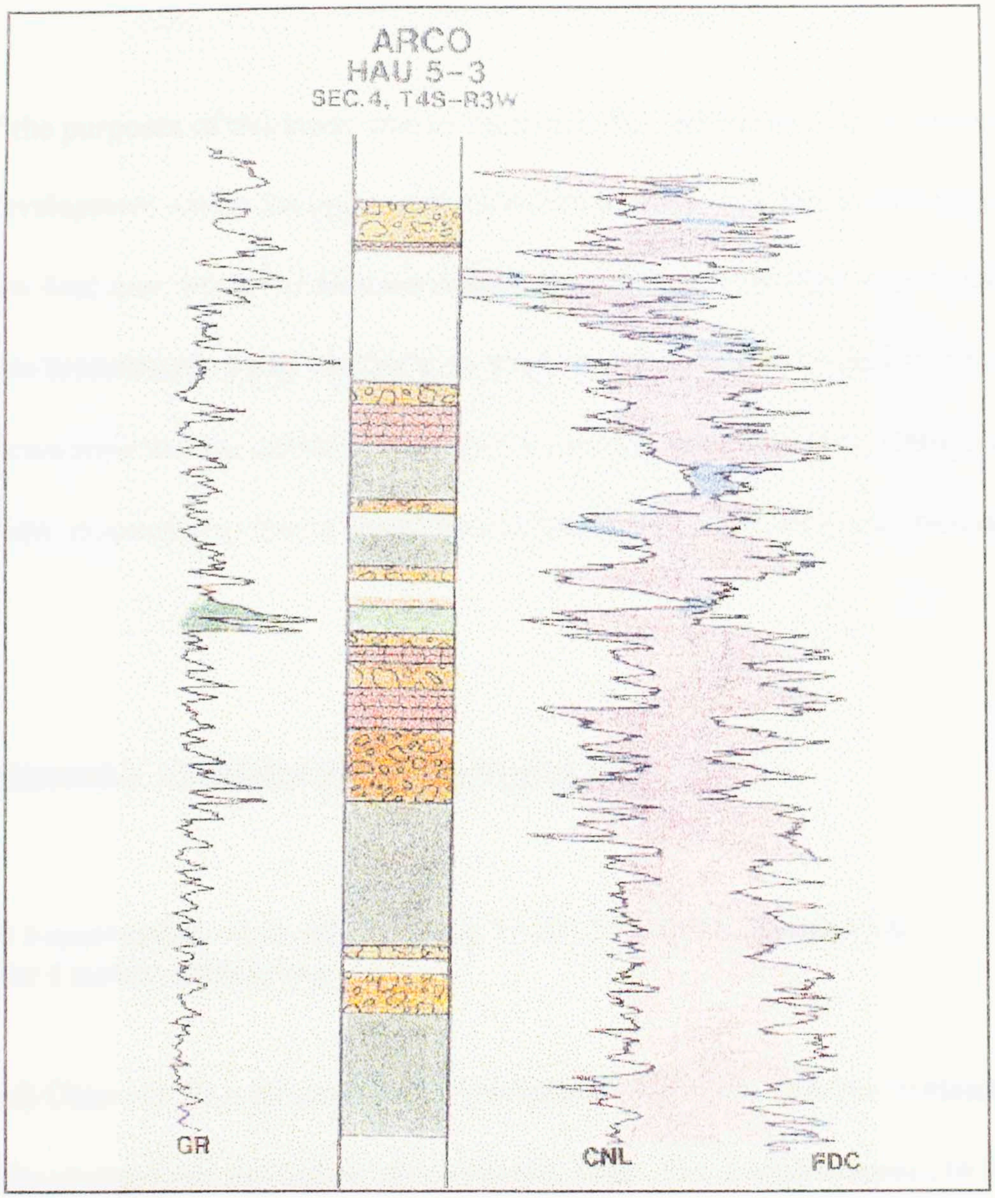


Figure 24(a). Thin Sections from the HAU #5-3 core with blue epoxy in the pores. Upper picture shows mosiac breccia w/open interstices (porosity); lower picture of intercrystalline porosity found in the lower section of HAU #5-3 Core, the vuggy dolomitic portion. Lower picture at 48x's resolution.

Figure 25. Dark and light green, varve-like, silty karst infill with soft sedimentation, HAU #5-3 well, T4S-R3W, Section 4, Carter County, Oklahoma.

Kerans (1989) also showed the relation of karst development to well log response. This method was also applied to the HAU #5-3 GR-CNL/FDC log (Figure 26). The karst breccias have a ragged, high response on the CNL and Gamma Ray logs due to the high clay content of the breccia infill. The vuggy dolomite has a lower and smoother response. The green silty karst fill has a very high neutron response because of the high silt and clay content.



Orange= Chaotic Breccia Red=Mosaic Breccia Light Green=Silty Karst Infill

Dark Grey-Green=Vuggy Dolomite

Figure 26. GR and CNL-FDC logs covering the Brown zone interval from the HAU #5-3 well, T4S-R3W, Section 4, Carter County, Oklahoma. Karst breccias with silty infill reflect correspondence from high neutron response and high gamma ray response. Karsted interval has raggedy response, while vuggy dolomite in the lower portion shows a smoother, more uniform response.

Chapter V Dolomitization of the Upper Arbuckle Brown Zone

One of the purposes of this study was to determine the vertical and lateral extents of karst development within the upper Arbuckle (Wade, Bray, and Brown zones) in the Healdton field area. From the aforementioned core studies it has been determined that extensive dolomitization and karstification are primarily confined to the Brown zone. The Brown zone karsted dolomite reservoir occurs fieldwide, based on wellsite drilling and sample examination observations (Jack Latham, pers com, 1991) and production history.

A. Stratigraphic Variability within the Brown zone

1. Core Examination of the Shell Chase #1-28, T3S-R3W, Section 28, Carter County, Oklahoma

The Shell Chase #1-28 well was cored from 16,900' to 17220'. This is correlated to be within the stratigraphic equivalent of the Brown Zone. The available cores (16,900-17,200) were examined in hand sample for the presence of karst breccias, vugular porosity, and general lithologic characteristics. The cored interval in the Shell Chase #1-28 well was primarily composed of dark gray to black carbonate muds (Figure 27). Karst breccias were not present and depositional fabrics of the primarily limestone interval were intact.

2. Stratigraphic Cross Section and Lateral Variation in Healdton Area

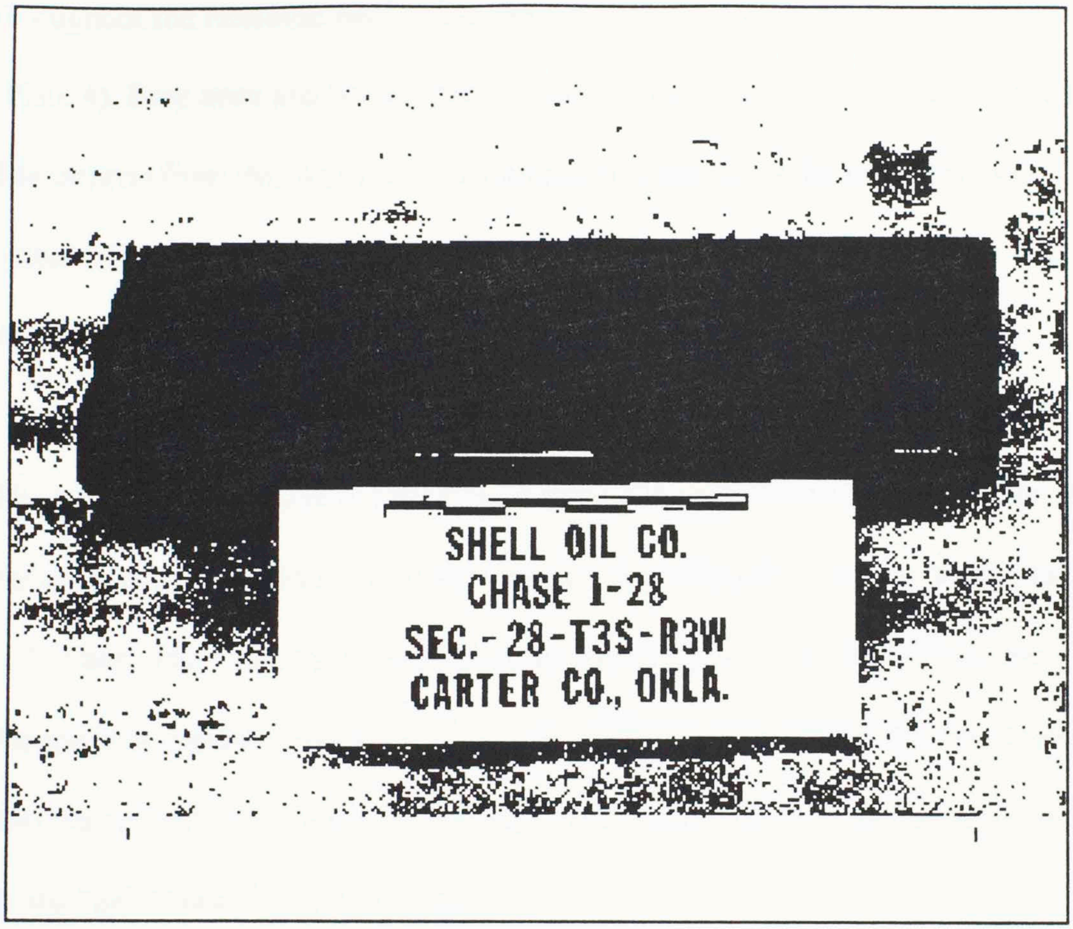


Figure 27. Core sample from the Shell Chase #1-28, T3S-R3W, Section 28, Carter County, Oklahoma. This sample is stratigraphically equivalent to the Brown zone in the Healdton field. Sample is composed primarily of dark grey to black carbonate mud. (Approximate length is 1.25 feet long, and representative of samples below 17,000 feet).

A stratigraphic cross section was constructed from the Shell Chase #1-28 well to wells throughout the Healdton field, using the top of the Arbuckle marker as the datum (Plate 4). Bray zone and Brown Zones markers were also correlated across the field. The interval from the top of the Bray zone to the top of the Brown Zone was correlated to test the relationship of interval thinning to karst and dolomite development of the Brown zone.

The top of the Bray zone to top of the Brown Zone interval shows an average interval thickness across the field of 600 feet; but the interval thickness in the Shell Chase well is 710 feet. The 110 foot thickness increase is attributed to the Bray Zone being deposited in a paleotopographic low north of the Healdton Field. This interpretation is also supported by the change in lithology of the Brown Zone from the Healdton field to the Shell Chase #1-28 well (Figure 27).

The Brown Zone was the substrate for the Bray Zone at the time of deposition. The lithologic change from shallow water carbonate and dolomite lithology in the Healdton Field to a dark subtidal carbonate mud lithology in the Shell Chase well reflects the change in water depth. Reading and Sellwood (1986) documents a change in depth of approximately 30 to 45 meters (98 to 148 feet) in modern environments is enough to change from a predominantly shallow upper intertidal facies to a deeper water subtidal facies. The area in the vicinity of the Shell Chase 1-28 would be sufficiently deep to preserve the limestone depositional fabric while diagenetic alteration was producing porous dolomite in the Healdton Field area.

B. Dolomitization Types and Mechanisms

The first dolomitization probably occurred soon after or possibly during deposition of the Brown zone on a paleotopographic high that encompasses what is presently the Healdton Field. Dolomitization enhanced the porosity of some of the shallow intertidal facies, and created a pre-existing porosity system prior to the first karst event. The rock is so heavily dolomitized that the nature of the original fabric is at times largely interpretive. However, the dolomitization seems to cross cut all recognizable lithofacies deposited in the supratidal, intertidal, and upper subtidal environments.

Dolomitization models have been proposed using a variety of processes. The following discusses the relevant models for both surface and deep burial dolomitization that could be applied to the Arbuckle Brown Zone. The seepage reflux and evaporative pump models are certainly applicable to the early shallow geologic setting, and the development of hydrothermal dolomite in the Brown Zone is an indication of a later episode of alteration.

1. Evaporative Pump Model

The Seepage Reflux Model and the Evaporative Pump Model (Land 1985) both rely upon the presence of a topographic high. In the Evaporative Pump model (Land

1985), water is evaporated in the upper portion of the lens. Dense lagoonal brines saturated with respect to magnesium are pumped back into pores of the lens that were occupied by freshwater and diagenetically alter limestone to dolomite (Figure 28). This is analogous to the Persian Gulf and other arid coastal plains.

2. Seepage Reflux Model

The Seepage Reflux model is similar in topographic setting. However, the flow of saturated magnesium waters through the pores is due to the density difference in the lake or lagoonal setting (Land 1985). The lagoonal waters become more dense due to evaporation and the density contrast causes the brines to flow through the limestone pores (Figure 29). The dense brines are saturated with magnesium and dolomitize the host rock. This generic model is not as widely accepted because field data do not totally support this model (Land 1985).

3. Proposed Arbuckle Brown Zone Model for Early Dolomitization in the Healdton Field

Both models require a topographically high area and a backwater lake or lagoon to develop the dense magnesium saturated brines for dolomitization to occur, although Land (1985) states that ordinary sea water is sufficient in itself to promote dolomitization. The Healdton field area would have been a paleotopographic high, adjacent to restricted waters, (lakes, lagoons), that would have supplied the dolomitizing fluids. As shown by core examination and stratigraphic cross section, a

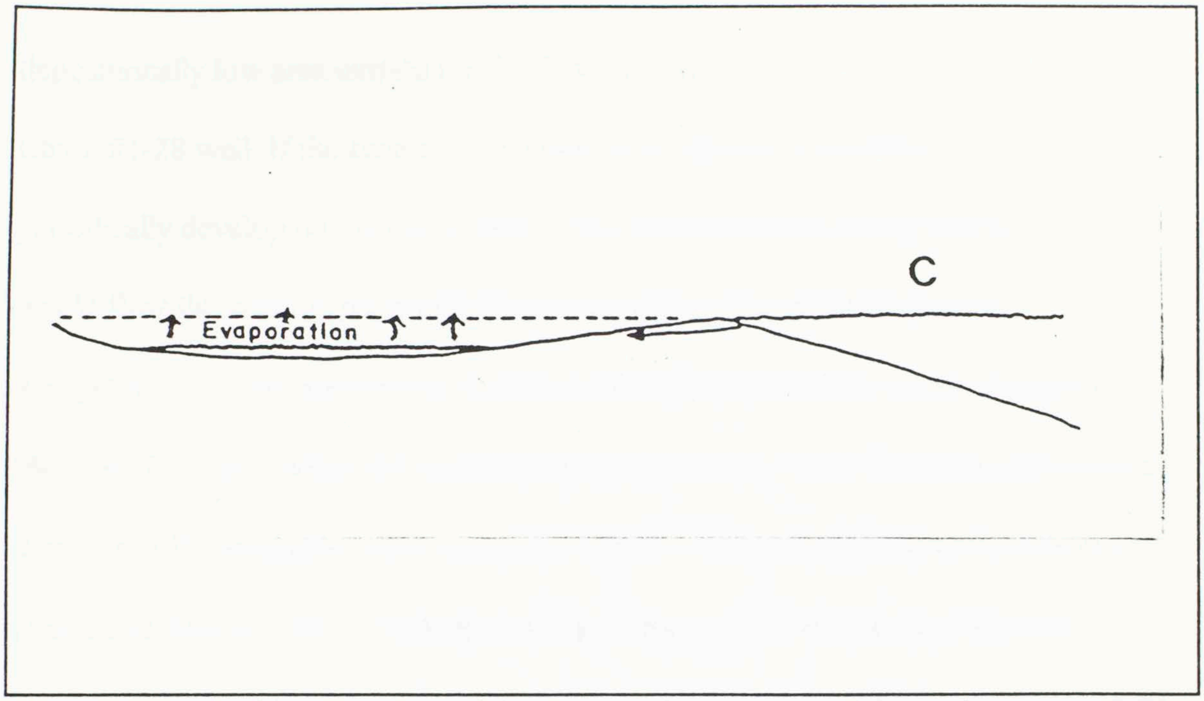


Figure 28. Land's (1985) review of the Evaporative Pump Model. Fresh water evaporates in upper lens. Dense lagoonal brines saturated with magnesium are "pumped" into the pores of the lens that were occupied by freshwater and diagenetically altered to dolomite.

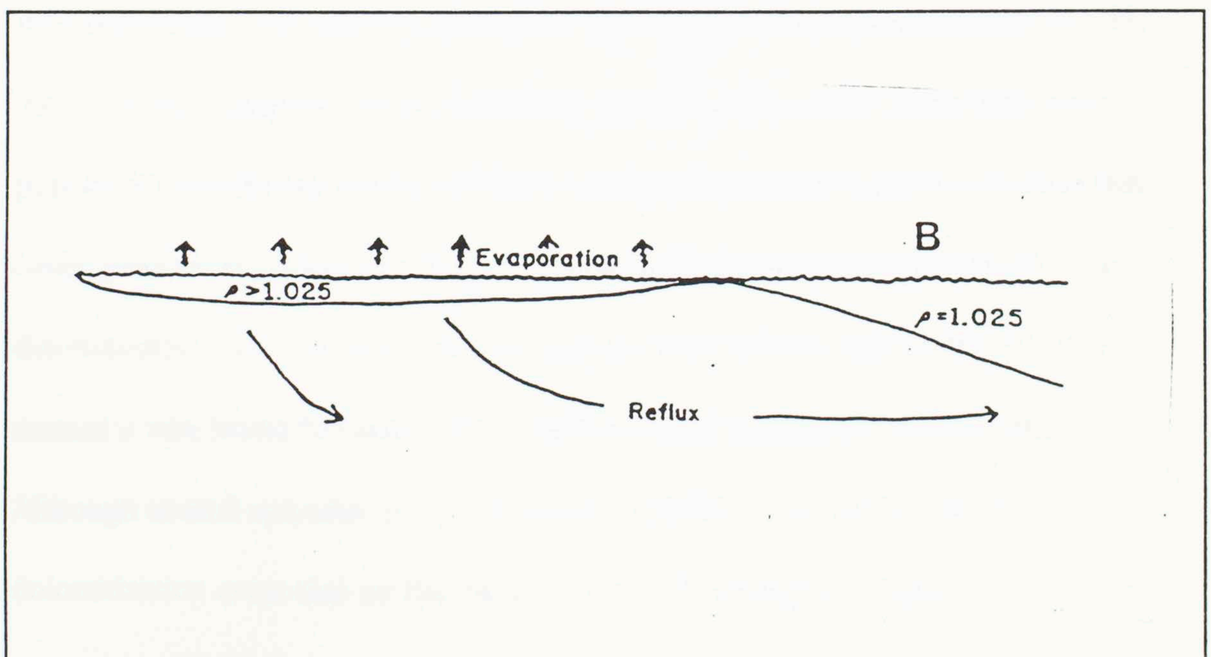


Figure 29. Land's (1985) review of the Seepage Reflux Model. Lagoonal brines evaporate and increase brine density. Density contrast of lagoonal brines causes flow through limestone pores, thus dolomitizing the rock.

depositionally low area existed north of the Healdton field in vicinity of the Shell Chase #1-28 well. If the Evaporative Pump were applied, a freshwater lens would periodically develop on the topographic high, and evaporate during the day. The brines would flow through the permeable limestone strata, thus dolomitizing the topographically high areas in the Healdton field. It is important to note the Ghyben-Herzberg Principle states that at hydrologic equilibrium, "The freshwater lens extends downward 40 meters for every one meter that the water table is above the sea level." (Budd and Vacher, 1991). Therefore, the entire area need not be exposed to the surface to achieve the massive extent of dolomitization observed in the Healdton field.

Selective dolomitization of the Brown zone in comparison with the entire upper Arbuckle strata might have been related to an abundant magnesium source, possibly the uplift and/or exposure of a magnesium rich formation. Also, particularly long periods of constant sea level would have produced restricted lagoons and lakes that could generate the fluids necessary to dolomitize the original limestone rock. The dolomitization not only enhanced the porosity of the Brown zone strata, but also created a very brittle formation that would be highly susceptible to fracturing. Although several episodes of dolomitization probably occurred, it was the first dolomitization event that set the framework for all subsequent diagenesis.

C. Model for Late Stage Hydrothermal Dolomitization

Hydrothermal dolomitization is characterized by saddle or baroque dolomite. Saddle dolomite has distinctively curved crystal faces, undulatory extinction , and forms at temperatures above 185°C (Figure 30) (Lee and Friedman, 1987). Saddle dolomite usually occurs as a vug filling cement in the Arbuckle, similar to the saddle dolomite in vugs and fractures in the West Texas Ellenburger described by Lee and Friedman (1987). Magnesium supply for deep burial carbonates can be (1) connate water, (2) dissolution of unstable minerals, (3) stylolitization, (4) compaction of shales, and (5) basinal brines (Lee and Friedman, 1991). Of the above supply sources, basinal brines are the most probable source of magnesium for the deep burial hydrothermal dolomite for the Arbuckle Brown zone.

The Southern Oklahoma Aulacogen was the third arm of a failed rift (Wickham, 1978). The aulacogen was one the most tectonically active regions in Oklahoma. Deep seated stress could have dilated the Brown zone pores and enhanced the permeability of the silty dolomite for the deep basinal fluids to migrate to the path of least resistance. The silty Brown Zone was the most permeable reservoir relative to the overlying and underlying strata, and offered the path of least resistance to hydrothermal fluid flow.

Saddle dolomite occludes porosity in the upper Arbuckle. Many thin sections examined from the HAU #5-3 exhibited bitumen rimming the saddle dolomite. The bitumen may have been an arresting agent for the further occlusion of the vugular

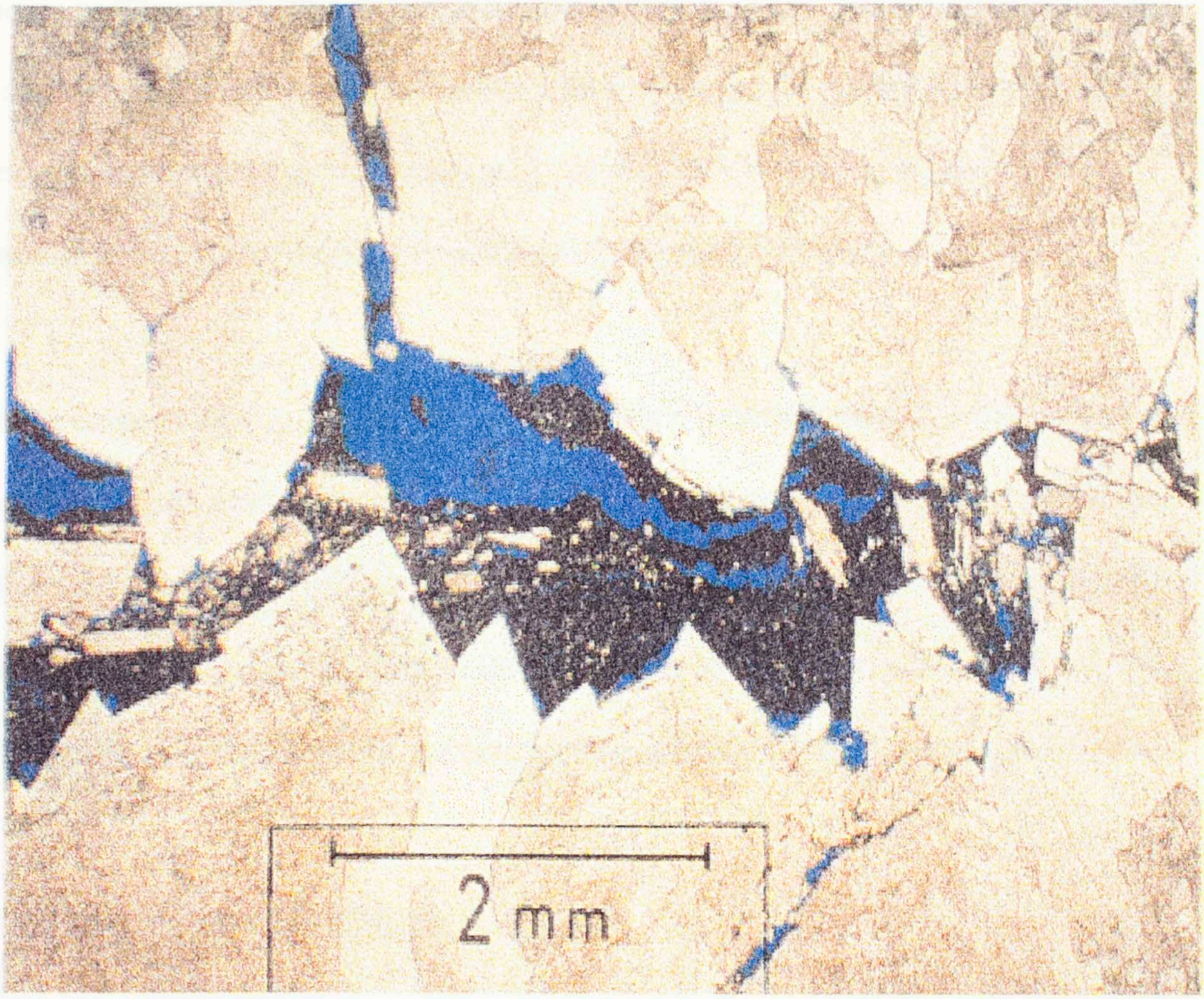


Figure 30. Saddle dolomite rimming pore in the Arbuckle Brown zone. Bitumen, in black rims the saddle dolomite. Bitumen establishes the last prominent flow of fluid through the pore system.

porosity (Figure 30). This sequence of dolomitization events was documented in Lee and Friedman's (1987) study of the West Texas Ellenburger according to their fabric, texture, and temperature of formation. Lynch's (1990) inventory of paleokarstic features categorizes these events similarly for the cores examined in Oklahoma.

In the author's opinion, the formation of the saddle dolomite requires a pre-existing porosity system that is quite vuggy in places. The limestone cores examined from the Wade and Bray zones had low to nil porosity; the highest porosity was associated with the dolomites in the Brown zone. Therefore, initial shallow dolomitic and subsequent dilatent porosity development was an important control on late stage dolomitization.

D. Fracturing and Lithologies

Field and experimental studies conducted by Stearns and Friedman (1972) have shown the relationship between brittle and ductile behavior of different lithologies. Fracture indices, the number of fractures found per 100 feet in the lateral dimension as measured by Stearns and Friedman (1972), show that dolomite has the second highest fracture index exceeded only by quartzite (Figure 31). In contrast, the much more ductile limestone has a much lower fracture index.

Although the Wade, Bray and Brown zone cores were examined primarily from separate wells, the Wade and the Bray limestone units had fewer fractures than the underlying Brown zone. Jack Latham (pers com, 1991) related his observations of the

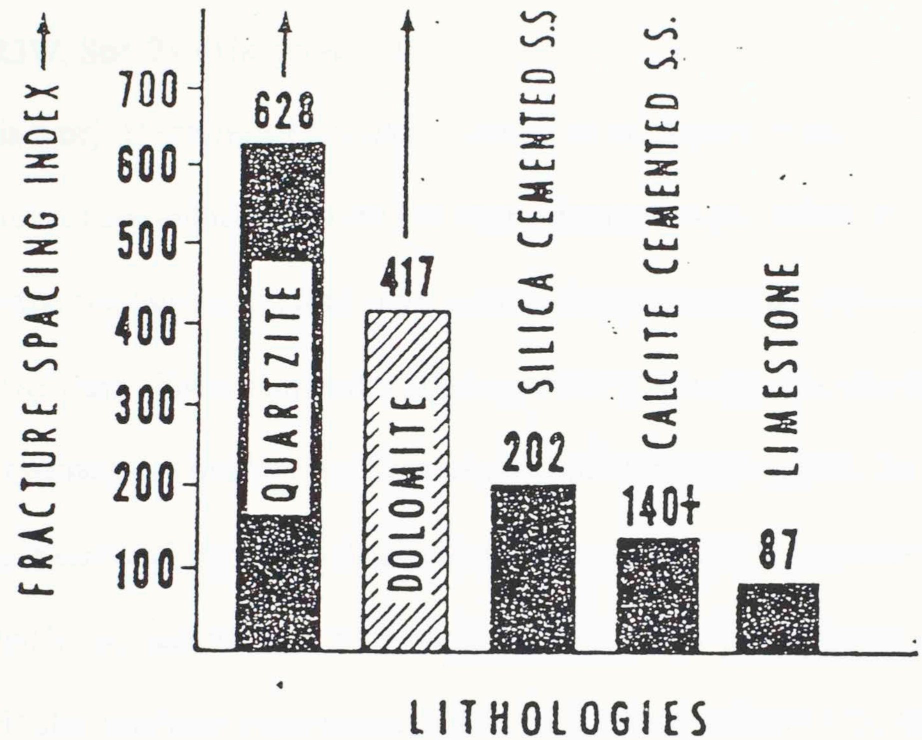


Figure 4. Histogram of fracture frequencies for various lithologies. All measurements, except that of dolomite, were made on same structure. Dolomite measurements came from different, but similar, structure.

Figure 31. Fracture index of sedimentary rocks indicating dolomites high susceptibility to fracturing. Stearns and Friedman (1972).

continuous core throughout the Wade, Bray, and Brown zones in the Naomi Freeman well (T4S-R3W, Sec. 2). (The present day location of the core is unknown to the author at this time). He recorded a marked increase in the degree of fracturing in the dolomitic Brown zone compared to the overlying limestone units. Although most fracture systems add little to the total pore volume, they significantly enhance the permeability network. The enhancement of the permeability is not only important to present day hydrocarbon production, but was also important as a conduit for the flow of diagenetic waters and hydrocarbon migration. The extensive fracture network is also supported by the uniform oil-water contact in the Brown zone throughout the Healdton field that produces from several distinct fault blocks (Figure 3, Latham 1968).

Early dolomitization of the Brown Zone created a pre-existing porosity system that provided a conduit for karst forming fluids. Although minor porosity was observed in the Wade and Bray zones, it is not comparable to that in the Brown Zone, thus the Brown Zone offered the permeability path of least resistance. The brittle dolomitic Brown Zone had greater susceptibility to fracturing contrasted to that of the overlying limestones units (Stearns and Friedman, 1972). Finally, the Morrowan uplift provided further relief and tectonic fractures which could have enhanced later karst development, giving the reservoir 1500' of closure (Latham, 1968).

Chapter VI Karst Development of the Arbuckle Brown Zone

Observations from cores examined in the Healdton field support a model with more than one period of karst development in the Brown Zone. Meteoric karst occurs when carbonates are exposed to meteoric waters at the surface. Hydrothermal karst occurs where deep basinal fluids flow through a permeable and porous host rock. The Healdton Field had opportunities for both to take place. The following will discuss **(A)** a generic meteoric karst model, **(B)** deep burial karst models, **(C)** a model of both meteoric and hydrothermal karst specific to the Arbuckle Brown Zone in the Healdton field, and **(D)** a brief summary of the timing and opportunities of diagenesis of the Brown zone from deposition to its present day condition, and the weight of evidence supporting each episode of diagenesis.

A. Meteoric Karst

Meteoric karst development is usually related to sub aerial exposure of carbonates to waters under saturated with respect to $CaCO_3$. Esteban and Klappa (1983) define a sub aerial exposure surface as a distinct land surface that indicates (1) non-deposition and commonly erosion, and (2) a break in sedimentary sequence. Karst dissolution occurs due to a net loss of $CaCO_3$, accompanied by a consumption of CO_2. Equation I shows how an increase in CO_2 drives the equation to the right, resulting in the dissolution of $CaCO_3$.

Equation I. Dissolution of Carbonates by Meteoric Water

$$CaCO_3 + H_2CO_3 \rightleftarrows Ca^{2++}{}_{(aq)} + 2HCO_3^{-}{}_{(aq)}$$

$$\updownarrow$$

$$CO_{2(g)} + H_2O_{(l)}$$

Kerans (1989) describes paleokarst occurring in three main zones due to sub aerial exposure: (1) the vadose zone, (2) the upper phreatic zone, (3) and the meteoric/marine interface.

1. Vadose Zone

The upper vadose zone (Figure 32, Esteban and Klappa, 1983) is characterized by physicochemical dissolution, biological corrosion, and moon-milk deposits (fine grained deposits made of random needle fibers of low magnesium calcite), (Esteban and Klappa, 1983). The karst producing waters flow downward through conduits of fractures and joints into the lower vadose zone (designated the percolation zone). Esteban and Klappa (1983) makes the salient point that flow is through pre-existing permeability pathways. At this stage, the waters are near equilibrium and carbonate dissolution is at a minimum. The percolation zone is poorly defined except near the upper portion of the phreatic zone, where speleothem precipitation is more abundant. Water movement in the vadose zone is primarily vertical and migrates downward through time.

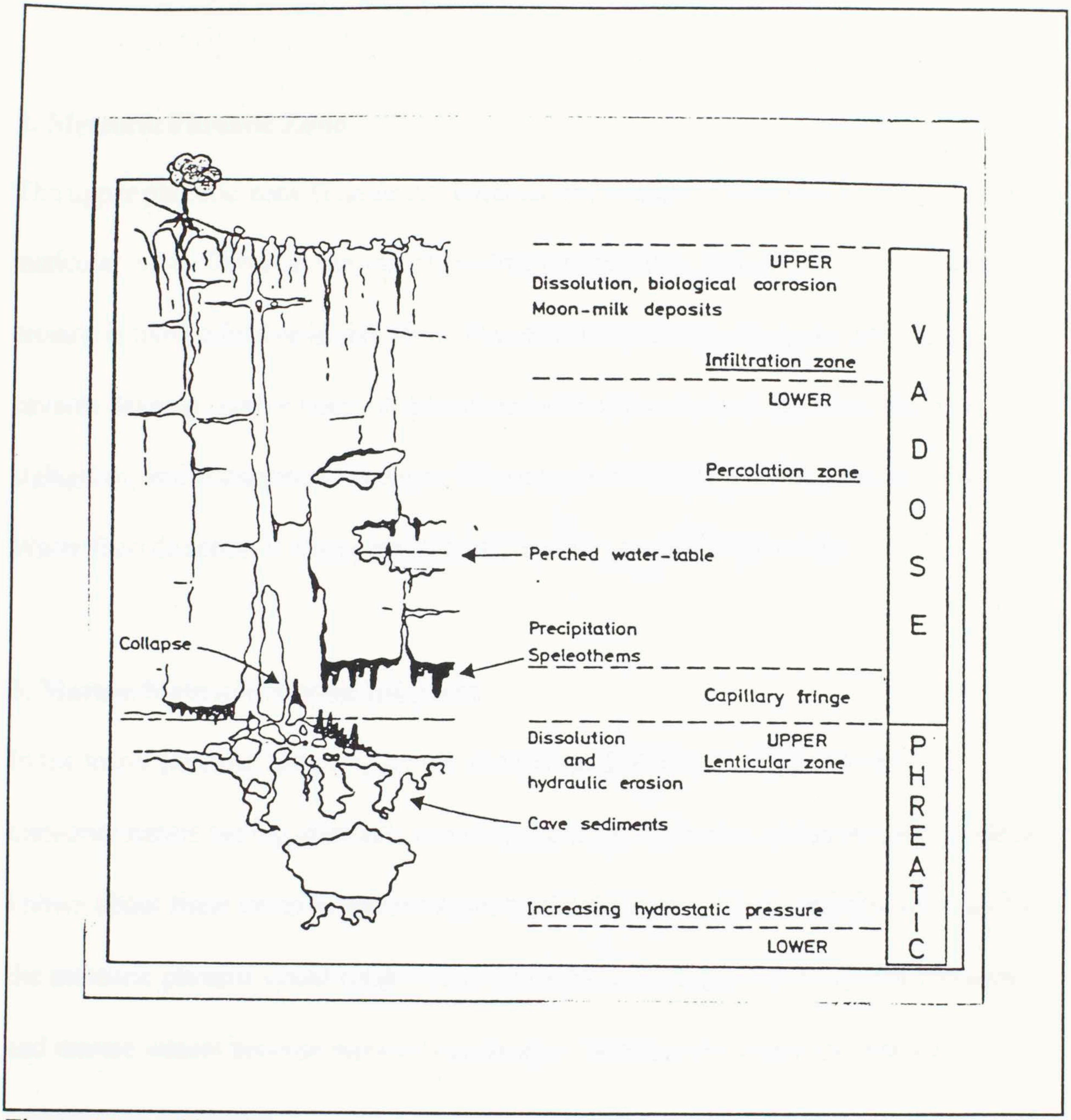


Figure 32. Authigenic karst profile. Esteban and Klappa (1983)

2. Meteoric Phreatic Zone

The upper phreatic zone (Figure 32, Esteban and Klappa, 1983) is referred to as the lenticular zone. This is at the top of the fresh water table. Dissolution and hydraulic erosion is most effective in this zone. The lenticular zone is where the spectacular caverns develop, with a wide variety of speleothems such as cave pearls, lily pads, stalagtites, and stalagmites. Collapse breccias are also most abundant in this zone. Water flow direction in the upper phreatic zone is primarily horizontal.

3. Marine/Meteoric Mixing Interface

In the lower phreatic zone (Figure 32, Esteban and Klappa, 1983), near the meteoric/marine mixing interface, more equidimensional caves are developed. Little is known about these caves in ancient karst models (Kerans, 1989), and downcutting by the meteoric phreatic could totally mask its imprint. As depth increases, the meteoric and marine waters become more in equilibrium. Dissolution ceases and marine cementation can occur.

B. Deep Burial Karst Model

Hydrothermal karst is due to dissolution of the host rock by deep basinal waters. Two models of deep burial karst will be discussed, (1) hydrothermal fluids and (2) a thermosulfate reduction model.

1. Hydrothermal Karst

Hydrothermal karst can occur when shales and other strata undergo dewatering in the deep basin. Hydrothermal karst models have been applied to Mississippi-Valley Type Lead-Zinc deposits. Sangster (1988) refers to MVT lead-zinc deposits as "mineral deposits hosted by carbonate rocks and contained in structures widely accepted as paleokarst phenomena, and named for the Mississippi Valley region where they were first recognized as a distinct deposit type". Sangster (1988) has chronicled the two schools of thought as to the origin of the Mississippi-Valley type deposits. The first school proposes the genetic origin of the lead-zinc breccias as a later and separate ore depositing event unrelated to the initial development of meteoric karst. The second theory proposes that the dissolution of the host rock and ore deposition occur from the same hydrothermal fluids. In Sangster's study, he calls into question the application of the meteoric karst model where no regional unconformity has been recognized immediately above the MVT deposits (as is the case of the Arbuckle Brown zone in the Healdton field).

Dolomitization is also common in MVT deposits. Sangster (1988) states that it is not obvious whether the dolomitization is due to regional diagenesis or a result of the ore-forming process. In a study of karst breccias in East Tennessee, the rocks within the breccia zone consist primarily of dolostone with a thin secondary dolomite halo around the breccia zone. The dolomitic breccia zone is encased in the limestone host rock. Ohle (1985) noted in the Jefferson City mine, East Tennessee, the breccia zone within the Knox Formation contained no limestone blocks even though the stratigraphic section contained limestone beds. He suggests the possibility of dissolution of the limestone section and subsequent dolomitization of the Jefferson City "breccia dome" (Figure 33). This is similar to the Brown zone in the Healdton field which contains primarily dolomitic breccia with little to no limestone within the karsted reservoir, and a lithologic change of the stratigraphic equivalent to a dark carbonate mud facies found in the Shell Chase #1-18 well 2-4 miles north of the Healdton field. The Knox Formation is stratigraphically equivalent to the Arbuckle.

The strong relationship of mineralization (including dolomitization) and karst development points toward an "essential simultaneous process" achieved by hydrothermal fluids. In Sass-Gustkiewicz et al's (1982) study of Polish ore deposits, she concluded that the "emplacement of the ores and the formation of the underground karst were parts of the same formative processes and essentially simultaneous" (Sass-Gustkiewicz et al, 1982). Evidence cited to preclude meteoric karst was the absence of oxidizing aqueous solutions between stages of mineralization, absence of speleothems, and scarcity of terra rosa (Sass-Gustkiewicz et al, 1982). Although the last two lean towards negative evidence that would be biased in 4" drilling cores (i.e., one might not expect to see such items even if they were in abundance), mining studies have access to large volumes of rock and intact samples that would make these two pieces of evidence more reliable.

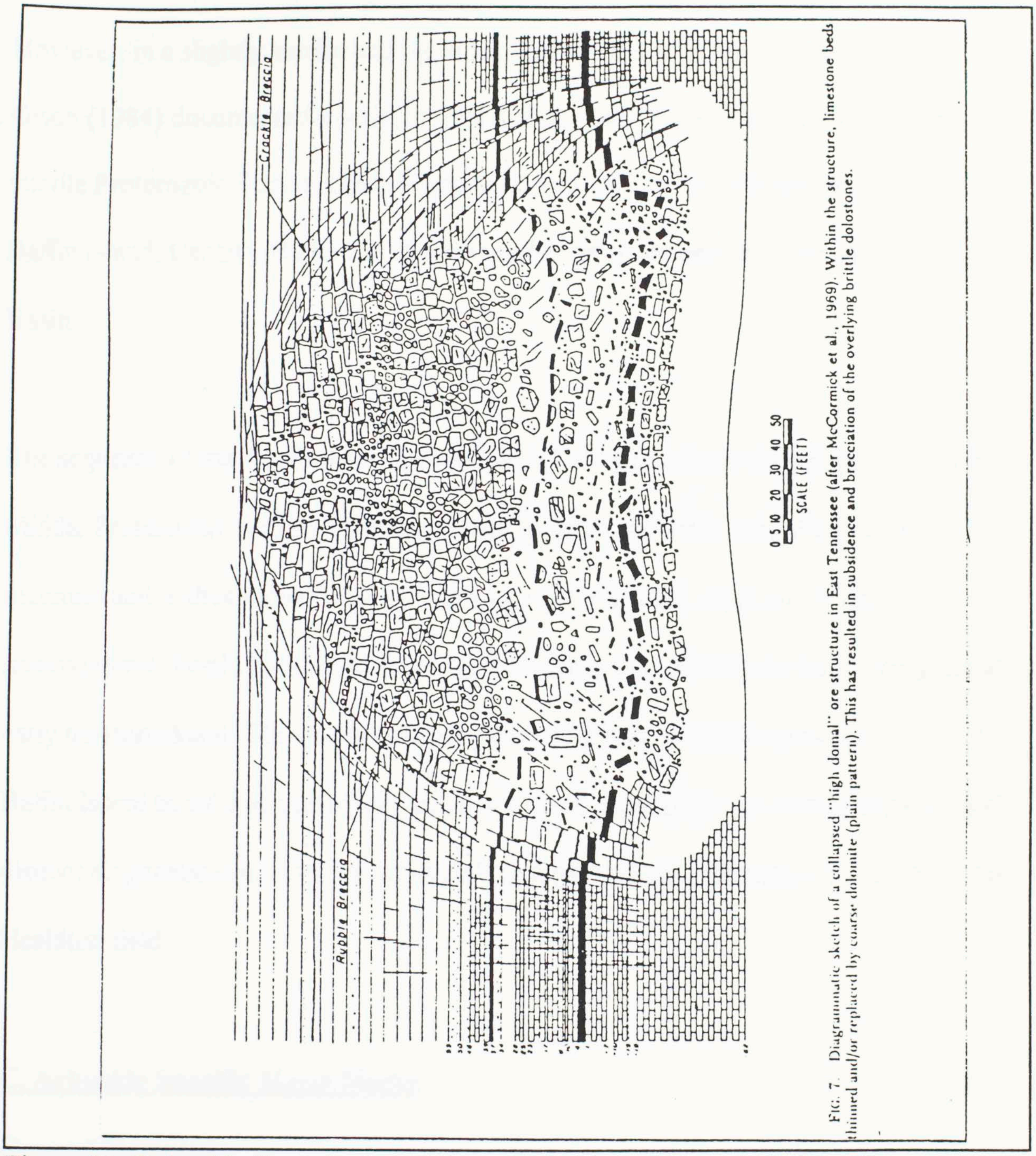


Figure 33. Dolomitic "breccia dome" from the Jefferson City mine, East Tennessee. Ohle (1985)

However, in a slightly similar setting to the Healdton field in the Ardmore Basin, Olson (1984) documented a series of five distinct karst events that occurred in the middle Proterozoic Society Cliffs Formation dolostone on the Borden peninsula, Baffin Island, Canada. Baffin Island is located in an aulacogen, as is the Ardmore Basin.

The sequence of events documented by Olson (1984) for the development of karst in Middle Proterozoic Society Cliffs dolostone in northern Baffin Island shows that meteoric and hydrothermal karst can take place in the same reservoir throughout geologic time. Ford (1981) states that hydrothermal dissolution may have enlarged the early meteoric karst. The documentation of several karst and dolomitization events on Baffin Island based upon geochemical data permits the analogy of several separate and distinct diagenetic events that produced the karsted Arbuckle Brown zone found in the Healdton field.

C. Arbuckle Specific Karst Model

General Overview

The following discussion describes possible episodes for karst development in the Arbuckle Brown zone in the Healdton field. The shallow marine facies of the Brown zone were heavily dolomitized with portions developing into a vuggy dolomite. Small vugs were enlarged into caverns by karst producing waters. The crackle breccia represents the cave floor and cave roof. As the caverns further enlarge, rocks fall from the roof and form a cone shaped pile of rubble. The lower section of the "collapse zone" (Kerans, 1989) is recognized by clast supported chaotic breccia. Periodic flooding of the cavern washed in silts and muds that occur in the upper portion of the collapse zone (matrix supported chaotic breccias and green silty karst fill). The cavern finally collapses and the roof and clasts in the upper portion of the collapse zone become heavily fractured (mosaic breccias). The following discussion chronicles each episode of karst development that could have taken place in the Arbuckle Brown zone and evidence supporting the probability of its occurence:

1. Meteoric Karst Model

i. Intra-Arbuckle Unconformity

The first karst episode could have occurred at an intra-Arbuckle unconformity located above the top of the Brown Zone. The conceptual model would be the Brown Zone exposed at the surface similar to Esteban and Klappa's (1983) generic sub aerial karst model. Meteoric waters would precipitate directly on the Brown Zone surface, and percolate down into the subsurface. The Ghyben-Herzberg Principle states there is a 40:1 displacement of sea water by freshwater for every unit of meter of freshwater above sea level (Budd and Vacher, 1991). This could allow for karst development of a large volume of rock during a relative local sea level fall. The continuous downcutting of the vadose and phreatic zones (fall of the water table due to the fall of the sea level) could have been the first episode of karst development in the Arbuckle Brown zone.

ii. Lower Ordovician Unconformity

The second possible karst episode could have occurred at the 2nd order cycle lower Ordovician unconformity. However, approximately 800-1100 feet of strata (Wade and Bray zones) lie between this unconformity and the Brown Zone over the greater extent of the Healdton field. Meteoric fluids could have gained access to the Brown zone through faults at the lateral extents and within the field. An extensive fracture network developed in the Brown zone dolomite would have provided a permeability network to distribute the karst fluids.

iii. Morrowan/Pre-Atokan Karst

The third episode of meteoric karst could have occurred in the Morrowan (Early Pennsylvanian) under conditions similar to those described for the lower Ordovician unconformity, except it would have the benefit of occurring after the fracturing produced by the Mississippian-Early Pennsylvanian structural activity. An important observation that Latham (1968) made is that the Healdton Field has a common oil-water contact throughout the many separate fault blocks. This stresses the point that the faults within the Healdton field are not sealing and could act as conduits. The Brown Zone would have been the most permeable and porous aquifer, and would have provided the least resistance to flow in contrast to the overlying and underlying strata.

2. Deep Burial Karst for the Arbuckle Specific Model

Dissolution by deep basinal fluids is a viable mechanism for the development of karst in the Arbuckle Brown zone in the Healdton field. The aquifer capabilities of the Brown zone have been observed on the surface at the Dolese Overbrook quarry. Fractures and faults also exist to facilitate the dispersal of the deep burial karst waters.

Hydrothermal karst has a special appeal for the Arbuckle Brown zone in the Healdton Field. The evidence of the deposition of saddle dolomite is an indication of the flow of hydrothermal waters within the Brown zone. Hydrothermal karst can also reconcile the fact that approximately 1100 feet of Arbuckle strata lies between the Brown zone and the lower Ordovician unconformity, the closest major recognizable unconformity (Latham 1968). No clear evidence for an unconformity exists at the top of the Brown zone. Derby (1991) found no clear unconformity at the Brown zone equivalent in his examination of the Amoco SHADS well in Rogers County, Oklahoma. Therefore, hydrothermal fluids are thought to have had a strong influence on the karst and late stage dolomite development of the Arbuckle Brown zone.

Latham (1968) describes the Brown Zone as a dolomite across the entire field. Latham (pers com 1991) has observed the Healdton field to be uniformly karsted (pers com, 1991). The karst breccias examined in this thesis are predominantly dolomite. Although it is not my intent to accept only the hydrothermal karst model and dismiss the importance of others, the hydrothermal karst model has strong evidence for the alteration and development of the Arbuckle Brown zone.

D. Capsule summary of the Brown zone reservoir development: Correlation of a related study on Brown zone dolomitization, karstification, and diagenesis

The previous paragraphs have discussed possible mechanisms and timing for the karst development based on the megascopic study described in this thesis. An unpublished paper by Forgotson, Blatt, and Liu (1993) examined the Brown zone in the Healdton field (along with other areas) to determine the paragenetic sequence of diagenesis. They used fluid inclusion thermometry, UV microscopy, and microprobe analysis on samples from the HAU 5-3 and other wells within the field.

The following section will briefly summarize the sequence of possible scenarios for the Brown zone dolomitization and karstification based on the megascopic study of this thesis and the paragenetic sequence from Forgotson's, et al (1993) study. The sequences will be divided into time periods, with a brief summary from each report. Finally, a synthesis will combine each report for each period to produce a capsule summary of diagenetic events.

1. Sedimentation to Lower Ordovician Unconformity

A. Megascopic Study

(1) Deposition of the Arbuckle Brown zone occurred in a tidal flat environment on a carbonate ramp; a shallow, quiet water setting.

(2) Early diagenetic dolomitization occurred soon after deposition of the Brown zone in the Healdton Field, which was located on a paleotopographic high. Many dolomitization models incorporate topographic highs as the locus for diagenetic alteration. The Shell Chase #1-18 well provides evidence for a deeper water

environment to the north where carbonate muds occur with original depositional fabric intact.

(3) An early meteoric karst event in the Arbuckle Brown zone prior deposition of the Bray zone would place the Brown zone at the surface (under sub aerial exposure), the most directly accessible position to karst waters. For this to have occurred, the depositional hiatus between the Brown zone and the Bray would have to be smaller than the faunal resolution of the rock record (Fay 1988, Derby 1991).

In Lynch's insoluble residue studies (Lynch 1990), he found no paleontological evidence to positively identify post-Arbuckle karst (i.e., complete lack of Simpson or Penn fauna (Lynch 1990). However, in the Cushing Field, an abundance of Pennsylvanian age conodonts occur directly above the Arbuckle unconformity, but not within the Arbuckle strata. Although this may be "negative evidence", Lynch's data seems to lean more towards meteoric karst development during or shortly after deposition of the Brown zone.

B. Microscopic Study (Forgotson, Blatt and Liu, 1993)

(1) After deposition of the Brown zone, compaction and the first phase of calcite cementation begin to occur at shallow burial (<1000'). As burial depth and time increases, replacement dolomitization of fine grained facies occur, primarily laminated and mottled mudstones. Irregular tension fractures occur in partially dolomitized bioturbated lime-mudstones.

C. Synthesis

(1) Both reports cite deposition and shallow burial dolomitization prior to the Lower Ordovician unconformity. The microscopic study limits the dolomitization primarily to the fine grained facies. Calcite cementation also occurred during this period. The megascopic study proposes the possibility of shallow burial meteoric karst, but also states that no recognized unconformity exists between the Brown zone and the Bray zone. No positive evidence was found in either study for early meteoric karst.

2. Lower Ordovician Unconformity to Morrowan Unconformity

A. Megascopic Study

(1) Deposition of the Wade and Bray Zones followed by the Lower Ordovician regional unconformity. This unconformity is recognized from the Hueco of Arizona to the Knox of Tennessee.

(2) During the subsidence and burial of Cambro-Ordovician sediments, diagenetic events occurred that are reflected in the dolomitization and cement stratigraphy. Hydrothermal dissolution due to basinal fluids could have occurred during this time period.

B. Microscopic Study (Forgotson, Blatt and Liu, 1993)

(1) As burial depth increases to 5000' in the Early Devonian, a second phase of replacement dolomitization occurred in the grain rich, algal rich, and heavily bioturbated mud facies. These dolomites were divided into (a) fine to silt sized crystals along a pressure solution seam, and (b) medium to coarse grained crystals with relict fabrics. However, fractures also appear as ghosts indicating that they might be the conduit for the dolomitizing fluids.

(2) From Late Devonian to Mississippian, the Brown zone reached a burial depth of 8000'. This interval was dominated by development of solution vugs, channels, and cavities primarily is the grain rich, algal rich and heavily bioturbated mud-rich facies. Deep burial dissolution also occured during this stage and was followed by the precipitation of saddle dolomite cement around the pore rims. Saddle dolomite cement is usually an indication of a high temperature environment.

C. Synthesis

(1) Both studies recognize the increasing burial depth and subsequent diagenesis. The microscopic study recognizes a second replacement dolomitization, followed by dissolution of the Brown zone and development of deep burial karst. The mega- and micro- scopic studies recognize saddle dolomite as an indication of hydrothermal fluid flow after dissolution.

Early Pennsylvanian to Mid-Pennsylvanian

A. Megascopic Study

(1) Uplift and possible karst development in the Healdton Field during the Morrowan. Although the Arbuckle was not exposed to the surface, meteoric waters could have gained access to the Brown zone using the fault system as a conduit. Fluid communication between the faults is present today as evidenced by a uniform oil-water contact.

(2) Cavern development and enhancement, and eventaul collapse.

B. Microscopic Study (Forgotson, Blatt and Liu, 1993)

(1) Early Pennsylvanian was dominated by fracturing and brecciation due to cavern collapse and tectonic deformation during uplift. Fractured and brecciated rocks have less cementation and lack dolomite cement. This enhanced reservoir porosity.

C. Synthesis

(1) Both studies are in agreement as to this period of uplift, dissolution and fracturing, and eventual cavern collapse. Both studies recognize the enhancement of poroisty due to brecciation that improves reservoir quality.

Mid-Pennsylvanian to Permian

A. Megascopic Study

(1) Migration of hydrocarbons and arrest of dolomite cementation. Hydrocarbons halted the further occlusion of the pores by saddle dolomite. This is the last fluid migration event.

B. Microscopic Study (Forgotson, Blatt and Liu, 1993)

(1) Migration of hydrocarbons and late phase calcite cementation. Deep burial karst may have continued during this time.

C. Synthesis

(1) As tectonic movement and subsidence began to acqueise, the last stage of diagenesis took place. The microscopic study suggests that deep burial karst contiued as did some late stage calcite cementation. Both studies recognize the migration of hydrocarbons as arresting any further cementation.

In summary, the prolific Brown Zone reservoir developed by way of: (1) replacement dolomitization, (2) subsidence and subsequent deep burial karsting, (3) uplift of the Healdton structure along with cavity/cavern collapse, (4) deposition of pore rimming saddle dolomite, and (5) finally hydrocarbon migration.

Chapter VII Exploration Strategies for Brown Zone Production

A. Upper Arbuckle Production and Exploration Strategies in Oklahoma

The Arbuckle has produced over 10 million barrels of oil in the Healdton Field (Dwight's Energy Data, 1991). A conservative estimate of the Brown Zone dolomite production is about 90% of all Arbuckle production within the Healdton Field. The Wade and Bray zone limestones have contributed approximately 10% of the Arbuckle production. The following discussion will briefly describe the geologic setting and associated trapping mechanisms for other large Arbuckle fields.

The upper Arbuckle in the ***Oklahoma City field*** produces from the ***dolomitic West Spring Creek*** (Gatewood, 1970). Unlike the West Spring Creek in the Southern Oklahoma Aulacogen, the upper Arbuckle of the Oklahoma City area is entirely dolomitized. Cumulative production from the Arbuckle in the Oklahoma City Field is approximately 18.2+ million barrels. Gatewood estimates that 75.5 million barrels of oil was originally in place, and that only 24% has been recovered because of water coning and inefficient completion and production practices. The trapping mechanism for upper Arbuckle in the Oklahoma City field is a prominent fold on the upthrown west side of a major north-south trending fault (Figure 34). The displacement of the fault to the east downthrown side is approximately 2400 feet. The pre-Pennsylvanian unconformity cuts into the upper Arbuckle on the crest of the fold.

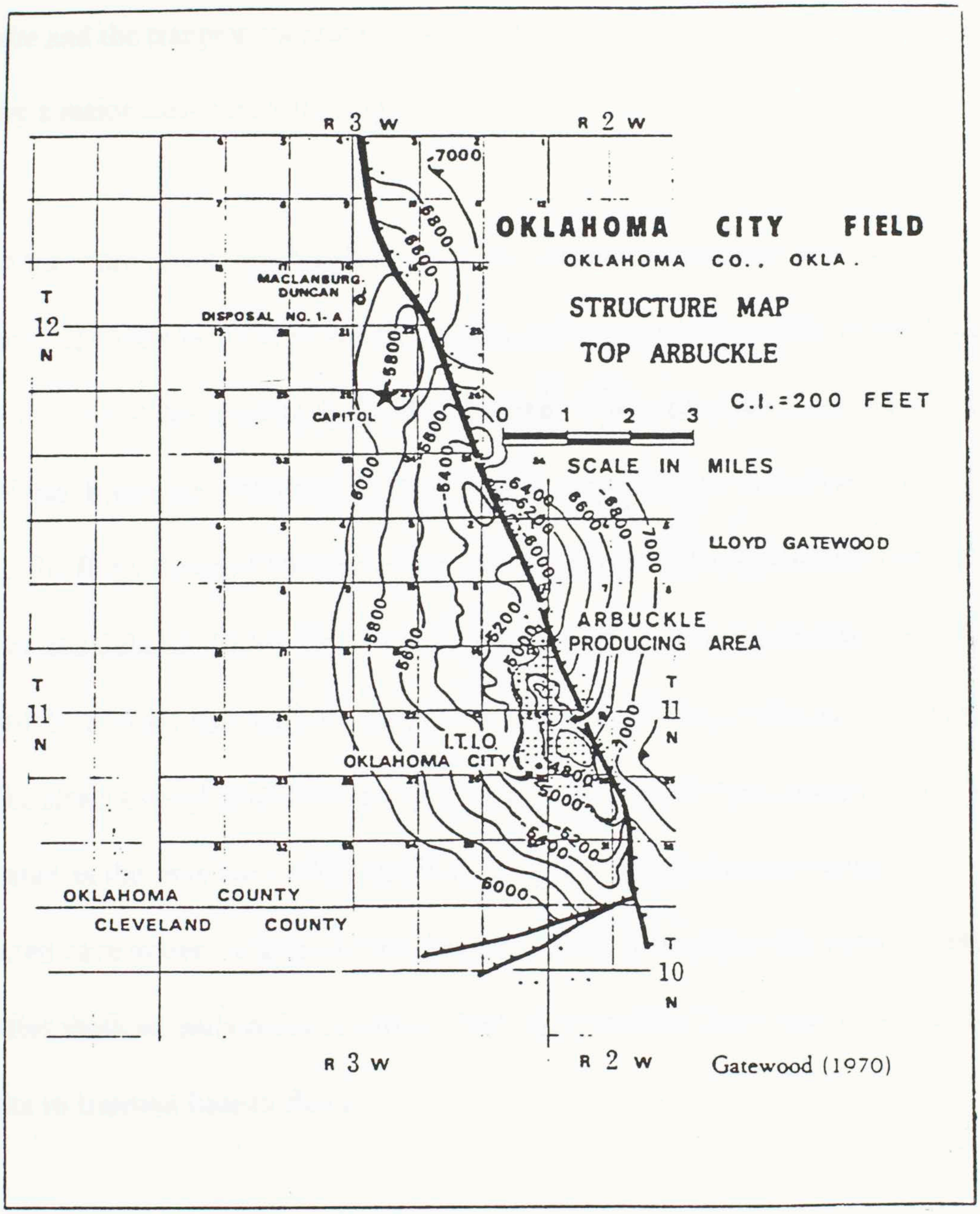


Figure 34. Upper Arbuckle structure map of the Oklahoma City field, Gatewood (1970).

Gatewood describes ***West Mayfield*** as producing from a ***fractured shelf facies dolomite*** and the trapping mechanism as several faulted horst blocks bounded on the north by a major east-west fault (Figure 35).

Two of the more recent notable discoveries of Arbuckle production are the Cottonwood Creek field in the Ardmore Basin and the Wilburton Field in the Arkoma Basin. The Arbuckle dolomite in the ***Wilburton field*** has estimated reserves of 400 BCF of gas. Carpenter and Evans (1991) have documented the Arbuckle producing zone as the ***West Spring Creek dolomite*** and the ***Brown zone dolomite*** (as defined Mescher and Schutlz, 1991). The trapping mechanism is a prominent fold bounded on the north by a major east-west trending fault with other faults within the field, (Figure 36). The strata overlying the Brown zone (middle and upper West Spring Creek) is designated as the cave roof, while the Brown zone is designated as one large connected cave system. Carpenter and Moore (1991) believe that the karst developed soon after shallow, early dolomitization. They also propose faults and fractures as conduits to transmit basinal fluids.

The author had the good fortune of examining some of the core and thin sections taken by CNG from the ***Cottonwood Creek Field***, and exchanging information with David Read, principal geologist for CNG at the time of the discovery. The 40 MMBO Cottonwood Creek field is a contrast in many ways to the dolomitic Arbuckle reservoirs.

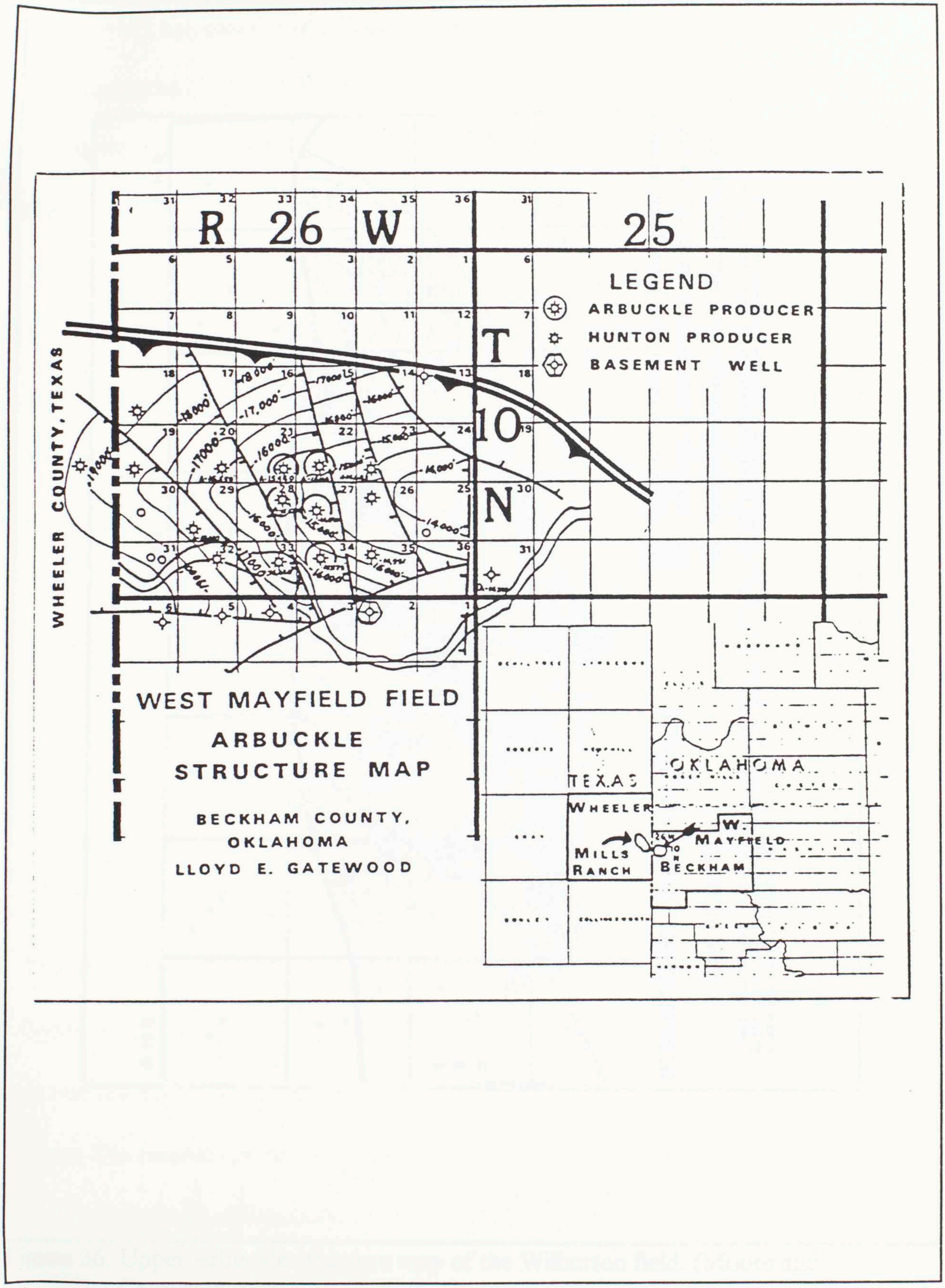


Figure 35. Upper Arbuckle structure map of West Mayfield, Gatewood (1970).

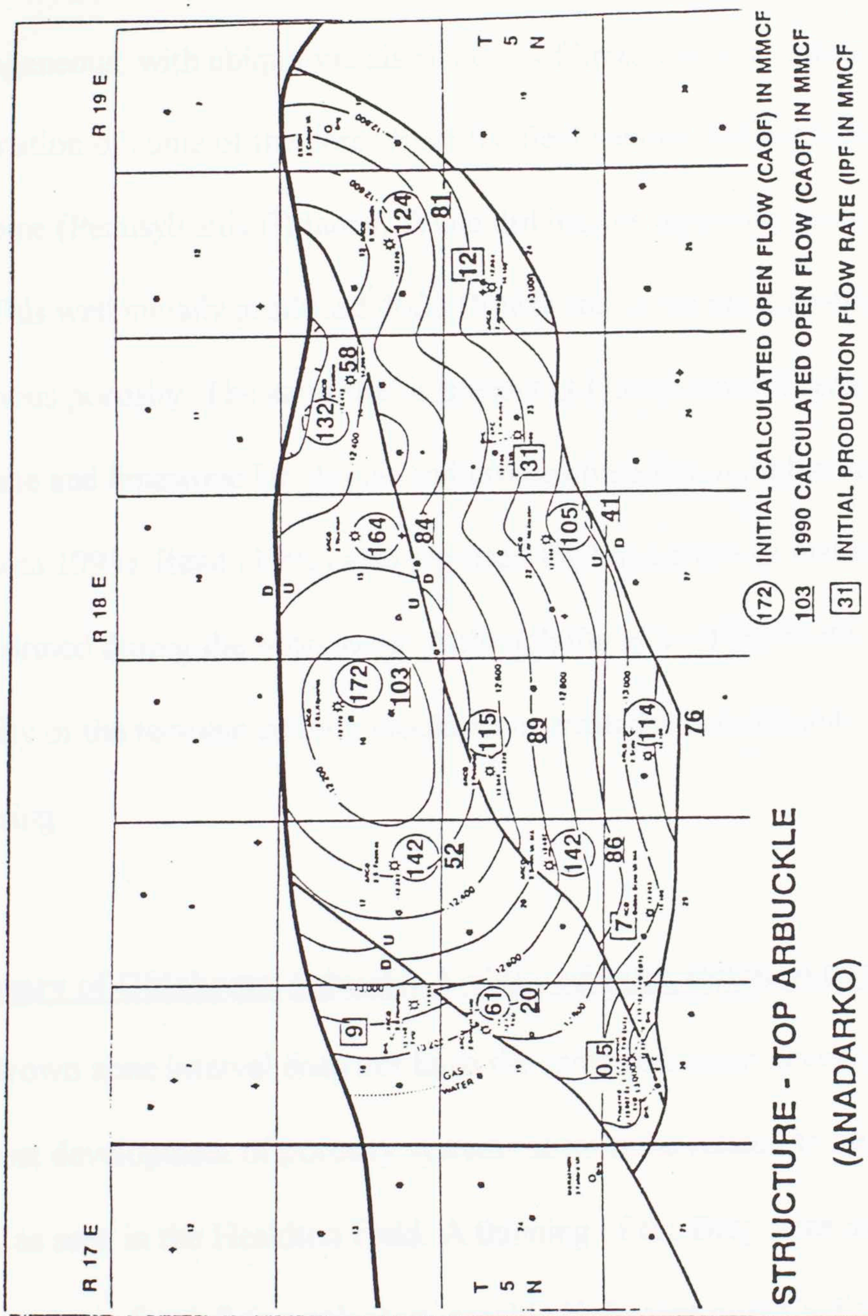


Figure 1. Structure map on top of Arbuckle Group over Wilburton field, Latimer County, Oklahoma. Numbers by wells show initial and 1990 calculated open flow (CAOF) potential in millions of CFGPD (cubic feet of gas per day) for tested wells, and actual initial and subsequent production flows (IPF) for untested wells. Base map is courtesy of Anadarko Petroleum Corp.

Figure 36. Upper Arbuckle structure map of the Wilburton field. (Moore and Carpenter, 1991).

Read (1991) has shown that the trapping mechanism is an overturned anticline, discerned by seismic data (Figure 37). Porosity logs show that the reservoir is heterogeneous, with ubiquitous distribution of limestone and dolomite. Derby's examination of some of the cores from the field yielded distinct Simpson sand grains, and some (Pennsylvanian?) fauna. While drilling the discovery well, the bit dropped 25 feet. This well initially produced 4000 BOPD and is the most probable indication of cavernous porosity. The karst that is present at Cottonwood Creek occurrs in both dolomite and limestone lithologies and crosses time stratigraphic boundaries (Latham, pers com 1991). Read (1991) also reported the karst to be of meteoric origin, and to have formed during the Morrowan. Although the bulk of the rocks are limestone, the intensity of the tectonic activity would have created a considerable amount of fracturing.

Summary of Oklahoma Arbuckle Fields and thier Relation to the Healdton Field

The Brown zone interval does not have the same dolomitic development regionally. The best development of porosity systems seem to be related to paleotopographic highs, as seen in the Healdton Field. A thinning of the Bray zone interval could be used as one criteria for defining paleotopographic highs that might indicate prospective areas. The reservoir in most Arbuckle fields is a fractured dolomite. It is imperative that diagenetic alteration occur to develop the reservoir.

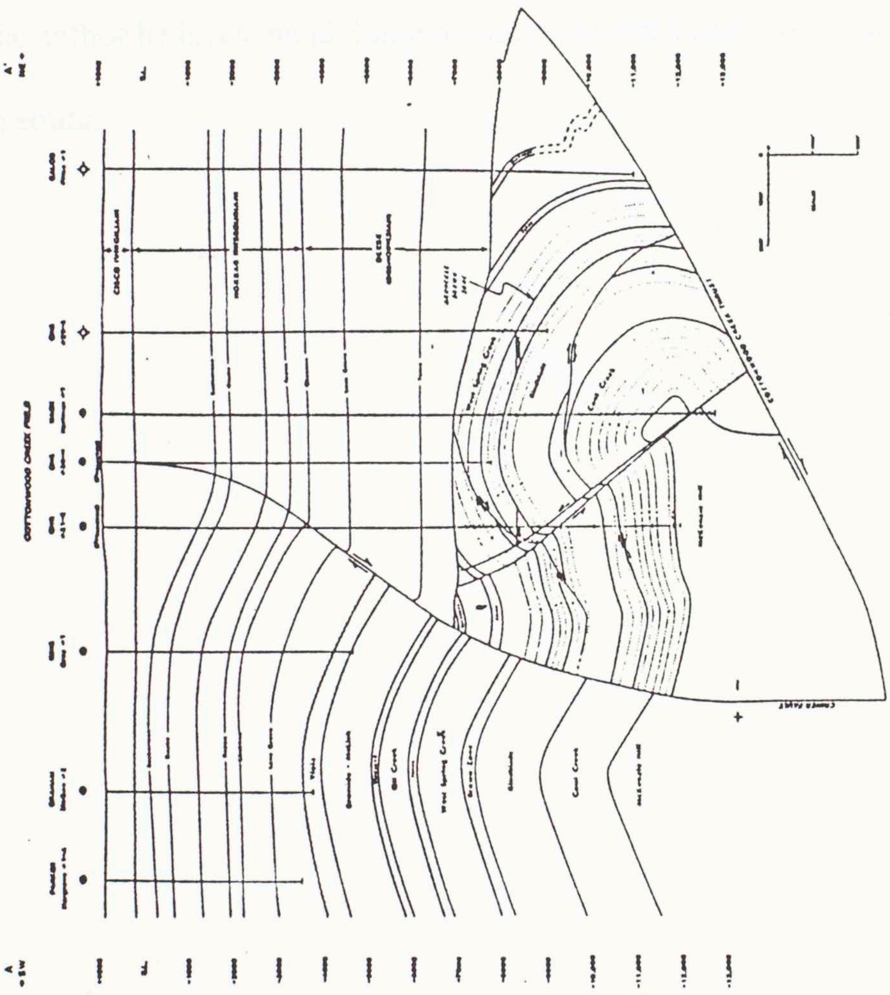


Figure 37. Cartoon cross section of the Cottonwood Creek field, Read (1991).

In the Healdton field, the Brown Zone is distinct from the Wade and the Bray Zones in that at some point in time, the Brown zone was dolomitized and the others were not. This first episode of dolomitization set the framework for all subsequent diagenetic alteration. The author believes initial dolomitization occurred prior to the deposition of the overlying strata.

Chapter VIII Summary and Conclusions

The aims of this study were to (1) provide insight into the reservoir development of the Brown zone and (2) look at exploration techniques that might best predict the similar reservoir developments in untested prospective areas. This was done by examining the upper Arbuckle vertically and the Brown zone laterally. Conclusions from this study of the upper Arbuckle are based on (A) lithology, (B) porosity and reservoir development, (C) karst development, (D) timing of the diagenetic sequences, and (E) comparison of other Arbuckle reservoirs in Oklahoma.

A. Lithology

(1) The Brown zone in the Healdton field was deposited in a shallow water environment.

(2) The Brown zone has undergone extensive replacement dolomitization; the Wade and Bray zones primarily have their original depositional limestone fabric intact.

(3) A depositional transition zone exists in the Brown zone between the Healdton field and the Shell Chase #1-28 approximately 2 miles north of the Healdton Field. The Brown zone stratigraphic equivalent in the Shell Chase #1-28 is a black carbonate mud with its original depositional fabric intact and was deposited in a deeper/quieter water environment than the Brown zone in the Healdton field.

B. Porosity and Reservoir Development

(1) The Brown zone has a variety of porosity types: intercrystalline from replacement dolomites, fracture porosity occuring from the time soon after deposition to the mid-Pennsylvanain, and breccia porosity from cavern collapse.

(2) The key component for all porosity development is the initial dolomitization; it provided a framework for further diagenetic fluids and increased the fracture potential far beyond that of the original limestone deposits.

C. Karst Development

(1) The Wade and Bray zones show comparatively little karst development, with low to nil effective matrix porosity and permeability. In contrast, the dolomitic Brown zone had a pre-existing porosity system that had the capacity to act as a conduit for karst developing fluids.

(2) The Brown zone has major karst development. Opportunities for both meteoric and basinal fluid karst (and dolomitization) development have existed at various times since deposition. The windows of opportunity for karst to develop are soon after deposition, deep burial subsidence, and after uplift of the Brown zone in the Morrowan.

(3) Fault planes and fracture networks provided an effective permeability pathway for karst fluids to enter the Brown zone.

D. Timing of Diagenetic Sequences

(1) A reservoir development model was proposed from the megascopic study. The broad contours of the paragenetic sequence were hypothesized as: (i) replacement dolomitization soon after deposition (ii) subsidence and subsequent deep burial karsting, (iii) uplift of the Healdton structure, (iv) deposition of pore rimming saddle dolomite, and (v) hydrocarbon migration.

(2) This sequence of diagenetic events was expounded upon and more closely defined by Forgotson, Blatt, and Liu in a detailed geochemical analysis of the cements from samples in the same area. The geochemical analysis provided a more definitive bracketing of the time period when dolomitization, karst development, and hydrothermal fluid flow occurred based upon burial depth, reservoir temperatures, and cement stratigraphy. This affirmed the broad contour sequence proposed in the megascopic study, and provided a more definitive sequence of diagenetic events.

(3) Uplift in the Morrowan enhanced the reservoir in two ways: (a) further fracture development of the brittle dolomite and (b) a possible late stage meteoric karsting episode.

FINAL THOUGHTS ON ARBUCKLE EXPLORATION

This study sought to provide insight as to why only one 600-800' zone is a prolific reservoir within an 8000-10,000' section of carbonates. Most Arbuckle reservoirs are a fractured and/or karsted dolomite, or a heavily fractured and karsted limestone (i.e., Cottonwood Creek). Dolomites have the highest fracture indice of all sedimentary rocks except for quartzite. One of the strongest conclusions from this study is that the initial development of replacement dolomitization was a major factor that would enable a number of porosity enhancements throughout the diagenentic and tectonic cycle. Based upon this study, a prospect within the aulacogen must be located in the optimum setting for dolomitization to occur. Therefore, one must do all that is possible to establish that the prospective area was an optimum site for replacement/secondary dolomitization.

One method to determine the optimum setting for dolomitization is to examine isopach interval thicknesses and available core samples. This method was tested by comparing lithologies and thicknesses over the Healdton field where dolomitization did occur to that of an area (Shell Chase well) that was most likely a depositional low and where the original limestone fabric was intact.

A salient point expressed by Arbuckle explorationist David Read (pers com, 1991) is "to realistically get an Arbuckle prospect tested it must be associated with structure", which is necessary for the trapping mechanism and fracturing. But tectonic movement now seems to have played a multiple role in creating the Brown zone reservoir: (1) to expose the Arbuckle reservoir to basinal fluids that can develop deep burial karst and subsequently deposit baroque dolomite, (2) subject the Brown zone to a high degree of fracturing during subsequent uplift (3) to create a structure for a trapping mechanism as a result of uplift.

Arbuckle reservoirs differ from one region to another (from Healdton to Wilburton to the Oklahoma City field). This study was focused primarily on Healdton type plays in the Southern Oklahoma Aulacogen. Expansion of these studies could better define the boundaries for each of these regions, and help determine the exploration strategy for each region.

Perhaps the strongest recommendation to advance the understanding of the Brown Zone and Arbuckle reservoirs is to take more conventional cores. This study would not have been possible if Sinclair and ARCO had not had the foresight to take whole cores of entire zones. To say that it is not cost effective to core the Arbuckle is myopic; the information derived from Arbuckle core will pay for itself many times over for Arbuckle explorationists.

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APPENDIX A

HAU # 5-3 THIN SECTION DESCRIPTIONS

(Using Folk and Dunham (1962) terminology where applicable)

3235	**Mosaic to chaotic dolomite breccia**, medium crystalline dolomite, euhedral to subhedral, fracture porosity, some of fractures filled gilsonite and micro breccia, possible precursor fabric: bioclastic pelletal dolomudstone
3242.3	**Chaotic dolomite breccia**, varying crystalline and clast size in filled with fine grained micrite and oil stain, large anhedral to subhedral crystals, others are medium to small subhedral to euhedral crystals, possible pelletal precursor fabric, interparticle breccia porosity to very low intercrystalline porosity.
3338.5	**Mosaic breccia**, fracture porosity, medium crystalline, tight dolomite clast matrix, clean interstices (between clasts), some microbreccia in between, possible mottle mudstone precursor fabric.
3593	**Crackle/fracture breccia**, medium crystalline, subhedral to euhedral, interstices filled with dolomite breccia, some lined with baroque dolomite
3747.0	**Dolomite**, medium crystalline, subhedral dolomite matrix, vuggy porosity, baroque dolomite cement, stylolites, some voids completely filled w/dolomicritic cement, infill of bitumen and detritus, shell fragment ghost

APPENDIX B

GENEVEA BRAY #1 THIN SECTION DESCRIPTIONS

(using Folk and Dunham (1962) terminology)

3293.8	**Ooid packstone, Oomicrite**. some ooids replaced by calcite, some rounded/mature, some centers are quartz grains, matrix is sparry micirite. Fair porosity, fair to low permeability, gravity/pendulus cement, aragonte radialized fresh water, oomouldic, intraparticle solution porosity.
3294.0	**Mudstone/sparry micrite, Biomicrite.** intramicrite some scattered quartz grains, vugular porosity with calcite cements, some vugs with micrite, small healed fractures. Possible ostrocod frag, vug with calcite cement, sponge spicules, pellets, very low interparticle porosity
3309.0	**Flat pebble conglomerate.** Rounded rip up mud clasts, ooids, crinoid plates, bivalve frags alternating with biopelmicrite layers, (small grains), poorly sorted
3317.5	**Criniodal grainstone, sorted biosparite.** Intermixed with micrite, gastropods, ostracods, pellets. Syntaxial overgrowths. **No visible porosity**
3644.0	**Spicular wackstone, Biomicrite.** possible trilobite fragment, Scour fill with dolomicrite, fractures with mosaic calcite, oosparite on top, rounded, **no visible porostiy**
3926.0	**Mudstone, Dismicrite**. Very few ooids Or medium inclasts, scattered quartz grains near or on stylolites, some calicified burrows in matrix, large fracture with calcite rim cement, infilled with micrite detritus, **no visible porosity**
3935.5	**Mudstone, Laminated Micrite** alt with dolomudstone and dolomicrite, scattered quartz grains, scour surface with quartz basal lag, micrite, basal lag quartz and ostracods, pellets some of matrix spar, calcite filled fractures, stylolites, **no visible porosity**