How do Active Sedimentary Basins Dewater as They Deepen and Compact? A Hypothesis in Which Pervasive Crustal Fracturing Provides Persistent Channels for Vertical Fluid Flow

Senior Thesis
Submitted in partial fulfillment of the requirements for the
Bachelor of Science Degree
At The Ohio State University

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2014

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TABLE OF CONTENTS

ABSTRACT

Through this research we propose sedimentary basins dewater through long-lived, nearly vertical mega-fractures in order to accommodate observed increases in compaction, and decreases in porosity with increasing depth. Mondol et al. (2007), and geologists before him, were able to prove that bodies of rock lose porosity through basin history due to compaction. Leading us to ask "How does pore fluid escape from these shrinking pores?". Evidence for the existence of fine-scale, ephemeral 'natural fractures', noted by Cosgrove (2001), proves that migration of subsurface fluids occur throughout basin history on a localized level. Thus, allowing us to hypothesize that crustal fracture systems, form drainage systems for subsiding sedimentary basins. We draw an analogy with transportation networks where: alleys lead to streets, streets to roads, roads to highways, and highways to superhighways. If this hypothesis holds true, these fracture systems may control the movement of subsurface fluids which may have implications for fracking operations.

ACKNOWLEDGEMENTS

I would like to thank Dr. Michael Bevis for donating his time, energy, and wisdom throughout this research project. I appreciate the guidance given by staff members within the School of Earth Sciences at The Ohio State University. I would also like to thank Shell Exploration and Production Company, as they gave me the opportunity to conduct this research by way of the Shell Undergraduate Research Experience summer internship in 2013. Last but not least, a big thanks to Daniel Dotson, Ohio State University librarian.

LIST OF FIGURES

PURPOSE OF THIS STUDY

As sedimentary basins subside and fill, their strata are progressively buried and compacted due to the weight of overlying sediments. The compaction process involves loss of porosity and pore fluids. But how are these pore fluids expelled from the sedimentary basin? What are the pathways for dewatering the basin as a whole? We develop a hypothesis based on the concept of pervasive orthogonal fracturing of the Earth's crust (Parker Gay Jr., 1973; Bevis and Gilbert, 1990). We hypothesize that mega-fracture systems that originated in basement rocks in the Precambrian, propagate upwards through younger sedimentary cover and so provide a vertical 'superhighway' network for the expulsion of pore fluids within actively subsiding sedimentary basins. We develop this hypothesis, and then consider some of its implications. Our goal here is to motivate, develop and explain this hypothesis, as a necessary precondition for its eventual testing.

LITERATURE REVIEW

Sedimentary basins are highly complex structures that have been created due to erosion, sediment deposition, and subsidence. In order for such basins to develop certain conditions must be met. Firstly, there needs to be an ample source of sediment; this could be any structure that is susceptible to weathering processes which cause erosion to occur. There must also be an area in which sediment deposition can occur. Over time, sediments accumulate allowing for the occurrence of subsidence, giving rise to a basin.

With the proper conditions, sediment deposition may allow for the preservation of fluids between grains, yielding primary porosity (Hart et al., 1995; Darrah, 2014). Sediment compaction and alteration, causing diagenesis, in response to subsidence and increasing overburden, alter the physical properties of sediment as time progresses (Puttiwongrak et al., 2013). Physical properties altered due to effective stresses include: density, porosity, permeability, and pore pressure. Sediment alteration creates what is called secondary porosity. Secondary porosity is created after lithification, where one may see the appearance of fractures or the creation of intragranular porosity due to applied stresses and water rock interactions (Darrah, 2014). Secondary porosity can either increase or decrease throughout basin history.

Mondol et al. (2007) compiled data from previous works to show how porosities, for various lithologies, change as depth of burial increase within an actively subsiding sedimentary basin. They found that all lithologies studied display decreases in porosity as subsidence and basin age increase (Figure 1). However, he also found that not all lithologies lose all of their porosity, meaning dewatering processes persist at depth. If this is true, how and where are these pore fluids being released?

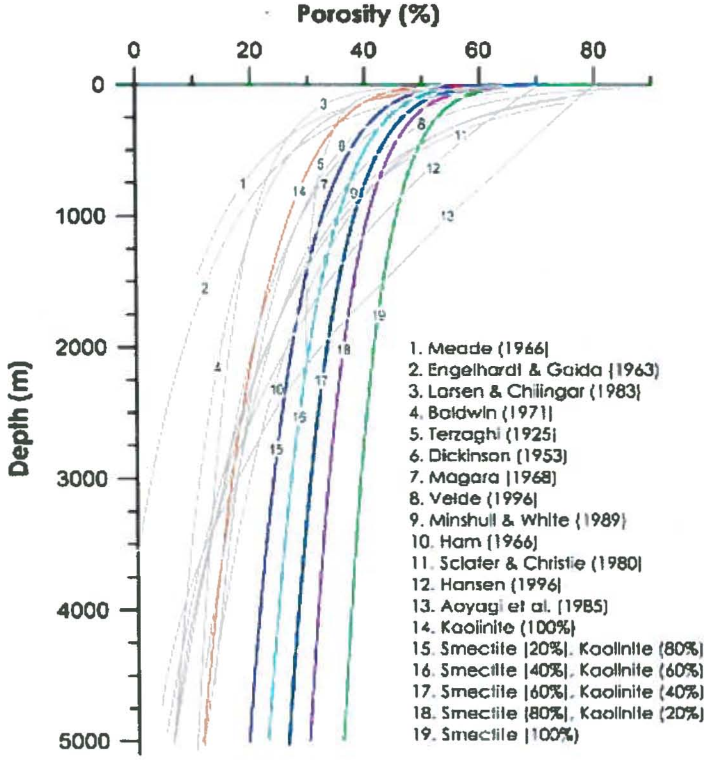


Fig. 1. Compaction curves for shales and agrillaceous sediments. The curves are selected from available published porosity-depth trends from different parts of the world. Mondo et al. (2007). Figure 1 shows that compaction reduction of pore volume continues throughout basin history.

The existence of over-pressured sediments underlying impermeable sedimentary layers, such as tight shales, implies that mechanical dewatering during burial is not always easily nor completely achieved (Secor, 1965; Cosgrove, 2001). Of course, it is possible that a small fraction of pore fluid may be absorbed in low temperature chemical reactions, but this cannot plausibly account for all fluid loss at depth (Darrah, 2014). Natural fracturing, during burial and diagenesis is important in the migration of fluids through and out of low-permeability sediments (Cosgrove, 2001). Natural fractures occur in bodies of rock in which the pore pressures have exceed the amount of stress necessary, lithostatic stress, to cause the body of rock in question to fail (Darrah, 2014). These failures are represented as fractures in bodies of rock.

Natural fractures of this kind can provide pathways for local pore fluid migration. However, these fractures are short-lived due to healing in response to hydrothermal processes such as pore pressure solution and precipitation of minerals as fluids move and come out of solution (Engelder, 1987; Engelder & Fischer, 1994; Cosgrove, 2001). Minerals precipitating in fractures provide evidence for the occurrence of natural fractures at depth (Figure 2). Precipitation causes pre-existing fractures to become larger (Wilson, 2014). It seems highly unlikely that all pore fluid migration at depth is achieved solely through these fine-scale, ephemeral fractures. What other components could be responsible for the mass migration of pore fluids in sedimentary basins?

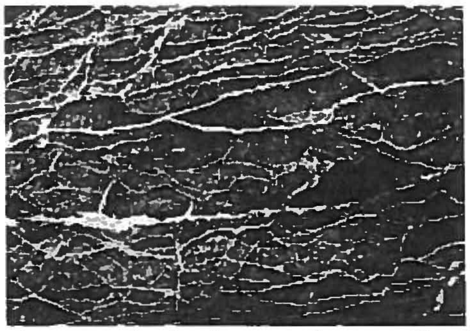
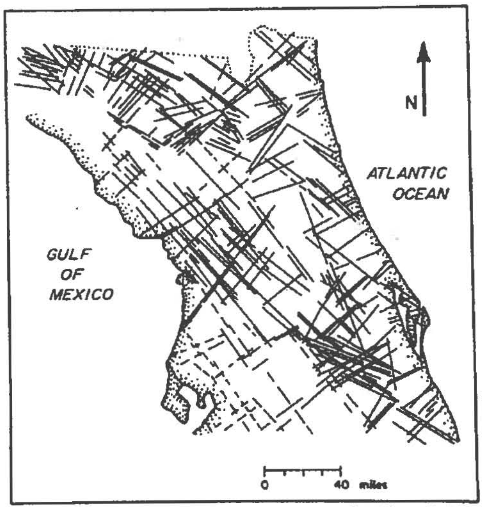


Fig. 2. A pervasive network of satin spar veins recording the pattern of hydraulic fractures that developed in the evaporite-rich horizons within the Mercia Mudstones (Cosgrove 2001).

The existence of continental lineations or lineaments has been recognized for quite some time. Lineations are surface expressions of underlying fault or fracture planes. Parker Gay Jr., in the 1970s, reviewed international geological literature regarding lineaments. Through his review he was able to determine that continents are pervaded by crustal-scale, vertical to sub-vertical fractures that intersect one another at nearly ninety degrees (Parker Gay Jr., 1973). He dubbed these intersecting fracture systems 'pervasive orthogonal fractures'. These fracture systems may or may not be faults, due to a lack of evidence proving there is measurable displacement along fracture planes.

Past research indicates that orthogonal fractures were emplaced in basement rocks that now underlie sedimentary cover (Plafker, 1964; Gay Jr. 1973). This is fitting because as sediments fill cracks they typically subside, especially if there is ample void space for compaction to occur. Hence, the sediment infill may not match the elevation of surrounding topography. The basement fractures are believed to have occurred during the Precambrian, which would have been before the sediment cover was deposited (Plafker, 1964). Then as sediment accumulated the fractures subsequently propagated upward through the overlying sedimentary cover, manifesting themselves as surface lineaments.

Plafker (1964) identified a large group of what he termed 'oriented lakes' in Central Bolivia whose linear borders were dominated by NE and NW azimuth. Vernon (1951) also noticed this same orientation of lineaments in northern Florida (Figure 3). Plafker (1964) argued that these oriented lakes were shallow surface depressions that had developed above platform sediments and therefore must be controlled by fractures. He also identified a similar dominant fabric of orthogonal fractures, Precambrian in age, in a nearby craton. He argued that these fractures, although exposed due to erosion, must have also pervaded through the basement platform sediments, and had also been propagated upward through sedimentary cover producing oriented lakes. Parker Gay Jr. also pointed out several areas in the United States where orthogonal lineament fields, identified in either sedimentary basins or platform sequences, had the same general directional fabric as orthogonal fracture systems exposed in adjacent basement windows. Interestingly enough, the basement fracture systems were always of Precambrian age.



from Vernon (1951)

Figure 3. Northern Florida airphoto lineaments from Vernon 1951.

Further research, by Bevis and Gilbert (1990), noted trans-continental dike swarms (i.e. MacKenzie Dike Swarm of the Canadian Shield) were produced in almost every craton after lithospheric stabilization during the mid-Proterozic. Stabilization refers to Earth's surface cooling and contracting in conjunction with the creation of stress fields. This observation proved that regional crustal fracturing, with a consistent directional fabric, was global in the Precambrian. In their work regarding the creation of the Mackenzie Dike Swarm, Heaman and Le Cheminant (1989) confirmed that tensional stress fields played a role in pathway creation along which magma could travel. The evidence for this is visible through igneous intrusions.

The Mackenzie Dike Swarm, the largest known radiating dike swarm on Earth, provides evidence for magma having the ability to travel for thousands of miles (Le Cheminant and

Heaman, 1989). Gudmundsson (2006) and Hou et al. (2010) discovered that magma pressures, along with paths of least resistance created by stress fields, i.e. fractures, are the perfect remedy for fluid migration. Together these observations can be interpreted that fluid migration can persist for hundreds to thousands of kilometers if there is enough fluid pressure.

Davies et al. (2012) discuss the vertical extent of natural fractures compared to stimulated fractures; the only results discussed herein from their work will be in regards to natural fractures. They collected seismic data from offshore Mauritania, offshore Namibia and offshore mid-Norway. In total they collected data for 726 natural fractures. Two-way-travel time was used to determine heights of natural fractures by converting times to heights using estimated seismic velocities for the host successions (Davies et al. 2012). The shortest vertical extent recorded for all fractures studied was 200 meters, while the longest vertical extent recorded was 1,106 meters with an average fracture height of 300 meters. The results of their study are shown below in, in which it can be seen that the tallest natural fracture occurrences are located in zones where there is a dense population of fractures, termed 'clusters' (Figure 4).

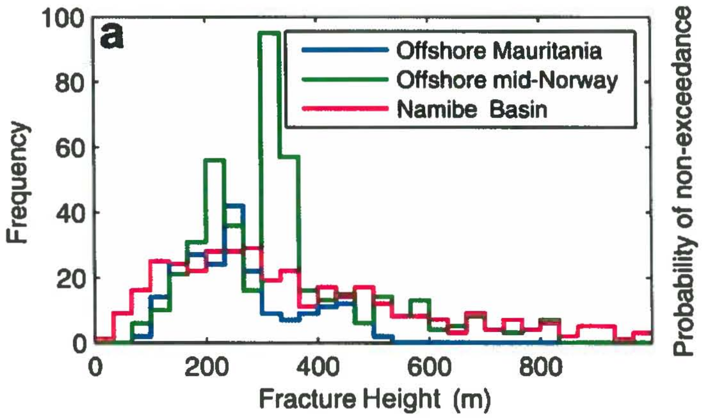


Figure 4. Graph of frequency against vertical extent for natural hydraulic fractures (pipes) identified on 3D seismic data from offshore Mauritania, Namibe Basin and, mid-Norway.

FINDINGS AND DISCUSSION

Understanding the mechanics of sedimentary basins is critical in determining the processes that drive fluid migration. It is obvious that an increase in depth of burial and overburden are key components in pore size reduction and pore pressure elevation. These two components are the culprits that create small-scale, ephemeral fractures due to overpressuring. Given the right conditions, these fractures may be preserved by mineral precipitation providing evidence for localized fluid migration along a conductive fracture. Furthermore, the existence of magma intrusions extending for hundreds to thousands of kilometers from a source provide proof that fluid migration is not limited to small, localized areas. Based on the compilation of previous studies and knowledge gained through an academic career in earth sciences, I believe that mega-fractures can act as conduits for deeply buried fluids to Earth's surface.

CONCLUSIONS

Through this research we propose sedimentary basins dewater through long-lived, nearly vertical mega-fractures in order to accommodate observed increases in compaction, and decreases in porosity with increasing depth. Mondol et al. (2007), and geologists before him, were able to prove that bodies of rock lose porosity through basin history due to compaction. That observation leads us to ask how does pore fluid escape from these shrinking pores? Evidence for the existence of fine-scale, ephemeral 'natural fractures' proves that migration of subsurface fluids occur throughout basin history, but only on a localized level as discussed by Cosgrove (2001).

The preservation of 'natural fractures' allow us to hypothesize that crustal fracture systems, which are nearly vertical and long-lived, form a drainage system for subsiding sedimentary basins. We draw an analogy with transportation networks where: alleys lead to streets, streets to roads, roads to highways, and highways to superhighways. The hypothesis stated above seems plausible, but needs to be tested. Finally, if this hypothesis holds true, these fracture systems may control the movement of oil and gas, as well as water. This might have implications for fracking operations in new shale gas plays, and might also have implications for induced seismicity at injection wells for disposal of returned fluids from shale wells.

RECOMMENDATIONS FOR FUTURE WORK

The concept of pervasive orthogonal fracturing is largely based on the analysis of geomorphology and near-surface geology. The extensive subsurface datasets available to the oil and gas industry should allow this concept to be tested much more rigorously. Thus, geologists may be able to determine how orthogonal fracture systems control the movement of subsurface fluid.

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