GEOLOGIC CONTROLS ON RESERVOIR QUALITY OF THE VIOLA LIMESTONE IN SOLDIER FIELD, JACKSON COUNTY, KANSAS

by

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Abstract

Jackson County, Kansas is situated on the west side of the Forest City Basin, location of the first oil discovery west of the Mississippi River (KGS), Production in the area is predominately from the Viola Limestone, and a noticeable trend of oil fields has developed where the basin meets the Nemaha Anticline. Exploration has been sluggish, because of the lack of an exploration model. Production rates have varied widely from well to well, even when they are structurally equivalent. The goal of this study was to determine the factors controlling reservoir quality in the Ordovician-aged Viola Limestone so that a better exploration model could be developed.

A two township area was studied to examine relationships between subsurface variations and production rates. In the absence of an available core through the Viola, drill cuttings were thin-sectioned and examined under a petrographic microscope to see the finer details of porosity, porosity type and dolomite crystal-size that are not visible under a binocular microscope. Production appears to be controlled by a combination of structural position and dolomite crystal size, which was controlled by secondary diagenesis in the freshwater-marine phreatic mixing zone. The best wells exhibited a Viola Limestone made up of 100% very coarsely crystalline, euhedral dolomite crystals. These wells occur on the east and southeast sides of present day anticlines, which I have interpreted to be paleo-highs that have been tilted to the east-southeast.

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Chapter 1 - Introduction

Exploration for petroleum in Kansas began with the initial discovery in 1860, and it has been a major economic contributor to the state ever since. Currently, the price of oil is near $100/barrel, which is creating a boom in the oil and gas industry and fueling exploration efforts. Even though production has continued for over 150 years, there is a lot more oil left in place, and new exploration paradigms are expected to increase the proven reserves in Kansas. It is estimated that only 31% of Kansas petroleum has been discovered (Kansas Geological Survey, 2012), therefore new exploration models are needed to discover the remaining 69% of Kansas' petroleum and unlock the potential of the under explored reservoirs.

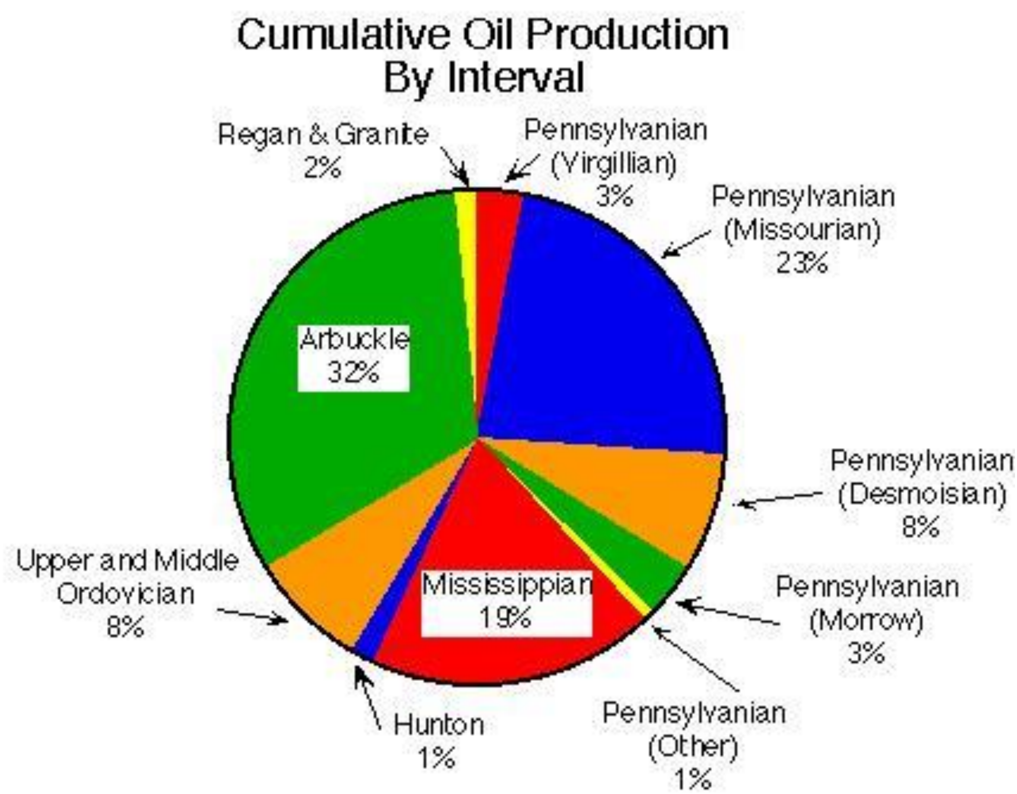

Figure 1.1 Kansas oil production by reservoir (Franseen et. al 2004)

As seen in Figure 1.1, nearly 75% of all oil produced in Kansas comes from only 3 reservoir systems (Mississippian, Arbuckle and Pennsylvanian). As such, these 3 major reservoirs are better understood while the others reservoirs are not, and are sometimes completely bypassed when drilling.

Study Area

The study area consists of 2 townships that are centered on Soldier Field, a newly discovered, producing oil field, located in northern Jackson County. Geologically, the study

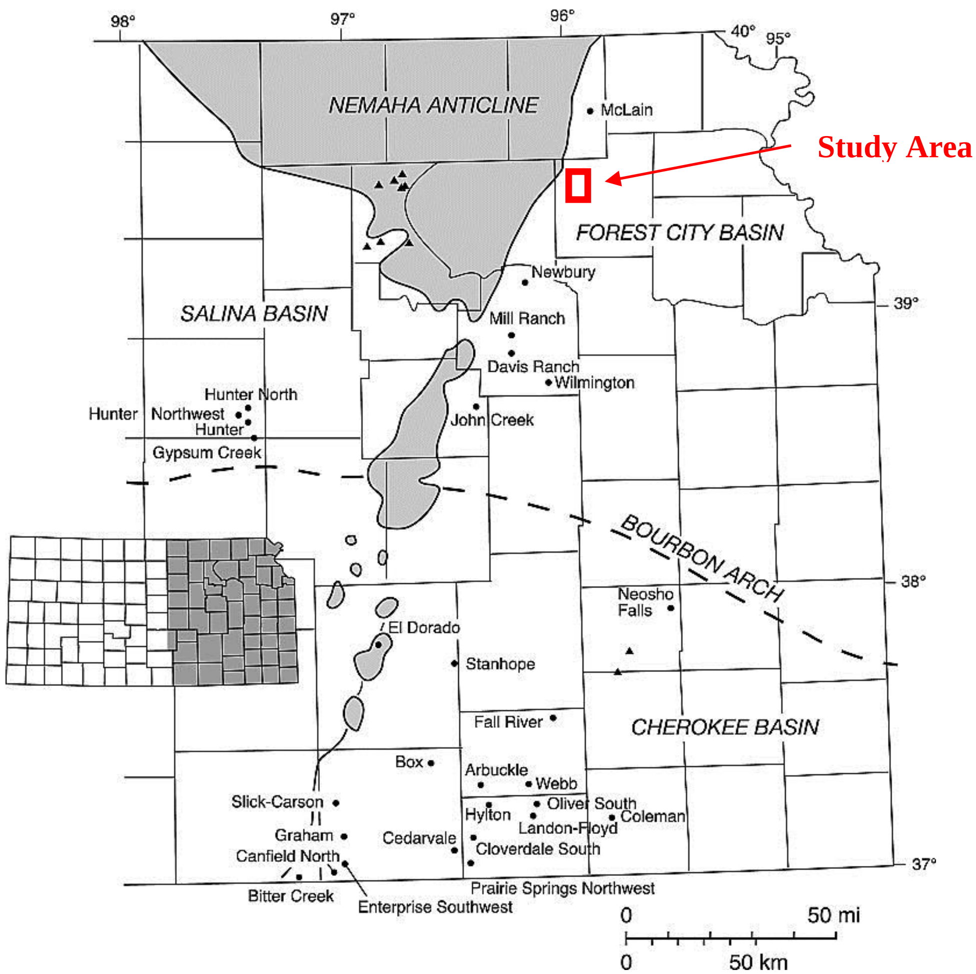

Figure 1.2 Location of study area with respect to major oil fields and provinces of Eastern Kansas. Unnamed triangles represent Kimberlites.

area is located on the western edge of the Forest City Basin that converges with the Nemaha uplift (Figure 1.2). It is situated in a line of producing fields that runs parallel to the trend of the Nemaha anticline and the Humboldt Fault. This trend can be followed SSW from the Kansas-Nebraska border in Nemaha County through Jackson and Wabaunsee Counties, and ending in Morris County (Figure 1.3). Fields along this trend include the McClain, Davis Ranch, and John Creek fields which have produced a cumulative of 21.3 million barrels of oil to date from the Viola Limestone (KGS). The majority of the smaller oil fields along the trend have produced several hundred thousand barrels of oil each. There at least 17 of these 'smaller' fields with a minimum cumulative production of one hundred thousand barrels of oil. Cumulatively, these 17 fields have produced 6.38 million barrels of oil.

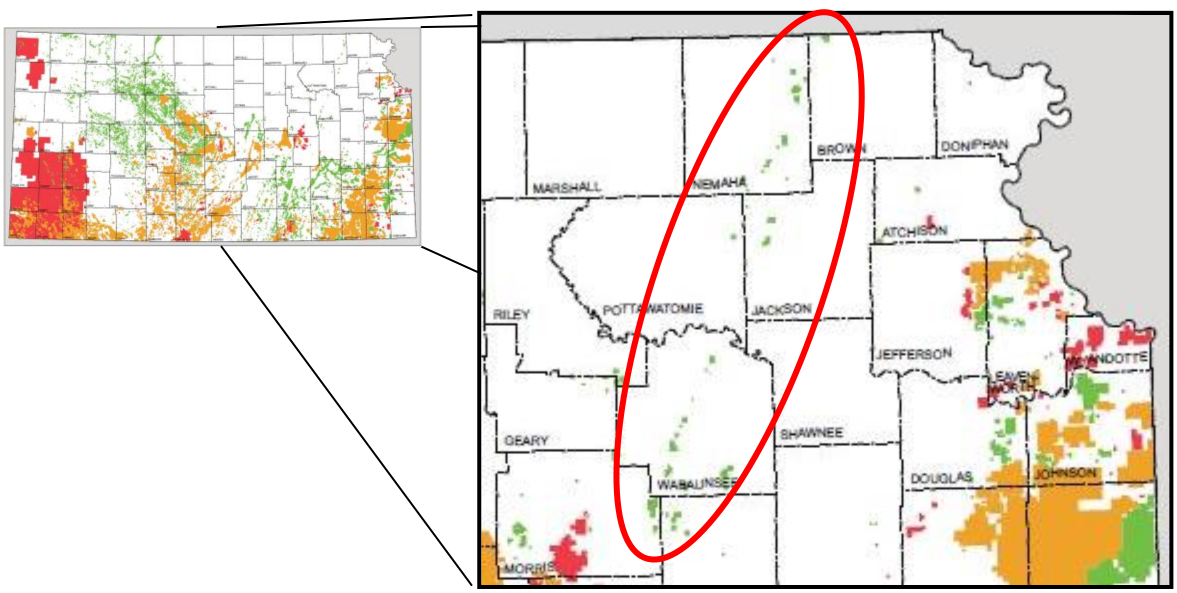

Figure 1.3 Trend of producing Viola Limestone oil fields along western edge of the Forest City Basin (modified from KGS)

Stratigraphy

Middle Ordovician rocks above the Arbuckle Group comprise the Simpson Group, which includes unnamed beds of sandstone and shale, the St. Peter Sandstone, and the Platteville Formation, and the Viola Limestone. The Viola Limestone of Kansas, which is upper Middle Ordovician, represents only part of the Viola present in Oklahoma. It consists of dolomite and limestone strata containing some cherty beds characterized by black flecks and spicular and

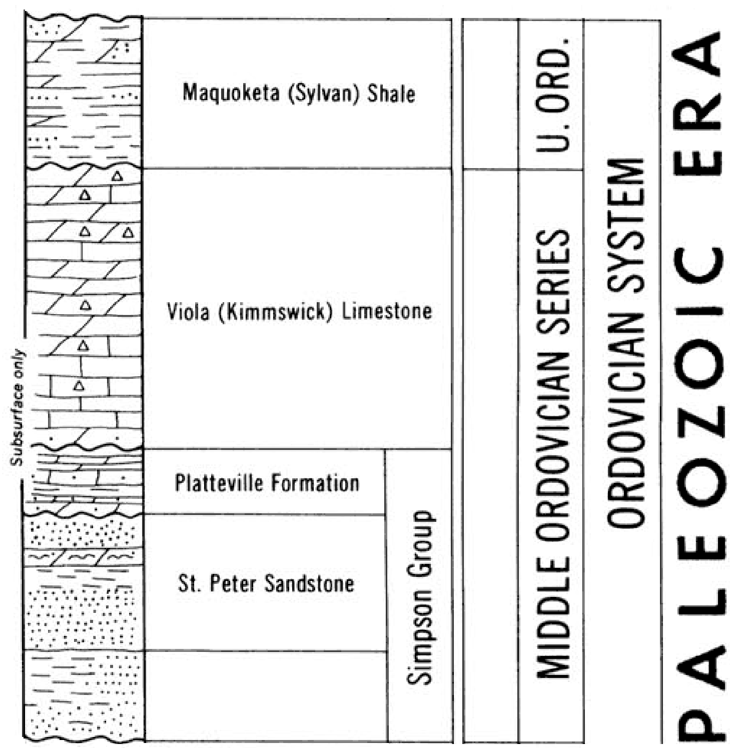

Figure 1.4 Stratigraphy of Middle and Upper Ordovician Series (modified from Zeller, 1968)

tubelike fragments of microorganisms. In deep parts of the North Kansas basin, the carbonate rocks of the Viola are dominantly dolomite, but toward margins of the basin earthy and granular limestone beds are present, especially at the base (Lee, 1943). The Viola occurs throughout the State except in places on the Central Kansas uplift, in northwestern Kansas, on the Chautauqua arch, and on the northern end of the Nemaha anticline. In Kansas it is bounded both above and below by unconformities (Zeller et al, 1968). It is at its maximum thickness of 310 feet at the Kansas –Nebraska border in Washington County, and gradually thins to 20 feet thick in the southwest part of the state.

In the study area, fine to coarsely crystalline dolomite composes over 95 % of the Viola Limestone. It replaces both micrite matrix and grains, and occurs as void-filling intergranular cement. Depositional textures (e.g., grains and types of porosity) are difficult to distinguish due to pervasive dolomite replacement, which obliterates original textures. For the most part, this dolomite is thought to have formed relatively early, perhaps in the freshwater-marine phreatic mixing zone (Caldwell and Boeken, 1985).

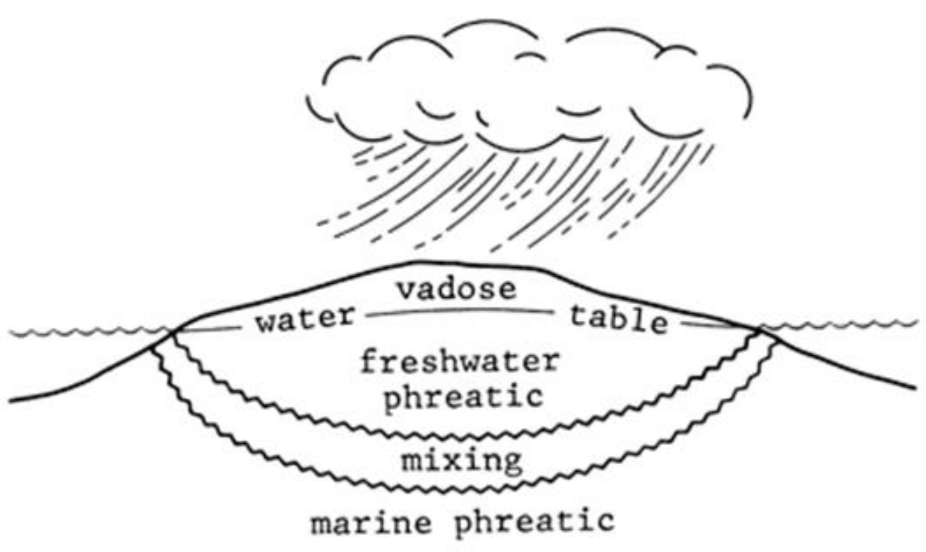

Figure 1.5 Idealized, shallow-subsurface carbonate diagenetic environments, not to scale. Dolomitization takes place in the freshwater-marine mixing zone (from Caldwell and Boeken, 1985)

In areas of Kansas where the Viola has not undergone complete dolomite replacement, original depositional textures are still visible. In these areas, the Viola consists of mixed-skeletal packstones, wackestones, and mudstones (Caldwell and Boeken, 1985 and St. Clair, 1981). More specifically, in the Forest City Basin, biota (echinoderms, brachiopods, and bryozoans) in the upper part of the formation suggest deposition on a relatively shallow, open-marine shelf in waters a few meters to a few tens of meters deep. However, planar and cross-stratified grainstones and packstones of the lower Viola suggest deposition in shallower, more agitated, marine waters (Caldwell and Boeken, 1985).

Paleogeography and Depositional Setting

During the time period in which the Viola was deposited, North America was located near the equator and an extensive epicontinental sea covered the majority of the continent (Barnes, 2004). Sedimentation was controlled by this and the Transcontinental Arch (Ross, 1976). Kansas was split from the northwest corner to the southeast by the Central Kansas Arch which was part of the Transcontinental Arch (St. Clair, 1981).

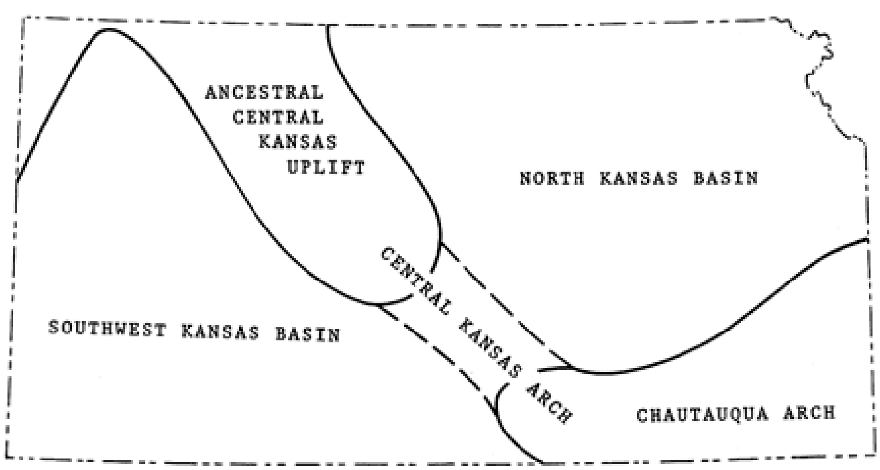

Figure 1.6 Major influencing structures present in Kansas during time of Viola deposition (from Merriam, 1963)

This created a shallow sea across the North Kansas Basin, where the study area would have been located at the time, which created an environment suitable for limestone deposition. Because the Viola was deposited in this type of environment, it is considered to be a shelf carbonate. Also, during deposition there were two marine transgressions (Bornemann et al., 1982), which are represented in some areas by differing petrology throughout the formation (St. Clair, 1981 and Newell, 2000).

After deposition, there have been multiple erosional events that have affected the Viola, and have removed it from some of the structural highs across Kansas, so it is now completely absent from the subsurface in roughly 30% of the state (Newell, 2000). The area being studied was also affected structurally by the Nemaha Uplift, which created the Nemaha Anticline. The anticline is faulted along this eastern side in several areas by high angle reverse and normal faults (Merriam, 1963). Splays from these faults may be present in the study area. This structural activity produced hydrocarbon traps along the eastern side of the Nemaha Uplift and the western edge of the Forest City Basin. The Viola is missing on all of the structural highs in Kansas, including the Nemaha Anticline, so there is speculation on the possibility of a stratigraphic trap (Lee, 1943), though based on regional structure and regional dip this seems very unlikely.

Importance of Viola Reservoirs

The Viola Limestone has been a proven hydrocarbon producer across the state of Kansas for over 100 years, and a study of ultimate oil recovery across the midcontinent (Adler, 1971) estimated that 11% of all oil production will come from the Middle to Upper Ordovician-aged formations. The last report of petroleum production from Kansas was published by the Kansas

Geological Survey in 2004, but at that time an estimated 275 million barrels of oil had already been produced from the Viola alone. The state of Kansas has remained a top 10 oil producing state since the 1900s, but for that to continue, new or under explored reserves must be realized. One of those under explored reservoirs is the Viola Limestone, especially in the Forest City Basin of northeast Kansas.

The oil fields that make up the trend being investigated produce mostly, or solely, from the Viola Limestone. The 20 largest Viola fields in the trend have produced a cumulative of 27.7 million barrels of oil. This production accounts for 10% of the total Viola production from Kansas, and all of this is contained in parts of five counties. Despite this proven production, research to examine future petroleum potential from the Viola formation has been concentrated in areas of Kansas where petroleum production is the greatest. These areas include the Hugoton Embayment and the Sedgwick Basin. In these areas the Viola is typically a secondary exploration target. In the Forest City Basin, the Viola is most often a primary target, but exploration in this area has historically been slow compared to the before mentioned petroleum basins. A limited number of producing reservoirs makes exploration riskier here, and there is not a thorough exploration model, which adds to the risk. The goal of this study is to explain the variations in reservoir quality and to contribute to the development of a new exploration model.

Chapter 2 - Porosity and Dolomitization

Carbonate Porosity Types

Porosity plays a key role in determining the quality of a reservoir. Porosity is simply the volume of the void spaces within the rock. It is an important reservoir characteristic to predict, because the more pore space a rock has, the more oil and gas it can potentially hold. Also critically important in hydrocarbon production is permeability, which is a measure of the connectedness of those pore spaces. The type of porosity can positively or negatively impact the amount of permeability, which in turn, affects the hydrocarbon recovery. Therefore, the ability to identify different types of porosity is important in this study.

Porosity types used in this study will be based on the definitions as defined by Choquette and Pray's (1970) classification of carbonate porosity. They defined 15 different types of carbonate porosities; however, in this study I will only refer to intercrystalline, vuggy, fracture and moldic porosity types.

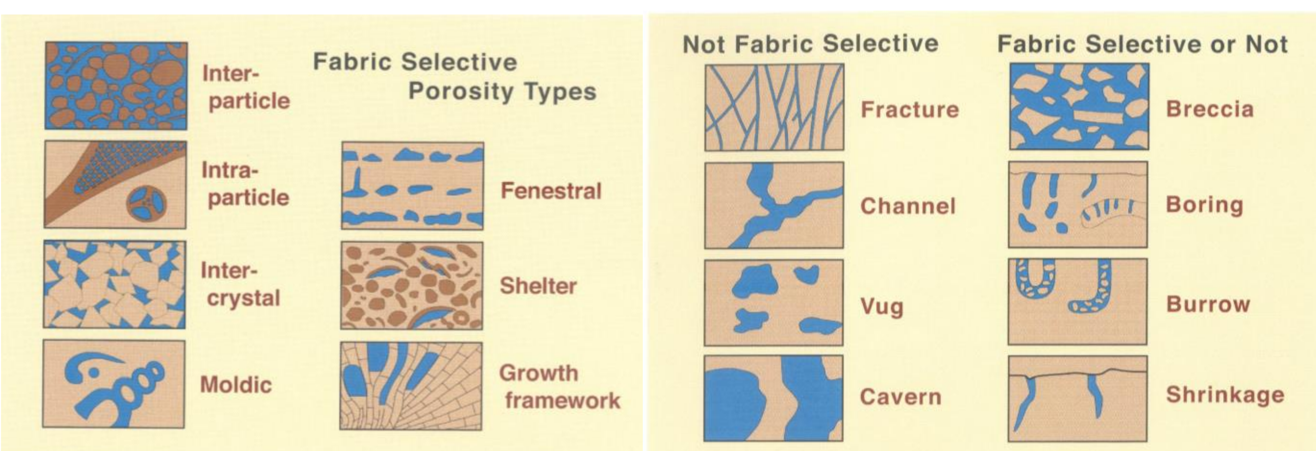

Figure 2.1 Carbonate porosity types (from Scholle and Ulmer-Scholle, 2003, originally modified from Choquette and Pray, 1970)

Intercrystalline, or intercrystal, porosity occurs between crystals of similar size that have formed by mineral recrystallization or dolomitization. This occurs as the fluid chemistry changes within the rock. The chemistry can change late in burial, due to hydrocarbon maturation, or earlier if the limestone is influenced by meteoric water caused by an unconformity. The size of the crystals being formed has an impact on permeability. Permeability will decrease as the size of the crystals decrease, because of excessive surface tension effects (Choquette and Pray, 1970).

Vuggy porosity is described as irregular holes that can cut across grains and cement boundaries within the rock. Vugs and vuggy porosity are probably the most commonly used porosity type when referring to carbonates, as definitions and usages vary widely by geologist. According to Choquette and Pray (1970), a "vug" is a pore that (1) is somewhat equant, or not markedly elongated, (2) has a diameter greater than 1/16 mm (and visible to the unaided eye), and (3) is not fabric selective. Vuggy porosity is dominantly a secondary porosity and most often occurs because of dissolution. Most vugs may represent solution enlargement of fabric-selective pores and occur at a stage in digenesis when solution is apparently indiscriminate of fabric elements.

Fracture porosity is porosity formed by fracturing. "Fracture porosity generally is used for porosity occurring along breaks in a sediment or rock body where there has been little mutual displacement of the opposing blocks." In carbonates, fractures can originate in a number of ways. Most common is due to any kind of tectonic deformation, but may also come about from collapse or slumping due to dissolution (Choquette and Pray, 1970). Fractures are important in reservoir rocks because they connect pores, creating permeability that may not have been present originally.

Moldic porosity is a secondary process in which grains are removed by dissolution. In order for this process to occur there needs to be a distinct difference in solubility between the grains and the framework (Choquette and Pray, 1970). Moldic porosity can create good permeability if pores are interconnected.

Dolomitization

Dolomite is a complex mineral, and despite its economic importance in the petroleum industry, it remains poorly understood. The mineral dolomite can precipitate directly from solutions containing magnesium, calcium and carbonate ions to form cement or unlithified sediment (protodolomite), however, most dolomite forms through the chemical alteration of precursor carbonate rock or sediment; primarily limestone or calcareous muds. When these precursor materials are exposed to magnesium-rich fluids, a portion of the calcium ions may be replaced by magnesium ions to form the more stable magnesium calcium carbonate known as dolomite. This process of forming secondary or replacement dolomite is called dolomitization (Mishari, 2009).

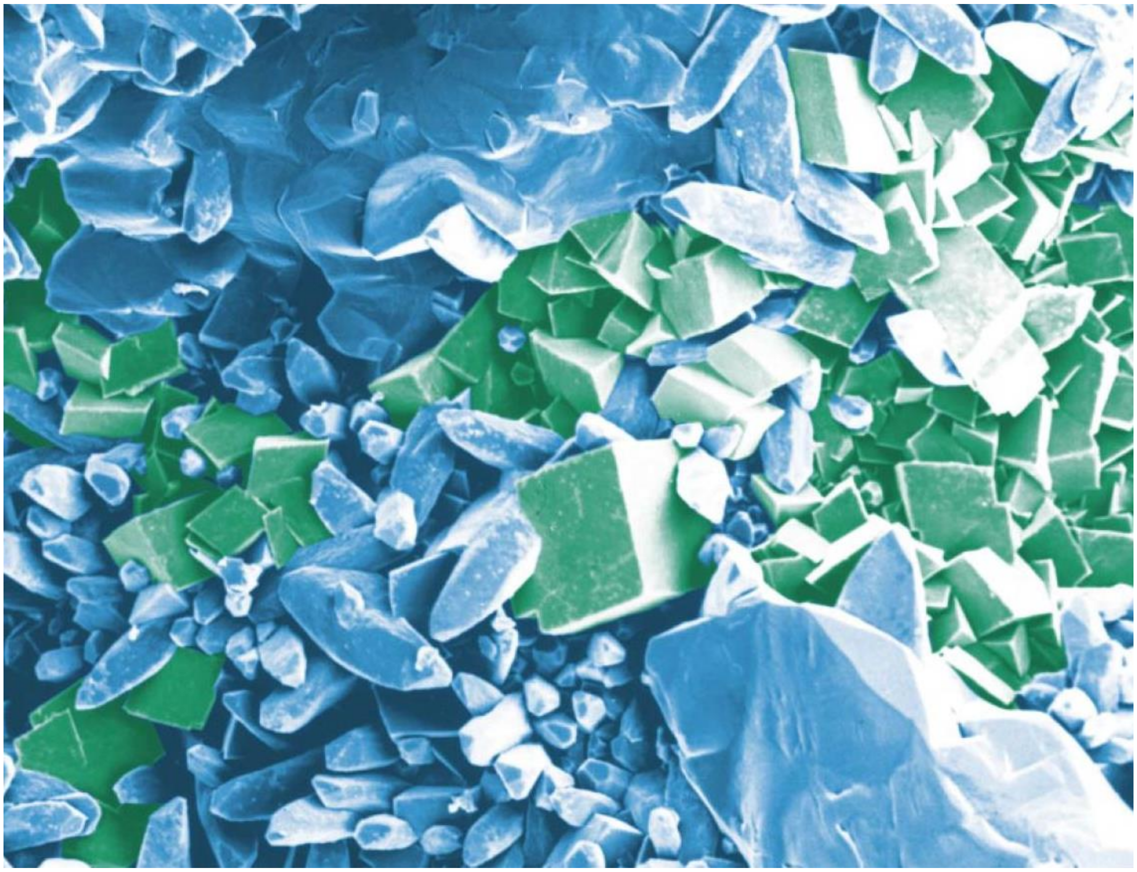

Figure 2.2 SEM image of dolomite replacement. Dolomite rhombs (green) growing over original calcite (blue) that was high in magnesium (from Nurmi and Standen, 1997)

Dolomitized limestones are important because they make up some of the world's largest oil and gas reservoirs, and dolomites typically make better reservoirs than limestones. Exploration efforts specifically targeted at dolomite reservoirs have paid off in the form of numerous oil and gas fields around the world. It is estimated that up to 50% of the world's carbonate reservoirs are in dolomite, and in North America that estimate ranges up to 80% (Warren, 2000).

The most important consequence of replacement dolomitization is an accompanying increase in porosity. Dolomite has a more compact crystal structure than calcite, so in theory total dolomitization of a limestone should result in a porosity increase of 13%, barring any subsequent compaction or cementation (Nurmi and Standen, 1997). While this is true in theory, it normally does not correlate to the actual rocks. Dolomitization generally creates greater effective porosity, but most diagenetic changes tend to reduce overall porosity. Effective porosity lacks a single definition, but it is best described as “the porosity of a rock or sediment available to contribute to fluid flow through the rock or sediment.” Studies have shown that the planar grains of dolomites create polyhedral pores (Nurmi and Standen, 1997). Consequently, as the rhombs develop they produce sheet pores and throats, rather than the tubular pores and throats that characterize limestones (Figure 2.2). Sheet pores and throats allow greater fluid flow, thus increasing effective porosity, even though overall porosity may have stayed the same or even decreased.

Dolomite crystal formation plays another role in reservoir quality. Dolomite frequently forms larger crystals than the calcite it replaces. Enlarged crystal size is associated with increases in pore-throat size and pore smoothness, which boost permeability in dolomites (Mishari, 2009). So more coarsely crystalline dolomites should have better permeability than those with fine or micro- sized dolomite crystals.

Allan and Wiggins (1993) evaluated the quality and characteristics of dolomite and limestone reservoirs around the world and found that dolomite reservoirs also hold their original porosity better at greater depths than limestones do

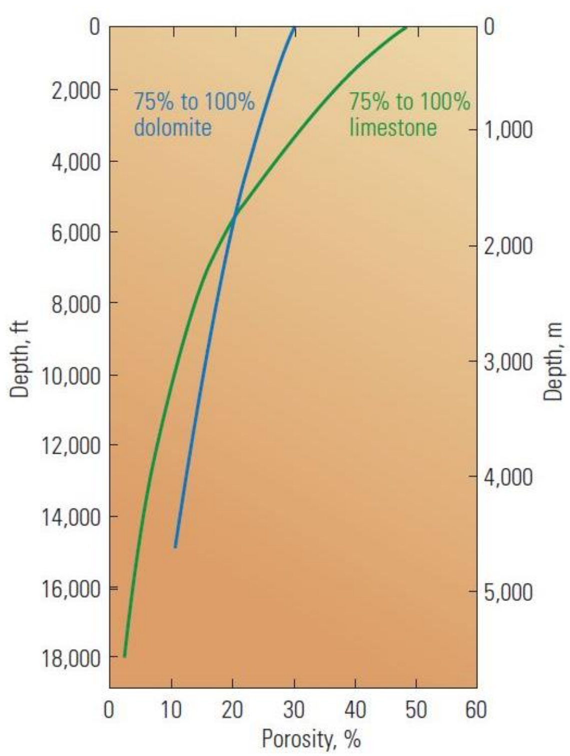

Figure 2.3 Progressive loss of porosity with depth (from Allan and Wiggins, 1993)

(Figure 2.3). This is very important for dolomite reservoirs around the world as exploration targets deeper and deeper reservoirs, but not as much for Kansas petroleum reservoirs. Wells in Kansas are rarely drilled to depths where this would become a factor.

Chapter 3 - Methods

Creating the Database

A data base was compiled comprising all known wells in Townships 6S-13E and 7S-13E, Jackson County, Kansas. Most well header information, including spot location, well symbols, operator, unique well identification number, lease name, and well remarks, was downloaded from public access information available from the Kansas Geological Survey website. Some well information for new wells being drilled in the Soldier Field was generously provided privately by George Petersen and L.D. of L.D. Drilling. This information was imported into Petra software, made available on an academic license to KSU from IHS, Inc. The location of each well was entered and referenced using the North American Datum 83.

Also obtained from the Geological survey were wire line logs and tops data in the study area. The Kansas Geological survey had sixty wire line logs available, and formation tops listed for approximately one-fourth of the wells. Each top that was imported into Petra was checked using scout cards and wire line logs from Walter's digital library in Wichita, Kansas. Dozens of tops taken from the KGS were incorrect, and had to be corrected by log evaluation to insure quality data for mapping. In addition, many wells had no formation top data listed by the KGS, so these had to be found using wire line logs or scout cards. Since the well logs are scanned photocopies of the original paper logs, and not digital, each log had to be calibrated so that Petra could recognize depths. All cartographic data that were imported into the map module of Petra were downloaded from the Kansas Geospatial Community Commons website (http://www.kansasgis.org/). The data downloaded included county lines and public land survey system. Compiling all of the data was very time consuming because all data had to be manually entered into Petra.

Using Petra

Using the cross-section module in Petra, tops for the Hunton Limestone, Maquoketa Shale, Viola Limestone, and Simpson Sandstone were hand-picked for all wells with available well logs. Tops were picked by interpreting log signatures of the gamma ray curve, neutron curve, density curve, and induction curve. Each formation looks significantly different in their log characteristics (Figure 3.1). No type log had been established for Jackson County which made picking tops more challenging. Eventually, cross referencing logs from the Leach Field and the McClain Field in township 4S-14E proved to be the most reliable, as they are the most intensely drilled fields around the study area.

After all tops were picked, structure maps were constructed to aid in determining current day structure, paleostructure, and stratigraphy. Structure maps were constructed on the top of the Hunton, Maquoketa and Viola formations, using the map module in Petra. A structure map of the Simpson was created, but a lack of deeply drilled wells makes it somewhat unreliable. The main module in Petra calculated the thickness of the formations for all wells. Isopach maps of the Viola Limestone and Maquoketa Shale were constructed using the calculated formation thickness values. The purpose of creating this variety of maps was to aid in interpreting the data. Structure maps were combined with production data to determine the control of structure on production. Isopach maps combined with production data were created to determine if thickness has influence on the quality of the reservoir. A variety of wells were chosen to examine well cuttings based upon the different maps and well logs. The array of wells that were chosen had variable production rates.

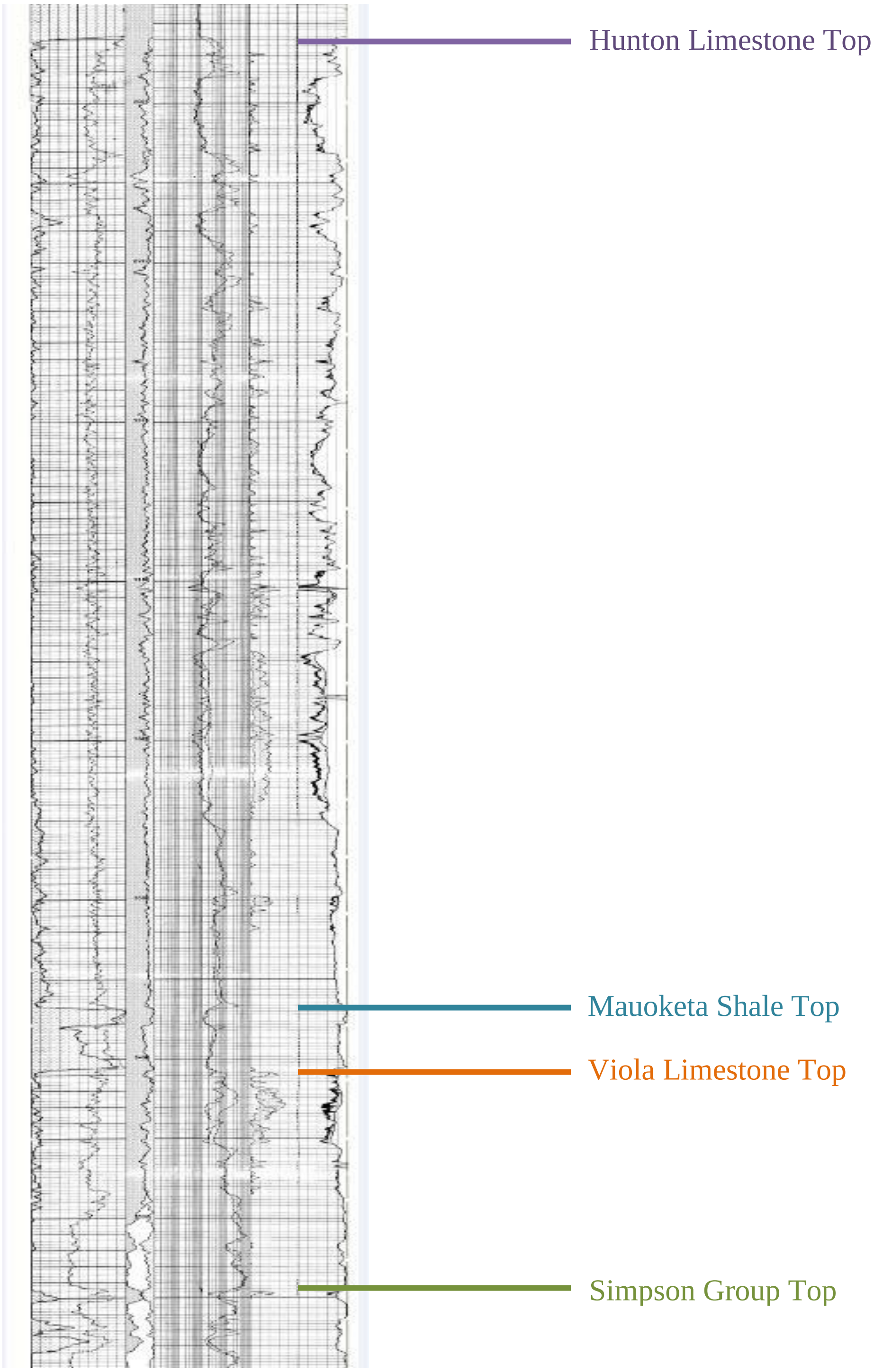

Figure 3.1 Differences in log characteristics for the Hunton, Maquoketa, Viola and Simpson formations.

Well Cuttings

Twelve wells were picked for drill-cutting study and obtained from the Kansas Geological Survey Well Sample library in Wichita, Kansas. Before viewing the cuttings for each well, the lag time was estimated from the log data and drill time data, in order to correctly predict the sample depth that contains the samples from the Viola Limestone formation. The Viola was easily distinguished from the overlying Maquoketa Shale, which made finding the correct sample depths easier. All cuttings at the depth of the Viola were first examined using a binocular microscope. The cuttings were viewed to get a sense of the type and amount of porosity present, crystalline size and texture, and determine if any oil staining was still present. Individual cuttings were then hand-picked from each well and mounted as grain mounts. These were mounted using an epoxy resin, and then hand polished to a thickness of approximately 30 microns using corundum powder to create the thin section. Each thin section was carefully viewed under a petrographic microscope to more clearly examine variations in crystal size and shape, and porosity types in greater detail than the binocular microscope allows.

Chapter 4 - Results

Thin Sections

Table 4-1 lists the results of the drill cutting examination done by creating thin sections and viewing under a petrographic microscope. Thin sections were viewed to see porosity, determine porosity type, and to see the dolomite crystal size and shape to determine if any of these factors were controlling reservoir quality. Crystal size and shape descriptions were based on Scholle and Ulmer Scholle's (2003) Guide to the Petrography of Carbonate Rocks. Figure 4.1 shows names given for crystal sizes and Figure 4.2 shows differences in crystal shapes. Images of thin sections can be found in the Appendix.

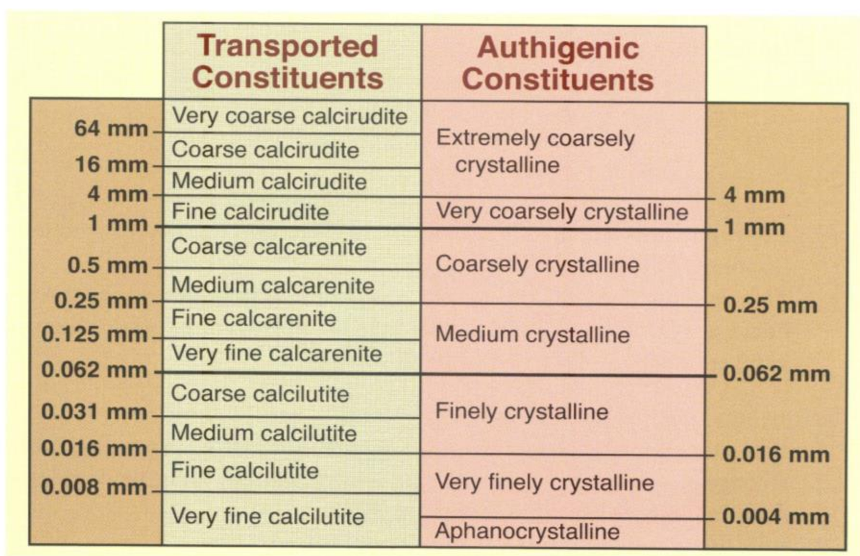

Figure 4.1 Names for crystal sizes used in Table 4.1 (from Scholle and Ulmer-Scholle, 2003)

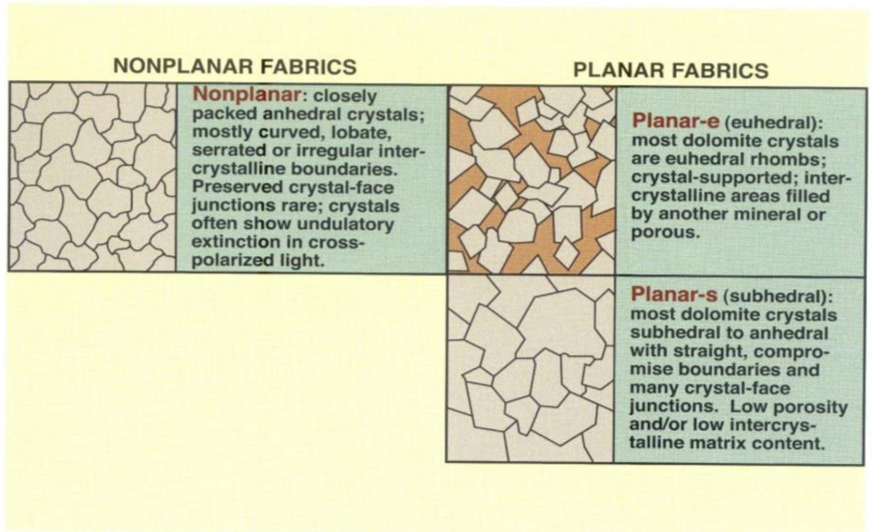

Figure 4.2 Description of crystal fabrics seen in replacement dolomites

Table 1 Descriptions of thin sections

Field	Well	Depth (ft)	Porosity Type	Comments	Figure
Soldier	Henry Trust 4	3340-3350	Vuggy, Intercrystalline	Great porosity, euhedral, very coarsely crystalline	7.1
Soldier	Henry Trust 4	3340-3350	Vuggy, Intercrystalline	Very coarsely crystalline, euhedral	
Soldier	Henry Trust 4	3350-3360	Vuggy, Fracture, Intercrystalline	Very coarsely crystalline, euhedral	
Soldier	Henry Trust 4	3350-3360	Intercrystalline	Very coarsely crystalline, euhedral	
Soldier	Henry Trust 4	3360-3363	Vuggy, Intercrystalline	Very coarsely crystalline, euhedral	

Soldier	Henry Trust 4	3363-3370	Fracture, Intercrystalline	Dolomite crystals begin to get smaller, coarse to very coarse, subhedral to euhedral	7.2
Soldier	Henry Trust 4	3370-3380	None	A few calcite crystals remain, coarsely crystalline, subhedral	
Soldier	Henry Trust 5	3375-3380	Vuggy, Intercrystalline	Very coarse to coarsely crystalline, euhedral	7.3
Soldier	Henry Trust 5	3380-3390	Intercrystalline	Very coarse to coarsely crystalline, euhedral	7.4
Soldier	Henry Trust 5	3390-3400	Intercrystalline, but not abundant	Coarsely crystalline, subhedral	
Soldier	Henry Trust 5	3400-3410	Intercrystalline, but not abundant	Coarsely crystalline, subhedral	
Soldier West	Dugan 1	3410-3416	Vuggy, Intercrystalline	Euhedral, Very coarsely crystalline, but rhombs smaller than in Henry Trust 4	7.5
Soldier West	Dugan 1	3416-3420	Intercrystalline	Perfectly euhedral dolomite rhombs, very coarse to coarsely crystalline	
Soldier West	Dugan 1	3420-3430	Vuggy	Subhedral, coarsely crystalline	
Soldier West	Dugan 1	3430-3440	None	Subhedral, medium crystalline	

Soldier West	Dugan 2	3400-3407	Intercrystalline	Euhedral to subhedral, very coarsely crystalline, but rhombs smaller than Henry Trust 4	
Soldier West	Dugan 2	3407-3410	Intercrystalline, Vuggy	Euhedral to subheadral, very coarse to coarsely crystalline	
Soldier West	Dugan 2	3410-3420	Intercrystalline	Coarsely crystalline, subhedral	7.6
Soldier West	Dugan 2	3420-3430	None	Subhedral to nonplanar, coarse to medium crystalline, some calcite remains	
Soldier West	Dugan 2	3430-3440	None	Individual crystals not identifiable	
Wildcat	Rieschick 1	3400-3410	Vuggy	Coarsely crystalline, subhedral	
Wildcat	Rieschick 1	3410-3420	Intercrystalline, Vuggy	Coarse to medium crystalline, subhedral	7.7 7.8
Wildcat	Rieschick 1	3420-3430	Slightly vuggy	Medium crystalline, subhedral to nonplanar	
Wildcat	Rieschick 1	3430-3440	None	Medium crystalline, subhedral to nonplanar, calcite present	
Wildcat	Carl V Smith 1	3530-3540	Slightly vuggy, Fracture	Medium crystalline, subhedral to nonplanar. No effective porosity	7.9
Wildcat	Carl V Smith 1	3540-3550	Fracture	Cannot distinguish individual crystals, nonplanar	

Wildcat	Carl V Smith 1	3550-3560	None	Cannot distinguish individual crystals, nonplanar, some calcite remaining	
Wildcat	Waters 1	3400-3404	None	Nonplanar; mass of dolomite. No effective porosity. Striations and twinning in dolo.	
Wildcat	Waters 1	3400-3404	None	No individual crystals	
Wildcat	Waters 1	3400-3404	None	No individual crystals	
Wildcat	Waters 1	3404-3410	None	No individual crystals	
Leach	Wykert 1	3320-3325	Vuggy (smaller vugs)	Poor effective porosity; small pore throats. Subhedral, coarse to medium crystalline	7.10
Leach	Wykert 1	3325-3330	Vuggy (smaller vugs)	Coarse to medium crystalline, subhedral, some dol. rhombs have dark inclusions	7.11
Leach	Wykert 1	3330-3340	None	Subhedral to nonplanar, coarse to medium crystalline, some unreplaced calcite remains	7.11
Leach	Bennett A 5	3200-3210	Intercrystalline, Vuggy	Very coarse to coarsely crystalline, euhedral to subhedral	
Leach	Bennett A 5	3210-3212	Intercrystalline, Vuggy	Very coarsely crystalline, euhedral to subhedral	7.12

Leach	Bennett A 5	3212-3220	Intercrystalline, Vuggy	Very coarsely crystalline, euhedral to subhedral	
Leach	Bennett A 5	3320-3330	Intercrystalline	Coarsely crystalline, subhedral	
Leach	Bennett A 5	3330-3340	Intercrystalline	Coarsely crystalline, subhedral	
Leach	Leach 'A' 1	3270-3280	Intercrystalline, Vuggy, Fracture	Coarse to very coarsely crystalline, euhedral to subhedral, but smaller than Bennett A 5	7.13
Leach	Leach 'A' 1	3280-3290	Intercrystalline, Vuggy	Coarse to very coarsely crystalline, euhedral to subhedral	
Leach	Leach 'A' 1	3290-3300	Slight intercrystalline, Vuggy, Fracture	Coarsely crystalline, subhedral, increasingly smaller crystals with depth	7.14
Leach	Leach 1	3230-3240	Excellent intercrystalline, Vuggy, Moldic	Very coarsely crystalline, up to 3 mm, perfectly euhedral, larger pores probably from selectively dissolved crystals (moldic porosity)	7.15
Leach	Leach 1	3240-3250	Intercrystalline, Vuggy	Very coarsely crystalline, euhedral	
Leach	Leach 1	3250-3260	Intercrystalline, Vuggy	Very coarsely crystalline, euhedral to subhedral	

Leach	Leach 1	3260-3270	Intercrystalline	Very coarse to coarsely crystalline, euhedral to subhedral	
Leach	M. A. Beightel 1	3320-3330	Intercrystalline, Vuggy	Very coarse to coarsely crystalline, euhedral to subhedral, limited intercrystalline porosity b/c of smaller crystal size	
Leach	M. A. Beightel 1	3330-3340	Intercrystalline, Vuggy	Coarsely crystalline, subhedral, rapid loss of porosity wih depth	7.16
Leach	M. A. Beightel 1	3340-3350	Slightly vuggy	Coarsely crystalline, subhedral	
Leach	M. A. Beightel 1	3350-3360	None	Medium to coarely crystalline, subhedral, no efective porosity, calcite	7.17

Subsurface Maps

The following maps were created to determine how different attributes control production. All maps were created using the Petra software and data collected through well log analysis, thin-section descriptions and formation thickness calculations. Maps labeled as structure maps show subsea structure of the top of a formation. Subsea data is used to eliminate variations in drilling depth caused by surface elevation changes.

Base Map

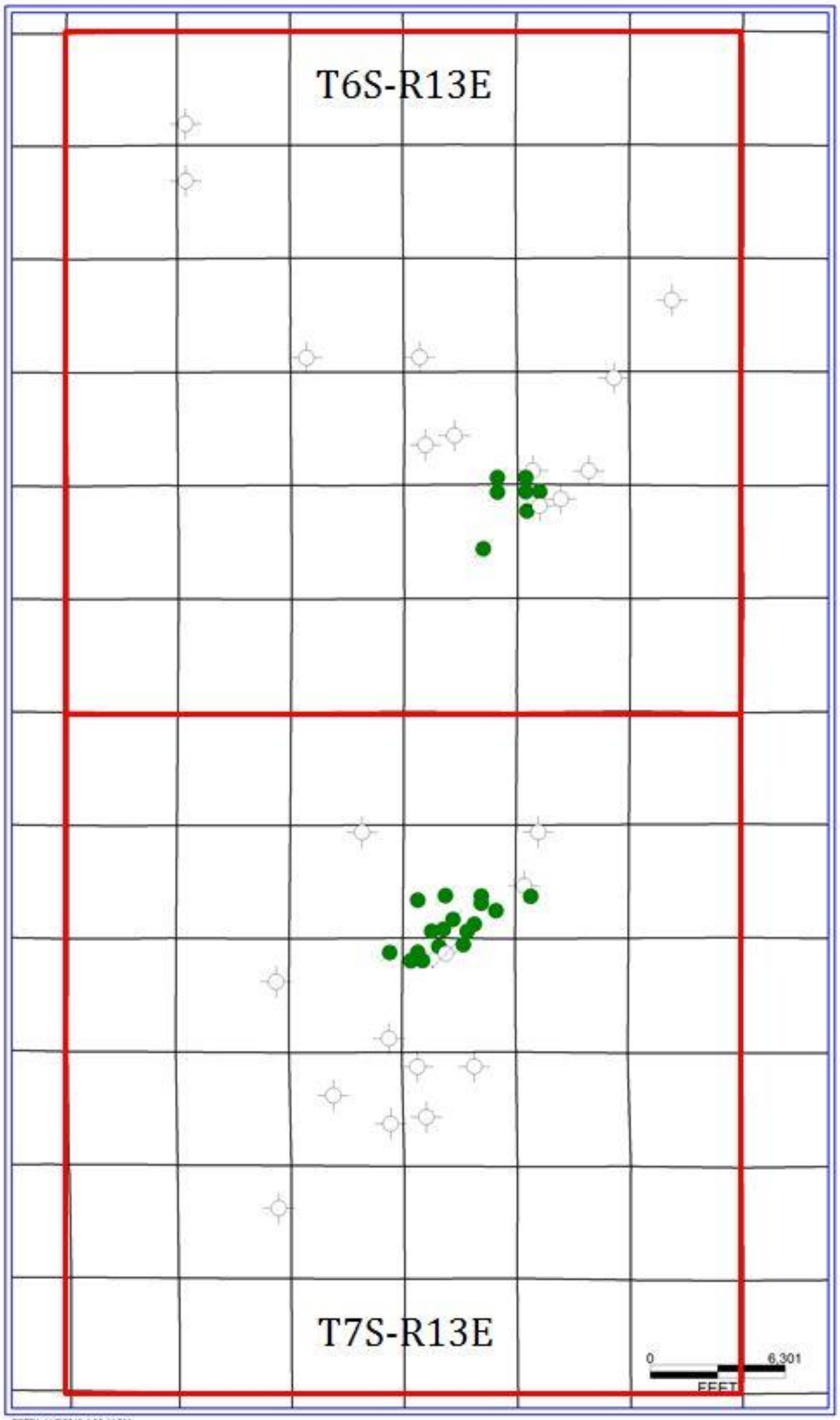

Figure 4.3 Base map of study area displying well location and symbols

Viola Structure

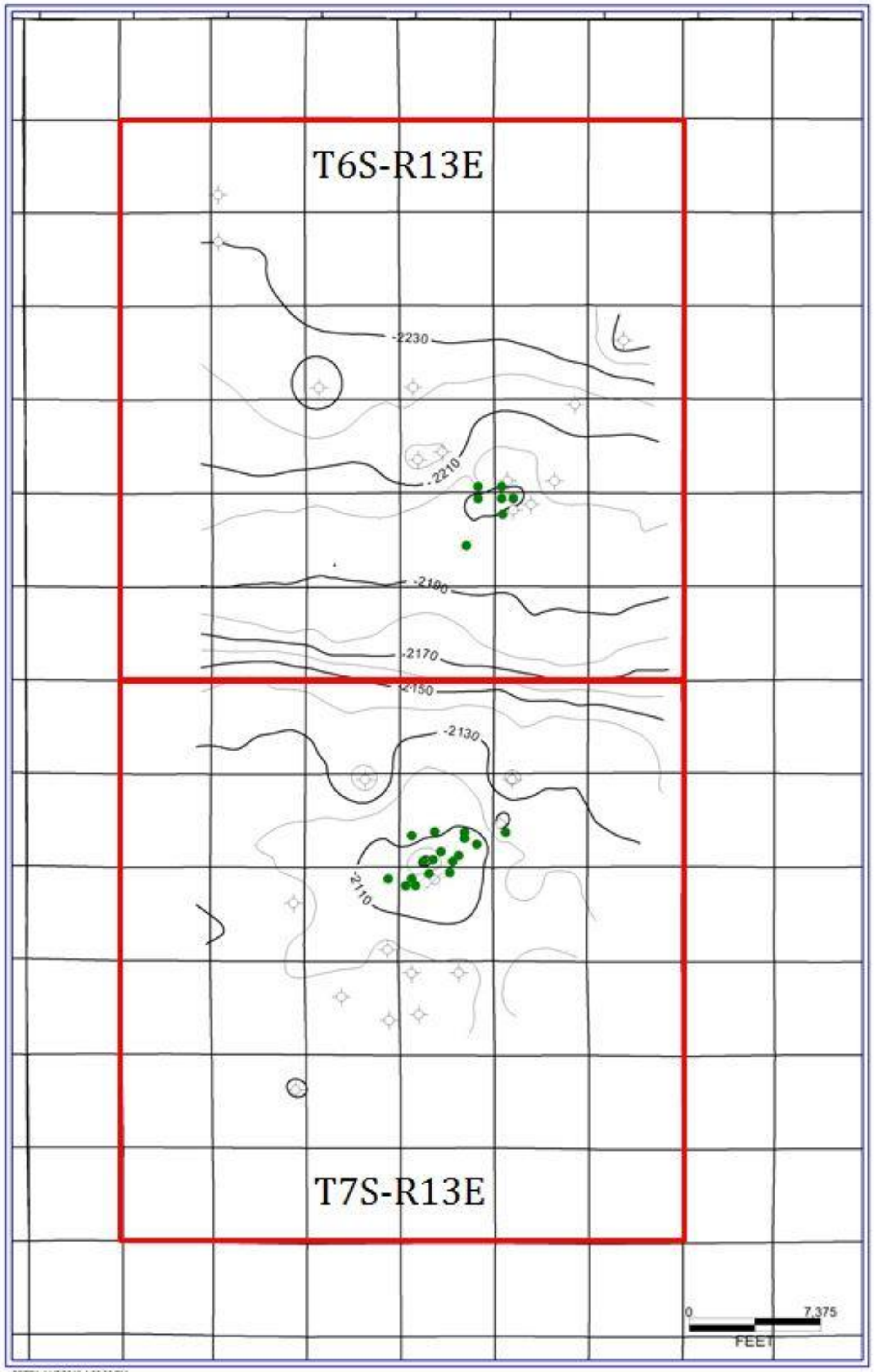

Figure 4.4 Structure of the Viola Limestone. Contour interval is 10 feet

Cuttings Locations

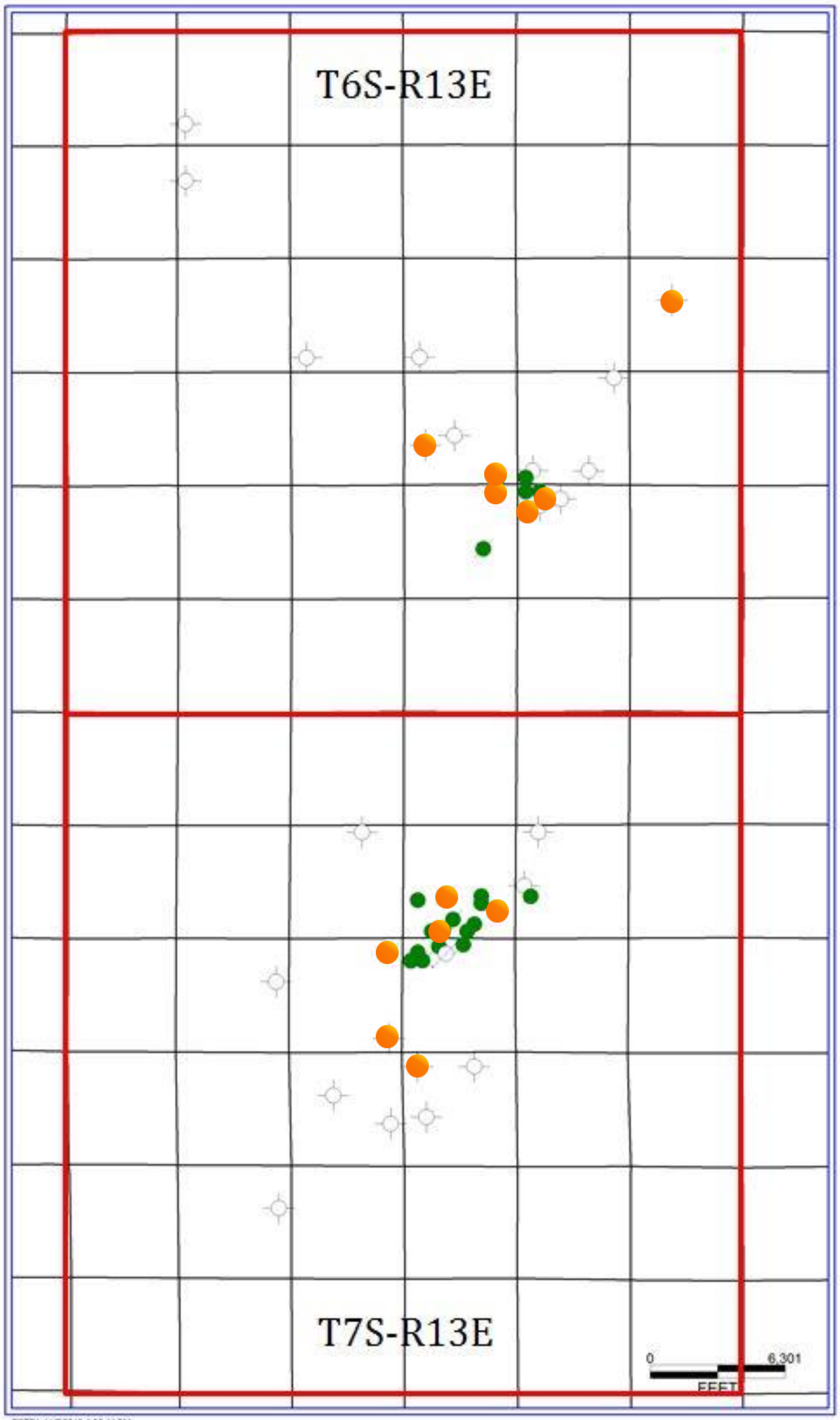

Figure 4.5 Map displays wells where drill cuttings were collected and examined

Cuttings Locations Relative to Structure

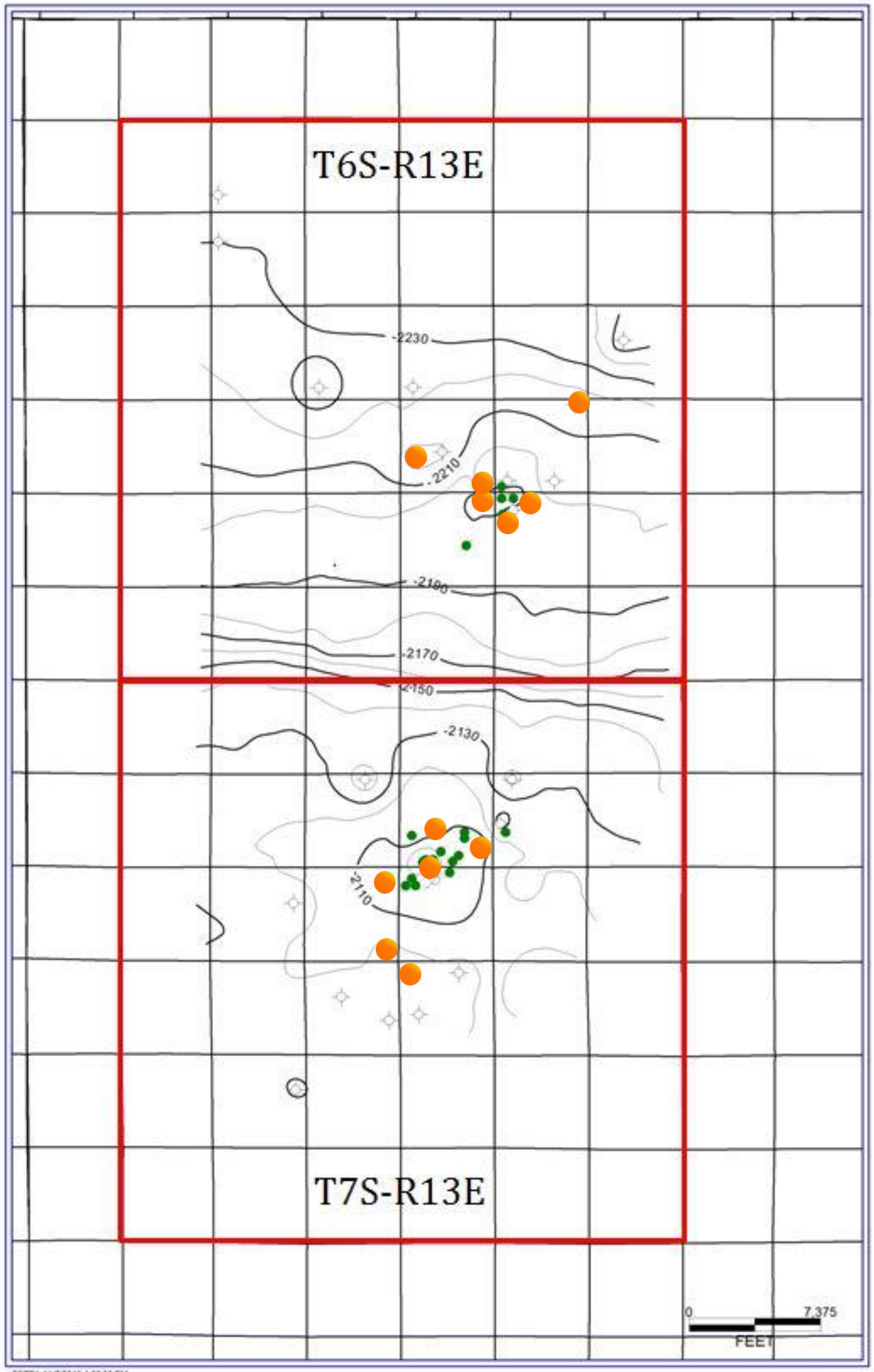

Figure 4.6 Map displaying drill cuttings locations with respect to Viola Structure

Viola Isopach

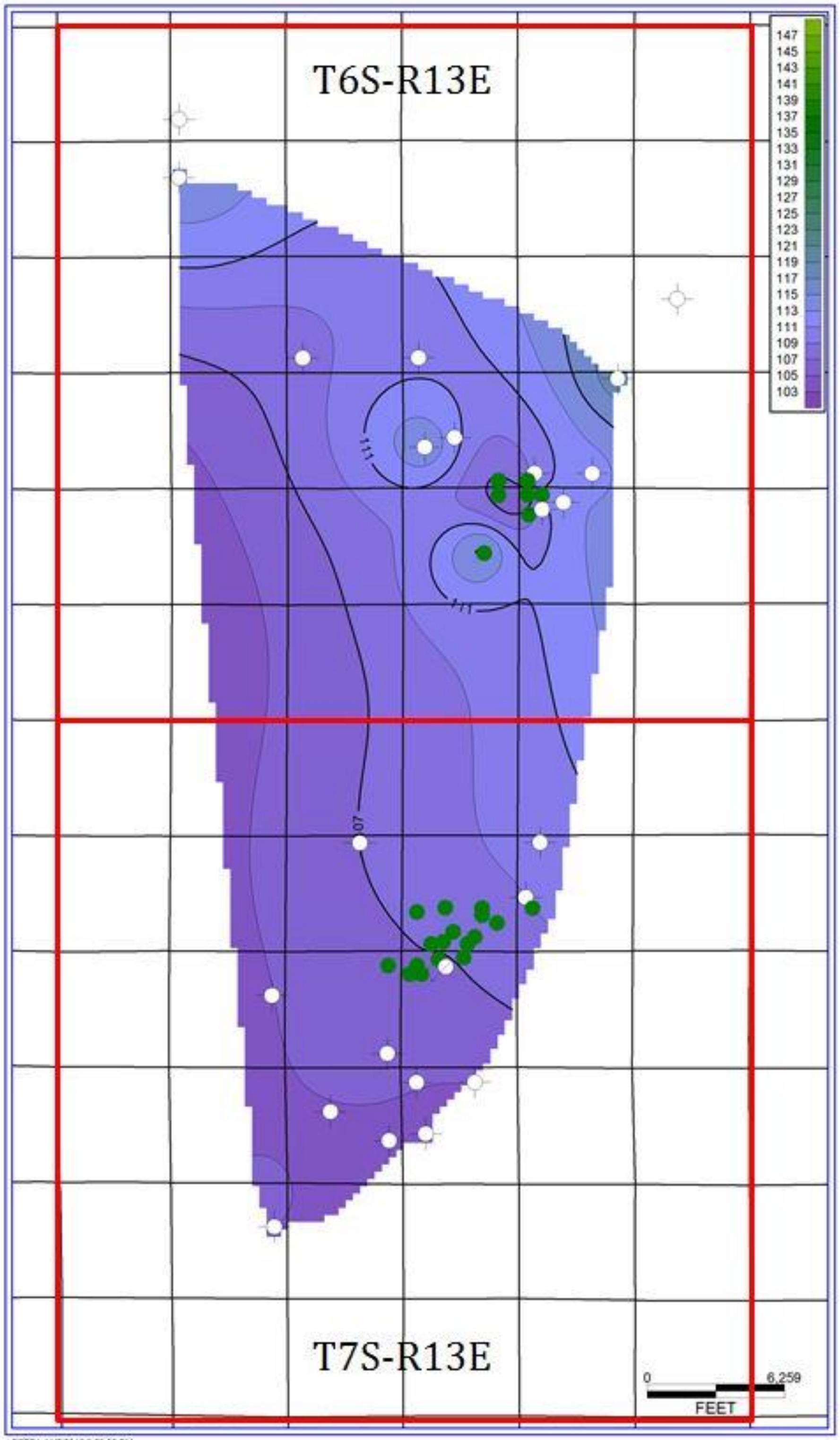

Figure 4.7 Isopach map of the Viola Limestone. Contour interval is 1 foot

Maquoketa Structure

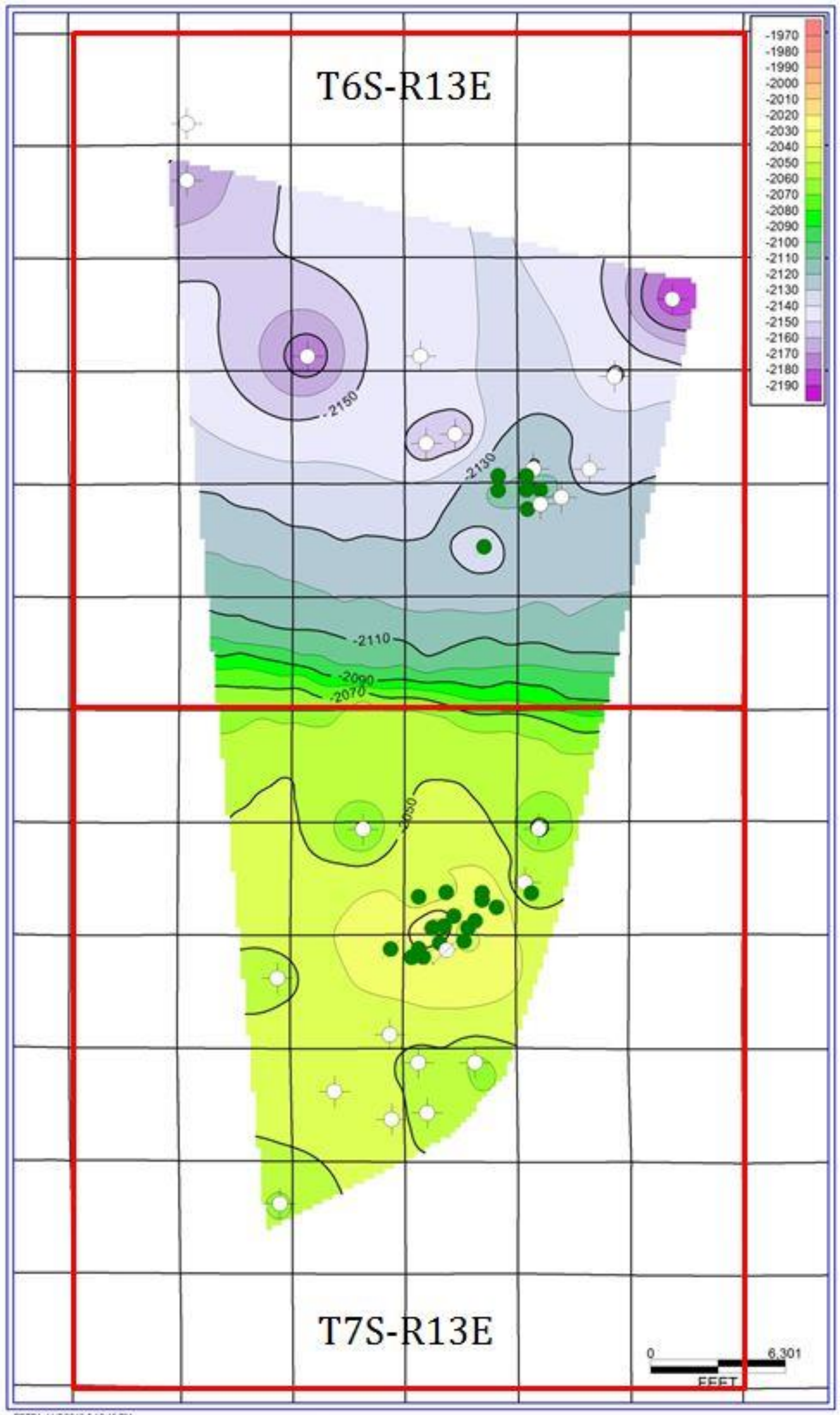

Figure 4.8 Structure of the Maquoketa Shale which directly overlies the Viola. Contour interval is 10 feet

Simpson Structure

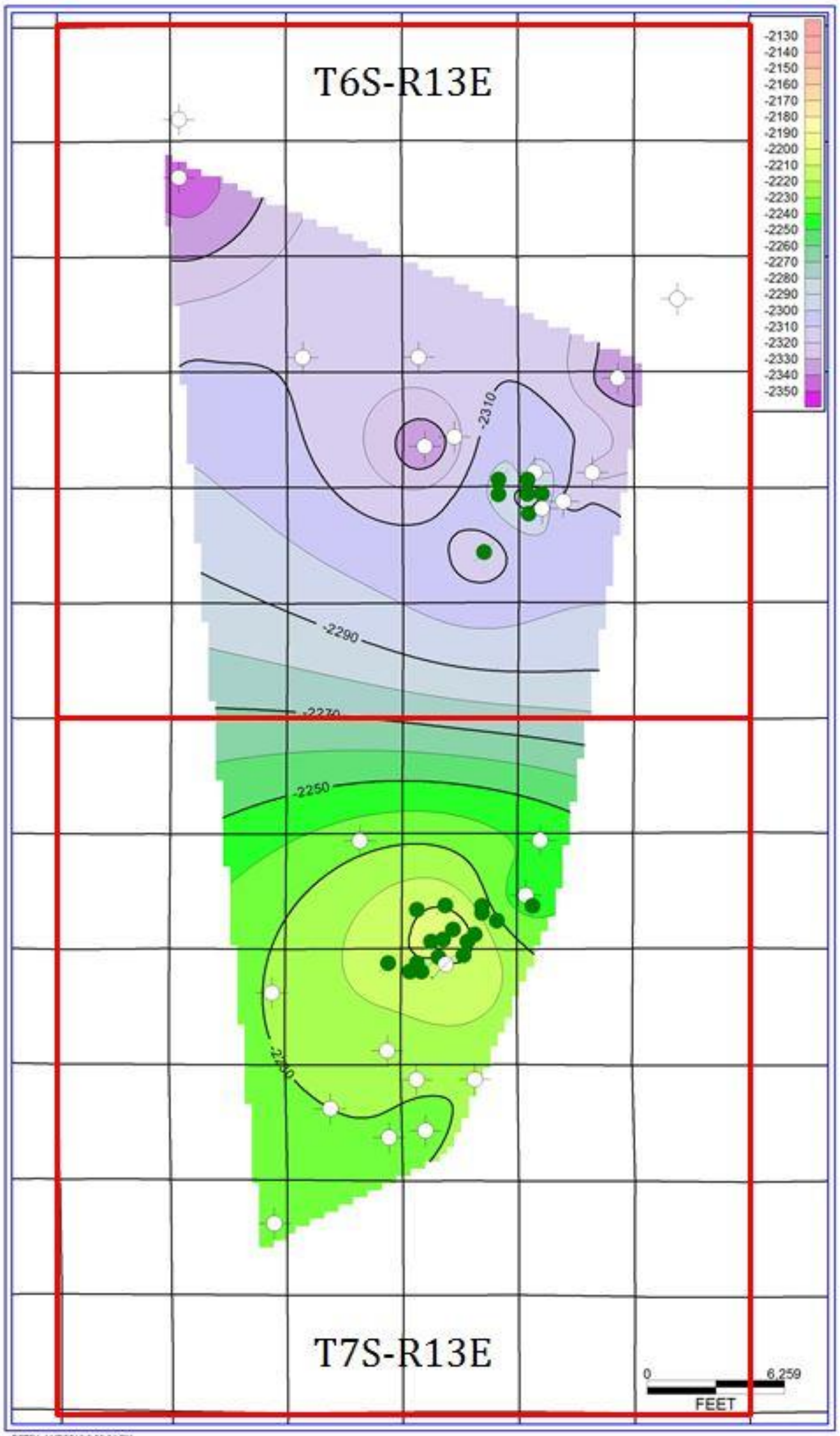

Figure 4.9 Structure of the Simpson Group which lies at the Viola base. Contour interval is 10 feet

Chapter 5 - Discussion

Structure and Production

Oil discoveries correlated well with the structure map of the top of the Viola Limestone. Anticlines with closure that are trending NE are the trapping mechanism for the Soldier and Leach Fields. But looking at how long wells produced and which are still producing raised a question: Why are some wells on top of the structure plugged after as little as 1 month, when others on the limbs produce for years?

Here is one example referring to the arrowed wells in Figure 5-1. The well on the left is the Dugan 1 and the well to the right is the Henry Trust 4. The Viola top is 15 feet higher at the Dugan 1 well than at the Henry Trust 4. However, the Dugan 1 was plugged only 1 month after completion, while the Henry Trust 4 has been producing oil for 6 months and is still going. The Henry Trust 4 well also had a drill stem test that flowed oil to the surface, even though it was the last completed producing well on the structure. So while structure did determine where oil would be encountered, some wells located on structure did not produce commercially, whereas some wells did even though they were beginning to be slightly off structure. The differences in production must be a function of reservoir quality.

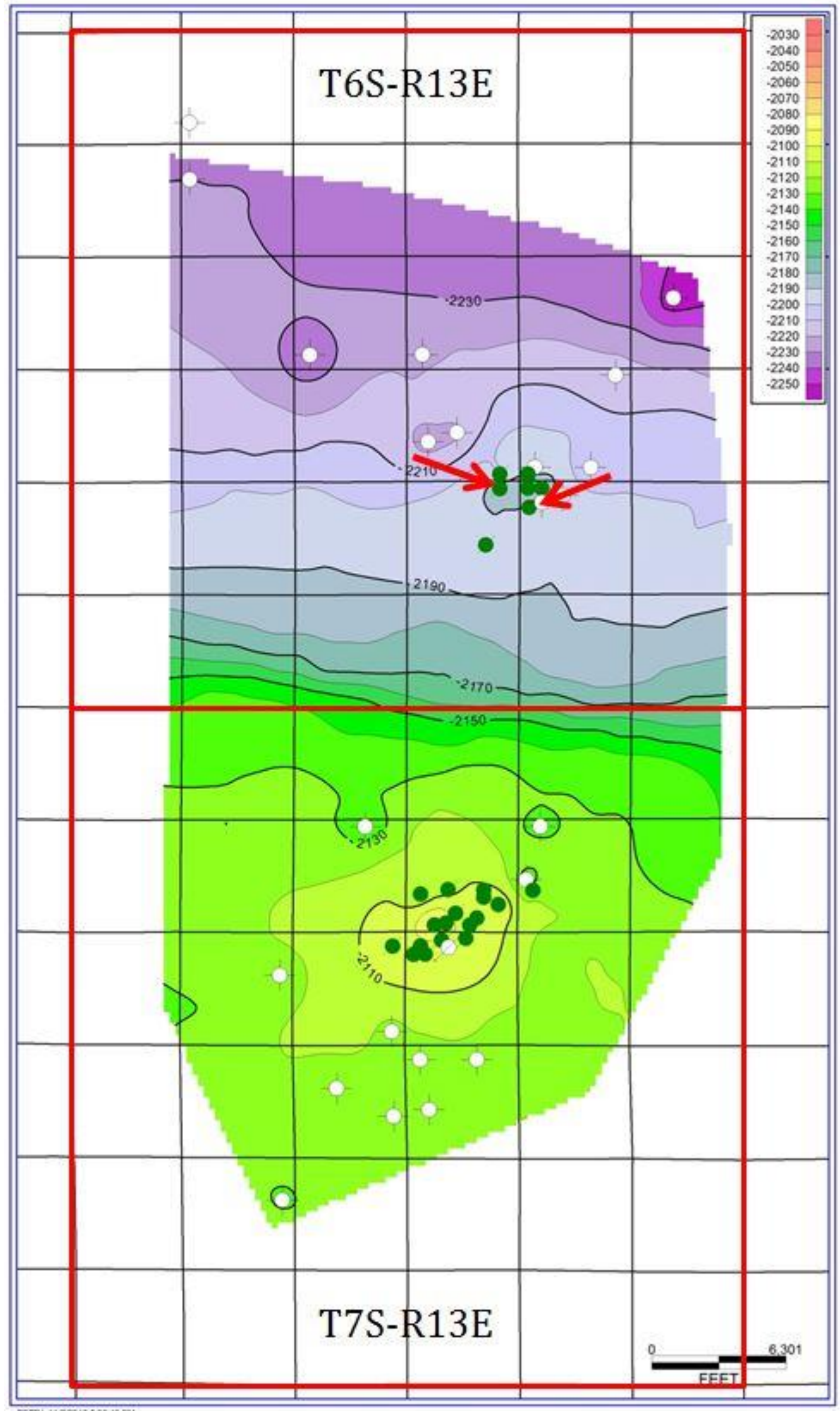

Figure 5.1 Viola structure. Arrowed wells are Dugan 1 (left) and Henry Trust 4 (right). Viola top is 15 feet higher at Dugan 1 compared to Henry Trust 4. Contour interval is 10 feet.

Dolomitization and Structure

Viewing the thin sections under the petrographic microscope showed that there was a wide range of dolomite crystal sizes and fabrics, and this seems to be the controlling factor for reservoir quality. Dolomite crystals ranged in size from .125 mm (medium crystalline) all the way up to 3.5 mm (very coarsely crystalline). Along with crystal size, the crystal fabric (shape) had a wide range, seeing both planar types as well as nonplanar. After viewing samples from only a few wells, it became clear that dolomite crystal size and fabric was the main force controlling reservoir quality. In wells that were at the top of structures, the upper Viola was composed of 100% dolomite in very coarsely crystalline, euhedral (planar-e) crystals. Wells located in structural lows showed a Viola composed of medium crystalline, subhedral (planar-s) to nonplanar dolomite crystals, and some even showed up to 20% calcite remaining.

Reservoir Quality

Nearly all wells had samples that showed vuggy porosity, but samples with the large, euhedral dolomite crystals always had more effective porosity. These samples came from wells on the top and eastern limbs of the anticlines (Figure 5.2), and had very good intercrystalline porosity. Because of the larger crystal size, dolomite rhombs could not fit together tightly, leaving void space between them (Figure 5.3). This porosity is extremely beneficial because the intercrystalline porosity is well connected, which in turn connects the many vugs present. As wells moved off structure crystal size began to shrink, and so too did the intercrystalline porosity. The smaller crystals were easier to pack and compress together, which squeezed the pore throats, getting rid of the intercrystalline porosity and the permeability it produces. So while a medium to coarse crystalline dolomite may show good log porosity because of vugs, those vugs are not connected, which makes the effective porosity of the rock close to zero.

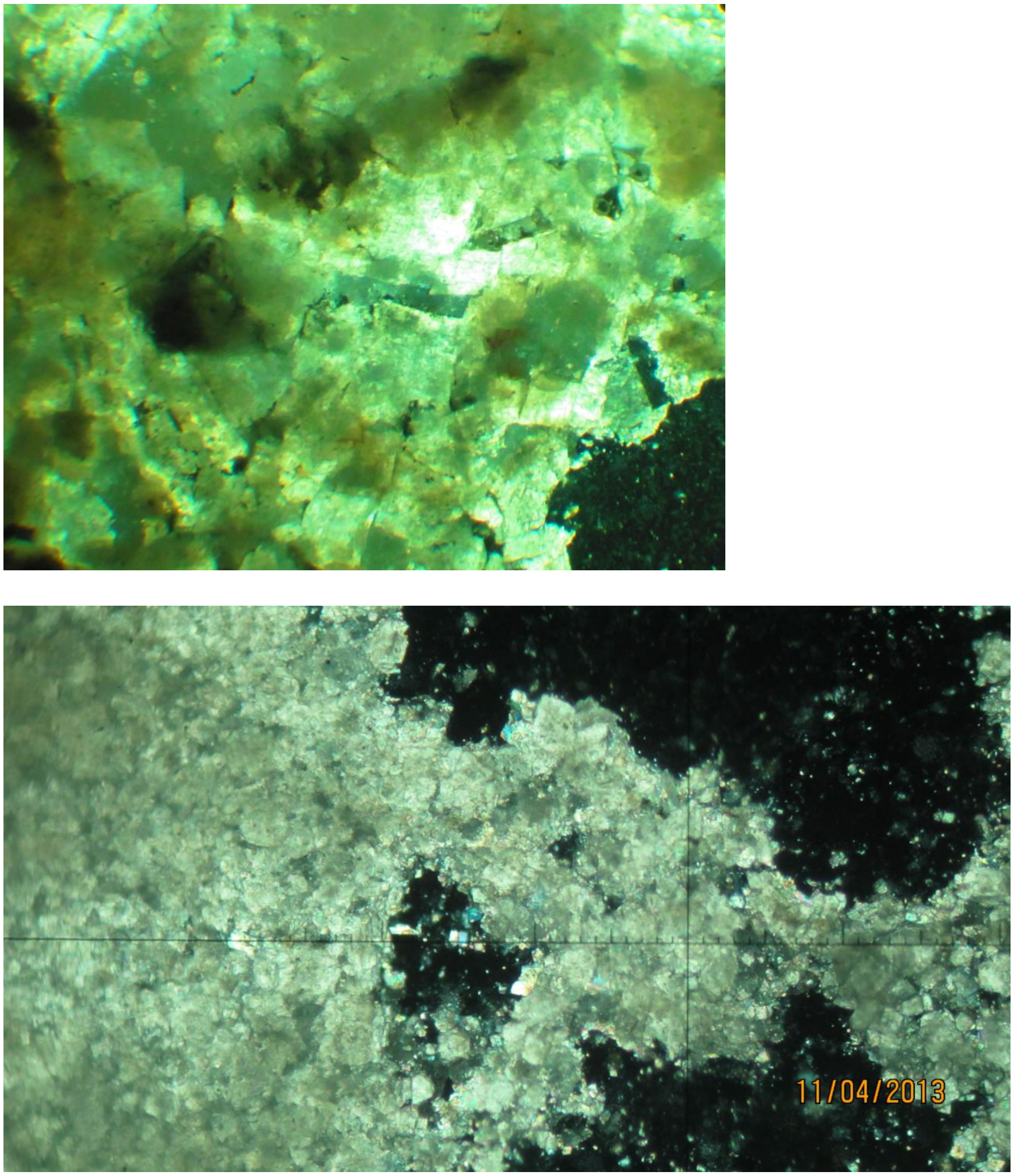

Figure 5.2 Examples of good reservoir (upper) vs. poor reservoir (lower) quality at same scale. Larger euhedral crystals connect pores in good reservoirs. In poor reservoirs, smaller subhedral to nonplanar crystals lack permeability and isolate vugs. Apparent intercrystalline porosity in lower image is caused by extinction.

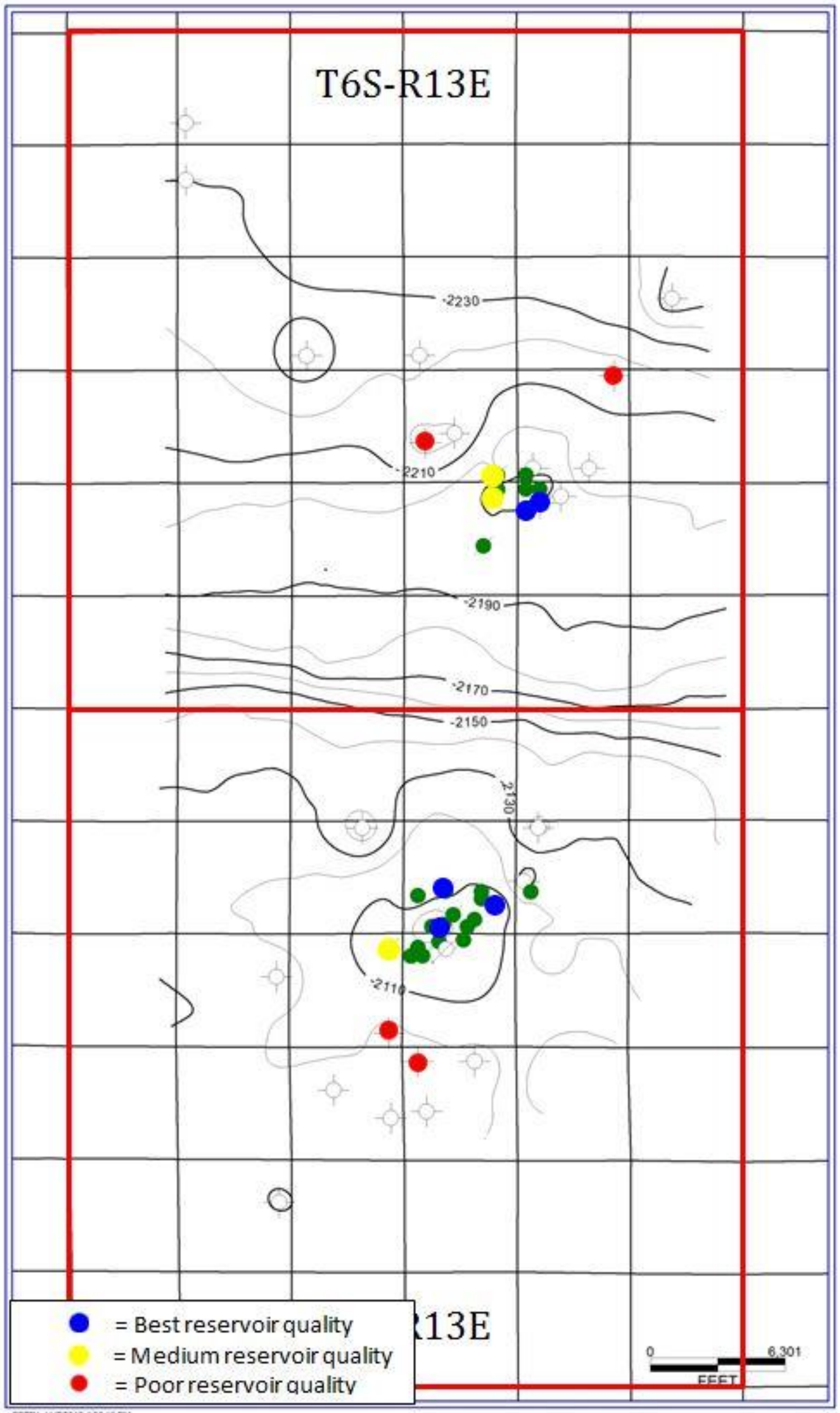

Figure 5.3 Map displaying reservoir quality with respect to Viola structure

Dolomitization and Maquoketa Isopach

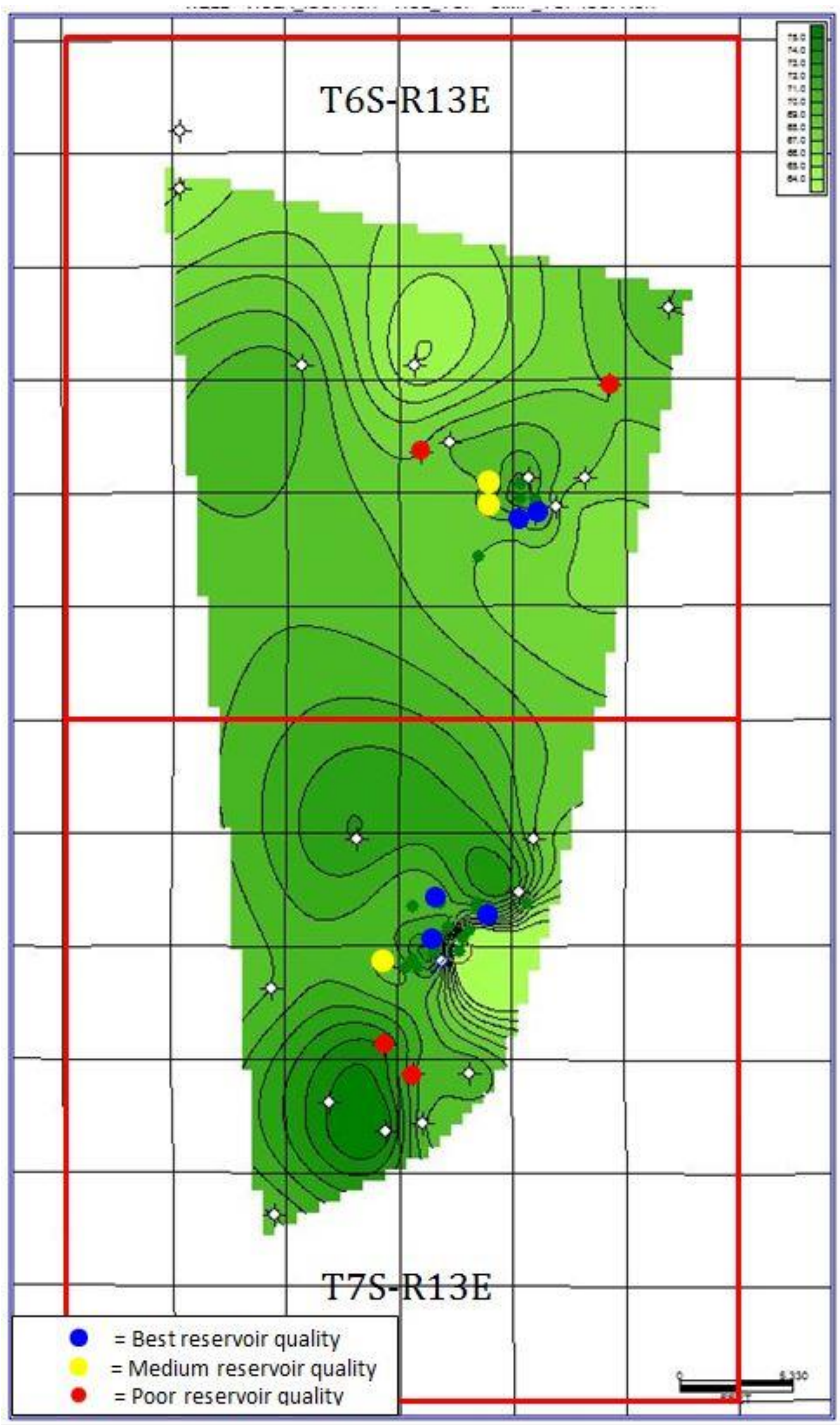

Figure 5.4 Map displays reservoir quality's relation to Maquoketa Shale thickness

It was originally thought that the trapping structures may have developed before the Maquoketa Shale was deposited. If this were the case, then the Maquoketa should be noticeably thinner on top of structures, and thicker off-structure. During exploration, one could then just measure how much Maquoketa was drilled, and determine whether or not that location was on a structural high. Looking at Figure 5.3 it looks as though this idea is not true. The Maquoketa thickness seems to have no relation to production or reservoir quality. It is actually thicker on top of the Soldier field anticline than in surrounding areas, and shows a range of thicknesses across the Leach field anticline.

Key to Understanding the Results

As seen in Figure 5.1, the structure of the Viola Limestone controls where oil will be encountered. It did not however explain why productive wells on the east sides of the anticlines studied produced more, and longer, than those on the west sides, even when wells were at equal elevations. Viewing the drill cuttings as thin sections under a petrographic microscope provided the most useful information in regards to reservoir quality, which controls prolonged production. Figure 5.2 shows how differences in dolomitization are closely related to differences in production. The greater production on the east sides of anticlines is caused by larger, more euhedral dolomite crystals that make up the Viola Limestone there. The larger crystal size produces a better reservoir because of greater overall porosity and increases pore throat size, which makes permeability higher. Why they occur along the east flanks became a puzzling question, and the answer was found in research done by Wallace Lee in the Forest City Basin (Lee, 1943).

The study was characterized by Lee as a "report embodies the results of a study of the stratigraphy and structural history of that part of the Forest City basin lying in northeastern Kansas. It is based on the microscopic examination of samples from wells and the correlation and interpretation of the lithologic units recognized in the area." The first thing Lee found was that a major period of deformation occurred almost immediately after the middle and late Ordovician Series were deposited, creating local highs in the Viola and Maquoketa. As the basin then continued to sink and be buried, those local highs continued to rise and deform into anticlines with greater relief. This caused the highs and lows of the Viola to go through diagenesis and dolomite recrystallization at different times, producing different crystal sizes and fabrics.

Lee also found that the regional dip of the east side of the Forest City Basin has changed directions over time. After the Ordovician system had been deposited, regional dip of the area was slightly to the northwest, but during the Nemaha uplift of late Paleozoic-age, that regional dip was reversed to a steeper southeast direction. By changing dip direction, the paleo-highs of the earlier formed anticlines are now located on the east and southeast limbs of the structures seen in the subsurface today, which explains the trend of better reservoir quality of the east and southeast sides of the Soldier and Leach field anticlines.

Chapter 6 - Conclusions

Subsurface mapping of all wells in a two township area in northeast Jackson County, Kansas was done in order to predict where petroleum accumulations occur in the Viola Limestone formation. Oil was found on top of structural highs, as is common in the majority of Kansas' reservoirs. Structure maps did not, however, explain why production rates vary from well to well across those structural highs.

To better understand the difference in production rates in the Viola, drill cuttings were collected from various wells that represented a range of different structural locations and petroleum productions. Thin sections were made out of drill cuttings samples so that they could be examined under a petrographic microscope. Thin section evaluation allowed porosity, porosity type, and dolomite crystal attributes to be seen in detail. These findings were combined with production data (when available) to establish the quality of the reservoir and determine what factors, if any, were controlling production rates.

The variation in production rates of wells producing from the Viola Limestone is explained by varying reservoir quality, which is controlled directly by dolomite crystal size and fabric. Porosity and permeability were best developed on Paleozoic highs that underwent diagenesis and dolomitization at different times than the lows. Differences in dolomite crystal size and fabric were the result. Larger, more euhedral dolomite crystals create increased effective porosity and permeability by creating enlarged pore sheets that allow greater fluid flow.

The best exploration model for Viola production along the western flank of the Forest City Basin is to identify structural highs in the subsurface. Mapping the Viola itself, or the overlying Hunton Limestone, can accomplish this. Once structural highs are identified, wells on the east and southeast sides of the anticline will see the greatest production and well longevity.

Those wells will encounter the Viola that was a paleo-high during the time it went through dolomitization, giving it the coarsest, most euhedral crystals, and thus the greatest effective porosity and permeability.

Chapter 7 - References

Adler, F. J., 1971, Future petroleum provinces of the Midcontinent, region 7; in, Future Petroleum Provinces of the United States--Their Geology and Potential, I. H. Cram, ed.: American Association of Petroleum Geologists, Memoir 15, p. 985-1,120.

Allan, J.R. and Wiggins W.D., 1993, Dolomite Reservoirs: Geochemical Techniques for Evaluating Origin and Distribution, American Association of Petroleum Geologists, AAPG Continuing Education Course Notes, Series 36, 129 p.

Anderson, K H., Wells, J. S., Forest City Basin of Missouri, Kansas, Nebraska, and Iowa: American Association of Petroleum Geolgists Bulletin, v. 52, no. 2, p. 264-281.

Barnes, C.R., Ordovician oceans and climates, in Webby, B.D. et al, The great Ordovician biodiversification event, Columbia University Press, 2004, p. 72-76.

Bornemann, E., Doveton, J. H., St. Clair, P. N., 1982, Lithofacies Analysis of the Viola Limestone in South-central Kansas: Kansas Geol. Survey, Petrophysical Series 3, 50 p.

Caldwell, C. D. and Boeken, R., 1985, Wireline log zones and core description of upper part of the Middle Ordivician Viola Limestone, McClain and McClain SW fields, Nemaha County, KS *in* Subsurface Geology 6, ed.: Kansas Geological Survey, p. 17-35.

Choquette, P.W., and Pray, L.C., 1970, Geological nomenclature and classification of porosity in sedimentary carbonates: American Association of Petroleum Geologists Bulletin, v. 54, p. 207-250.

Flenthrope, C., 2007, Developing an exploration model by investigating the geological controls on reservoir production within the Fort Scott limestone, Ness County, KS: Unpub. M.S. thesis, Kansas State University, 75 p.

Franseen, E.K., Byrnes, A.P., Cansler, J.R., Steinhauff, D.M., and Carr, T.R., 2004, The Geology of Kansas--Arbuckle Group; in, Current Research in Earth Sciences: Kansas Geological Survey, Bulletin 250, part 2.

Jewett, J. M., 1951, Geologic structures in Kansas: Kansas Geological Survey, Bulletin 90, pt. 6, p. 105-172.

Kansas Geological Survey. 2012. The University of Kansas Geological Survey <http://www.kgs.ku.edu/index.html>.

Lee, W., 1943, The Stratigraphy and Structural Development of the Forest City Basin in Kansas: Kansas Geol. Survey, Bull. 51, p. 1-142.

Merriam, D. F., 1963, The geologic history of Kansas: Kansas Geological Survey Bulletin 162, 317p.

Merriam, D. F., 2005, Origin and development of plains-type folds in the mid-continent (United States) during late Paleozoic: American Association of Petroleum Geolgists Bulletin, v. 89, no. 1, p. 101-118.

Mishari, A., et. al., 2009, Dolomite: Perspectives on a Perplexing Mineral, Oilfield Review 21, no. 3, 45 p.

Newell, D.K., 2000, Depositional and diagenetic controls on porosity development in the Ordovician Viola Formation, south-central Kansas, in Johnson, K. S. (ed.), Platform carbonates in the southern Midcontinent, 1996 symposium: Oklahoma Geol. Survey Circular 101, p. 107-115.

Nurmi, R. and Standen, E., 1997, Carbonates: The Inside Story *in* Middle East Well Evaluation Review, v. 18, p. 26-41.

Ross, R. J. Jr., 1976, Ordovician sedimentation in the western United States; *in*, The Ordovician System: Proceedings of a Palaeontologic Association Symposium, Birmingham, September 1974, M. G. Bassett, ed.: University of Wales Press and Natural Museum of Wales, Cardiff, p. 73-106.

St. Clair, P. N., 1981, Depositional history and diagenesis of the Viola Limestone in south-central Kansas: Unpub. M.S. thesis, University of Kansas., 66 p.

Scholle, P. A. and Ulmer-Scholle, D. S., 2003, A Color Guide to the Petrography of Carbonate Rocks: Grains, textures, porosity, diagenesis, AAPG Memoir 77, 474 p.

Warren, J., 2000, Dolomite: Occurrence, Evolution and Economically Important Associations, Earth and Science Reviews, no. 1-3, p. 1-81.

Zeller, D. E., ed., 1968, The stratigraphic succession in Kansas: Kansas Geological Survey, Bulletin 189, 81 p.

Appendix A - Thin Section Images

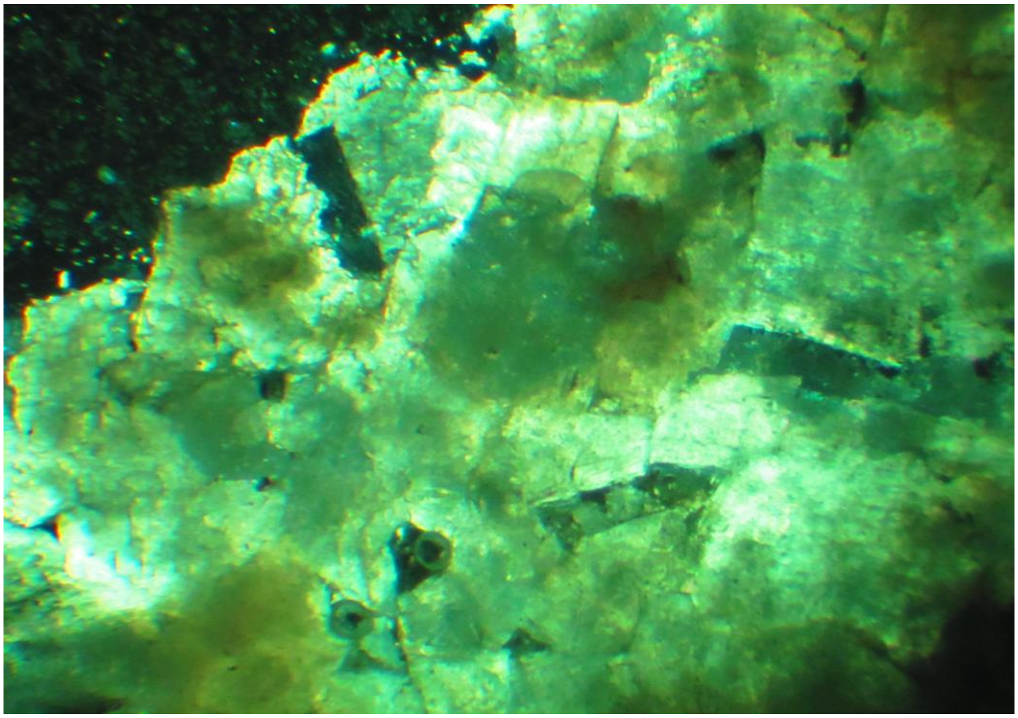

Figure 7.1 Thin section of cutting sample from well Henry Trust 4

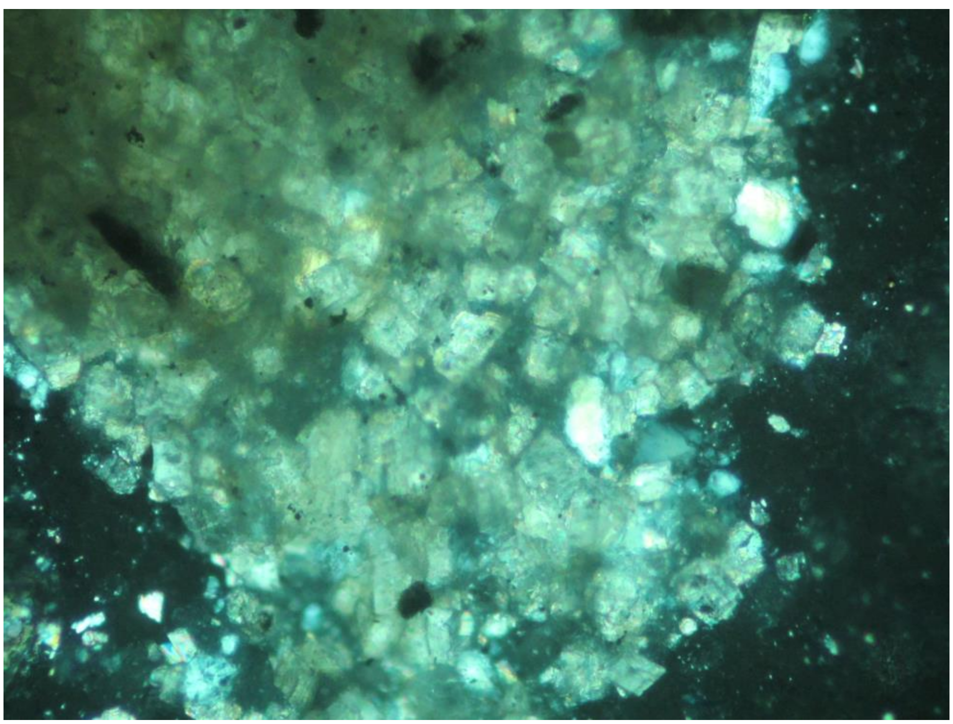

Figure 7.2 Thin section of cutting sample from well Henry Trust 4

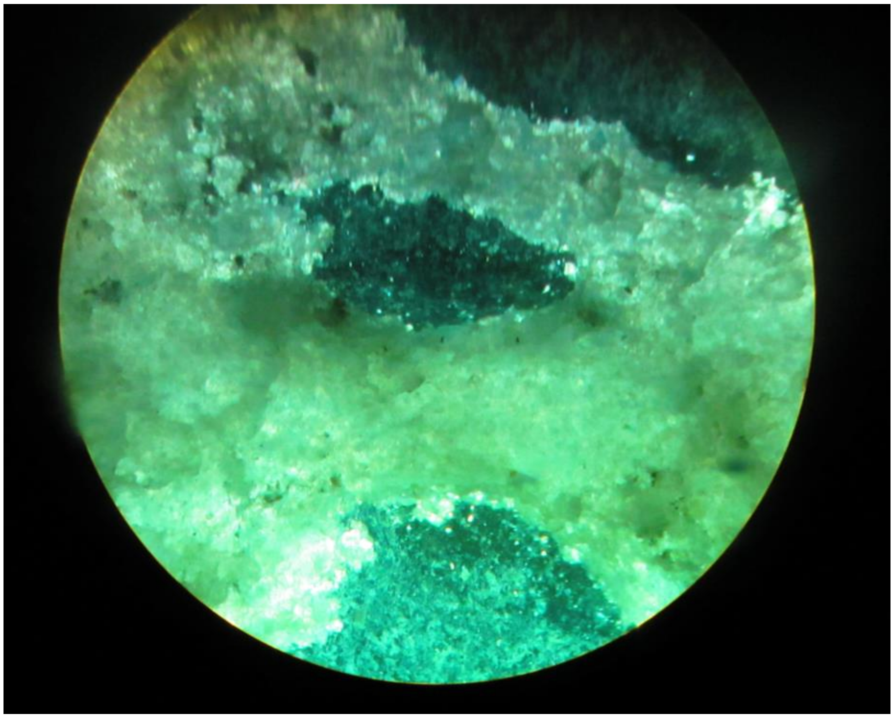

Figure 7.3 Thin section of cutting sample from well Henry Trust 5

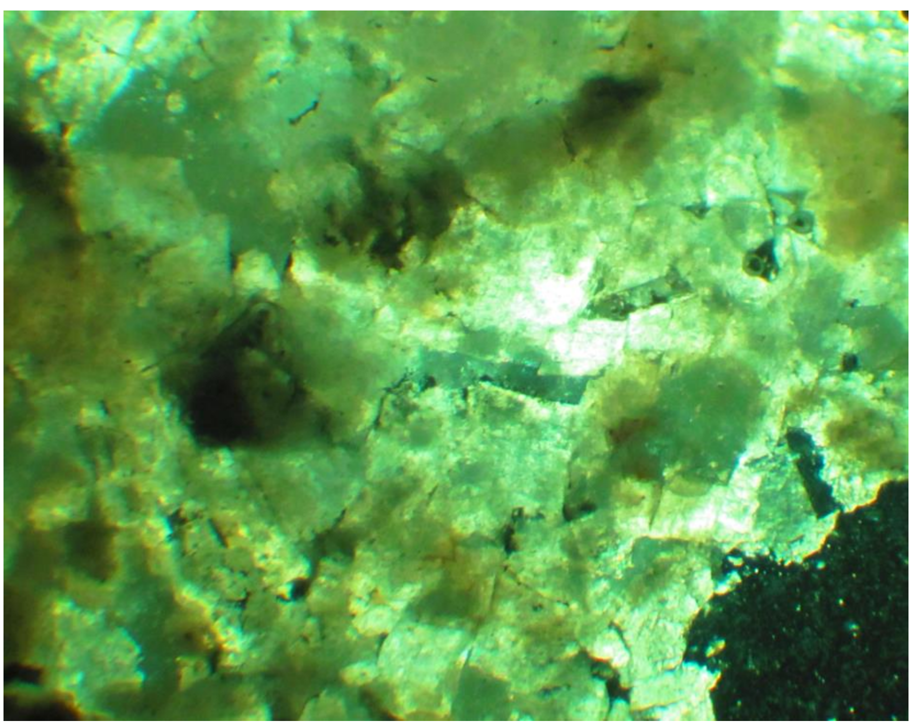

Figure 7.4 Thin section of cutting sample from well Henry Trust 5

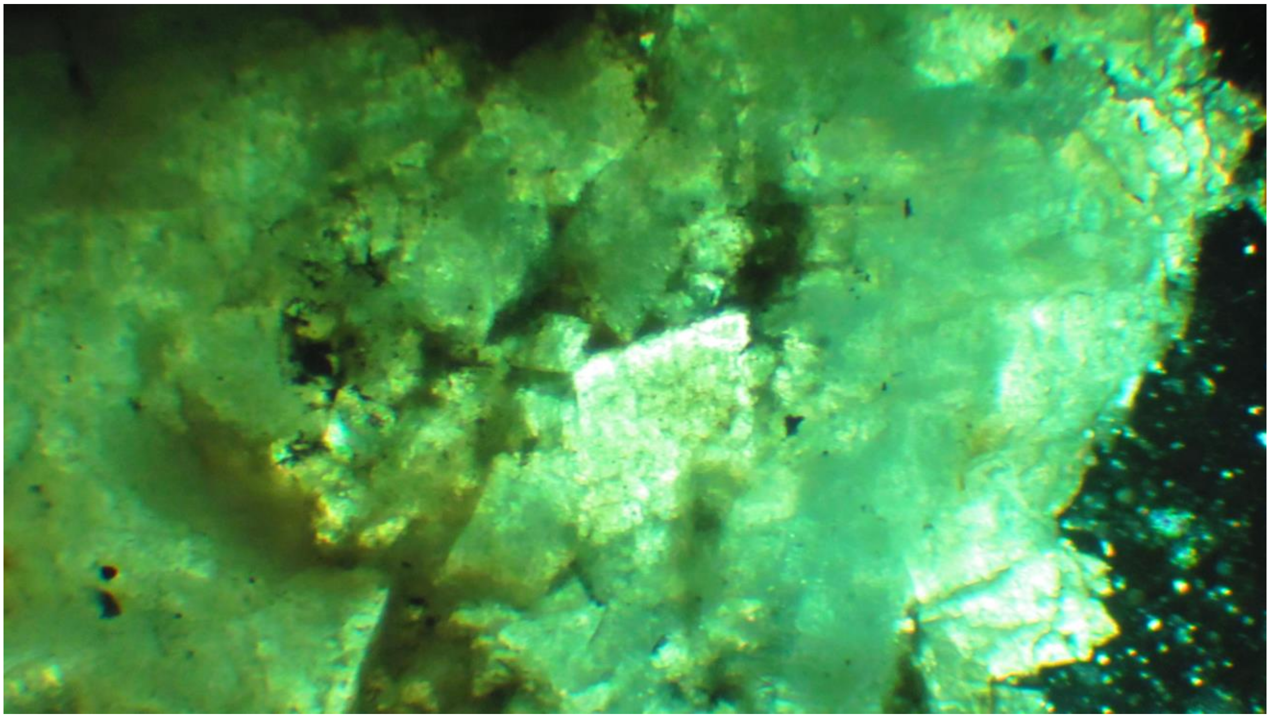

Figure 7.5 Thin section of cutting sample from well Dugan 1

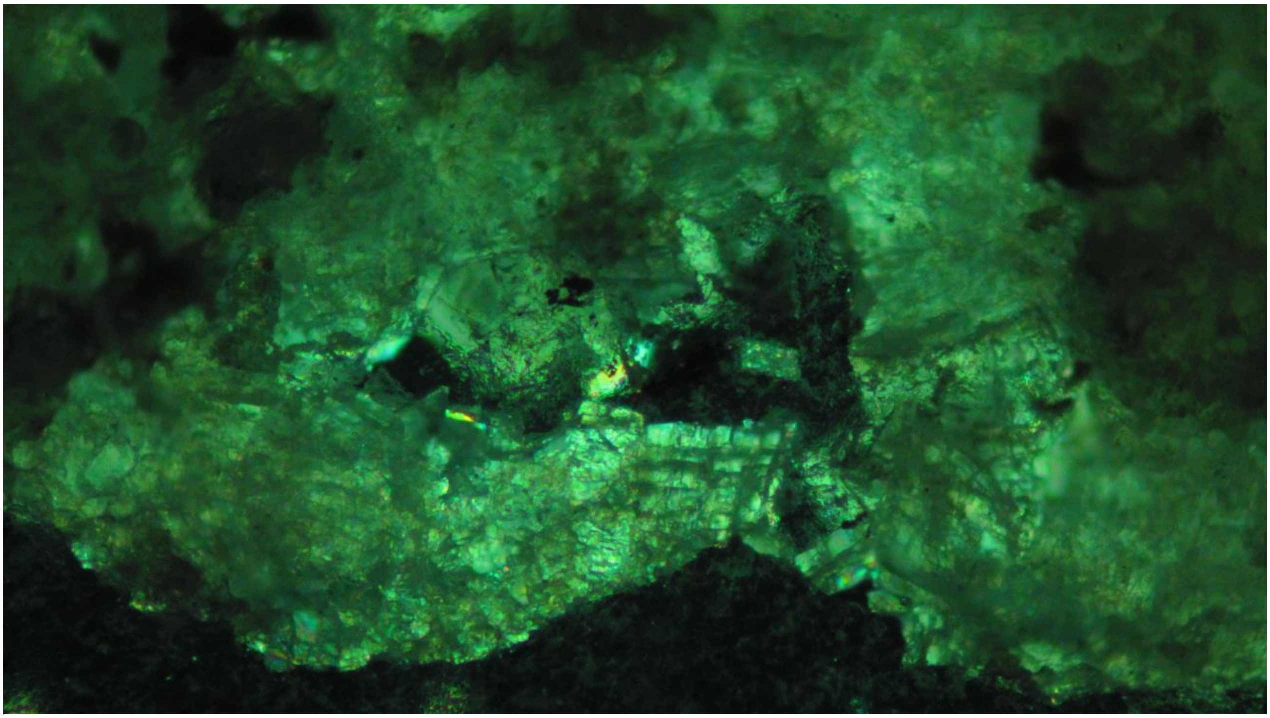

Figure 7.6 Thin section of cutting sample from well Dugan 2

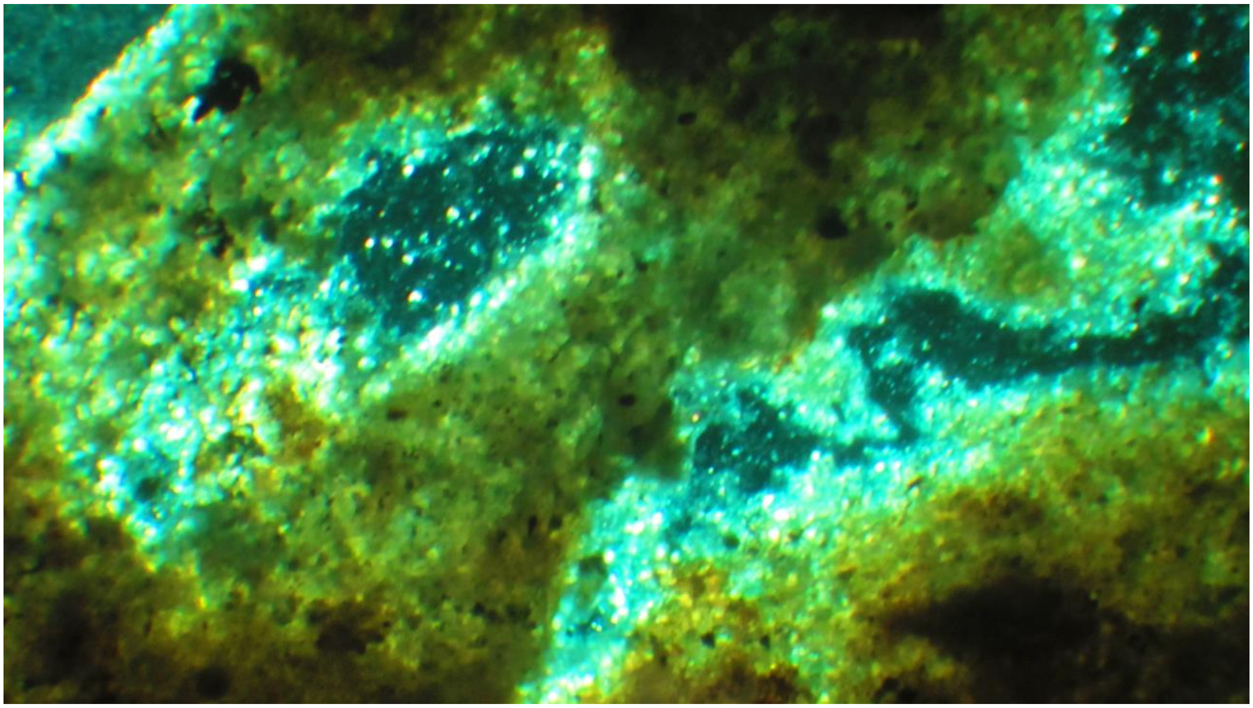

Figure 7.7 Thin section of cutting sample from well Reischick 1

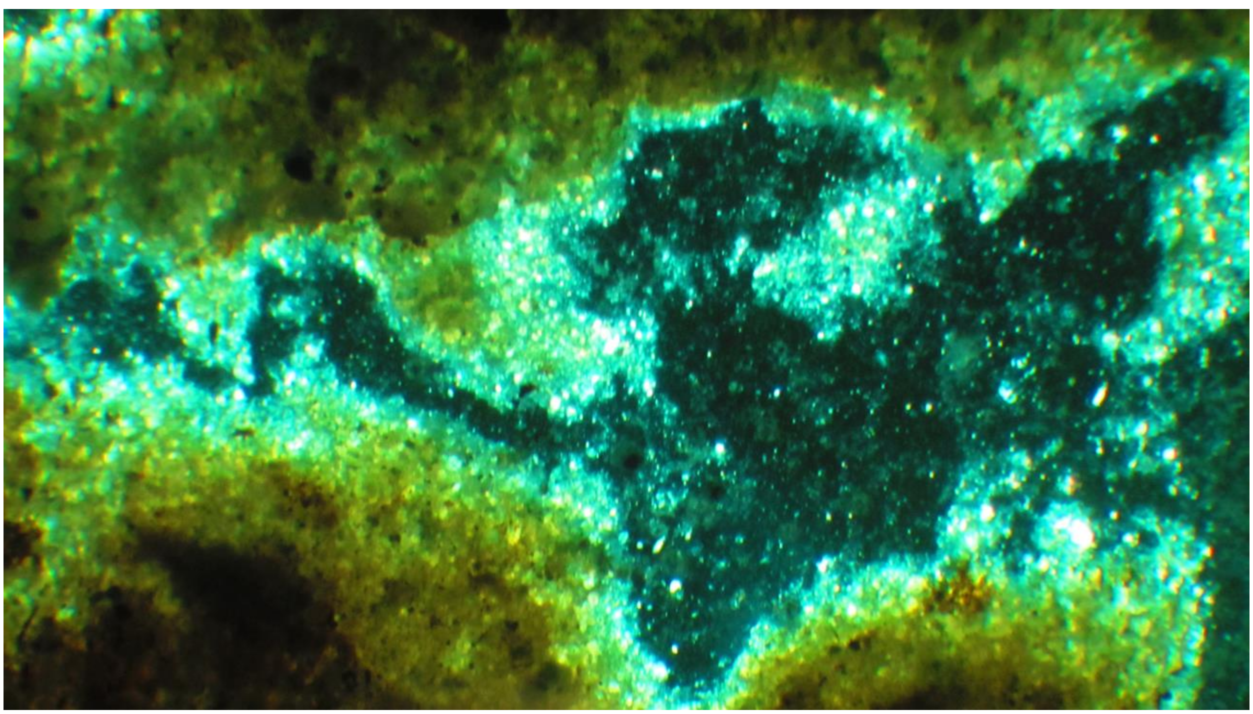

Figure 7.8 Thin section of cutting sample from well Reischick 1

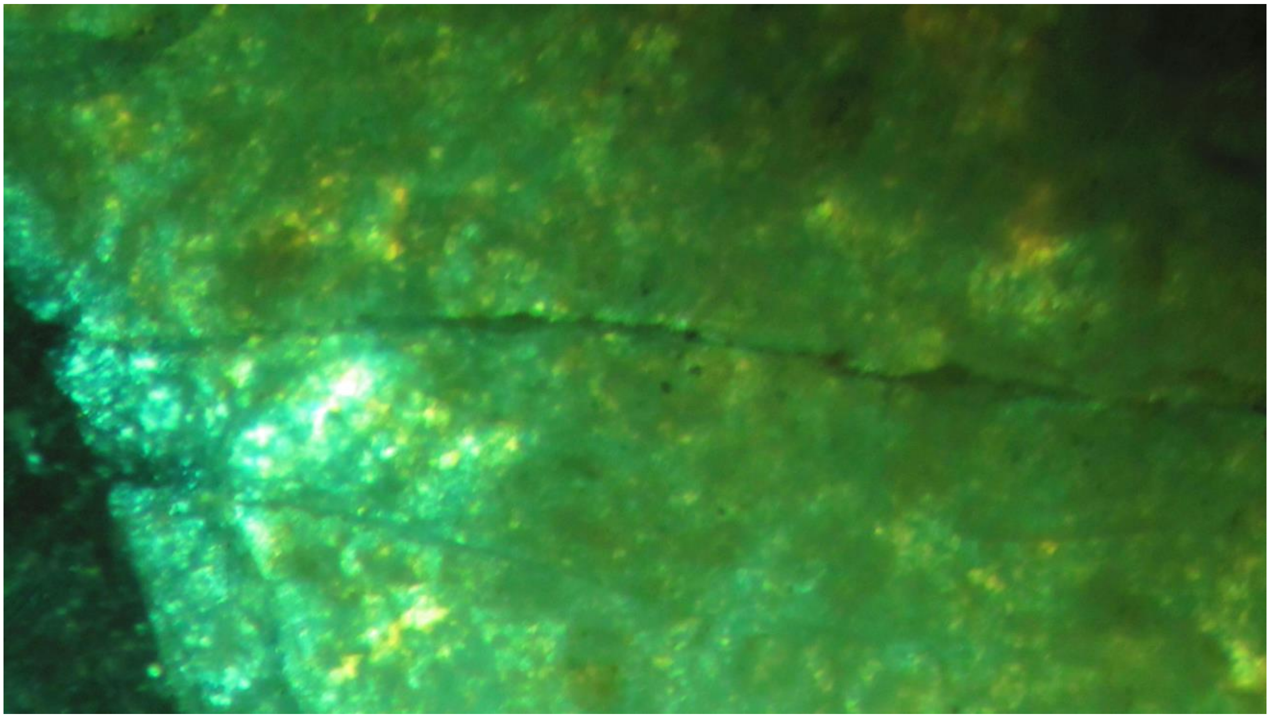

Figure 7.9 Thin section of cutting sample from well Carl V Smith 1

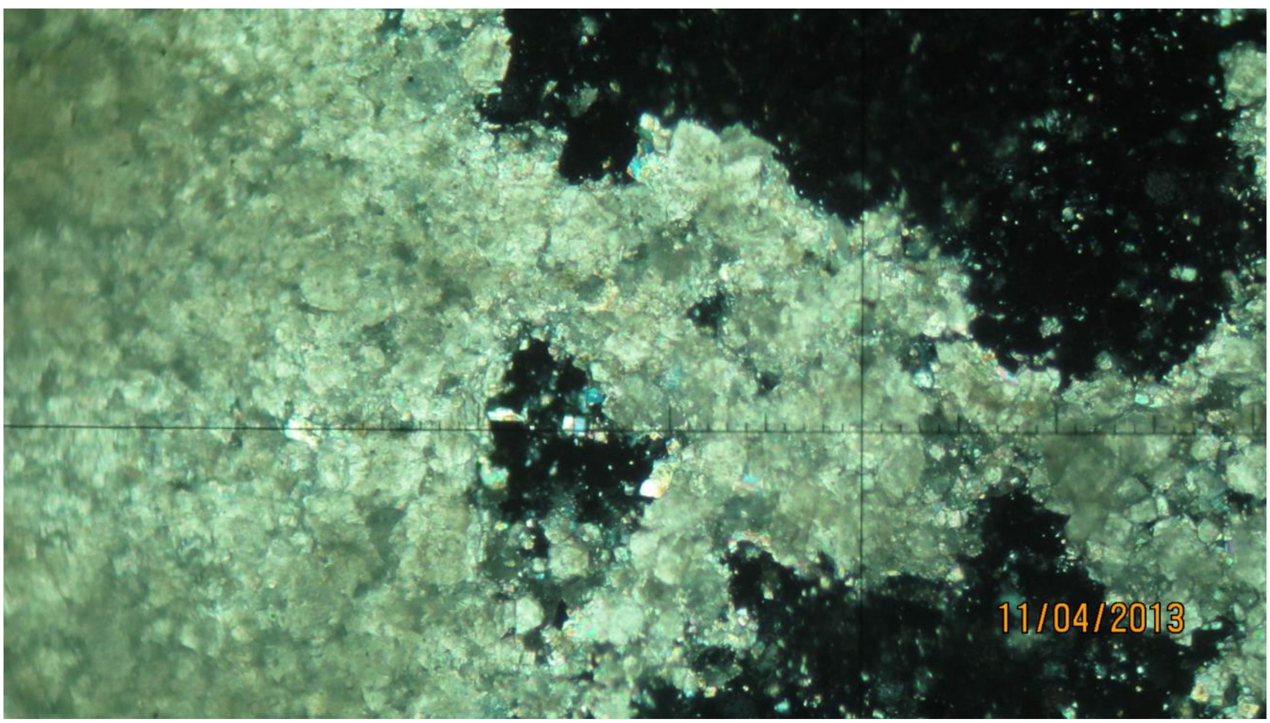

Figure 7.10 Thin section of cutting sample from well Wykert 1

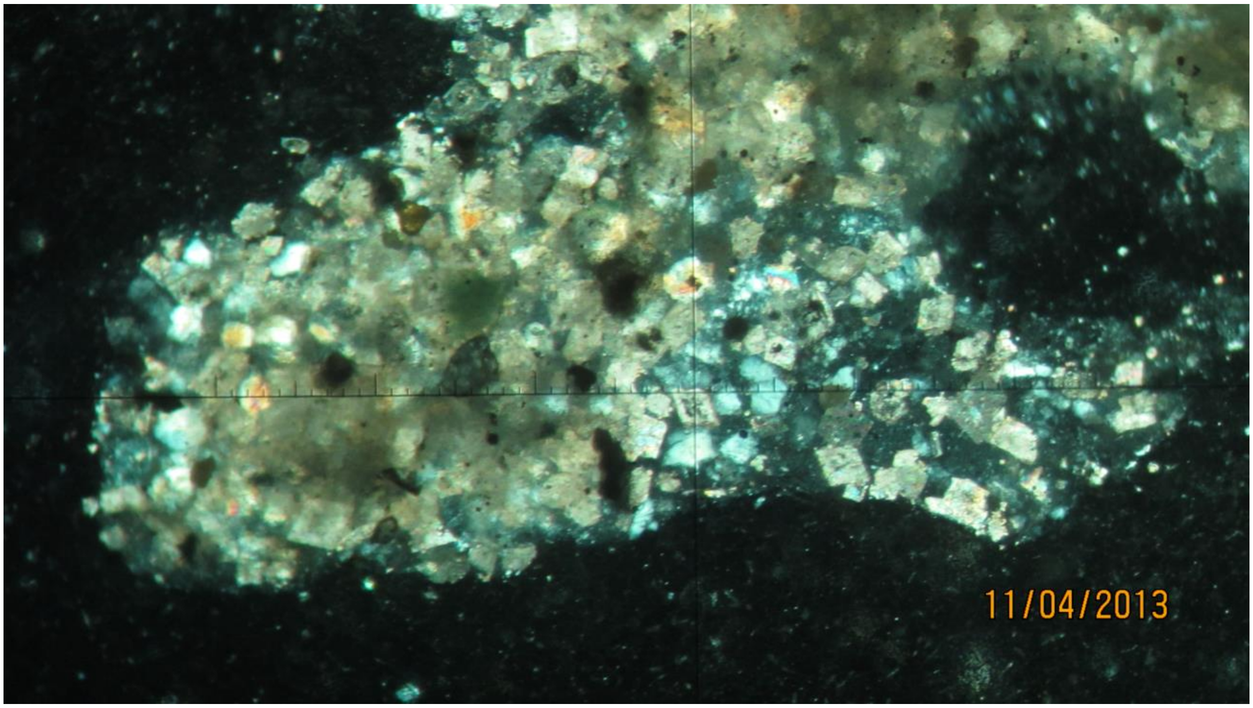

Figure 7.11 Thin section of cutting sample from well Wykert 1

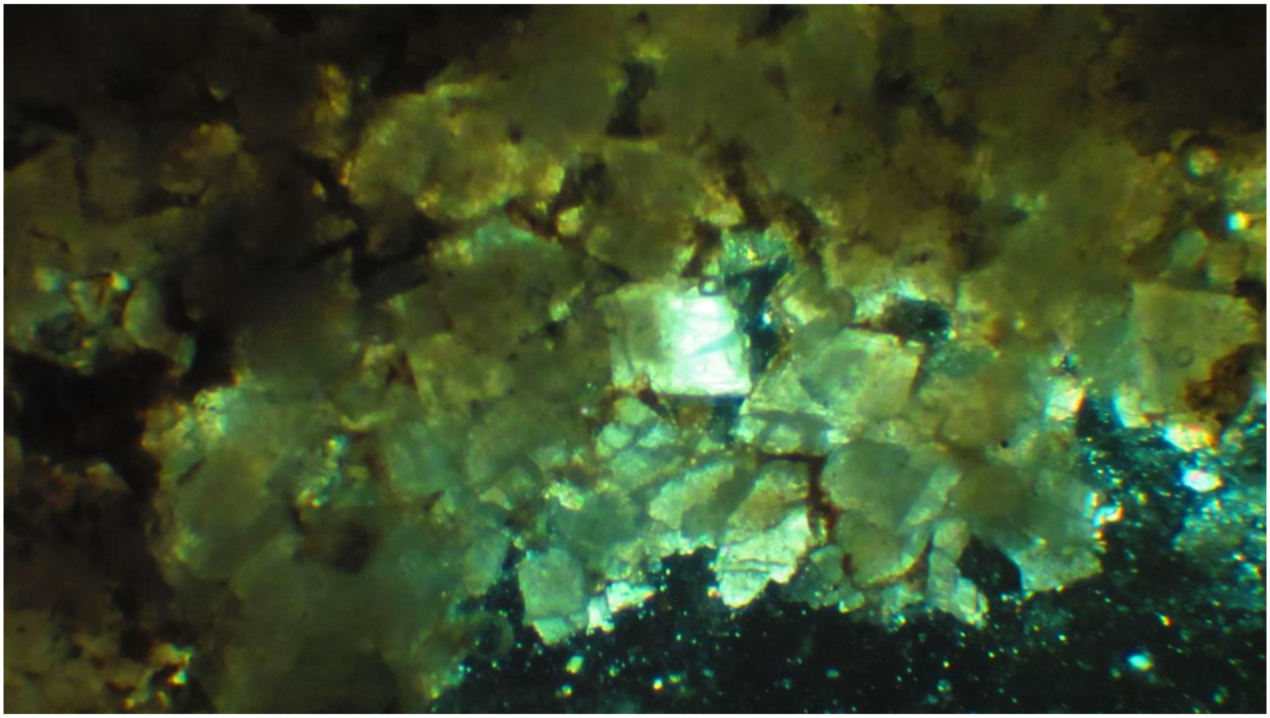

Figure 7.12 Thin section of cutting sample from well Bennett A 5

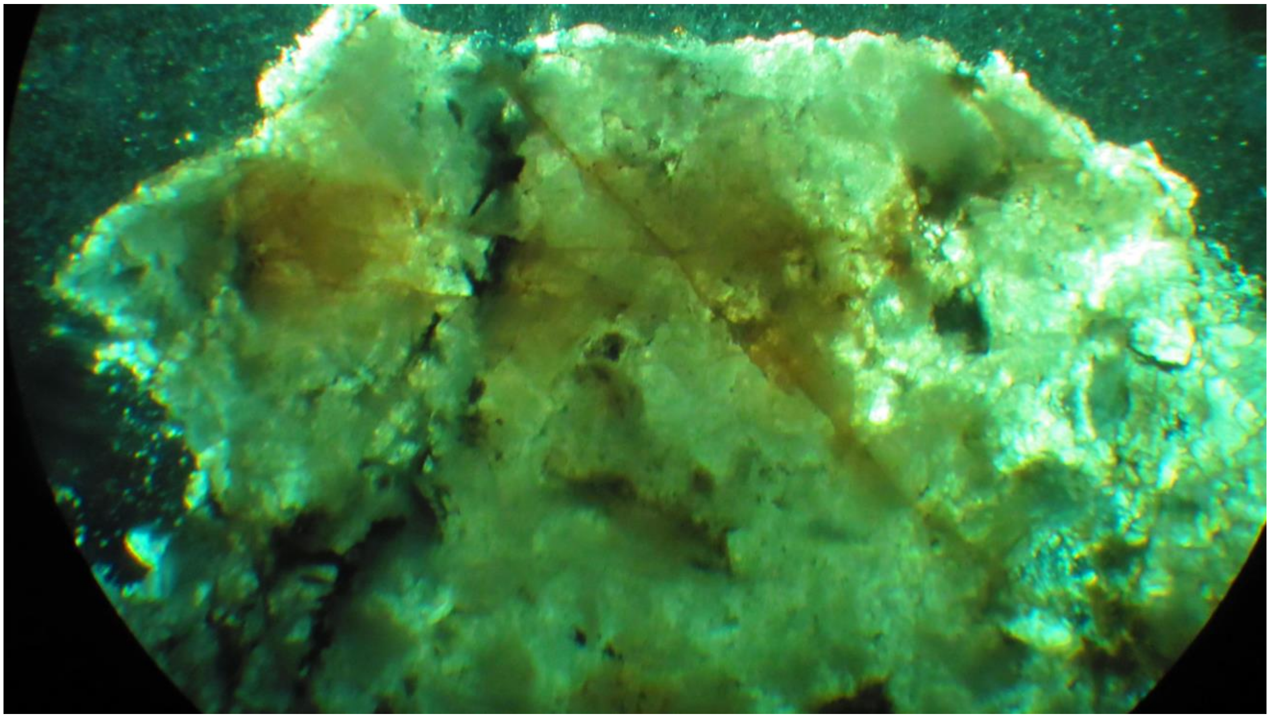

Figure 7.13 Thin section of cutting sample from well Leach 'A' 1

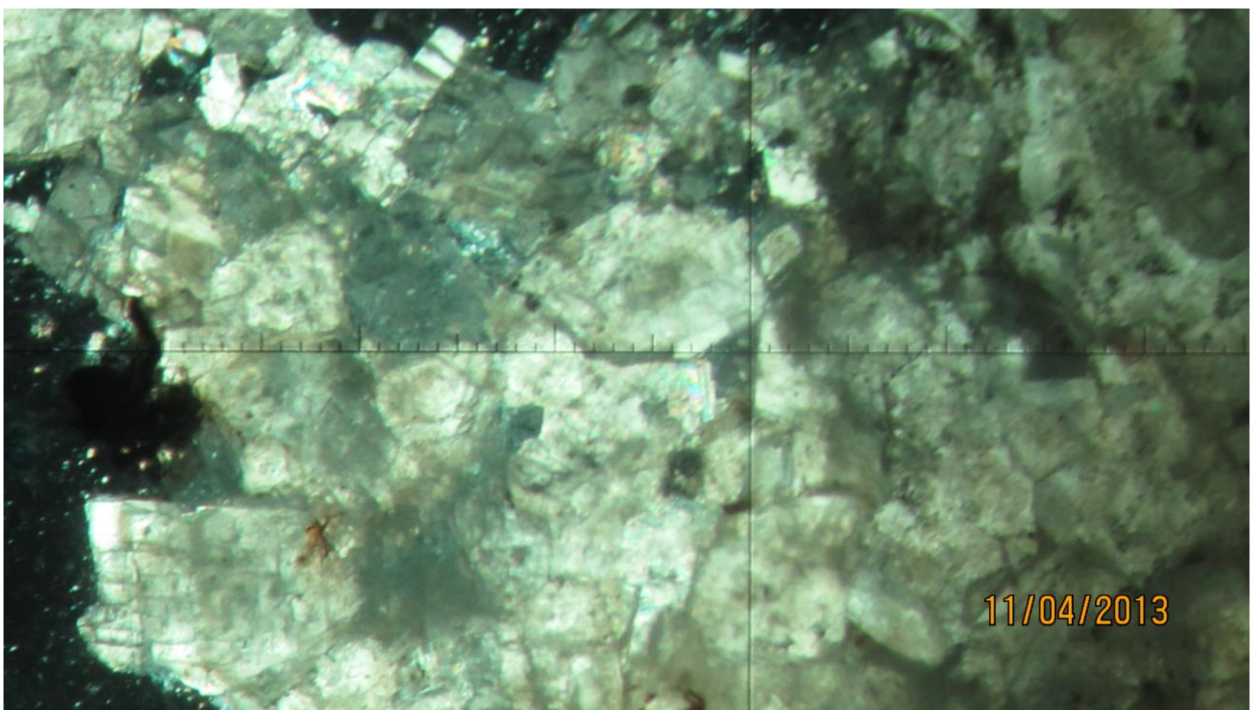

Figure 7.14 Thin section of cutting sample from well Leach 'A' 1

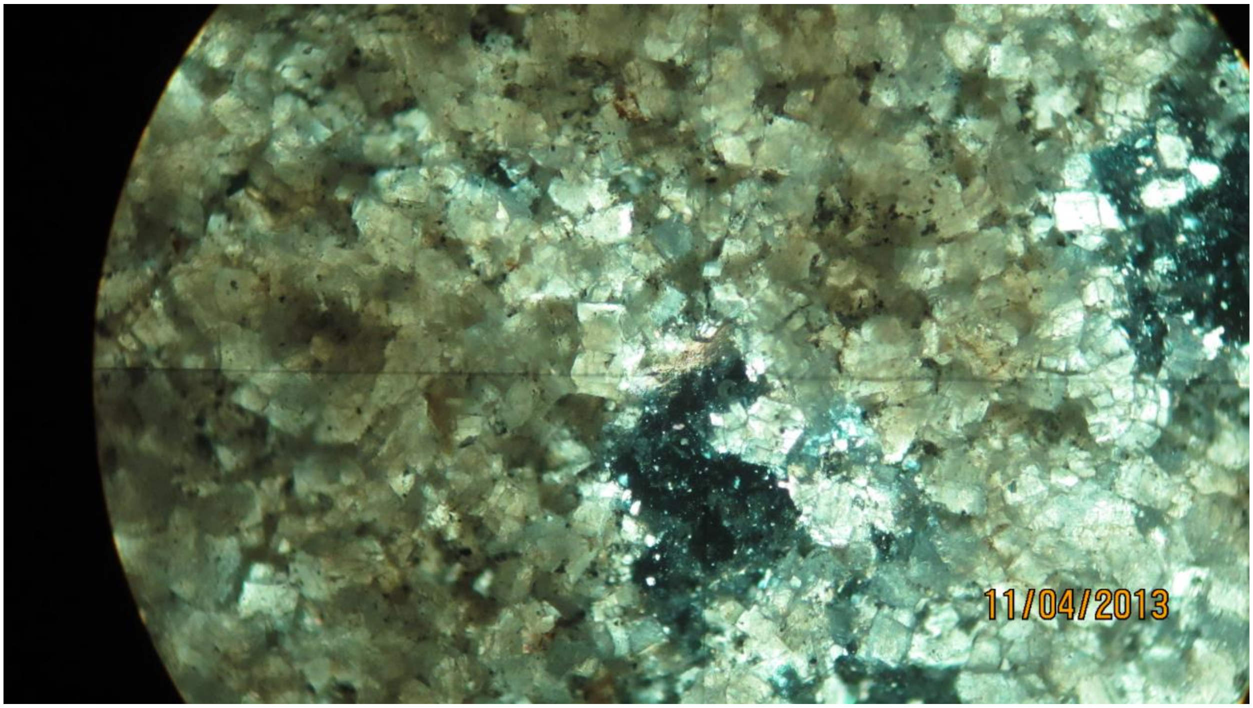

Figure 7.15 Thin section of cutting sample from well Leach 1

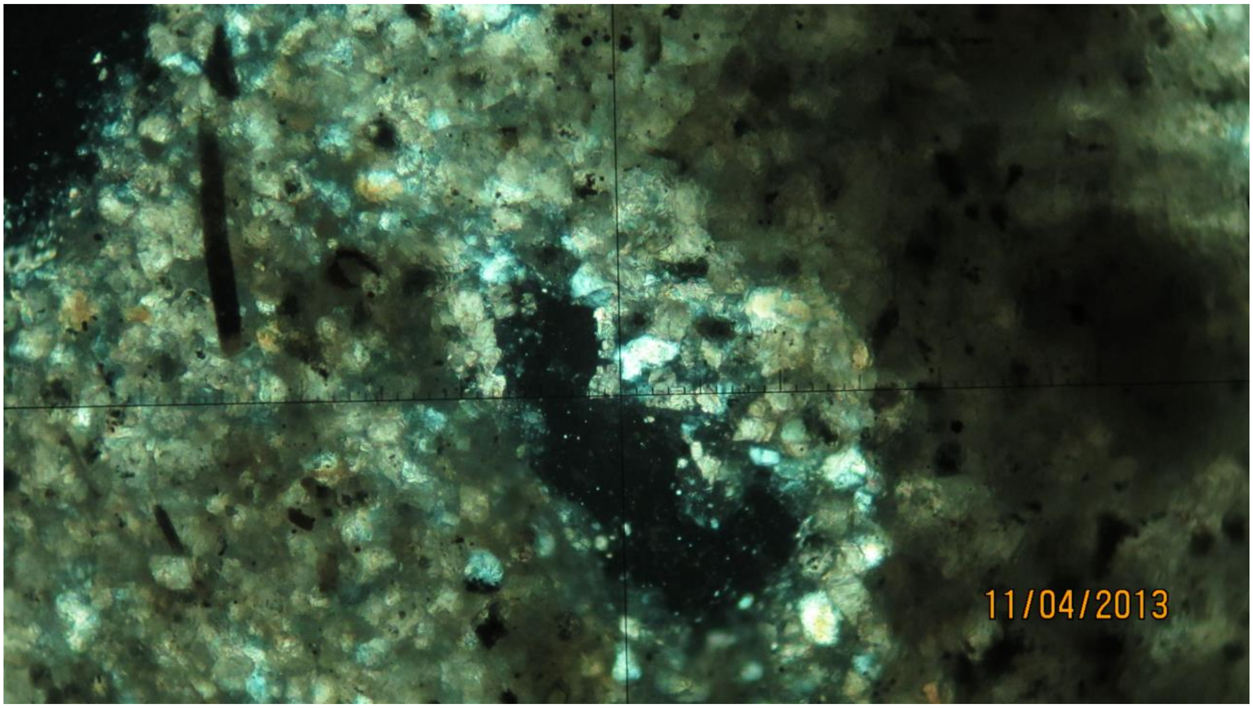

Figure 7.16 Thin section of cutting sample from well M.A. Beightel 1

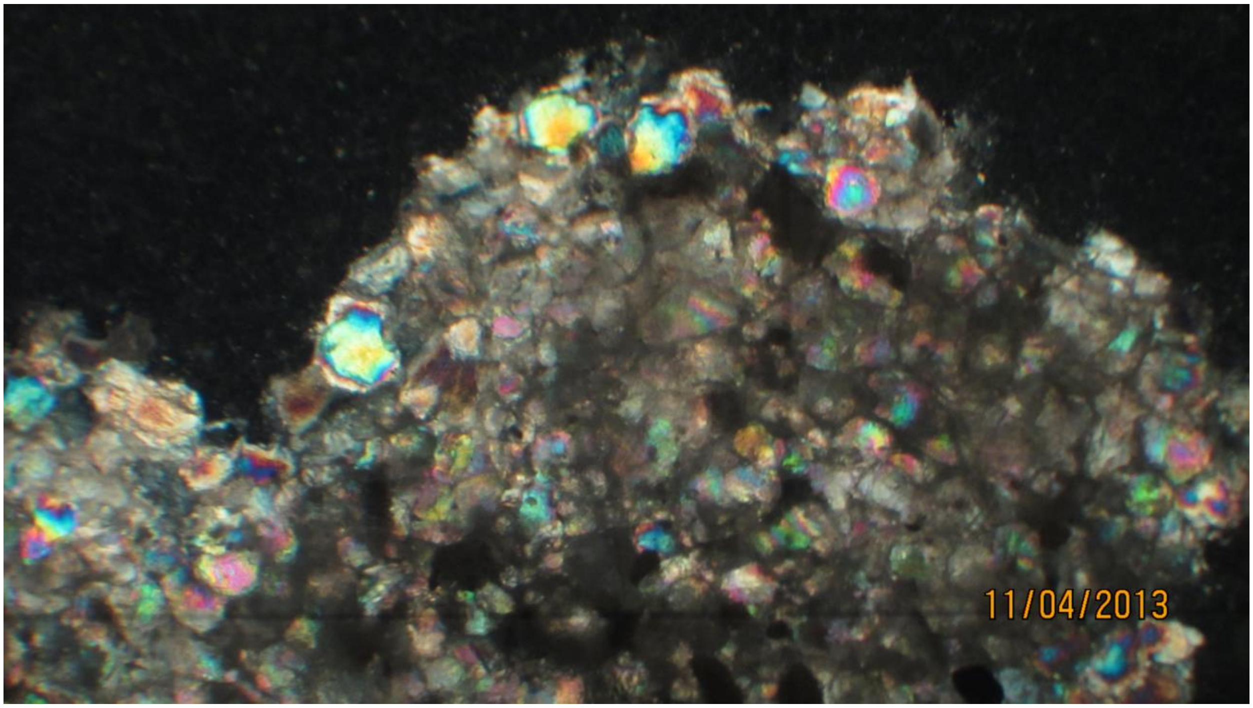

Figure 7.17 Thin section of cutting sample from well M.A. Beightel 1