NDIC Contract No. G-045-89

Start Date of Contract: September 1, 2018

July 2019 Status Report

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Introduction:

This report serves as the second status report outlining the progress of the Ph.D. projects since the conclusion of the first report, which was due on January 31, 2019. As a refresher, according to the contract, the Department of Petroleum Engineering (DPE) at UND was expected to support 9 Ph.D. students from the NDIC funding, plus 6 additional students supported by the DPE to work on project topics proposed by the NDIC and listed in the contract as the followings:

- Big Data Analytics/UAS/Data Mining
- CO2-EOR
- Sulfate Deposition
- Machine Learning/Refracking

IN Table 1, the updated titles of the projects that have been assigned to each Ph.D. student are given. Some projects have slight changes in their direction which is the nature of research work. Those are shown by (*) next to the numbers in the first column. In this Table, the title of additional 8 Ph.D. projects that are undertaken in the department is listed in the Table too in order to inform NDIC of other projects that the DPE is undertaking.

The impact of this funding in terms of the growth of the research in the Department has been significant. In 2019 to date 47 papers have been published or submitted to journals and conferences. Also, the students have attended a number of conferences within and outside the USA. The list of publications and conferences that the students attended are given at the end of the report. This has brought a great reputation for the department. We therefore appreciate the provision of this funding by the NDIC.

In the following a brief summary of each project progress since the last report is given We hope the contract can be renewed for the next term to provide financial support to the current students to complete their projects to the highest expected quality.

Attached to this report is powerpoint presentation slides which summarizes the progress of the project to date.

Industry Seminar:

As requested in the first report, in addition to the current report, as part of the requirements of the contract, we would like to organize a one-day industry seminar as soon as possible and workable for the NDIC and invite the NDIC board to listen to the presentation of the projects progress by Ph.D. students. If agreed by the NDIC, we also would like to announce the event to the industry in North Dakota to attend this seminar to provide their technical feedback about each project. This will help us to ensure that the projects will carry the industry applications and give us the opportunity to discuss the technical aspects of each project with the industry and request their support in terms of providing data. If preferred by the NDIC, the seminar can be organized via webinar or skype.

Table 1: List of current Ph.D. students' projects at the DPE

	Student	Advisor	Project Title	Project Area
1*	Karthik Balaji	Rabiei	Enhanced Financial and Regulatory Planning for Carbon Capture & Sequestration (CCS) Infrastructure using an Algorithmic Approach	Data Mining
2*	Zifu Zhou	Rabiei	Drilling Parameters optimization based on Machine Learning Models and Data Mining Techniques	Machine Learning/Block Chain
3	Matt Dunlevy	Rabiei/ Rasouli	Accelerating Pipeline Leak Detection Through Unmanned Aircraft Systems Based Routine Surveillance and Data Mining	UAS/Big Data Analytics
4	Xincheng Wan	Rasouli/ Rabiei	An integrated Data Mining and Simulation to Optimize Refracturing Design	Refracking/Data Mining
5	Olusegun Stanley Tomomewo	Mann	Studying the Mechanism of Barite Scales Formation & its Removal/Prevention in McKenzie and Williams Counties, Bakken Formation, ND	Barite Scales Formation
6*	Abdulaziz Ellafi	Jabbari	Experimental and Numerical Investigation of the CO2-EOR Mechanisms in Unconventional Rich Liquid Reservoirs (Bakken Fm, Williston Basin, ND)	CO2 EOR
7*	Nidhal Badrouchi	Pu	Bakken Tertiary Oil Recovery: CO2 based solvent EOR	CO2 EOR
8	Ogochukwu Ozotta	Ostadhassan	Geomechanical Impact of CO2-EOR on the Bakken Formation	CO2 EOR
9	Hao Fu	Ling	Using Pressure Distribution to Detect the Blockage and Leakage in the Pipelines	Pipeline Leakage/UAS
10*	Nejma Djabelkhir	Rasouli	Lattice simulations of lab scale hydraulic fracturing	Hydraulic Fracturing
11	Aldjia Djezzar	Rasouli/ Rabiei	Impact of Stress on the Characterization of Flow Units in the Complex Three Forks Carbonate Reservoir, Williston Basin	Machine Learning/ Petrophysics Three Forks

12	Dezhi Qiu	Rasouli/ Rabiei	Discrete Fracture Network (DFN) Modelling of Hydraulic Fracturing	DFN (Discrete Fracture Network)/Artificial Intelligent
13*	Omar Akash	Rasouli	Simulations of Near Wellbore Hydraulic Fracturing Through Perforations	Cased Hole HF
14	Lingyun Kong	Ostadhassan	Replicating Bakken Shale Rock for Petrophysical Experiments Using 3D Printing Technology	3D Printing Shale
15	Arash Abarghani	Ostadhassan	Multi-Scale Organic Material Characterization of the Bakken Source Rock	Organic Mat. Characterization
16*	Hyeon Seok Lee	Ostadhassan	CO2 sequestration and EOR capacity of the Bakken Formation through Molecular Simulation & Characterization	Kerogen MM
17*	Seyed Alireza Khatibi	Ostadhassan	Fine scale characterization of organic matter using analytical methods: Raman and NMR spectroscopies	Spectroscopy
18	Siamak Koloushani	Rasouli	Lattice Numerical Simulations of Hydraulic Fracturing in High Permeable Formations	HF in High Permeable Formation
19*	Sofiane Djezzar	Rasouli	Fracture detection and prediction in unconventional reservoirs for finding sweet spot	Fracture Mapping
20	Yanbo Wang	Ling	Lab Experiments Using a Two-phase Flow Loop Unit and Numerical Simulations	Multiphase Flow
21	Foued Badrouchi	Rasouli	Cuttings Transportation Optimization: Lab Experiments Using a Large Scale Slurry Loop Unit and Numerical Simulations	Borehole Cleaning
22	Ahmed Ismail	Rasouli	Automated Directional Drilling: Lab Experiments and Numerical Simulation	Directional Drilling
23	Imene Bouchakour	Rasouli	Crack Geometry Prediction in Replicated Rock Samples During Triaxial Testing Using Velocity Data	Acoustic Emission

Publications:

1. Abarghani, A., Gentzis, T., Shokouhimehr, M. and Ostadhassan, M. (2019) 'Nanoscale heterogeneity of organic matter in geomaterials by AFM based IR spectroscopy', International Journal of Coal Geology (Submitted).
2. Abarghani, A., Ostadhassan, M., Bubach, B. and Zhao, P. (2019). 'Estimation of thermal maturity in the Bakken source rock from a combination of well logs, North Dakota, USA', Marine and Petroleum Geology, 105, pp.32-44.
3. Abarghani, A., Ostadhassan, M., Gentzis, T., Carvajal-Ortiz, H. and Bubach, B. (2018) 'Organofacies study of the Bakken source rock in North Dakota, USA, based on organic petrology and geochemistry', International Journal of Coal Geology, 188, pp.79-93.
4. Abarghani, A., Ostadhassan, M., Gentzis, T., Carvajal-Ortiz, H., Ocubalidet, S., Bubach, B., Mann, M. and Hou, X. (2019) 'Correlating Rock-Eval™ Tmax with bitumen reflectance from organic petrology in the Bakken Formation', International Journal of Coal Geology, 205, pp.87-104.
5. Abarghani, A., Ostadhassan, M., Gentzis, T., Khatibi, S. and Bubach, B. (2019) 'The effect of thermal maturity on redox-sensitive trace metals concentration in the Bakken source rock, North Dakota, USA', Chemical Geology (Submitted).
6. Abarghani, A., Ostadhassan, M., Hackley, P., Pomerantz, A. and Nejati, S. (2019) 'A chemo-mechanical snapshot of in-situ conversion of kerogen to petroleum', Geochimica et Cosmochimica Acta (Submitted).
7. Ahmadinejad, A., Rahimzadeh Kivi, I., Ameri, M. and khatibi, S. (2019) 'Experimental Study of the Hydro-Mechanical Response of Tight Sarvak Carbonates to Hydrostatic and Deviatoric Stress Changes', 53nd US Rock Mechanics/Geomechanics Symposium.
8. Akash, O., Vamegh, R., Damjanac, B., Zhang, F. and Badrouchi, F. (2019) Lattice Simulations of Hydraulic Fracture Reorientation from Perforations, 53rd US Rock Mechanics / Geomechanics Symposium edn., NewYork: American Rock Mechanics Association.
9. Akash, O., Vamegh, R., Djabelkhir, N. Badrouchi, F., Damjanac, B., and Zhang, F. (2019) 'Lattice Simulations of Hydraulic Fracture Reorientation from Perforations', Proceedings of ARMA 53rd US Rock Mechanics / Geomechanics Symposium New York City 23 - 26 June 2019
10. Almetwally, A. and Jabbari, H., June 2019: "Development of Novel Workflow to Replicate Pore Network of Porous Core Samples Through 3D Printing Technology" American Rock Mechanics Association 53rd Symposium, New York.
11. Almetwally, A. and Jabbari, H., June 2019"CT-Scan Image Processing for Accurate Pore Network Modeling and Core Samples 3D Printing: Polynomial Interpolation & Geostatistical QC" American Rock Mechanics Association 53rd Symposium, New York.
12. Alexeyev, A., Ostadhassan, M., Bubach, B., Boualam, A., Djezzar, S. 2017. Integrated Reservoir Characterization of the Middle Bakken in the Blue Buttes Field, Williston Basin, North Dakota. SPE Western Regional Meeting, Bakersfield, California.
13. Badrouchi, F., Bouchakour, I., Djabelkhir, N., Damjanac, B. and Rasouli, V. (2019) Lattice Simulation of Fracture Containment in Middle Bakken Formation, 53rd US Rock Mechanics / Geomechanics Symposium edn., NewYork: American Rock Mechanics Association.

14. Badrouchi, F., Rabiei, M., Badrouchi, N. and Rasouli, V. (2019) Estimation of Elastic Properties of Bakken Formation Using an Artificial Neural Network Model, 53rd US Rock Mechanics / Geomechanics Symposium edn., NewYork: American Rock Mechanics Association.
15. Badrouchi, F., Wan, X., Bouchakour, I., Akash, O., Rasouli, V., and Damjanac, B. (2019) 'Lattice Simulation of Fracture Propagation in the Bakken Formation', Proceedings of ARMA 53rd US Rock Mechanics / Geomechanics Symposium New York City 23 - 26 June 2019
16. Badrouchi, N., Jabbari, H. and Badrouchi, F. (2019) Comparison of Unsteady-State Permeability Measurement methods for Middle-Bakken Core Samples, 53rd US Rock Mechanics / Geomechanics Symposium edn., NewYork: American Rock Mechanics Association.
17. Badrouchi, N., Jabbari, H., Badrouchi, F. and Tomomewo, O.S. (2019) Comparing Different Methods of Permeability Measurement for Bakken Core Samples: Steady-State vs. Aspike & Multi-pulse, 53rd US Rock Mechanics / Geomechanics Symposium edn., NewYork: American Rock Mechanics Association.
18. Balaji, K., Rabiei, M., Suicmez, V., Canbaz, C. H., Agharzeyva, Z., Tek, S., … Temizel, C. (2018, June 8). Status of Data-Driven Methods and their Applications in Oil and Gas Industry. Society of Petroleum Engineers. doi:10.2118/190812-MS
19. Balaji, K., Zhou, Z., & Rabiei, M. (2019, April 22). How Big Data Analytics Can Help Future Regulatory Issues in Carbon Capture and Sequestration CCS Projects. Society of Petroleum Engineers. doi:10.2118/195284-MS
20. Boualam, A., Djezzar, S., Rasouli, V, Rabiei, M., 2019. 3D Modeling and Natural Fractures Characterization in Hassi Guettar Field, Algeria. 53rd US Rock Mechanics/Geomechanics Symposium New York, NY, USA, 23–26 June 2019.
21. Boualam, A., Rasouli, V, Dalkhaa, C, Djezzar, S., Rabiei, M. 2019. integrated reservoir characterization of the Three Forks formation, Williston basin. Journal of Marine & Petroleum Geology (in process).
22. D. Qiu, V. Rasouli, B. Damjanac, and X. Wan (2019) 'Lattice Simulation of Fracture Propagation in the Bakken Formation', 53rd U.S. Rock Mechanics/Geomechanics Symposium, 23-24 June, New York, NY, USA
23. D. Qiu, V. Rasouli, B. Damjanac, X. Wan (2019) 'Narrow versus Wide Fairway Fracture Geometry', 53rd U.S. Rock Mechanics/Geomechanics Symposium, 23-24 June, New York, NY, USA
24. Djabelkhir, N., Song, X., Wan, X., Akash, O., Rasouli, V., and Damjanac, B. (2019) 'Notch Driven Hydraulic Fracturing in Open Hole Completions: Numerical Simulations of Lab Experiments', Proceedings of ARMA 53rd US Rock Mechanics / Geomechanics Symposium New York City 23 - 26 June 2019
25. Djezzar, S., Rasouli, V, Boualam, A., Rabiei, M. 2019. An integrated workflow for multiscale fracture analysis in reservoir analog. Arabian Journal of Geosciences (in process).
26. Djezzar, S., Rasouli, V, Boualam, A., Rabiei, M. March 2019. Integration of Seismic Curvature and Illumination Attributes in Fracture Detection on a Digital Elevation Model: Methodology and Interpretational Implications. Joint Geological Society of America, Section Meeting South-Central, North-Central, and Rocky Mountain Sections. 25–27 March 2019, Manhattan, Kansas.

27. Djezzar, S., Rasouli, V, Boualam, A., Rabiei, M., June 2019. A New Method for Reservoir Fracture Characterization and Modeling using Surface Analog. 53rd US Rock Mechanics/Geomechanics Symposium New York, NY, USA, 23–26 June 2019.
28. Djezzar, S., Rasouli, V, Boualam, A., Rabiei, M., March 2019. Fractal Analysis of 2-D Fracture Networks of Naturally fractured Reservoirs Analog in south Algeria. Joint Geological Society of America, Section Meeting South-Central, North-Central, and Rocky Mountain Sections. 25–27 March 2019, Manhattan, Kansas.
29. Djezzar, S., Rasouli, V, Boualam, A., Rabiei, M., March 2019. Fractography Analysis of Cambro-Ordovician Reservoirs through Surface Analog. Mouydir Basin, Algeria. Joint Geological Society of America, Section Meeting South-Central, North-Central, and Rocky Mountain Sections. 25–27 March 2019, Manhattan, Kansas.
30. Djezzar, S., Rasouli, V, Boualam, A., Rabiei, M., March 2019. Size Scaling and Spatial Clustering of Natural Fracture Networks Using Fractal Analysis. 53rd US Rock Mechanics/Geomechanics Symposium New York, NY, USA, 23–26 June 2019.
31. E. Bakhshi, V. Rasouli, A. Ghorbani, M. Fatehi Marji, B. Damjanac, and X. Wan (2019) 'Lattice Numerical Simulations of Lab-Scale Hydraulic Fracture and Natural Interface Interaction', Rock Mechanics and Rock Engineering, 52(5), pp. 1315–1337.
32. Ellafi, A. and Jabbari, H (2019) 'Coupling Geomechanics with Diffusion/Adsorption Mechanisms to Enhance Bakken CO2-EOR Modeling', American Rock Mechanics Association (ARMA), (), pp.
33. Ellafi, A., Ba Geri, M., Bubach, B. and Jabbari, H. (2019) 'Formation Evaluation and Hydraulic Fracture Modeling of Unconventional Reservoirs: Sab'atayn Basin Case Study', American Rock Mechanics Association (ARMA), (), pp.
34. F. Badrouchi, X. Wan, I. Bouchakour, O. Akash, V. Rasouli, and B. Damjanac (2019) 'Lattice Simulation of Fracture Propagation in the Bakken Formation', 53rd U.S. Rock Mechanics/Geomechanics Symposium, 23-24 June, New York, NY, USA
35. Fu, H., Long, Y., Wang, S., Wang, Y., Yu, P. and Ling, K. (2019) The Development of CO2 Plume in CO2 Sequestration in the Aquifer, Houston: 2019 Carbon Management Technology Conference.
36. H. Liang, S. Zhang, Y. Kang, K. Ling (2018) 'Separation Performance of Supersonic Separator with a Rear-Set Helical Guide Blade', 2018 AIChE Spring Meeting, 22-26 April, Orlando, FL, USA
37. H. Liang, S. Zhang, Y. Kang, K. Ling (2019) 'Research on Natural Gas Separation Flow Laws in a New Type of Supersonic Cyclone Separator', 11th International Petroleum Technology Conference (IPTC), 26-28 March, Beijing, China
38. H. Liang, S. Zhang, Y. Kang, K. Ling, S. Wang (2017) 'Research on Separation Performance of Supersonic Separator with a Forward Helical Guide Blade', 2017 AIChE Annual Meeting, 29 October-3 November, Minneapolis, MN, USA
39. Khatibi, S., Ostadhassan, M. and Aghajanpour, A. (2018) 'Geomechanical and Geochemical Characterization of Organic Matter by Raman Spectroscopy', 52nd US Rock Mechanics/Geomechanics Symposium.
40. Khatibi, S., Ostadhassan, M. and Aghajanpour, A. (2018) 'Raman spectroscopy: an analytical tool for evaluating organic matter', Journal of Oil, Gas and Petrochemical Sciences, 1(1), pp. 28-33.
41. Khatibi, S., Ostadhassan, M., Aghajanpour, A. and Farzay, O. (2018) 'Evaluating Single-Parameter parabolic failure criterion in wellbore stability analysis', Journal of Natural Gas Science and Engineering, 50(1), pp. 166-180.

42. Khatibi, S., Ostadhassan, M., Aghajanpour, A. and Mohammed, R. (2018) 'NMR T1-T2 Map of Different Hydrogen Contents of Bakken Formation', International Journal of Chemical Engineering and Applications, 9(3).
43. Khatibi, S., Ostadhassan, M., Aghajanpour, A. Kovaleva, Y. and Mohammed, R. (2018) 'Various effect of faults on mechanical earth models: A case study of integrated study', Geomechanics and Geodynamics of Rock Masses, pp. 1395-1401.
44. Khatibi, S., Ostadhassan, M., Aghajanpour, A. Kovaleva, Y. and Mohammed, R. (2018) 'Drilling deviated wells in a highly unstable gas field in southern part of Iran', Geomechanics and Geodynamics of Rock Masses, pp. 1387-1395.
45. Khatibi, S., Ostadhassan, M., Farzay, O. and Aghajanpour, A. (2019) 'Seismic Driven Geomechanical Studies: A Case Study of an Offshore Gas Field ', 53nd US Rock Mechanics/Geomechanics Symposium.
46. Khatibi, S., Ostadhassan, M., Hackley, P., Tuschel, D., Abarghani, A. and Bubach, B. (2019) 'Understanding organic matter heterogeneity and maturation rate by Raman spectroscopy', International Journal of Coal Geology, 206, pp.46-64.
47. Khatibi, S., Ostadhassan, M., Tuschel, D., Gentzis, T., Bubach, B. and Carvajal-Ortiz, H. (2018) 'Raman spectroscopy to study thermal maturity and elastic modulus of kerogen', International Journal of Coal Geology, 185, pp. 103-118.
48. Khatibi, S., Ostadhassan, M., Tuschel, D., Gentzis, T., Bubach, B. and Carvajal-Ortiz, H. (2018) 'Evaluating molecular evolution of kerogen by raman spectroscopy: correlation with optical microscopy and rock-eval pyrolysis', Energies, 11(6), pp. 1406-1425.
49. Khatibi, S., Ostadhassan, M., Xie, Z. H., Gentzis, T., Bubach, B. Gan, Z. and Carvajal-Ortiz, H. (2019) 'NMR relaxometry a new approach to detect geochemical properties of organic matter in tight shales', Fuel, 235, pp. 167-177.
50. Kong, L., Ostadhassan, M., Hou, X., Mann, M., Li, C. (2019) 'Microstructure Characteristics and Fractal Analysis of 3D-printed Sandstone Using Micro-CT and SEM-EDS', Journal of Petroleum Science & Engineering, 175(), pp. 1039-1048.
51. Kong, L., Ostadhassan, M., Tamimi, N., Samani, S., Li, C. (2019) 'Refracturing: Well Selection, Treatment Design and Lessons Learned- A Review', Arabian Journal of Geosciences, 12(), pp. 117
52. Kong, L., Ostadhassan, M., Zamiran, S., Liu, B., Marino, G., Sakhaee-Pour, A., Li, C. (2019) 'Geomechanical Upscaling Methods: Comparison and Verification via 3D Printing', Energies, 12(3), pp. 382.
53. Lee, H., Ostadhassan, M., liu, K., Bubach, B (2019) 'Developing an amorphous kerogen molecular model based on gas adsorption isotherms', Computational Geosciences. [Under review, Online early access]. DOI:10.26434/chemrxiv.7965152. Published Online: April 09, 2019. https://chemrxiv.org/s/dbfe102258d971e948f6
54. Lee, H., Ostadhassan, M., Shakib, F.A., Shokouhimehr, M., Bubach, B., Kong, L. (2019) Optimal separation of CO2/CH4/brine with amorphous kerogen: a thermodynamics and kinetics study. Journal of Physical Chemistry C. [Under review]
55. Li, C., Ostadhassan, M., Abarghani, A., Fogden, A. and Kong, L. (2019) 'Multi-scale evaluation of mechanical properties of the Bakken shale', Journal of materials science, 54(3), pp.2133-2151.
56. Li, C., Pu, H. and Zhao, J. (2019) 'Molecular Simulation Study on the Volume Swelling and the Viscosity Reduction of n-Alkane/CO2 Systems', Ind. Eng. Chem. Res., 58(20), pp. 8871-8877.
57. Li, C., Pu, H., Zhang, S. and Zhao, J. (2019) 'Effect of Nanoparticles and Surfactants on Oil/water Interfacial Tension: A Coarse-Grained Molecular Dynamics Simulation Study', Unconventional Resources Technology Conference, 22-24 July, Denver.

58. N. Djabelkhir, X. Song, X. Wan, O. Akash, V. Rasouli, and B. Damjanac (2019) 'Notch Driven Hydraulic Fracturing in Open Hole Completions: Numerical Simulations of Lab Experiments', 53rd U.S. Rock Mechanics/Geomechanics Symposium, 23-24 June, New York, NY, USA
59. Ostadhassan, M., Liu, k., Li, C. and Khatibi, S. (2018) Fine Scale Characterization of Shale Reservoirs: Methods and Challenges, 1st edn.: Springer.
60. Ozotta, O. and Ostadhassan, M. (2019) Geomechanical Analysis of CO2 Sequestration in the Bakken Formation, AAPG Annual Convention and Exhibition.
61. Ozotta, O., Ostadhassan, M. and Liu, K. (2019) A Review: Impact of CO2 on Geomechanical Properties of Shale Reservoir., Journal of Petroleum Science and Engineering. (Under review)
62. Temizel, C., Balaji, K., Canbaz, C. H., Palabiyik, Y., Moreno, R., Rabiei, M., … Ranjith, R. (2019, April 8). Data-Driven Analysis of Natural Gas EOR in Unconventional Shale Oils. Society of Petroleum Engineers. doi:10.2118/195194-MS
63. Tomomewo, O.S., Jabbari,H., Badrouchi, N., Onwumelu,C. and Mann, M. (2019) Characterization of the Bakken Formation using NMR and SEM Techniques, 53rd US Rock Mechanics / Geomechanics Symposium edn., New York: American Rock Mechanics Association
64. Wang, Y., Fu, H., Yang, L., Wang, S., Liang, H. and Ling, K. (2019) Study the Boundary of Two-Phase Flow Regime from Bubble to Slug Flow, Las Vegas: 4th Thermal and Fluids Engineering Conference.
65. Wang, Y., Ling, K., Fu, H., Yang, L., Wang, S. and Liang, H. (2019) Study of Pressure-Drop in Two-Phase Flow Based on Experiment and CFD Simulation, Las Vegas: 4th Thermal and Fluids Engineering Conference.
66. Wang, Y., Wang, S., Yang, L., Pu, H., Ling, K. (2018) A New Model to Evaluate Polished Rod Load of Sucker Rod Pumping System, Midland, Texas, USA: Society of Petroleum Engineers.
67. X. Wan, J. Ge, W. Li, and H. Pu (2018) 'Potential Thermoelastic and Poroelastic Stresses Effects During the Fracture Propagation of Hydraulic Fracturing Treatments in Horizontal Bakken Wells', 52nd U.S. Rock Mechanics/Geomechanics Symposium, 17-20 June, Seattle, Washington, USA
68. X. Wan, V. Rasouli, B. Damjanac, M. Torres, and D. Qiu (2019) 'Numerical Simulation of Integrated Hydraulic Fracturing, Production and Refracturing Treatments in the Bakken Formation', 53rd U.S. Rock Mechanics/Geomechanics Symposium, 23-24 June, New York, NY, USA
69. Xun Zhong, Hui Pu, Yanxia Zhou, Julia Xiaojun Zhao (2019) 'Comparative Study on the Static Adsorption Behavior of Zwitterionic Surfactants on Minerals in Middle Bakken Formation', Energy & Fuels, 33(2), pp. 1007-1015.
70. Yang, L., Fu, H., Liang, H., Wang, Y. and Ling, K. (2019) Analysis of Pressure Distribution along Pipeline Blockage Based on the CFD Simulation, Las Vegas: 4th Thermal and Fluids Engineering Conference.
71. Yang, L., Ling, K., Fu, H., Liang, H. and Wang, Y. (2019) A Systematic Instruction for Selecting Methods to Detect Pipeline Leakages, Las Vegas: 4TH Thermal and Fluids Engineering Conference.

72. Zhao, P., Ostadhassan, M., Shen, B., Liu, W., Abarghani, A., Liu, K., Luo, M. and Cai, J. (2019) 'Estimating thermal maturity of organic-rich shale from well logs: Case studies of two shale plays', Fuel, 235, pp.1195-1206.

Conferences attended:

1. Akash, O., February 2019: Graduate Workshop: Organizing and Managing Your Research, North Dakota. Participated.
2. Akash, O., March 2019: Graduate Workshop: In-Depth Searching for a Literature Review, North Dakota. Participated.
3. Akash, O., November 2018: Panel Discussion on Sales Pitch and Negotiation, North Dakota. Participated.
4. Akash, O., October 2018: Engineering isn’t easy…. managing engineers isn’t any easier, North Dakota. Participated.
5. Akash, O., September 2018: Geomechanics of Reservoir Stimulation by Hydraulic Fracturing, North Dakota. Participated.
6. Akash, O., September 2018: Workshop on Entrepreneurship and Leadership North Dakota. Participated.
7. Almetwally, A., June 2019: American Rock Mechanics Association 53rd Symposium, New York. Participated.
8. Almetwally, A., June 2019: American Rock Mechanics Association 53rd Symposium, New York. Participated.
9. Badrouchi,F., June 2019: 53rd US Rock Mechanics / Geomechanics Symposium, NewYork. Oral Presentation and Poster Presentation.
10. Badrouchi,F., March 2019: 2nd International Conference on Artificial Intelligence and Information Technology, Algeria. Participated.
11. Badrouchi,F., March 2019: SEG Drilling Conference and Exhibition, Algeria. Oral Presentation and Poster Presentation.
12. Badrouchi,F., March 2019: The 9th North Africa Petroleum Exhibition & Conference NAPEC, Algeria. Participated.
13. Balaji, K., April 2019: SPE Western Regional Meeting 2019, Conference, San Jose, CA. Oral Presentation.
14. Balaji, K., July 2019: The Bakken Conference & Expo, Conference, Bismarck, ND. Oral Presentation & Panel Discussion.
15. Balaji, K., May 2018: The Midwest Big Data Hub, Workshop, Ames, Iowa. Participated.
16. Boualam, A., June 2019: 53rd US Rock Mechanics/Geomechanics Symposium, New York. Participated/Poster presentation.
17. Boualam, A., June 2019: 53rd US Rock Mechanics/Geomechanics Symposium, New York. Participated/Poster presentation.
18. Boualam, A., June 2019: 53rd US Rock Mechanics/Geomechanics Symposium, New York. Participated/Poster presentation.
19. Boualam, A., March 2019: Joint Geological Society of America, Section Meeting South-Central, North-Central, and Rocky Mountain Sections, Manhattan, Kansas. Participated/ Poster presentation.
20. Boualam, A., March 2019: Joint Geological Society of America, Section Meeting South-Central, North-Central, and Rocky Mountain Sections, Manhattan, Kansas. Participated/ Oral presentation.
21. Boualam, A., March 2019: Joint Geological Society of America, Section Meeting South-Central, North-Central, and Rocky Mountain Sections, Manhattan, Kansas. Participated/ Poster presentation.
22. Djezzar, S., June 2019: 53rd US Rock Mechanics/Geomechanics Symposium, New York. Participated/Poster presentation.
23. Djezzar, S., June 2019: 53rd US Rock Mechanics/Geomechanics Symposium, New York. Participated/Poster presentation.
24. Djezzar, S., June 2019: 53rd US Rock Mechanics/Geomechanics Symposium, New York. Participated/Poster presentation.

25. Djezzar, S., March 2019: Joint Geological Society of America, Section Meeting South-Central, North-Central, and Rocky Mountain Sections, Manhattan, Kansas. Participated/ Poster presentation.
26. Djezzar, S., March 2019: Joint Geological Society of America, Section Meeting South-Central, North-Central, and Rocky Mountain Sections, Manhattan, Kansas. Participated/ Oral presentation.
27. Djezzar, S., March 2019: Joint Geological Society of America, Section Meeting South-Central, North-Central, and Rocky Mountain Sections, Manhattan, Kansas. Participated/ Poster presentation.
28. Ellafi, A., July 2019: The Bakken Conference & Expo 2019, Bismarck, North Dakota. Oral Presentation.
29. Fu, H., April 2019: 4th Thermal and Fluids Engineering Conference, Nevada. Oral presentation.
30. Fu, H., July 2019: Carbon Management Technology Conference, Texas. Participated.
31. Khatibi, S., June 2018: 52nd US Rock Mechanics/Geomechanics Symposium, Petroleum Geomechanics, Seattle. Poster and Oral presentation.
32. Khatibi, S., June 2019: 53nd US Rock Mechanics/Geomechanics Symposium, Petroleum Geomechanics, New York. Poster and Oral presentation.
33. Kong, L., December 2018. American Geophysics Union Fall Meeting, Washington D.C. Participated.
34. Kong, L., June 2017: American Rock Mechanics Association, San Francisco. Participated.
35. Kong, L., June 2018: American Rock Mechanics Association, Seattle. Participated.
36. Kong, L., October 2017: Society of Exploration Geophysicists Annual Meeting, Houston. Participated.
37. Kong, L., October 2018: Society of Exploration Geophysicists Annual Meeting, Los Angeles. Participated.
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42. Li, C. July 2019: Unconventional Resources Technology Conference, Denver. Oral presentation.
43. Li, C. May 2018: Nalco Champion Technical Training, Williston. Participated.
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46. Liang, H., March 2019: 11th International Petroleum Technology Conference (IPTC), Beijing, China. Poster presentation.
47. Liang, H., October 2017: 2017 AIChE Annual Meeting, Minneapolis, MN. Poster presentation.
48. Patil, S., July 2019: URteC 2019. Participated. (Attended Through EERC)
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50. Patil, S., May 2018: Williston Basin Petroleum Conference. Participated

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53. Wan, X., April 2019: Refrac Well 2019, Seattle. Oral presentation.
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55. Wan, X., June 2018: 52nd U.S. Rock Mechanics/Geomechanics Symposium, Seattle. Oral presentation.
56. Wan, X., June 2019: 53nd U.S. Rock Mechanics/Geomechanics Symposium, Seattle. Poster presentation.
57. Wan, X., May 2018: Williston Basin Petroleum Conference, Bismarck. Participated.
58. Wang, Y. July 2019: Unconventional Resources Technology Conference, Denver. Participated.
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62. Zhong, X., March 2018: SPE EOR Conference at Oil and Gas West Asia, Muscat. Oral presentation.
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Enhanced Financial and Regulatory Planning for Carbon Capture & Sequestration (CCS) Infrastructure using an Algorithmic Approach

Karthik Balaji

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Problem Statement:

With rising concerns about controlling carbon emissions throughout the world, the International Energy Agency identified Carbon Capture and Sequestration (CCS) as one of the significant technologies that could have a significant impact in controlling carbon emissions (IEA, 2011). However, the cost associated with these commercial-scale CCS projects are large. Under such circumstances, there is a constant need to evaluate the cost and risk with the project and compliance to regulatory standards (Stauffer & Middleton, 2014).

North Dakota is making significant strides towards the development of working commercial CCS projects with the evaluation for Project Tundra in association with the Milton R. Young coal-fired power plant (Peck. 2018). Such projects require immense capital planning and infrastructure design. These designs and decision-making ability depend on the support and backing of educated estimation of capital and operating costs based on real-field based models. The current infrastructure modeling and routing of CO2 planning is built on the backbone of conventional technology and the usage of software such as SimCCS (Keating & Middleton, 2012; Bettele, 2018). However, these methodologies fail to capture uncertainty in terms of subsurface property variations as well as injection wellsite uncertainty along with effect of varying nature of supply and demand.

This proposal aims at the development of an integrated pipeline, wellsite infrastructure system which incorporates geologic parameters into the planning along with wellsite uncertainties. The projects aim at a 3 pronged approach of developing cost efficient pipeline routing with contingency of future expansion; cost efficient modeling of wellsite infrastructure with the presence of varying injection scheduling(Gupta, 2013) and development of reduced order models for a full-scale reservoir fluid flow simulator using artificial intelligence (Keating & Harp, 2016). This would be followed with the integration of each component into a single system code, which would be able to assess the effects of various events and parameter changes on the overall project costs, leading to better decision-making aid. This projects also entails integration of a few regulatory constraints on the system, making it a stepping-stop for future coupled techno-economic-regulatory infrastructure model. The idea is an extension of algorithmic regulation-based compliance monitoring which enables constant monitoring and update of system components using codes (Yeung, 2017).

Objectives:

- Development of a coupled techno-economic model for CCS wellsite and pipeline infrastructure taking into account geologic uncertainty
- Development of a reduced-order model using Artificial Intelligence to mimic full-scale reservoir flow simulator to be able to factor in the subsurface spread of carbon-dioxide spread over time

- Introduce the concept of irregular injection scheduling to the wellsite model to identify effects on overall project
- Introduction of regulatory constraints in terms of infrastructure placement, engineering limits and subsurface carbon-dioxide spread to the model
- Check the effects of over-sizing and under-sizing of pipeline to check the effects on project cost to factor in future-project expansion options

Methodology:

- Identify point of maximum probability of non-compliance and project risk.
- Utilize the SimCCS softwares' opensource nature to develop pipeline infrastructure model for North Dakota's various source-sink combination, starting with a singular source-sink link and growing it into multi source-sink combination
- Develop, the constraints and base wellsite pipeline infrastructure and equipment placement for optimal cost efficiency. This will serve as an extension of the previous step using Multi-integer Liner Programing and Multi-Integer non-linear programing
- Run full-scale simulations models under varying injections schema to generate a database of outcomes. The varying conditions will be generated using probability distribution function of most relevant injection trends
- Generate reduced order models consisting of only the most significant parameters from the database of simulation results to mimic behavior of the reservoir using artificial intelligence
- Link the pipeline-infrastructure model to the reduced order reservoir model
- Introduce irregularity in supply and injection schedule to better tune the coupled model
- Conduct sensitivity analysis of various pipeline configurations for planning of future project expansion

Significance:

- Opportunities for stakeholders involved in CCS activities to reduce cost in terms of pipeline routing and wellsite pipeline infrastructure
- Ability to better incorporate geologic uncertainty and reservoir performance into CCS planning and scheduling activity
- Ability to identify the performance of various regulations
- Increase in the general safety related to CCS activity.
- Help to predict instances of non-compliance and prevent violations
- Ability to plan future expansion to existent or planned CCS infrastructure

Project Milestone and Timing:

- Task 1: Literature Survey
- Task 2: Risk Assessment and Identification on pain points in CCS Project
- Task 3: Data Collection & Constraint Identification

- Task 4: Development of Linear Programming algorithms
- Task 5: Running of Full-scale Reservoir Simulation Models
- Task 6: Generation of Reduced Order Reservoir Models
- Task 7: Integration of Pipeline & surface infrastructure models with reservoir models
- Task 8: Sensitivity Analysis for demand-supply variation and injection fluctuations
- Task 9: Development of future Infrastructure Expansion Strategy

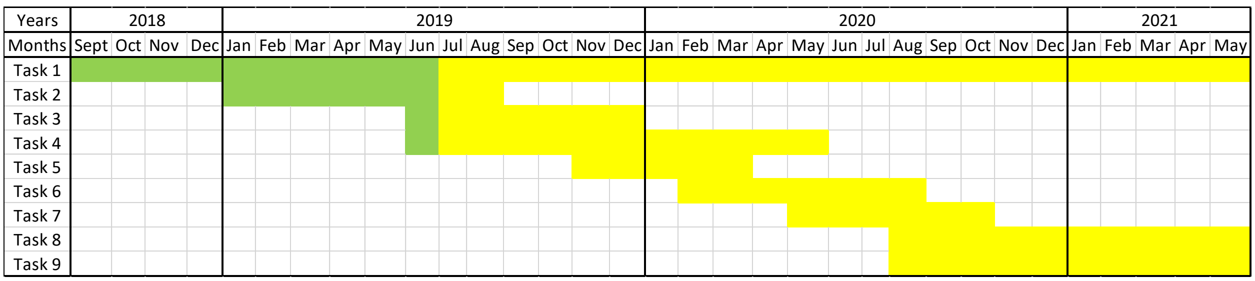

Figure 1. Project Milestones

Progress to date:

As of June 2019, a significant amount of literature has been reviewed in relation to CCS technology and regulations related to CCS technology. There has also been significant review of methodologies to convert generation of Linear Programming models and algorithms for global optimization and generation of reduced reservoir simulators. There have been significant strides in pinning down constraints required to make the model more realistic for tracing cost factors and environmental risk.

For the present scope of the project we focus on the coal-fired power plants within the state of North Dakota as discrete sources of carbon-dioxide for sinks, as seen in Table 1 and with modern capture potential of upto 85% (conservative assumption), there is potentially 29 Million tons to be utilized for storage.

Table 1. Source List (Source: EIA; ND Lignite Council)

Source Name	Capacity	CO_2 production (tons/yr)	Potential to Capture (85%)
Coal Creek Station	1100	11094477	9430305.45
R.M.Heskett Station	100	682083	579770.55
Milton R. Young	705	5862979	4983532.15
Lelands Old Station	669	4808205	4086974.25
Antelope Valley Station	900	8696067	7391656.95
Coyote Station	420	3658089	3109375.65

In terms of sinks, the project is aiming at both saline aquifers and depleted aquifers (Table 2). Since the scope of the projects deems the necessity for various geologic data such as porosity, permeability and depths, we are in talks with the Energy and Environmental research Centre for potential data for best suited sinks to be considered for case of North Dakota.

Table 2. Geological Carbon Storage Sites (Saeedi et al., 2012)

Geological Setting	Advantages	Disadvantages
Coal Seams	Capacity Enhanced Hydrocarbon Recovery	High-Cost Geographically limited
Salt Domes	Safety Ideal Design	High-Cost Geographically limited
Saline Aquifers	Capacity Geographically wide-spread	Safety
Depleted Hydrocarbon Fields	Proven Safety Enhanced Hydrocarbon Recovery Infrastructure in-place	Geographically limited Timely Availability Problems with multi-phase flow

Another major issue, which will be focused on during this project being the unstable nature of supply of carbon-dioxide and the resultant variation of injection into reservoirs as can be observed through figure 2. The study will utilize reduced order modeling along with Multi-integer Linear Programming to incorporate this facet into the study.

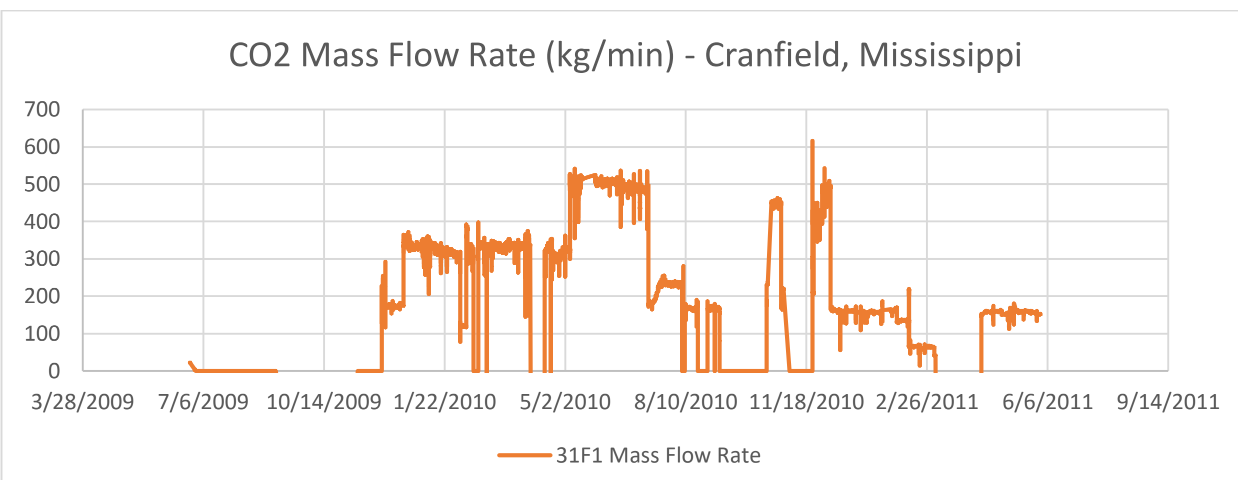

Figure 2. Injection Variation– Unsteady CO_2 supply (Source: SECARB, Gulf Coast Carbon Center)

Papers produced include:

- "How Big Data Analytics can help future Regulatory Issues in Carbon Capture and Sequestration (CCS) projects" SPE Western regional Meeting, April 2019, San Jose, CA

- “Data-Driven Analysis of Natural Gas EOR in Unconventional Shale Oils” SPE Oklahoma City Oil & Gas Symposium, April 2019, Oklahoma City, OK.

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Drilling Parameters optimization based on Machine Learning Models and Data Mining Techniques

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Problem Statement:

Oil & gas well drilling is one of the most important and expensive part of the oil industry. Drilling optimization and minimizing the operation costs is hot research topics in the academy during decades. Especially when the price of crude oil drops, the high cost of upstream oil exploration and development coupled with downstream efficiency requirements forces most companies to reduce costs. Machine learning models and data mining techniques are widely used to extract information from existing dataset and predict future performance. Based on the reasonable parameter prediction, decision making process of drilling design will be simplified, as well as trial and error cost will decrease sharply. Deriving knowledge from existing dataset in order to develop a functional relationship between input and output is a challenging task requiring advanced modelling techniques as well as human intuition and experience. Many works have been done on designing the oil & gas drilling operating system and a number of researchers are trying to predict certain parameters to increase the drilling efficiency. Artificial Neural Network (ANN), Random Forest (RF) and Monotone Multi-Layer Perceptron (MON-MLP) models were applied to predict rate of penetration (Eskandarian et al, 2017). The Particle Swarm Optimization and Artificial Neural Network (PSO-ANN) model can be employed reliably to estimate the drilling fluid density at high temperature and high pressure condition (Ahmadi et al, 2018). Prediction models including decision tree (DT), adaptive neuro-fuzzy inference systems (ANFIS), artificial neural networks (ANN) were developed to make a quantitative prediction on lost circulation of drilling fluid. (Sabah et al, 2019). Bit type selection is discussed by employing a method of combining Artificial Neural Network (ANN) and the computation of Genetic Algorithm (Momeni et al, 2018).

From the practical perspective, only information recorded form the drilling site and published on the NDIC website will be used in this research to avoid any mistakenly ideal assumption and reach the real word situation. Experimental variables from lab such as mechanical specific energy and rock mechanical properties will be dropped unless further modeling is needed for prediction comparison.

Objectives:

- Analyzing drilling operation to determine the various components (drilling company, bit size, bit type, bit dull code, true vertical depth, drilling footages, running hour, rate of penetration, weight on bit, pump pressure, mud weight, mud viscosity, drilling operation description, formation, core sample description) in dataset associated with this workflow.
- Identifying target value (such as rate of penetration) as output parameter based on economic significance, collection difficulty and research topic.
- Feasibility study on the recorded data from field as input parameter.
- Classification and regression machine learning models implementation.
- Identifying the essential hyper parameters required for implementing an advanced machine learning model, using optimization algorithms to find them.
- Checking accuracy of predicted output parameter, making prediction for the undrilled area.

Methodology and Workflow:

- Systematic collection of public drilling dataset from NDIC
- Target clarification and detailed research design
- Digitize text dataset into appropriate categorical and numerical form
- Govern the behavior of input parameters using common data science packages (e.g. NumPy, Pandas, Matplotlib on Python)
- Different classification and regression machine learning models (such as support vector machine, artificial neural network) implementation including code scripts writing and editing
- Results interpretation and prediction explanation
- Deliver presentations and publications in oil & gas industry

Expected outcome:

- Comprehensive machine learning model design for appointed reservoir or formation
- Drilling bit selection and drilling operation recommendation
- Reasonable drilling parameters prediction for undrilled area
- Decision making process optimization for drilling company and knowledge preservation for academia

Significance:

Machine learning models are such strong tools to capture features between input and output parameter, perform the computational modeling, and unfold the knowledge behind the dataset. They make full use of previous work to reduce future trial and error costs. Based on the existing dataset published on NDIC, A comprehensive statistical solution for drilling design will be provided in the end of the total research. With the right mix of research, coding capability and prediction interpretation, the proposed algorithmic machine learning mode will provide an adaptable approach for practical application in oil field. It represents an opportunity for oil industry to increase profitability in today's economic environment and well into the future. The understanding of what is required to move this next machine learning or artificial intelligence generation forward is vitally important for the industry and academy.

Progress to Date:

1. Fully understand the mathematical methodology behind every widely used machine learning models.
2. A comprehensive literature review is finished. The most recently published papers related with machine learning application on petroleum engineering, drilling optimization, and drilling parameters prediction are collected and reviewed.
3. Systematic collection of public drilling data has been done. More than 100 wells drilled from 2015 to 2019 were selected in the research.
4. Machine learning models such as decision tree, support vector machine, artificial neural network, convolutional neural network are coded and templated.
5. Hyper parameter tuning, variable optimization algorithm and visualization tool box are fully operational to enhance the accuracy of the prediction.
6. Digitizing parameters such as depth, lithologies, bit records, wellbore condition, drilling fluid properties, samples description of formations is still on progress.
7. Rate of penetration should be one of the target values of this research. Target value feasibility of other parameters such as weight on bit, wear condition of bit should be discussed later during the research progress.

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Accelerating Pipeline Leak Detection Through Unmanned Aircraft Systems Based Routine Surveillance and Data Mining

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I am happy to report fruitful research and that the project is currently ahead of schedule. So far, I am also on track with the objectives of technology identification, pilot project coordination, cost/benefit analysis, and process development including artificial intelligence applications.
True to form with the Gantt chart I submitted regarding the project milestones and timing, I have completed my preliminary data analysis by the 18th of June. My findings indicate that further data will need to be collected from the air. I already have an understanding of UAS and this has helped me in the selection process of sensors, aircraft, flight profiles, etc. Before I undertook this project, I also already had a significant amount of data from UAS sensors available to me, and the data was neither collected for the purposes of research nor by members of the University of North Dakota. Figure 1 shows an example of the Bakken formation pipeline images collected recently by a UAS.

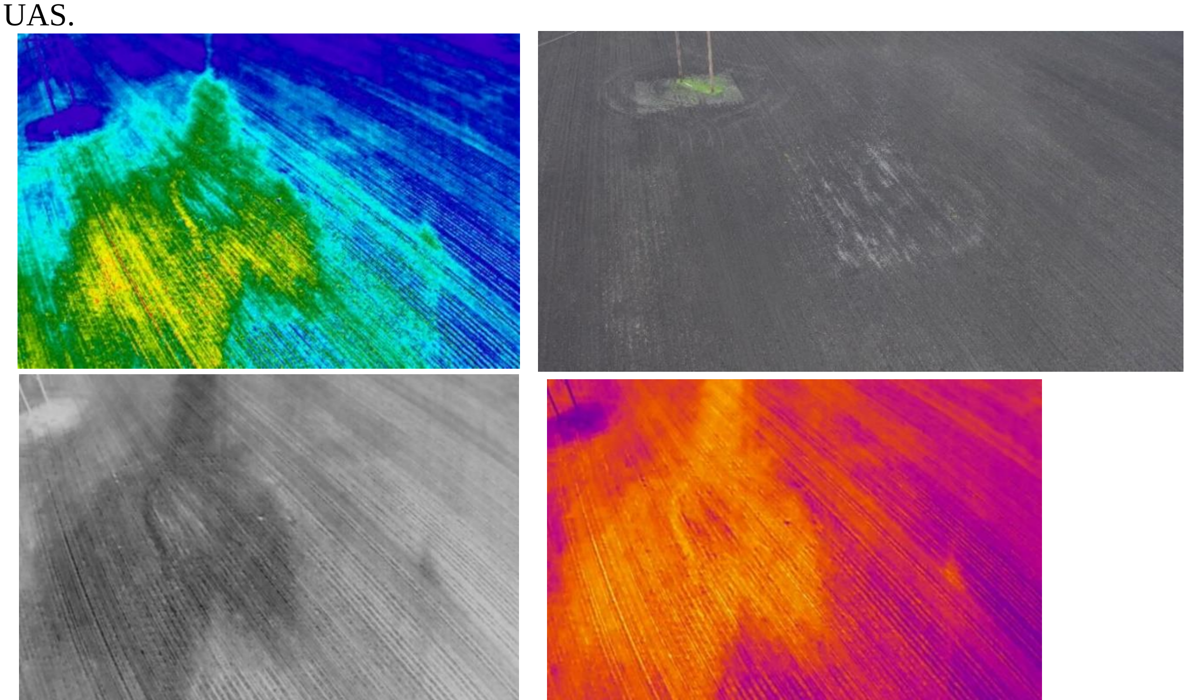

Fig 1. UAS Collected EO/IR images of a Bakken Oil Pipeline Alkalinity-Based False Positive

The significance of this data in Figure 1 is to show one of the biggest problems with aerial data collection over pipelines and artificial intelligence in post-processing: false positives. These electro-optical and different color palette images of the same IR wavelength make pilots, and oilfield subject matter experts alike, suspicious of an oil leak. The heat differential in this situation is, instead of an oil leak, an anomalous change actually in the alkalinity of the ground. It is clear through these efforts that flying hyperspectral sensors and comparing the data with IR images could yield results that make a reflectivity signature, such as alkalinity, reduce false positives with a vibration signature such as a change in heat from an oil leak.

The data presented need not be approved through committee as it was conducted for commercial purposes, though I have indeed completed the "Committee on Unmanned Aircraft Systems Research Ethics & Privacy Research Project Application Form" and anticipate getting approval to hire someone to fly the unmanned aircraft systems in August, September, and October. These missions would be conducted with me as a member of the University of North Dakota and under the purview of the Northern Plains Unmanned Systems Authority.

The data collected and shown above was captured with, albeit a previous generation, an aircraft manufactured by the same company that designed and sells the two I propose to use. These new aircraft, to which I have great access, will serve to fly in a safer and effective way for the data collection. This first aircraft in Figure 2 is the DJI M210 and would either be flown with the FLIR 2 Duo as shown integrated in the photo, or the FLIR Zenmuse XTR in Figure 2, which would be able to show radiometric IR imagery for another important data point in the research. This aircraft/sensor combination is extremely reliable and will become a mainstay in oil plays in years to come.

Fig 2. Proposed IR Equipment: DJI M210, Adjacent: FLIR Zenmuse XTR Sensor

It has become clear in my research for this project that standard thermal and IR sensors, while they may yield publishable results, are inferior to the higher-end Optical Gas Imaging (OGI) sensors. At some point it may be of use to fly LiDAR sensors as well, but leak detection is best accelerated in the IR wavelengths. OGI sensors are similar though are able to work in tandem with laser spectrometers to both quantify PPMs and speciate the hydrocarbons. One of the most important tasks OGI sensors are able to accomplish is the detection of Hydrogen Sulfate, an extremely deadly and invisible gas that is potentially leaked near pipelines. It is extremely important to remember that both oil and gas leak from pipelines, and both types of leaks can be detected by UAS. I have found this during my research for sensors and aircraft and in commercial endeavors. I believe, therefore, that the DJI M600, shown in Figure 3, aircraft with the Infrared Cameras Inc. OGI sensor with laser spectrometer as shown integrated to the aircraft in this photo, or the FLIR OGI, shown adjacently in Figure 3, sensor are the only truly appropriate high-end aerial IR technologies applicable to this research.

Figure 3. Proposed OGI Equipment: DJI M600 with ICI Payload, Adjacent: FLIR OGI Sensor

Through the literature I am more familiar with the methodologies that these researchers and scholars have used to study and publish on similar topics to mine. I have also achieved some valuable insight into which software such as Pix4D and processing languages such as Python I intend to use in order to most-accurately mine the data collected with UAS and generate actionable oil intelligence.

On the subject of artificial intelligence/algorithm designation, I have reached out to the chair of the Department of Electrical Engineering Dr. Ryan Adams in order to discuss AI applications on this project. Last semester I completed a three-credit 593 course with Dr. Rabiei centered around big data, artificial intelligence, data mining, computer vision, and machine learning in oil. Consequently, fuzzy logic, decision trees, and neural networks will naturally be part of the research. During the upcoming data collection missions, I will also soon commence the process of mining the flight/sensor data. I have also been working on a similar project with Dr. Ranganathan titled “Heat Loss Estimation Using UAS Thermal Imagery,” which has been both presented and published multiples times. Through this work, I am more familiar with how edge detection, u-values, radiant flux, and Dominant Color Masking (DCI) variables will transfer from one area to the next. In particular, flying IR UAS missions over basic structures will show how best to execute, interpret, analyze, and further refine data from IR UAS missions over oilfield structures. As a guidepost on the research, I have been using the equations from the Kato study of 2007, and Plank’s law below and to the left:

$$E(\lambda, T) = \frac{2hc^2}{\lambda^5} * \frac{1}{e^{\left(\frac{hc}{\lambda kT}\right)} - 1}$$

h = Planck’s constant = $6.626 * 10^{-34}\ J * s$
c = speed of light = $2.997925 * 10^{8}\ m / sec$
λ = wavelength (m)
k = Boltzmann’s constant = $1.381 * 10^{-23}\ J/K$
T = temperature (K)

$$C_{\text{Ground}} = F_{\text{Ground}} + (t_{\text{R}} \times N_{\text{R}}) \times H_{\text{Ground}} \quad (1)$$

$$C_{\text{Aerial}} = F_{\text{Aerial}} + (t_{\text{R}} \times N_{\text{R}} + t_{\text{CF}} \times N_{\text{CF}}) \times H_{\text{Ground}} \quad (2)$$

In terms of financial feasibility, another final product of the research, the Schweitzke study figure above and to the right, describes the topic when the scholars mention:

“The LDAR cost-effectiveness of each platform was determined based on the cumulative detected CH4 emission rates and deployment cost as follows. Total Phase 1 costs, CGround and CAerial, for ground and aerial teams, respectively, were calculated using equations 1 and 2. Where FGround represents the deployment costs for the ground teams. FGround accounts for the deployed conventional ground LDAR teams consisting of one person per team for OGI-based leak detection and one person each for leak quantification using the Hi-Flow instrument.” Here tR represents one hour of leak repair time, HGround represents the hourly rate on the ground, NCF is the ground team hourly rate applied to each facility where a ground team confirmed an aerially detected facility, and NR is the number of facilities where a leak needs to be repaired. After my first considerations here, it is clear that UAS are at least equally financially feasible, if not more so, than manned aircraft and ground methods.

In conclusion of this letter, I'd like to thank you, the Department of Petroleum Engineering, and the North Dakota Industrial Commission for the opportunity to lead this research project. Given the progress on demonstrating an improved pipeline monitoring method and compliance assurance, I am certain that this research is going to advance two of the most important industries, both here at the university, and in the state of North Dakota as a whole. I intend to publish the findings in an academic journal within a year or two and then also a comprehensive capstone paper.

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Konstantin Ivushkin, et. al., "UAV Based Soil Salinity Assessment of Cropland," Geoderma 338, no. 1 (September 2018): 502-512, https://www.sciencedirect.com/science/article/pii/S0016706118309509, (accessed June 6, 2019).

An integrated Data Mining and Simulation to Optimize Refracturing Design

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Summary of Current Progress

- Built an integrated single stage hydraulic fracturing-production-refracturing-post refract production model using XSite and FLAC3D.
- Published and presented a paper (ARMA 2019-104) to the 53RD ARMA SYMPOSIUM.

Detailed results

1. Hydraulic Fracturing Simulation

XSite was used to simulate hydraulic fracturing in the Middle Bakken Formation. Input parameters for all the simulations were chosen based on typical reservoir rock properties and in-situ stresses of the Middle Bakken Formation, as are shown in Table 1. For simplification, reservoir model geometry in all simulations was assumed to be cubic with side length L=40 m. The reference point was located at the center of the right top side of the cube. A horizontal well was placed at the center of the model. Lattice resolution was set to be 0.4 m, thus there were 100 cells in each side of the cube and a total of 1,000,000 cells in the reservoir model. The pumping schedule was simplified by injecting slick water with viscosity of 1 cP ($0.001 Pa \cdot s$) at constant injection rate of $0.078\ m^3/s$ (about $30\ BPM$). XSite used 40-70 Ottawa Sand as the default proppant. The proppant concentration was set to be $30\ kg/m^3$ during the injection. The slurry was injected at the center of the wellbore for $10\ s$ and a penny shaped hydraulic fracture with a radius of about $6\ m$ was obtained as are shown in Figure 1. The result shows that the hydraulic fracture has been initiated and propagated perpendicular to the x direction, i.e. the $\square_h$ direction. During the simulation of hydraulic fracturing, proppants were filled into the induced fractures, resulting in high permeability (> 1 $darcy$) in the hydraulic fracture zones. This high permeability zone was used to represent the geometry of hydraulic fracture and was imported into FLAC3D to simulate production from the hydraulic fractured well.

Table 1 Reservoir properties for numerical simulations

Parameters	Value
Young's modulus, E (GPa)	90
Poisson's ratio, ν	0.2
Uniaxial compressive strength, UCS (MPa)	130
Tensile strength, T (MPa)	13
Fracture toughness, KIC ($MPa \cdot m$^0.5)	1
Friction angle, ∅ (°)	37
Permeability, k (mD)	0.001
Porosity, n (%)	1
Vertical stress, σ_v (MPa)	69

Maximum horizontal stress, σ_H (MPa)	62
Minimum horizontal stress, σ_h (MPa)	55
Reservoir pressure, P_p (MPa)	30

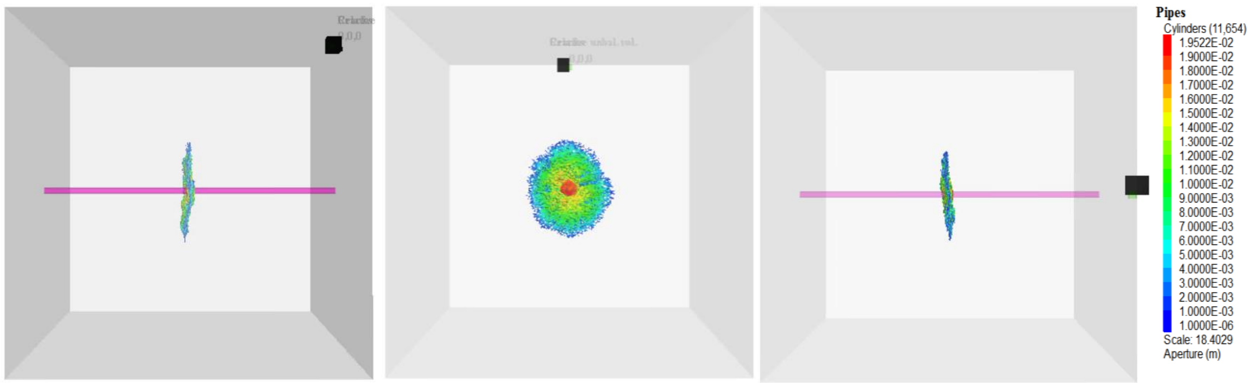


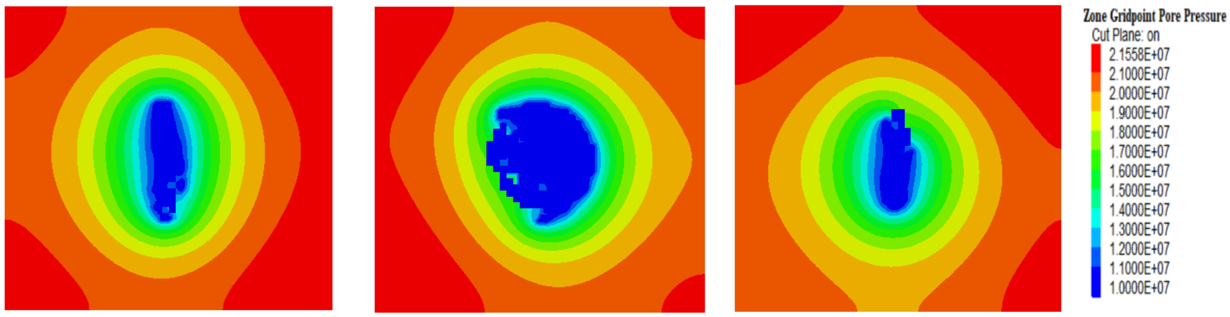
Figure 1. Reservoir model, well location and aperture contours for hydraulic fracture (a) general view, (b) front view, (c) side view, (d) top view

2. Well Production Simulation

The volume of the fracture zones could be considered as the stimulated reservoir volume (SRV) which contained the hydraulic fractures. The boundary conditions for the FLAC3D models are as followings:

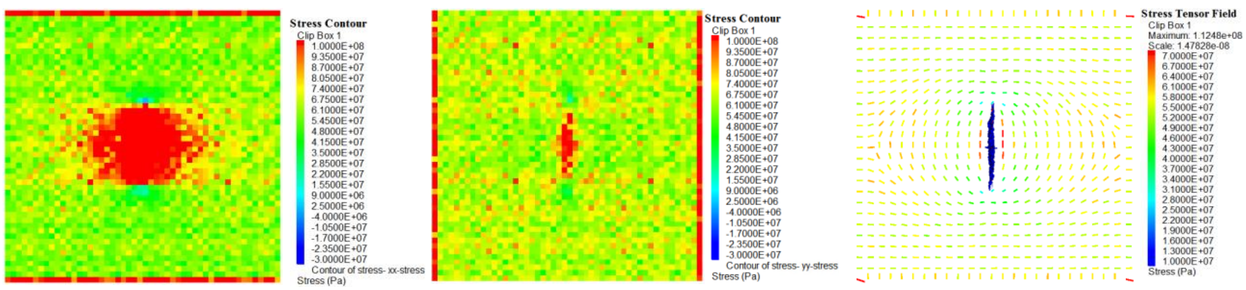
- Initial constant reservoir pressure in the reservoir matrix: $p_i = 30\ MPa$;
- Constant pressure in the fracture zones equal to bottom hole pressure: $p_w = 10\ MPa$;
- No-flow at the model boundaries: $-40\ m < x < 0, -20\ m < y < 20\ m, -40m < z < 0$;
- Constant stresses applied to the model boundaries: $\sigma_{zz} = \sigma_v = 69\ MPa, \sigma_{yy} = \sigma_H = 62\ MPa, \sigma_{xx} = \sigma_h = 55\ MPa$;

The stress distribution before production was calculated in XSite, as is shown in Figure 3. Then the model was simulated in FLAC3D for one year ($31{,}536{,}000\ s$) of well production. The simulated pore pressure distribution was imported back to XSite for calculation of stresses, as is shown in Figure 4. After one year of well production, the pore pressure decreases faster near fracture zone than away from the fracture zones, as is shown in Figure 2. Due to the reservoir depletion and the change of pore pressure, the minimum horizontal stress near the fracture tip rotates and decreases in magnitude, as is observed by comparing Figure 4 (c) with Figure 3 (c). Before depletion, the minimum horizontal stresses near the fracture tip are generally in the x direction, as is observed in Figure 3 (c), thus they are favorable for the fracture to propagate in the initial direction. After depletion, the minimum horizontal stresses near the fracture tip rotate to the y direction, as is observed in Figure 4 (c). The stress rotation results from the change of pore pressure and creates a stress reversal regime near the fracture tip.



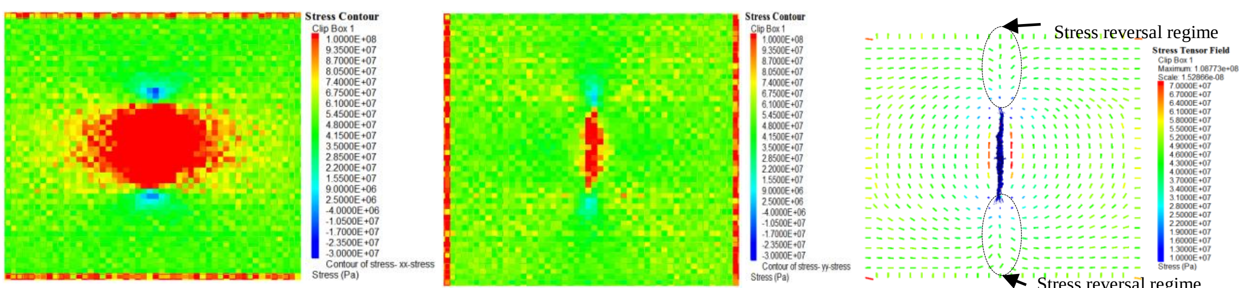
(a) (b) (c)

Figure 2. Model geometry (a) and pore pressure contours after 1 year of production: (b) center XZ plane, (c) center YZ plane, (d) center XY plane



(a) (b) (c)

Figure 3. Distribution of total stresses before well production at the center XY plane: (a) x direction total stress σ_{xx}, (b) y direction total stress σ_{yy}, (c) tensor field of the minimum horizontal stress



(a) (b) (c)

Figure 4. Distribution of total stresses after 1 year of production at the center XY plane: (a) x direction total stress σ_{xx}, (b) y direction total stress σ_{yy}, (c) tensor field of the minimum horizontal stress

3. Refracturing Simulation

Pore pressure distribution obtained from well production simulation in FLAC3D was imported back to the previous XSite hydraulic fracturing model to simulate refracturing. The simulation was run for another 100 s with a larger injection rate of 0.156 m^3/s (about 60 BPM) and a larger proppant concentration of 60 kg/m^3. The fracturing fluid was kept the same with the previous hydraulic fracturing simulation.

It was observed that several branches of secondary fractures were initiated and propagated perpendicular to the initial maximum horizontal stress direction near the tip of the initial hydraulic fracture, as is shown in Figure. 5. The observation is corresponding to the stress reversal regime indicated by Figure 4 (c). The results suggest refracturing operation can create multiple secondary fractures near the tip of the initial hydraulic fracture where stress reversal occurs, thus potentially increasing SRV and boosting production after the operation.

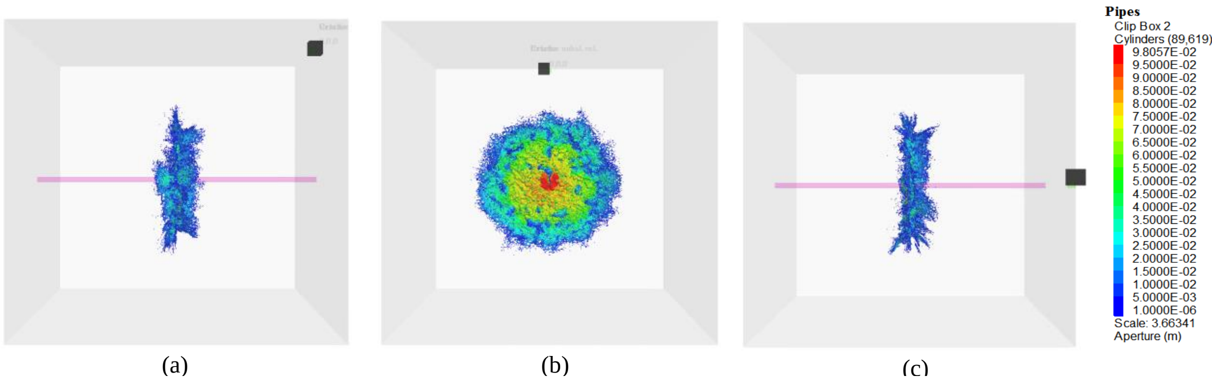
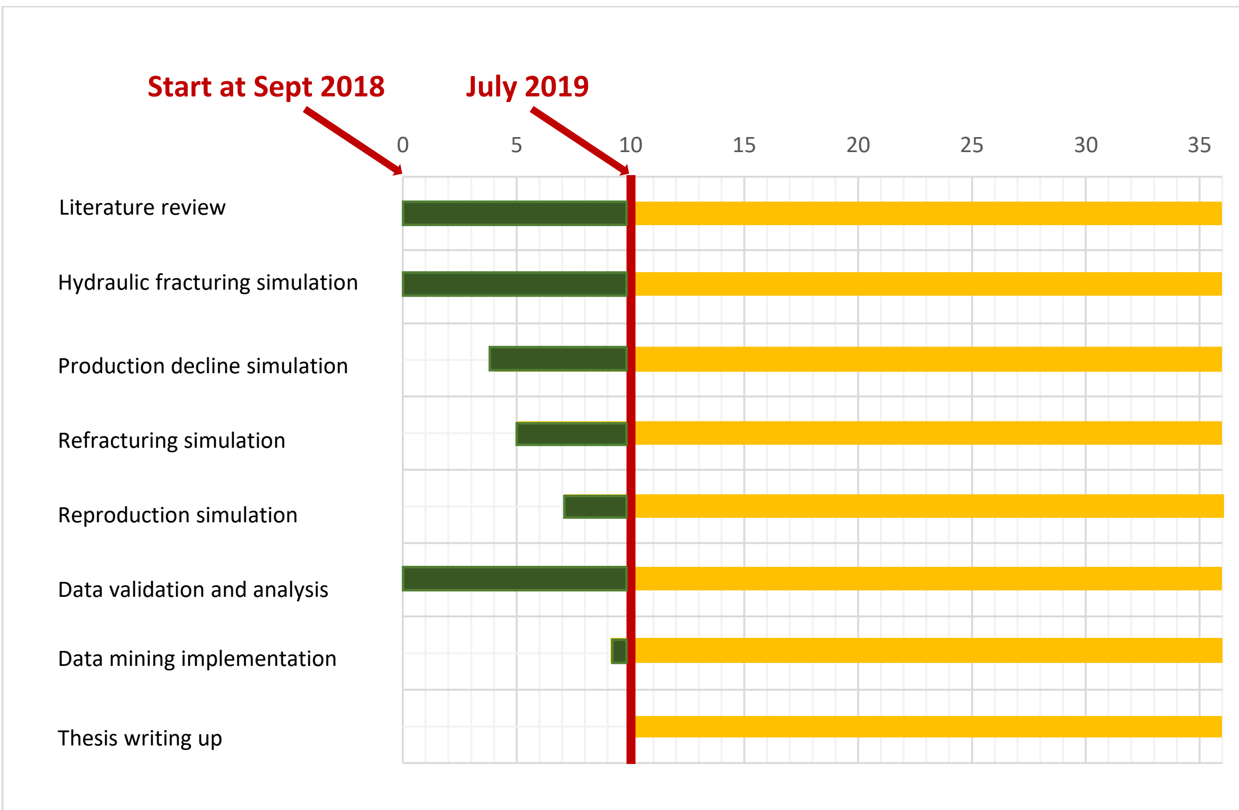


Figure. 5 Reservoir model, well location and aperture contour for initial hydraulic fractures and refractures: (a) general view, (b) front view, (c) side view, (d) top view

Project Milestone and Timing



Studying the Mechanism of Barite Scales Formation & its Removal/Prevention in McKenzie and Williams Counties, Bakken Formation

OLUSEGUN TOMOMEWO

Ph.D. student, Department of Petroleum Engineering, UND

Olusegun Tomomewo has been working with the Institute for Energy Studies to develop and demonstrate a novel thermal desalination technology for hypersaline brines. This Department of Energy funded project is being performed in conjunction with Envergex LLC, Doosan Heavy Industries and Creedence Energy Services. The support provided from Mr. Tomomewo's Graduate Research Assistantship is providing approximately 1.6% of the required 20% DOE cost share.

Produced water from oil & gas operations, as well as other industrial sources such as mines and power plants has high total dissolved solids (TDS > 50,000 mg/L) and organics (~2,000 mg/L) and needs to be treated for disposal or re-use. Commercial technologies such as reverse osmosis (RO) and nano-filtration are not directly applicable due to membrane fouling (too high TDS); while others such as evaporative desalination are ineffective for organics destruction. None achieve zero liquid discharge (ZLD).

Water above its critical point becomes non-polar and precipitates out the dissolved solids. Supercritical water desalination (SCW) represents an approach to both destroy organic contaminants and treat very high TDS brine into clean water and pure solids, resulting in ZLD. However, for SCW to be feasible there are several challenges that must be addressed, including: **i)** achieve energy parity with RO, **ii)** resistance to corrosion, fouling and degradation, **iii)** achieve continuous and reliable separation of solids, **iv)** offset capital costs for sustaining supercritical conditions, **v)** achieve complete destruction of organics, **vi)** potentially exploit opportunity to recovery value-added metals/salts as separate products, and **vii)** be a modular design.

The proposed solution, Supercritical Water Extraction – Enhanced Targeted Recovery (SWEETR™), is a novel SCW technology that can solve the above challenges. Key features of SWEETR™ include: **i)** novel multi-functional additives to dramatically reduce energy requirements for SCW (~5X) and eliminate corrosion and scaling, **ii)** integration with low-cost solar thermal energy and/or stranded gas, **iii)** catalyzed destruction of organics, **iv)** simple continuous solids separation, **v)** zero liquid discharge – pure water and solids, **vi)** potential for in-situ separation of individual salts/metals, **vii)** skid-mounted and plug & play – easy field deployment and relocation, **viii)** achieve cost of less than $1.5/m^3 water treated.

The overall objective of the proposed project is to demonstrate the technical and economic feasibility of the SWEETR™ technology for hypersaline brine treatment, such as that produced from oil & gas operations. The project will focus on laboratory-scale optimization, larger scale skid-mount testing/optimization, as well as process modeling and techno-economic analysis. At the completion of the project, the technology will have been demonstrated to be technically and economically feasible and ready for subsequent pilot-scale field demonstrations.

The GRA funding provided to Mr. Tomomeweo as a part of this NDIC is currently being used to develop relationships between the solubility of key salts across the pressure and temperature range of the SWEETR system. These results will be used to specify the design of various system components to determine the optimal configuration of the subsystems with the primary goal of developing a robust system with minimal operating challenges and a secondary goal of minimizing treatment cost.

SUMMARY OF WORK DONE WITHIN THE LAST QUARTER

Evaluation of the Effect of Temperature and Pressure on Solubility and Solids Separation

The tests conducted on solubility during this quarter focused on the evaluation of the effect of experiment constraints on the solubility of simulated salt solutions exiting the reactor at supercritical temperatures. The experiments were performed using a combination of varied temperatures and constant pressure (as detailed in **Table 1.1**), and a feed made up of a known concentration of salts was fed to the supercritical reactor at the test temperature for that run.

Table 1.1: Parameters for salts solubility experiment.

Parameter	Levels	Description
Salinity (wt.%)	Up to 4	Salinity levels: 5%, 10%, 15%, 25% (5% actual)
Temperature	Up to 5	Temp: 200°C, 300°C, 350°C, 390°C, 400°C
Pressure	Up to 2	Pressure: 240 bar, 280 bar (Maximum)

During each run, the inlet and the outlet streams were strictly monitored for flash points that notify when to start the collection of effluent for analysis. The collected effluent was allowed to cool and then analyzed for total dissolved solids (TDS) using the conductivity meter. In addition, at the end of each experiment, the reactor was always dismantled, and each section was carefully washed with deionized water in order to verify the extent of salt dissociation and removal from the solution.

The experiment was conducted with a 5% $CaCl_2$ solution at the temperatures listed in **Table 1.1** above and at a constant pressure of **240 bar** and a feed flow rate of **2ml/min.** The conductivity was measured in millisiemens or microsiemens/centimeter **(mS/cm or µS/cm)**. The conductivity increased with the increase in salt concentration as depicted in Figure 1.1.

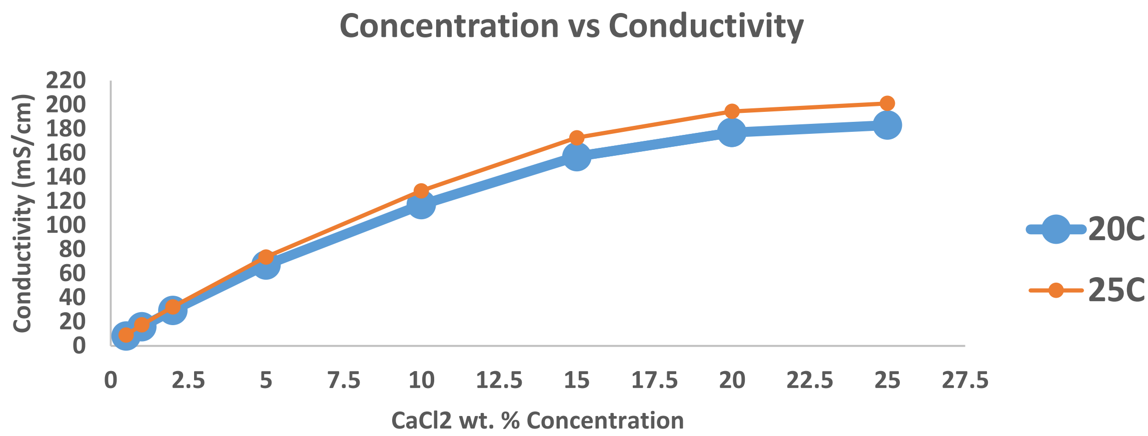


Fig 1.1 Salt Concentration Vs Conductivity.

The results so far show no solubility at 200°C, 5% at 300°C, and 35% at 400°C as shown in **Figure 1.2.**

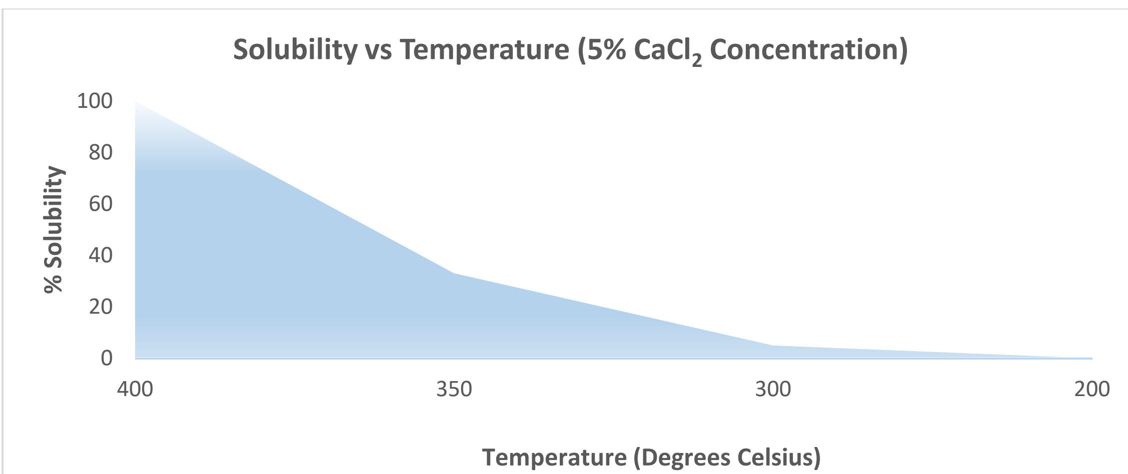


Fig.1.2: Solubility Curve for 5% CaCl2 Concentration

The steps in the solubility experiment are explained in **Table 1.2.**

Table 1.2: Plans for Next Quarter

Plans for Next Quarter
Model relevant salt components and concentrations as a function of temperature and pressure to provide input that can be used to assess pre-treatment requirements, anticipated fouling in primary heat exchangers, and help optimize the test requirements for the experimental portion of this project.
Begin experimental testing with the produced water samples with the aim of understanding the actual behavior in the supercritical reactor and to be able to map the dissolved salt removal as a function of processing temperatures and pressures.
Obtain all relevant data and also observe salt and other solid depositional characteristics in the supercritical reactor to begin evaluating solids removal strategies for the desalination reactor.

Experimental and Numerical Investigation of the CO_2-EOR Mechanisms in Unconventional Rich Liquid Reservoirs (Bakken Fm, Williston Basin, ND)

Abdulaziz Ellafi

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Problem Statement:

The oil recovery in unconventional reservoirs, such as Bakken Fm is believed to be less than 8% during primary production. These reservoirs produce with low recovery due to fractures depletions with small to no support from the rock matrix. As a result, around 3.8 billion barrels of oil is isolated by complex heterogeneity in the reservoir properties and unrecovered without using unconventional applications. Based on previous studies, applying CO_2-EOR is worthwhile and could increase the incremental oil by improving the long-term well productivity and contribute the cost-effective production less than other techniques. However, the EOR application in liquid-rich shale (LRS) reservoirs is still limited, and there are few field practices because of the CO_2-EOR mechanisms are yet to be understood completely, which are different than those applicable mechanisms in conventional reservoirs. To sum up, the implementation of the successful field of CO_2-EOR depends on CO_2 mechanisms and well/reservoir operation conditions that need to investigate and quantify in order to solve previous work issues in the field scale and provide general guidelines.

Objectives:

- Construct a comprehensive literature review to build a bank of data and general guidelines.
- Understand of geology, lithology, mineralogy, thermal maturity, fluid properties, and pore structures & connectivity in order to obtain a reliable assessment of CO_2-EOR.
- Investigate the Bakken characterization and geomechanical properties of a number of Bakken core samples from well # 24779 located in the Mountrail County, Bakken Fm., Williston Basin, ND.
- Model numerical simulation case study of well# 25688 located in the Mountrail County, Bakken Fm, Williston Basin, ND to investigate the coupling effects of geomechanics with CO_2-EOR mechanisms (Adsorption/Diffusion) in both perspectives of production performance and CO_2 storage.
- Perform sensitivity analysis under huff-n-puff CO_2-EOR experimental work on the same core samples used in the characterization study to understand the CO_2 mechanisms and obtain the optimum operation well/reservoir conditions.
- Evaluate the wettability alteration using chips samples under different CO_2-EOR scenarios.
- Evaluate the Bakken oil under CO_2 application to study the asphaltene precipitation during CO_2-EOR process.

- Quantify the amount of the asphaltene deposition and oil composition trapping using sensitivity analysis under different reservoir pressure and temperature conditions as well as CO_2 EOR operator factors.
- Construct reservoir simulation models to mimic the experimental results and upscaling to the field scale.
- Investigate the main factor that impact molecular diffusion mechanism.
- Repeat huff-n-puff experimental work using a chemical product with CO_2 as a hybrid EOR application in term of increasing diffusion mechanism and reducing surface adsorption on the rock.

Methodology:

- Gathering data from previous works by reviewing science journals, conference papers, PhD dissertations, and reports.
- Designing lab work experiments using Auto-lab 1500, core flooding apparatus, Gas Chromatography, and contact angle instrument.
- Performing reservoir simulation models using CMG simulator, Petrel, and Eclipse intersect simulator.
- Using computer programing language (VBA-Excel and/or MATLAB coding).

Significance:

The significance of this research is a comprehensive study in more details that includes both the laboratory experiment works and modeling numerical reservoir simulation studies to have a better understanding of physical and chemical reactions in the subsurface system in term of improving the incremental oil in the Bakken Fm. Then, the opportunities and challenges in the field scale will be discussed to provide general guidelines to have successful CO_2-EOR application.

Project Milestone and Timing:

Tasks	**Semesters**								
	F-18	SP-19	S-19	F-19	SP-20	S-20	F-20	SP-21	S-21
Courses									
Comprehensive Literature Review									
Ph.D. Qualifying Exam									
Experimental Works									
Simulation Studies									
Validate Results									
Ph.D. Comprehensive Exam									
Final Draft of Dissertation									
Final Defense									
F: Fall, SP: Spring, and S: Summer									

Progress to date:

- From Fall 2018, I performed some lab works:
  1. Sampling core plug from the Middle Bakken Member.
  2. Cleaning the cores.
  3. Measuring the absolute reservoir permeability, and the velocity VP and Vs to determine the geomechanical parameters. The permeability measurement in the lab at the Bakken condition showed that the Middle Bakken Fm permeability is in micro-Darcy range, and characterization and geomechanical properties lab results are in a good agreement with the literature review.
  4. Performing huff-n-puff experiment using core flooding apparatus. The outcomes indicated on the effect of the reservoir temperature on the performance of the CO_2 mechanisms, where the recoverable oil increases as the temperature increase until reach the optimum depends on the injection pressure phase. As overall outcomes from this research, the CO_2 huff-n-puff process has a good potential in the Lab and could be succeeded economically in field applications.
  5. The wettability alteration during CO_2 injection was studied, where the increase in the injection pressures yields to alter the wetting phase move from the oil wet toward the water wet system.
  6. Evaluation of the Bakken Oil was studied in term of asphaltene deposition after CO_2 injection. This task is still under investigation to quantify the impact of CO_2 due to the change in pressure and oil composition by detecting the well/reservoir operation conditions that yields to form the asphaltene in the subsurface.

- In the simulation part, I have constructed:
  1. Two different compositional simulation models (Dual Porosity /Dual Perm),
  2. Representative PVT model.
  3. Sensitivity analysis and history match using CMOST software.
  4. Optimization process by performing CO2-EOR injection.
  5. Using a 3D two-way coupling simulation model, we investigated the coupling effects of geomechanics and CO_2-EOR mechanisms during production and CO_2-EOR. It can be observed that CO_2-EOR in a tight formation can lead to higher incremental oil recovery (with cost-effective production) and reliable storage of anthropogenic CO_2 with minimal environmental footprint.

Bakken Tertiary Oil Recovery:

CO_2 based solvent EOR

Nidhal Badrouchi

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Problem Statement:

The Bakken is an extremely tight formation with ultra-low permeability that generated about 200 to 400 billion barrels of oil in place (Janet K. et al, 2001), which makes it an attractive petroleum exploration target. Meanwhile, the technology advances in horizontal drilling and multi-stages hydraulic fracturing enabled an economic recovery, the production rates are still quickly decline after few months and the recovery factor remains very low. Thus, other solutions, that enable a larger contact within the reservoir, need to be considered to increase the recovery factor. Because of the micro and nano-scale pores in such unconventional reservoirs the effect of capillary pressure and interfacial tension must be considered. It has been proven that the amount of residual oil in tight formations depends on the existing interfacial tension (Fundamentals of enhanced oil recovery Chap III p 83-83). In this project we intend to study the factors that contribute to a successful CO_2 EOR application in Bakken Formation.

Objectives:

- Investigate CO_2 EOR viability in Bakken Formation
- Solvent design to obtain first contact miscibility
- Determine key performance points for CO_2 EOR
- Study the effectiveness of the combination of solvent and wettability alternation surfactant
- Deliver innovative solutions for a successful CO_2 application

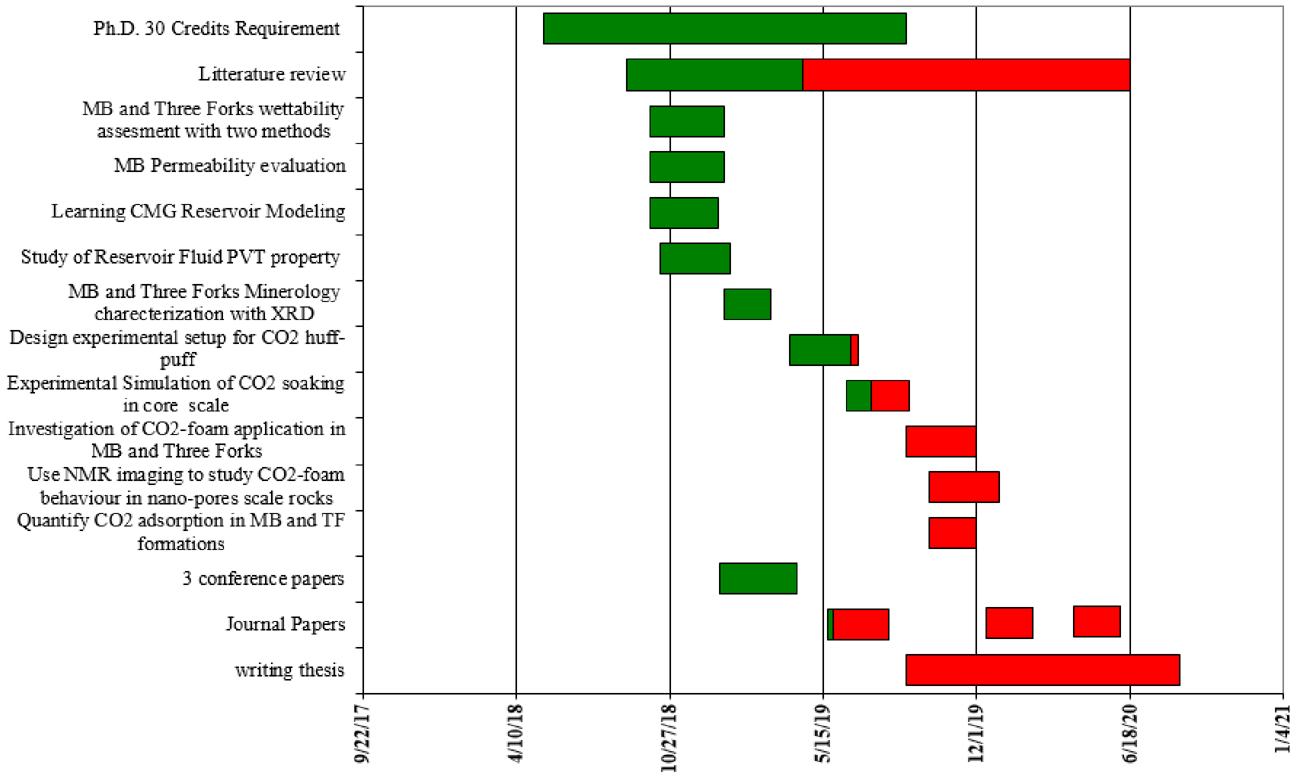
Methodology:

- Literature review
- CMG Reservoir Modeling for solvent design and forecasting optimization scenarios.
- Solvent adsorption and diffusion assessment using molecular simulation
- Design of lab experiment to determine the amount of solvent adsorbed in a Bakken Samples.
- Using molecular dynamic simulation for a better understanding of Rock-Solvent interaction.

Significance:

- Combine between numerical field simulation and core sample lab experiments
- Multi-purpose CO_2-Solvent use:
  - CO_2 hybrid fracturing
  - CO_2 and surfactant injection (CO_2-Foam)
- Discuss solvent design in extend, to find an optimum solvent that can provide the best results in Bakken in term of recovery factor.
- Evaluation of application parameters (soak time, injection time and cycles, etc.)

Project Milestone and Timing:



Progress to date:

- Reservoir fluid characterization
- PVT model in WinProp
- Reservoir model in CMG
- Permeability, wettability and rock mineralogy measurements
- Experimental simulation of CO_2 injection in one MB sample (3 more on ongoing)

References

Larry W. Lake . (2014). Petrophysics and Petrochemistry, Fundamentals of enhanced oil recovery (83-84). Society of Petroleum engineers.

Janet K. Pitman, Leigh C. Price, and Julie A. LeFever, 2001, Diagenesis and Fracture Development in the Bakken Formation, Williston Basin: Implications for Reservoir Quality in the Middle Member, U.S. Geological Survey.

Geomechanical Impact of CO_2 Storage in the Bakken Formation and its potential for fault reactivation in the Williston Basin

Ogochukwu Ozotta

Ph.D. student, Department of Petroleum Engineering, UND

This research aims to:

- Study CO_2 storage effect on rock matrix
- Pore structures of the shale reservoir in reaction to CO_2 storage.

Microfractures are generated in shale when CO_2 is injected into shale reservoir, causing swelling of shale matrix. CO_2 adsorption also weakens the mechanical properties of the shale. Mineral dissolution might influence diffusion properties by producing secondary pores and cracks in shale, which enhances the porosity and permeability. CO_2 in different phase state also caused a reduction in the uniaxial compressive strength test and Young's modulus.

Hypothesis

As pore pressure increases in the reservoir, the effective normal stresses on the fault's plane decrease, and may reactivate fault in the basin.

Investigation

- The host formation – chemical processes of fluid quantity, physical and chemical effects of CO_2 on mechanical properties of the host formation.
- Adjacent formation – rock matrix integrity, possible leakage, pathways of fissuring and fault reactivation.
- Regional stress state of the Williston Basin.

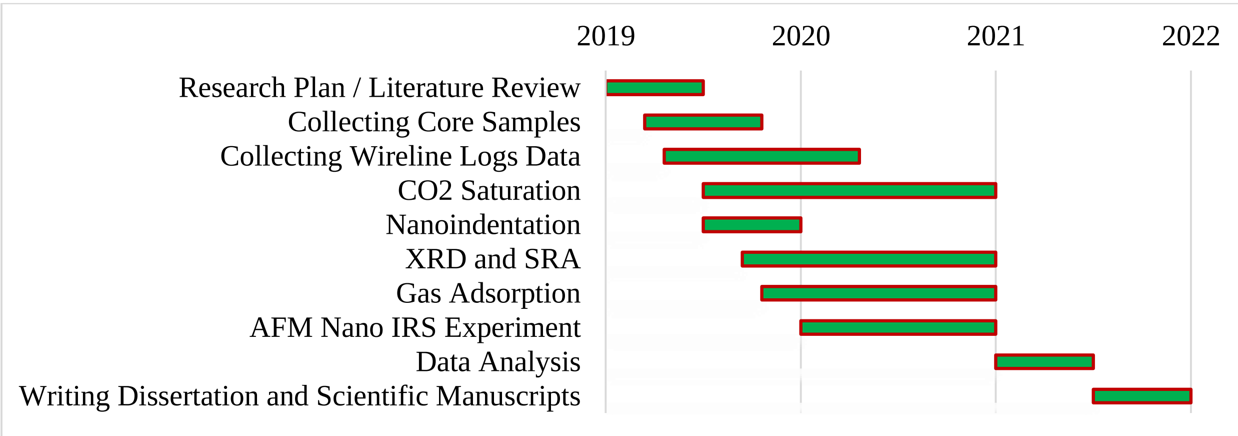
Methodology:

1. Measure uniaxial and triaxial strength test of the core samples using Nanoindentation and Nano AFM.
2. Create Field Emission Scanning Electron Microscopy (FESEM) to study the pore structure of the formation.
3. Pore structure of the core after CO_2 exposure.
4. Use X-Ray Powder Diffraction (XRD) to determine the mineral dissolution
5. Create model to mimic the pore structure
6. Simulation to determine the capacity of the reservoir
7. Incorporate field data

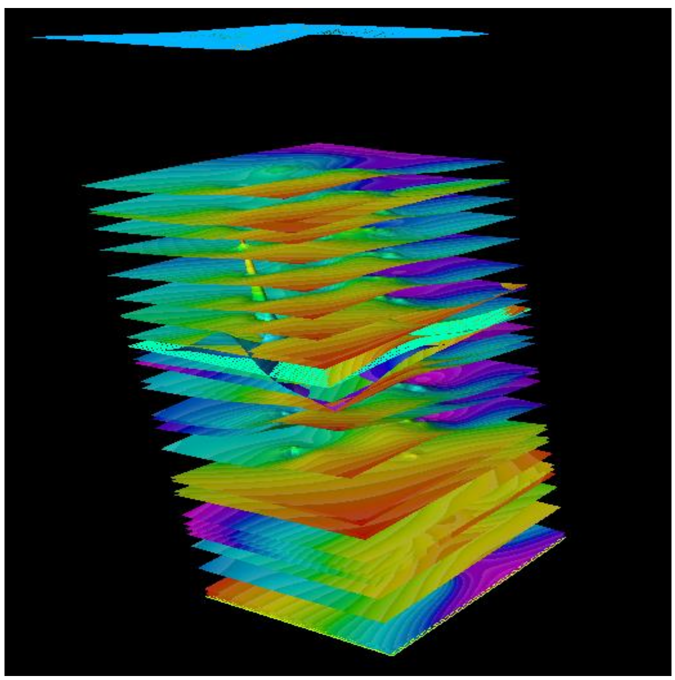
Scientific importance

This research will provide the mechanical information of the Bakken cores in reaction to load, water, and CO_2 exposure, and to ascertain if CO_2 storage will reactivate faults in the Williston Basin. This information will be used to determine the volume of CO_2 for storage and enhanced oil recovery, and capacity and integrity of each of the Bakken Formation member in North Dakota. If the mechanical and chemical properties are changing, how much of the changing is associated with the absorption of organic matter and how much of it is related to changes in the pore structures.

Project Milestone and Timing:



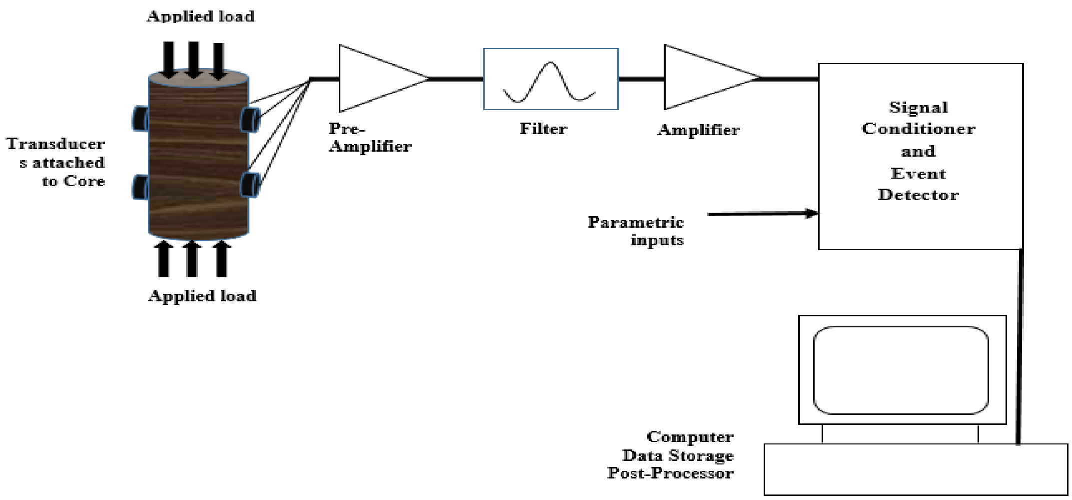
Progress till date:



- Literature review on the impact of CO2 saturation on the geomechanical properties of shale reservoir.
- Built a geological model of the field with all the formation properties.
- Saturation of core samples with CO_2
- Carrying out nanoindentation test on shale reservoir of the Bakken Formation
- Source Rock Analysis

- Field Emission Scanning Electron Microscopy (FESEM) characterization of the shale reservoir.

Next action:



- Carry out gas adsorption to understand pore structure on the caprocks
- Nanoindentation changes on the shale reservoir
- Nano Atomic Force Microscopy (AFM) on caprocks parallel and perpendicular to bedding plan for anisotropy.
- Will run a simulation of CO_2 storage in the geological model to determine its injectivity, capacity, caprock integrity and potential for fault reactivation in the basin.

Using Pressure Distribution to Detect the Blockage and Leakage in the Pipelines

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Experiments (multiple leaks & multiple blockages):

1. **Multiple leaks**

1.1 Experiment procedures

The experiment is used to figure out the relationships between the leak flow rate and pressure drop through the pipe during the multiple leaks scenarios. The experiment procedure is showed in the chart below. And experiment groups vary by adjusting the master valve.

Table 1. Specific procedure for the experiment of multiple leaks

Time (min)	Status
0	Open master valve to 90 ˚(or 60 ˚, 30 ˚), open 2 leak valves to 90 ˚, make sure no water flowing in the pipe system, open the recording software
1	Start the pump, keep recording 2mins
3	Switch 2 leak valves to 60 ˚meanwhile, keep recording 2mins
5	Switch 2 leak valves to 30 ˚meanwhile, keep recording 2mins
7	Close 2 leak valves to 0 ˚meanwhile, keep recording 1min
8	Open 2 leak valves to 30 ˚meanwhile, keep recording 2mins
10	Switch 2 leak valves to 60 ˚meanwhile, keep recording 2mins
12	Switch 2 leak valves to 90 ˚meanwhile, keep recording 2mins
14	Close 2 leak valves to 0 ˚meanwhile, keep recording 1min
15	Shut down the pump, still recording 1min
16	Close the recording software

1.2 Experiment results

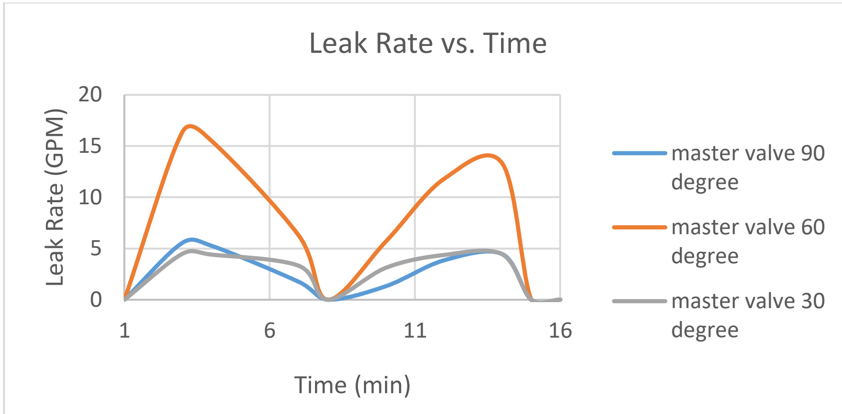

Figure 1. The relationship between leak rate and time in the experiment of multiple leaks

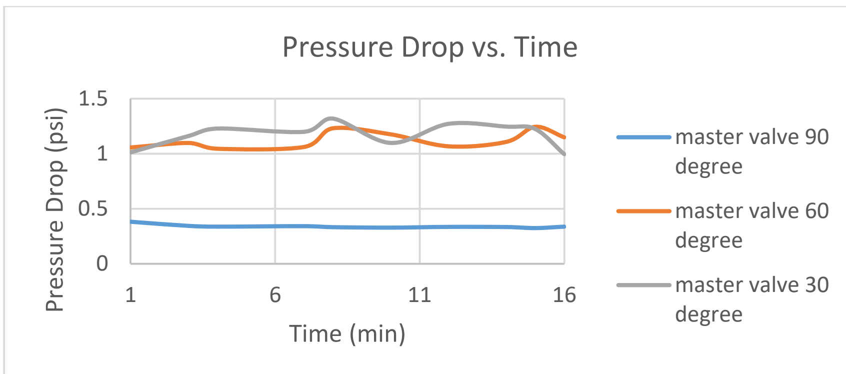

Figure 2. The relationship between pressure drop and time in the experiment of multiple leaks

1.3 Conclusions

When the leak rate is smaller, the pressure drop through the leak is smaller, and vice versa. When the leak rate is larger, the leakage location is more significant to the pressure drop through the leak. At the same leak rate, the pressure drop is larger when the leakage location is further from the inlet. At the same leak location, the pressure drop is larger when the leak rate is smaller.

2. Multiple blockages

2.1 Experiment procedures

At regular intervals, adjust the main valve to the corresponding angle. After 14 minutes, close the valve and end the experiment. Experiments can be divided into two parts according to different each blockage length.

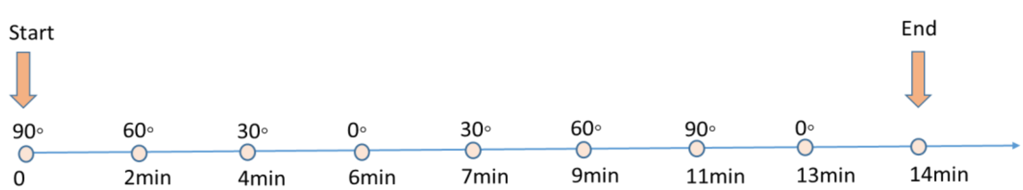

Figure 3. Schematic illustration for the experiment of multiple blockages

Part 1(Group #1-3): Each blockage length is 5% of the pipe length; blockage diameters are 0.24in, 0.34in, 0.5in; blockage locations are at 22% and 73% of the distance between the two pressure sensors.

Part 2(Group #4-9): Each blockage length is 10% of the pipe length; blockage diameters are 0.24in, 0.34in, 0.5in; blockage locations are at 18% and 48% or 72% of the distance between the two pressure sensors.

2.2 Experiment results

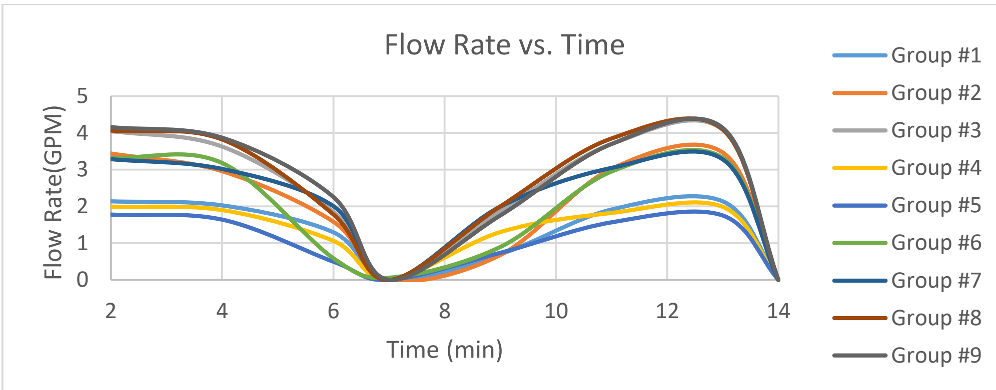

Figure 4. The relationship between inlet flowrate and time in the experiment of multiple blockages

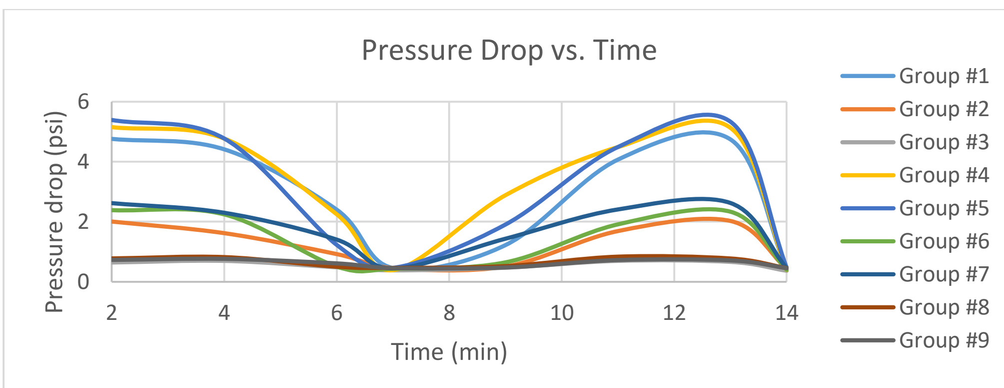

Figure 5. The relationship between pressure drop and time in the experiment of multiple blockages

2.3 Conclusions

The length, diameter of the blockage, and inlet flow rate have a significant effect on the pressure drop through the blockage. When blockage length is larger, the blockage diameter is small, or the inlet flow rate is larger, the pressure drop through the blockage is larger. The effect of blockage location to the pressure drop through the blockage is insignificant. However, when the location of the blockage is more close to the water inlet, the pressure drop is smaller.

Project Milestone and Timing

Table 2. Project timeline with milestones

Tasks	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
Task 1*:* Modify the experimental setup	■											
Task 2*:* Experiment for single blockage/leakage in a pipeline		■	■									
Task 3*:* Experiment for multiple blockages/leakages in a pipeline				■	■	■						
Task 4*:* Experiment for single blockage/leakage in parallel/looped pipelines							■	■	■	■		
Task 5*:* Develop simulation models to evaluate blockages/leakages in different scenarios							■	■	■	■	■	■
Task 6*:* Data validation and analysis										■	■	■

Progress to date:

By the end of June 2019, I clarified the purpose and significance of the experiment, finished the experimental operations for blockages and leakages in the single pipeline, started the experiments for the multiple blockages and leakages in a pipeline, and learned the methods to build simulation models. I expect to finish the rest experiments in the parallel/looped pipelines soon and develop simulation models to detect the blockages/leakages location in varied situations. For blockage and leakage detection, multi-flowrate tests are performed to determine the blockage/leakage location and evaluate the diameter and length of the blockage. And a dimensionless-variable approach will be used to locate the blockage/leakage and estimate the blockage/leakage size. Finally, we will provide an efficient and low computational cost method to detect blockages/leakages under different scenarios.

Lattice simulations of lab scale hydraulic fracturing

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Problem Statement:

Hydraulic fracturing is the principal stimulation technique applied to improve oil and gas recovery and enhance production from unconventional resources. Better understanding of these reservoirs and advanced tools make the production economically viable and more efficient. Unconventional reservoir has a very specific characteristic, such as complex mineralogy, lateral and vertical heterogeneity as well as anisotropy. These characteristics require detailed characterization and exploitation technologies.

In this study, we simulate hydraulic fracturing of lab scale experiments conducted on 10 cm cubical mortar samples. Lattice simulation, which is grain based numerical modelling. The simulations are done using the exact data used in the lab. Mechanical properties of the mortar samples and the three principal stresses applied to the sample in the lab were all used in the simulation. High viscosity for fracturing fluid and very low flow rate are desired in lab scale hydraulic fracturing in order to propagate the fracture very slowly and record the pressure data and monitor the fracture geometry during the experiment. The use of all these data leads to very long simulation time. In this study, we tackled this problem by using different resolutions for the model, where in fact the resolution along the fracture propagation is higher than other areas.

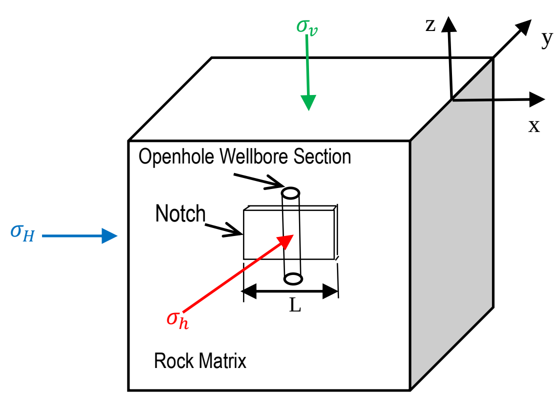


Figure 1: 3D Model Geometry

The use of a notch, as a predefined crack in the preferred fracture propagation direction is commonly done in lab experimental studies to assist the fracture to initiate more easily and direct the fracture propagation near wellbore. The use of notch in field hydraulic fracturing applications has also been reported. In order to enhance the model, we numerically simulate the impact of the notch geometry on fracture initiation and propagation pressure and geometry. The XSite, a particle based model was used to simulate some lab experimental data and the results showed the importance of notch length and its orientation on fracture propagation (Figure 2).

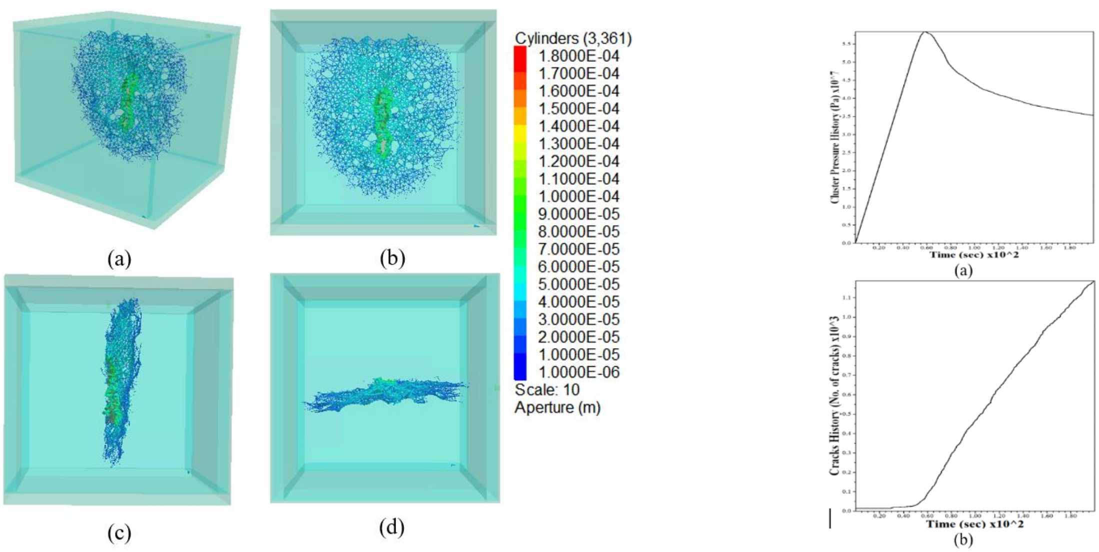


Figure 2: *Left:* Aperture distribution for open hole model Case 1: (a) general View, (b) front view, (c) side view, (d) top view *Right:* Cluster pressure and history of the number of microcracks for open hole model

Objectives:

- Simulate rock deformation and fracturing process
- Analyze the impact of the fluid flow in both fractures and matrix
- Validate the lab work using XSite by simulating the fracture propagation
- Record the fluid pressure changes in response to the deformation.
- Analyze the impact of the notch parameters (length and orientation) in guiding the fracture initiation near wellbore and the created fracture geometry

Methodology:

The methodology was divided in tow sections:

1. Lattice based numerical simulation:

- Simulations were performed using a lattice-based software XSite.
- The software uses the concept of bonded-particle model (BPM) and synthetic rock mass (SRM).
- Lattice simulation, which is grain-based numerical model, is a simplification of the BPM in which the finite-sized particles and contacts are replaced by nodes and springs.
- The SRM is implemented in XSite using bonded-particle assembly with multiple joints which represents brittle rock containing multiple fractures. It allows simulation of interaction between hydraulic fractures and natural fractures.

2. Model set up:

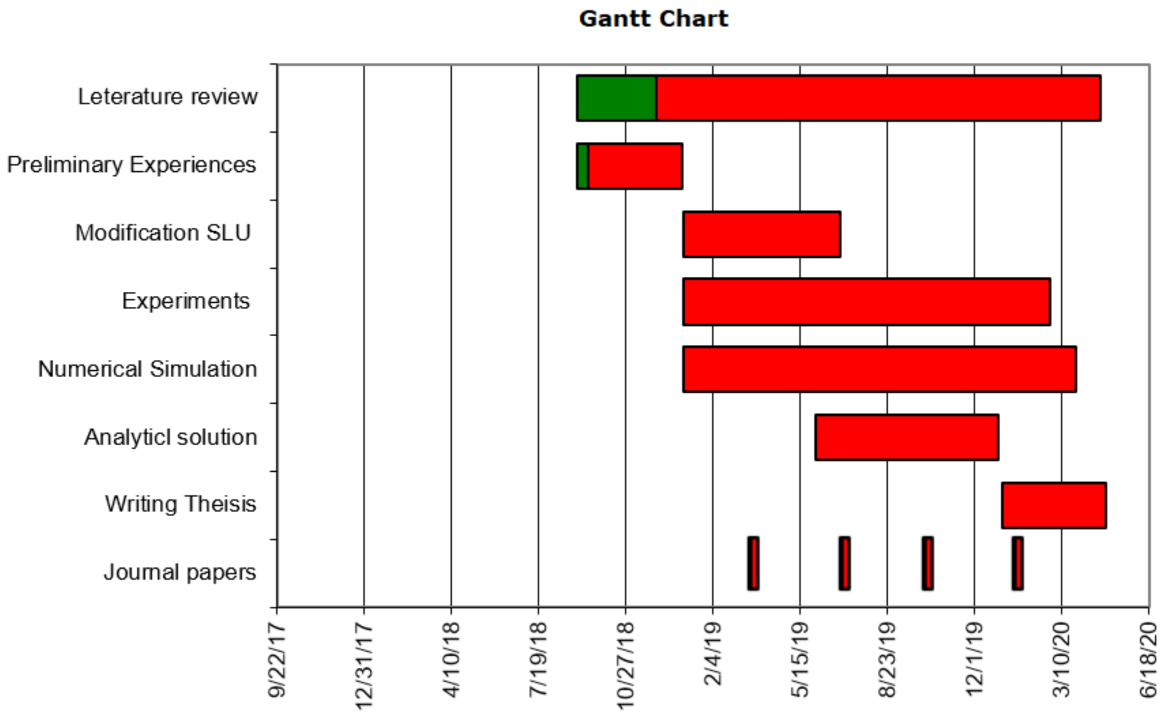
- Setup: we set up the model by applying the mechanical properties and the stresses.
- Excavation & Equilibrium: this is a preprocessing stage. We ran the model in the mechanical mode only. The open hole segment and the notch were excavated and equilibrated for 0.005 second to reach mechanical equilibrium.
- Mechanical & Fluid: after mechanical equilibrium, we ran the model in the coupled hydro-mechanical mode and injected fluid for 200 seconds.

Significance:

- The effect of notch size and width on open hole hydraulic fracturing in the lab scale. The results suggest that the introduction of notch generally creates a more favorable condition for fracture initiation and rock breakdown. However, closed notch may resist fracture initiation. A notch placed perpendicular to σ_h direction needs less pressure to initiate microcracks than that is placed parallel to σ_h.
- Application of notch in open hole hydraulic fracturing has presented some improvements in near wellbore problems. Enhancing the open hole fracturing technique by cutting a notch in the wellbore wall to serve as a weak point where the hydraulic fracture initiates.
- In all lab experimental studies, in order to facilitate the initiation of hydraulic fracture and reduce the initiation pressure, notches are placed along the direction perpendicular to the minimum stress direction, which is the desired direction for the fracture to open. In this

study, we investigate the impact of the notch length on fracture initiation pressure and its geometry.

Project Milestone and Timing:



Progress to date:

- The analysis of the lab experiment results was performed and is on going
- The literature review was carried out on different stages of this study
- The lattice simulations and hydraulic fracturing was actually used to evaluate various cases of fracture constriction in the near-wellbore region.
- The collaboration with ITASCA team was made to improve and validate the results

Impact of Stress on the Characterization of Flow Units in the Complex Three Forks Carbonate Reservoir, Williston Basin

Aldjia Boualam Djezzar

Ph.D. student, Department of Petroleum Engineering, UND

Phase I: Reservoir Characterization

Petrophysical analysis

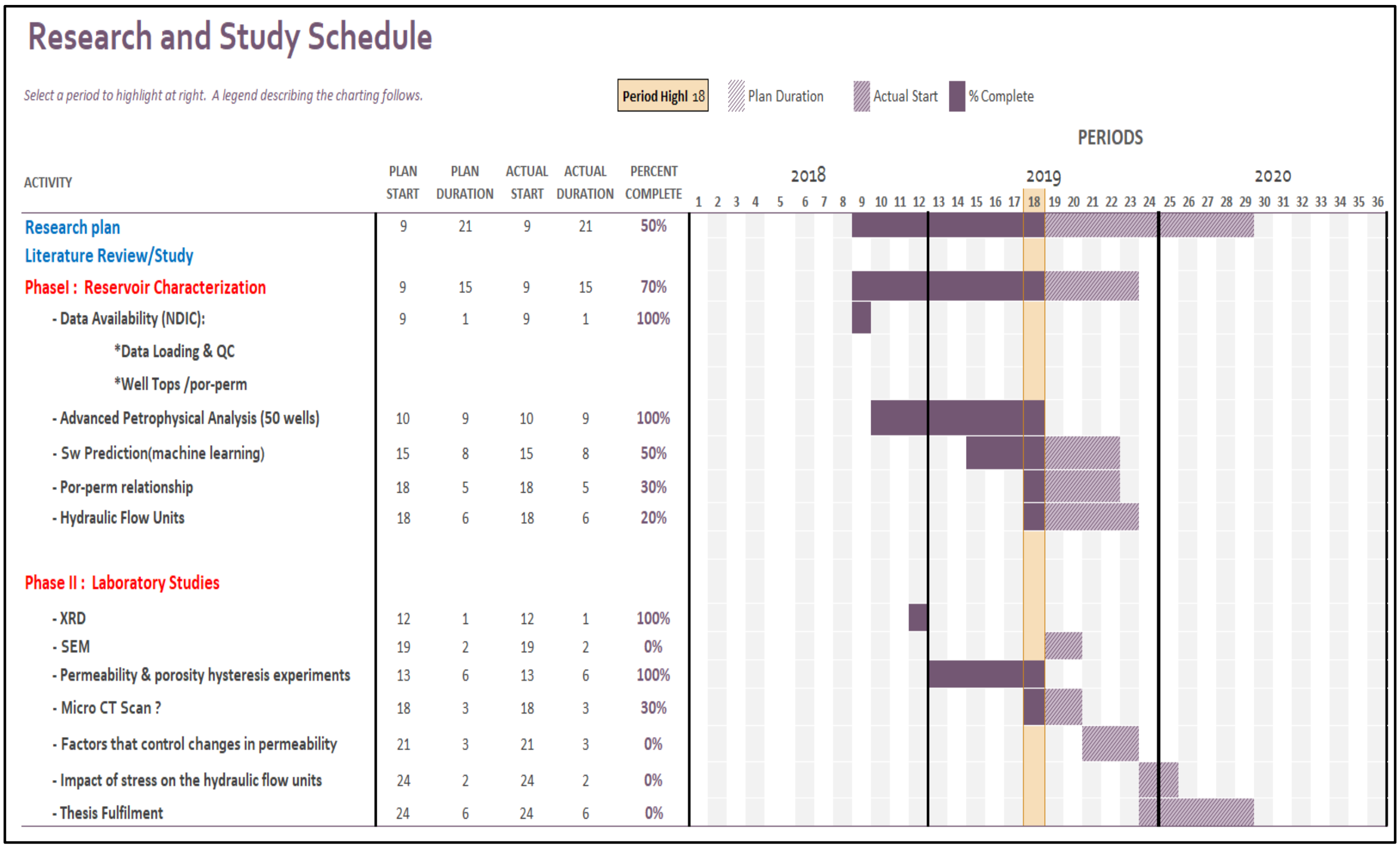
- 120 wells were selected and loaded onnto Techlog. After quality control of the data, the well logs were loaded onto petrel software for correlation and determination of the well tops that were used for petrophysical analysis.
- Four lithostratigraphic correlation panels were established to study the extension of different interval units (upper, middle and lower Three Forks).
- Two alternative approaches to thin beds petrophysical analysis were used in this study. The first approach to thin beds analysis is expressed by the integration of the advanced logging such as elemental capture spectroscopy (ECS), nuclear magnetic resonance (NMR), multifrequency array dielectric measurements, and triaxial induction resistivity in conjunction with the conventional logs in the workflow.
- A robust solution was applied in Quanti Elan to quantify the fluid and mineral volumes.
- Multi-mineral solver, a probabilistic approach, was used to establish the lithological model based on the input components and simultaneous optimization of different equations. First, the conceptual lithological model was constructed from the cross-plots and from XRD analysis. Then, a detailed multi-mineral model was derived by adding the elemental dry weight fractions quantified by ECS in conjunction with NPHI, PEF, and RHOZ to quantify the content of various matrix components. The complex lithological model is constituted by Illite, chlorite, quartz, dolomite, calcite, K-feldspar, anhydrite and pyrite.
- In the post-processing phase, after adding the permittivity (1-in vertical resolution) to the workflow, the effective porosity and water saturation (Sw) were calculated and compared to the core analysis. At this step, the non-reservoir facies which are interbedded with porous dolo-siltite facies, were better identified.
- The outputs of the petrophysical model were compared with special and routine core analysis (XRD, porosity and water saturation).
- The dielectric dispersion measurements from a multifrequency array dielectric tool were considered as the second substitute approach to thin beds petrophysical analysis. It was used to better estimate Sw independent of the resistivity and Archie parameters. The difference between the total porosity and the water-filled porosity from array dielectric measurements supplied a straightforward estimation of the Sw in the invaded zone.
- The petrophysical integration process focused on 50 key wells to build the model for extrapolation to the wells with a limited set of data.

- In the Three Forks reservoir, the lithology is characterized by significant vertical variability, which has a profound effect on reservoir quality. It can be seen from XRD analysis for different wells that the dominated lithological composition is primarily dolomite. Overall, the detailed multi-mineral model indicates a very accurate prediction of the mineral volumes compared to the XRD analysis in the studied wells. Also, an agreement was achieved between the estimated porosity, core porosity, and NMR total porosity. The Sw was accurately reproduced by the two applied models except for the intervals where the anhydrite is in abundance. The dielectric model gave better results compared to the Dean-Stark Sw across these intervals.
- NMR was recorded in most of the wells and was used to provide a mineralogical independent total porosity and to measure the pore size distribution. The porosity was divided into different pore size ranges. The large pores are associated with the free fluid, small pores in which the fluids are capillary-bound, and the micro-pores are associated with clay-bound fluids.
- T2 Log Mean, per well, versus the Dean-Stark Sw for a set of wells was plotted. The results showed varied reservoir characteristic related to different units. Two disparate clouds of points were highlighted. The first group has Sw ranging between 26% and 60 % with an average of T2 Log Mean per well equal or greater than 8 msec. The second group has a Sw value greater than 60 % with an average of T2 Log Mean less than 8 msec. The upper Three Forks is characterized mainly by large pores with an average T2 Log Mean of 12.79 msec for all the studied wells. In contrast, the middle and lower members have an average T2 Log Mean of 5.95 and 2.59 msec respectively. The results were confirmed by the increase of the capillary and clay bound fluids with depth.
- The relationship between T2 Log Mean and volume of chlorite versus Dean-Stark Sw was plotted. Correlation was observed between T2 Log Mean and the chlorite content. As the T2 Log Mean decreases, the volume of chlorite increases. This shows that the larger the volume of chlorite, the more complex the pore size structure mainly in the MTF. This correlation is accentuated in the lower interval, where the micro-pores are most abundant. Also, a strong correlation was observed between the cutoff of T2 Log Mean at 8 msec and the Dean-Stark Sw. The higher the values of T2 Log Mean (>8 msec), the lower the Sw and the larger the pore size.
- Based on 1100 samples, a cross plot core porosity versus permeability combined with Winland R35 lines was used to identify the different rock types. Six petrophysical rock types were identified from the cross-plot. Rock type 1 forms the poor reservoir interval, with porosity ranging from 1 to 10% and permeability less than 0.006 mD. In contrast, the rock type 6 has much better permeability (1 mD to 10 mD). Calculated R35 are 0.02 to 0.05 microns for rock type 1 and 1.5 to 4.5 microns for rock type 6. The average porosity is between 6 and 7.5%. However, the permeability is low, averaging at 0.13 mD.

Phase II: Laboratory studies

- Five horizontal plugs, 1.5 in. (3.8 cm) in diameter by about 3 in (7.6 cm) in length, were drilled in upper Three Forks formation (well Charlie Sorenson 17 -8 1-H) in a direction parallel to the slabbed face. The samples handling, preparation, and analytical procedures followed the API standard procedures.

- Laboratory preparation of the samples is directed toward the removal of liquid hydrocarbons, free water from the pores, and salt if is existed by using the method of solvent extraction, in addition to drying the samples in an oven.
- Experiments were conducted by first gradually increasing the confining pressure from 500 to 5000 psi or more. This was followed by subsequently reducing it back to 500 psi where the porosity and permeability were measured at each step (SEM-300).
- Two methods were used to measure the permeability and porosity hysteresis for the four samples. The Unsteady-state method (Core Measurement System, CMS-300) and steady-state method (CPMS). The experiments were conducted by first gradually increasing the net confining pressure from 1, 2.5, 4, 5, and 6 K. Then reduce the pressure gradually to 1 K where the porosity and permeability are measured at each step.
- Micro CT Scan and X-ray diffraction were carried out on 4 samples.



ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Research plan	9	21	9	21	50%
Literature Review/Study					
PhaseI : Reservoir Characterization	9	15	9	15	70%
- Data Availability (NDIC):	9	1	9	1	100%
*Data Loading & QC					
*Well Tops /por-perm					
- Advanced Petrophysical Analysis (50 wells)	10	9	10	9	100%
- Sw Prediction(machine learning)	15	8	15	8	50%
- Por-perm relationship	18	5	18	5	30%
- Hydraulic Flow Units	18	6	18	6	20%
Phase II : Laboratory Studies					
- XRD	12	1	12	1	100%
- SEM	19	2	19	2	0%
- Permeability & porosity hysteresis experiments	13	6	13	6	100%
- Micro CT Scan ?	18	3	18	3	30%
- Factors that control changes in permeability	21	3	21	3	0%
- Impact of stress on the hydraulic flow units	24	2	24	2	0%
- Thesis Fulfilment	24	6	24	6	0%

Discrete Fracture Network (DFN) Modelling of Hydraulic fracturing

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Model Accuracy Verification

Hydraulic fracturing interaction modeling was carried out using XSite with two natural fractures. The results were compared with experimental results to verify the accuracy of the model.

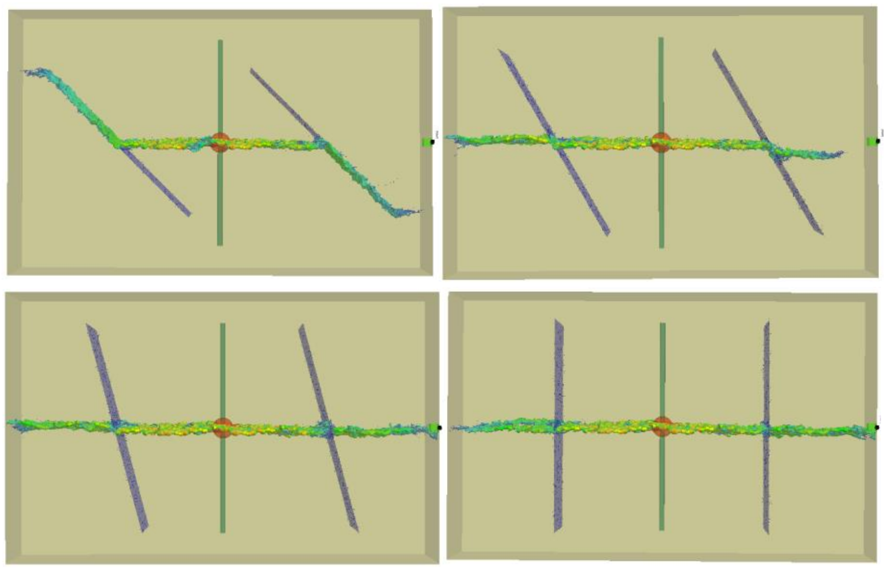


Figure 1 Hydraulic fracture (HF) propagation path when interacted with nature fractures (NF) placed at different directions

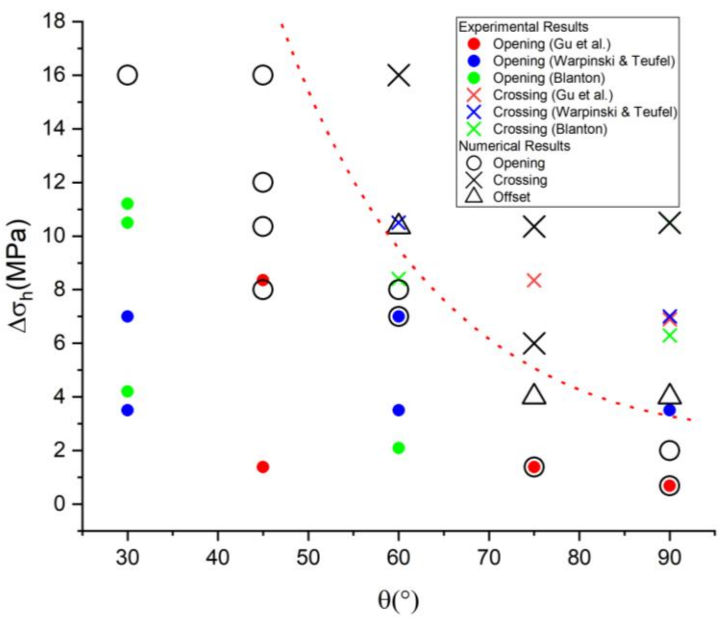


Figure 2 Comparison between the numerical model and experimental results for HF-NF interaction at different angle of approach and stress anisotropy

Fig.2, indicate good agree between the numerical and experimental results. Based on these results, a large scale simulation of hydraulic fracture modeling can be conducted.

Analysis of Narrow versus Wide Fairway Fracture Geometry

The impact of the stress ratio was simulated on orthogonal natural fracture networks. The microseismic clouds area was used to estimate the stimulated area. Fitting a 95% confidence ellipse to the microseismic points the aspect ratio of the microseismic ellipse (i.e. the ratio of the smaller to the larger diameter of the ellipse) was calculated. The results show, as expected, that by increasing the stress ratio, the stimulated area aspect ratio becomes larger, which means high-stress anisotropy can result in relatively planar fracture fairway, whereas low-stress anisotropy can lead to a wide and complex fracture system.

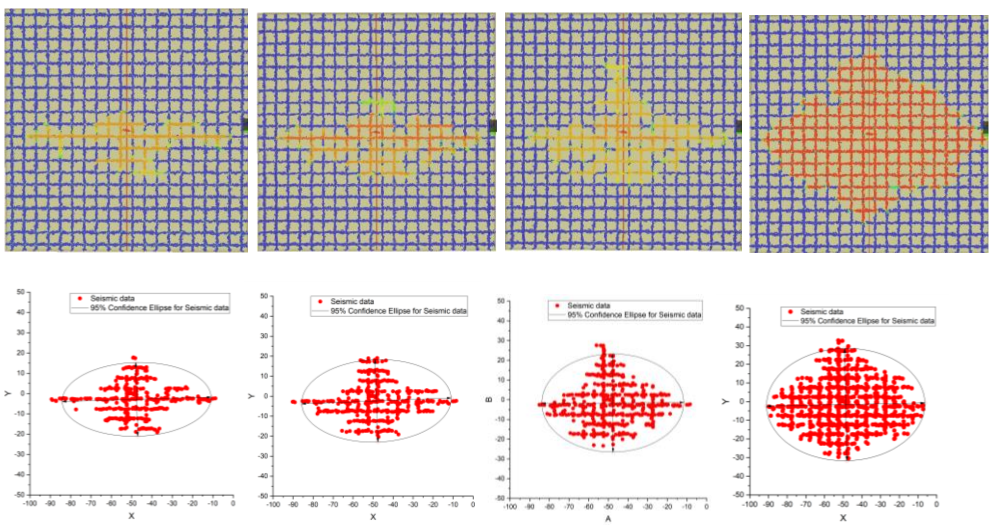


Figure 3 Ellipse of microseimic data corresponding to opened natural fractures at different stress ratios

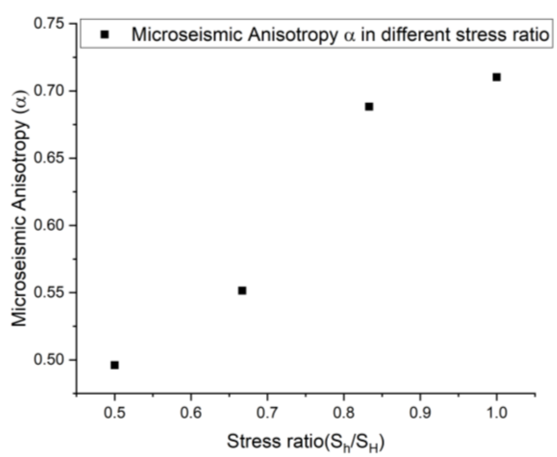


Figure 4 Change of aspect ratio of the anisotropic microseismic ellipse as a function of stress anisotropy

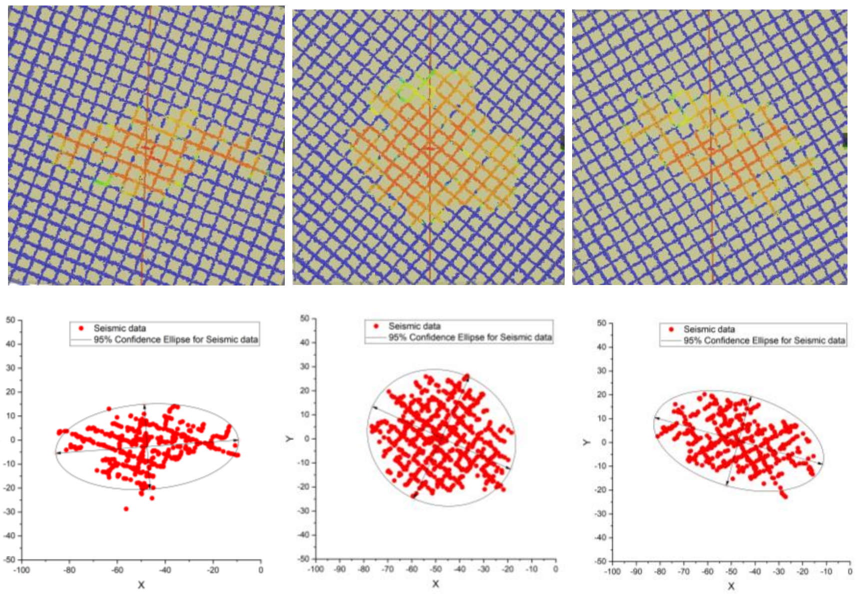


Figure 5 Ellipse of seismic data with different fracture orientation

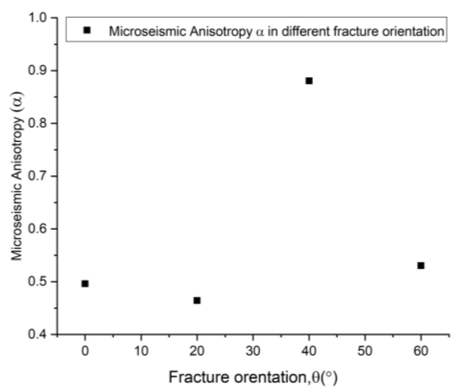


Figure 6 Change of microseismic cloud anisotropic ellipse geometry as a function of fracture orientation

The results also showed that at an orientation of 40° for the natural fractures with respect to the principal stress, it was observed that the fracture propagation is more planar due to the larger shearing potential of the natural fractures at this angle.

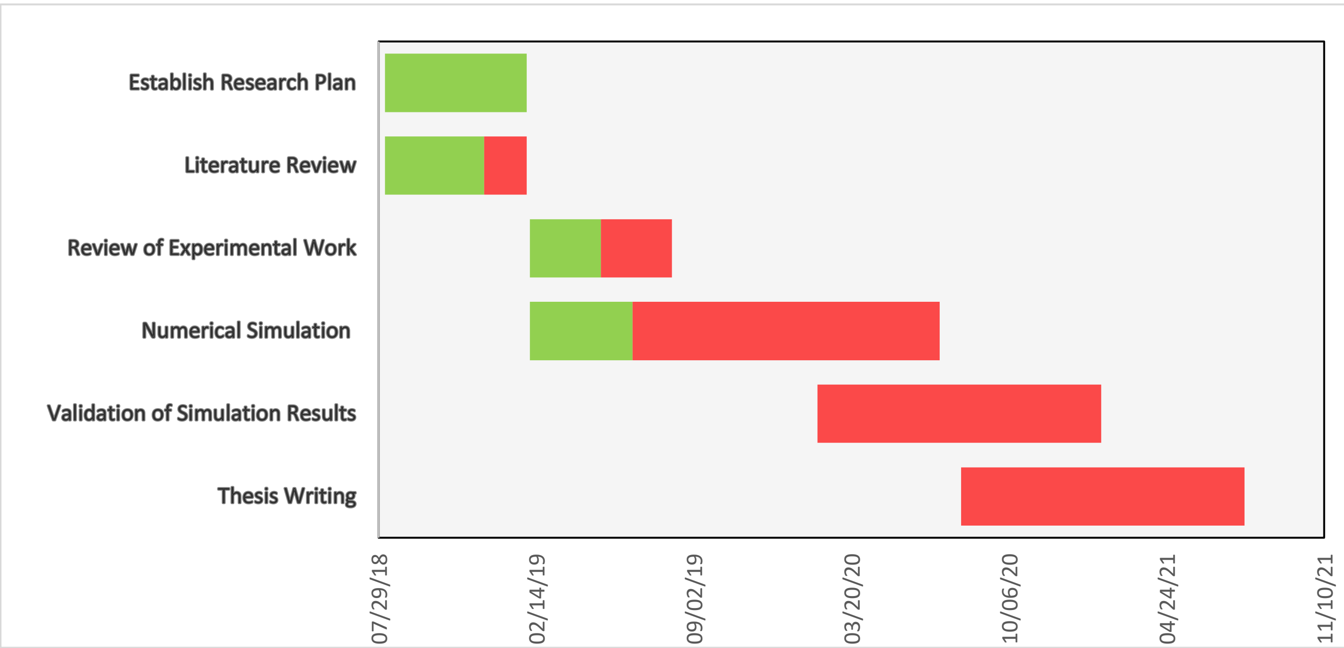
Simulations of Near Wellbore Hydraulic Fracturing Through Perforations

Omar Akash

Ph.D. student, Department of Petroleum Engineering, UND

I. Project Schedule:

Table 1: Project Gantt Chart



II. Project Literature Review:

- The literature relative to project topic has been reviewed.
- The literature was divided into four categories: field, experimental, numerical and analytical studies. While numerical studies were given more attention.
- It was found that some problems related to the project topic has been well studied in the literature such as perforations orientation relative to field stresses.
- It was found that other problems related to the project topic are currently under investigation such as limited entry perforations technique in hydraulic fracturing.

III. Numerical Simulation

- XSite (3D lattice numerical based method) was used to numerically investigate hydraulic fracturing behavior from perforated wellbores.

- Numerical model created to mimic laboratory experimental conditions.

- Numerical simulations performed, and results were compared to laboratory results taken from literature.

- Figure 1 shows numerical simulations results with perforations tunnel oriented in favorable orientation (A), and perforations tunnel oriented in unfavorable orientation (B).

- Figure 2 shows effect of natural fracture on hydraulic fracture behavior when taken into consideration in the numerical simulation practice.

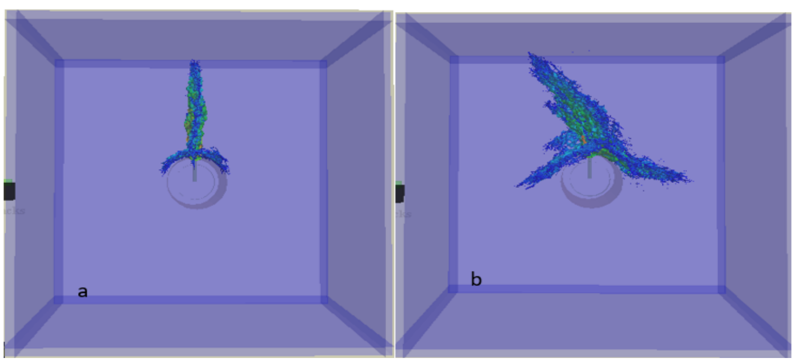


Figure 1: perforations tunnel oriented in favorable orientation (a), perforations tunnel oriented in unfavorable orientation (b).

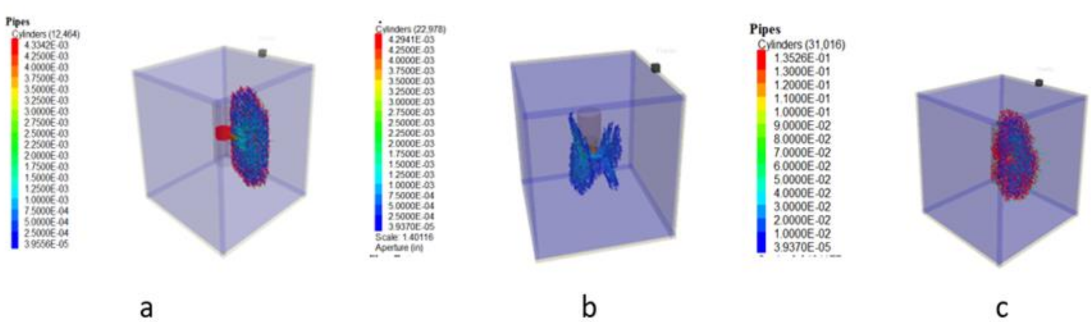


Figure 2: effect of natural fracture on hydraulic fracture behavior (a: vertical natural fracture, b: horizontal natural fracture, c: no natural fracture).

Highlights Progress to Date:

- Established a research plan.

- Practiced the simulation software that will be used in the study.
- Literature review of analytical models.
- Performed numerical simulations and compared the results with previous published experimental work.
- Authored and co-authored three conference papers relevant to the project.
- Presented my simulation work at UND research achievement day through poster presentation and networked with tens of the attendees.
- Participated in Petroleum Engineering Department Industry Advisory Council Banquet and networked with engineers from industry.
- Successfully completed eight courses relevant to the project:

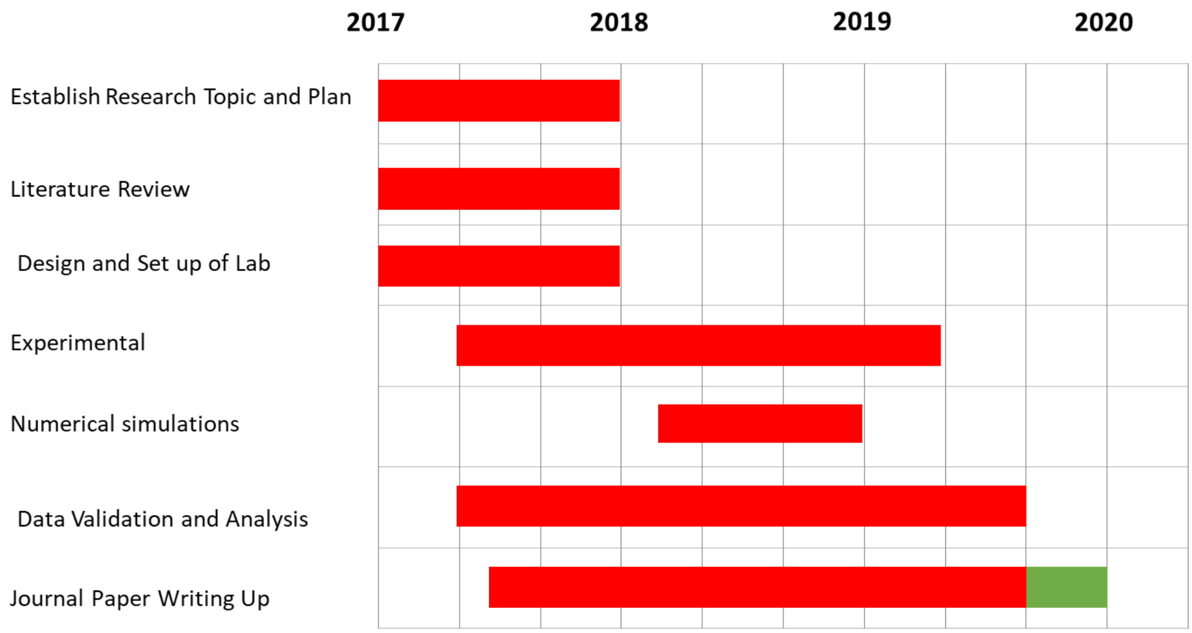
1- Fundamentals of Shale Plays.
2- Technology Ventures.
3- Petroleum Geo-mechanics.
4- Advanced Production Engineering
5- Petroleum Geo-statistics.
6- Advanced Stimulation Methods.
7- Numerical Simulations in Perforation Design.
8- Seismic Geo-mechanics

Replicating Bakken Shale Rock for Petrophysical Experiments Using 3D Printing Technology

Lingyun Kong,

Ph.D. student, Department of Petroleum Engineering, UND

Project Milestone and Timing:



Progress to date:

Up till now, June 2019, the second objective has been achieved. Natural rock types, porous model of sandstone, has been replicated by 3D printing.

1) The first application is to combine with digital rock physics and select which material is best suitable for porous rock replication. By using nano-CT, three different materials were utilized for manufacturing different rock anlogues that were analyzed and examined in terms of pore size distribution, pore shape and internal structures. The results showed that silica sand-based sample would have the widest range (25% to 75%) of the pore radius distribution, while resin-based sample accounts for the narrowest range of pores. Furthermore, the resin-based sample had the smoothest boundary in pores while the silica sand-based sample exhibited the least smoothness. Regarding the internal structure, resin-based samples have shown the most precise performance while the other two methods failed the expectations where the unbound powder was still remaining in the internal macropores.

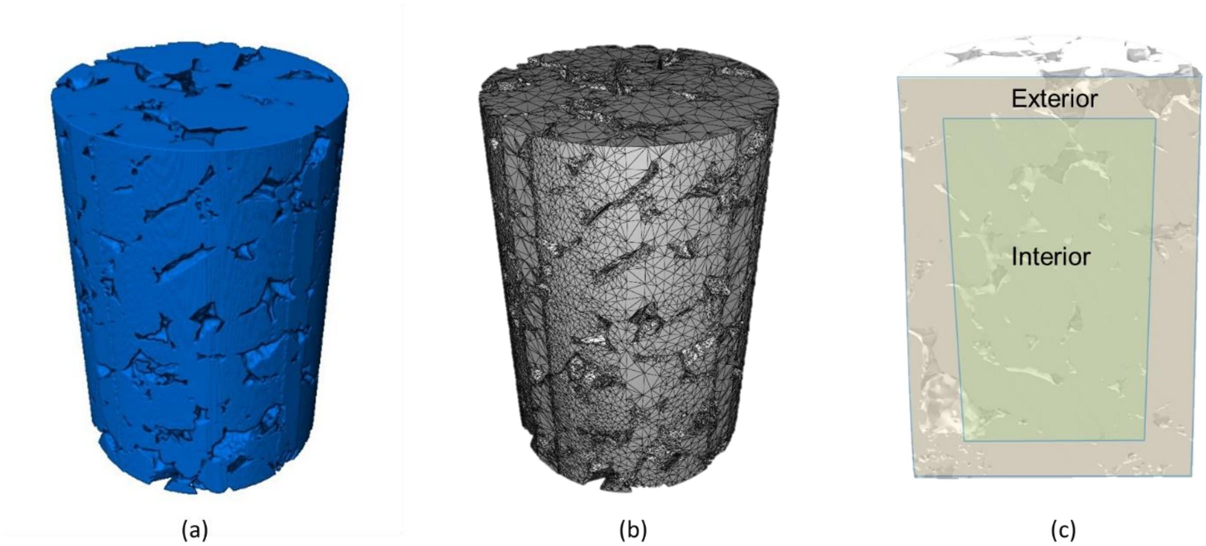


Figure 1 Digital analysis and reconstruction of Berea sandstone. (a)Volume rendering model of Berea sandstone, 1.905mm diameter and 2.857 mm length. (b) Triangular mesh of transformed model (20 folds) in STL file, 38.1 mm (1.5 inches) diameter and 57.15 m

Figure 2 Three 3D printed porous rock created by gypsum-powder, silica sand-powder, resin (from left to right, respectively).

2) The second application is taking advantage of simple component of 3D printed rocks to validate or calibrate the best upscaling methods that was a complicated issue in geomechanics study. This study attempted to validate the upscaling methods on geomechanical properties that were measured through a combination of nanoindentation experiments and triaxial testing, using 3D printed rocks as a linear elastic material with simple component instead of a rock that has complex constituents. The 3D printed samples

that have simple components of gypsum powder and binder, were first tested in nanoindentation experiments to measure Young's modulus and hardness of each grain/component, and then followed by a deconvolution method to separate the two existing phases in terms of peak value and frequency fractions.

Mori-Tanaka method, self-consistent scheme (SCS) method and different effective medium (DEM) method were examined for their performance for upscaling mechanical properties from microscale to macroscale. Comparing macroscale Young's modulus of 3D printed rocks that was obtained from M-T and SCS methods demonstrates more comparable values than DEM with macroscale values acquired from triaxial and UCS testing. It is suggested that M-T and SCS methods are used when dealing with upscaling problems related to a linear elastic medium, though more complicated materials with heterogeneity and anisotropy should be further examined for the best upscaling method.

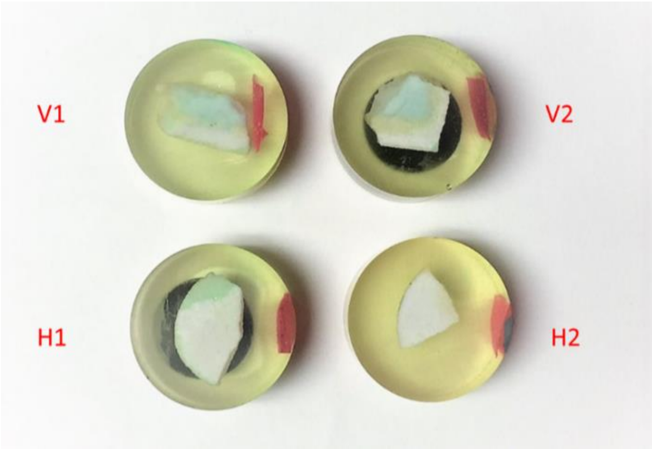


Figure 3 3D printed rock fragments for nanoindentation experiments. 'V' represents vertical, and 'H' denotes horizontal.

Table 1 Upscaling results of four samples using differential effective medium theory.

Sample	Porosity for Upscaling (Dimensionless)	Bulk Modulus (GPa)	Shear Modulus (GPa)	Young's Modulus (GPa)
Vertical 1	0.32	1.66	0.86	1.49
Horizontal 1	0.32	2.22	1.17	2.00
Vertical 2	0.32	3.01	1.52	2.71
Horizontal 2	0.32	1.48	0.73	1.33

3) The third case of applying 3D printed rocks in experiments is designing fractured rocks based on theoretical models and conduct the physical forward modelling which can be used to examine the inversion results with uncertainty. In this study, an emerging technology, 3D printing, was utilized to manufacture fractured models with different crack sizes for the

validation of effective elastic properties by TI background rock physics model. Comparing the measured P-wave and S-wave velocities of 3D printed rocks with various fracture lengths, it is concluded that increasing fracture lengths decrease the P-wave velocities and Vp/Vs ratios, while not for S-waves. By measuring under incremental confining pressures, one can summarize that higher confining pressures are associated with higher P-wave and S-wave velocities of all fractured samples. In the end, by predicting the effective elastic properties of fractured rocks, two rock physics models were compared with experimental results, which validates the advancement of the one considering transversely isotropic background.

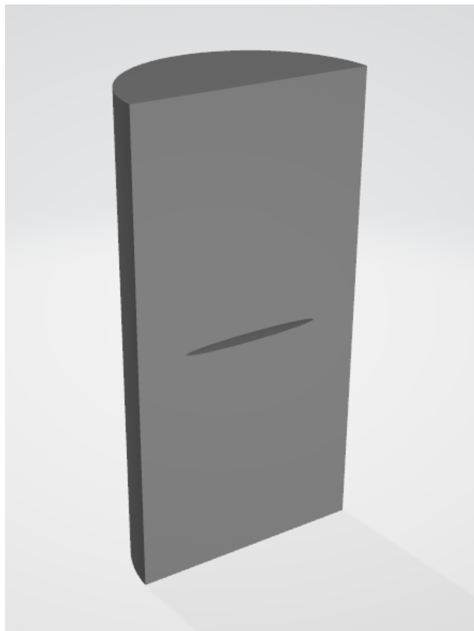


Figure 4 Sketch map of the fractured model (a split view)

Figure 5 Three groups of 3D printed rocks with fracture inside.

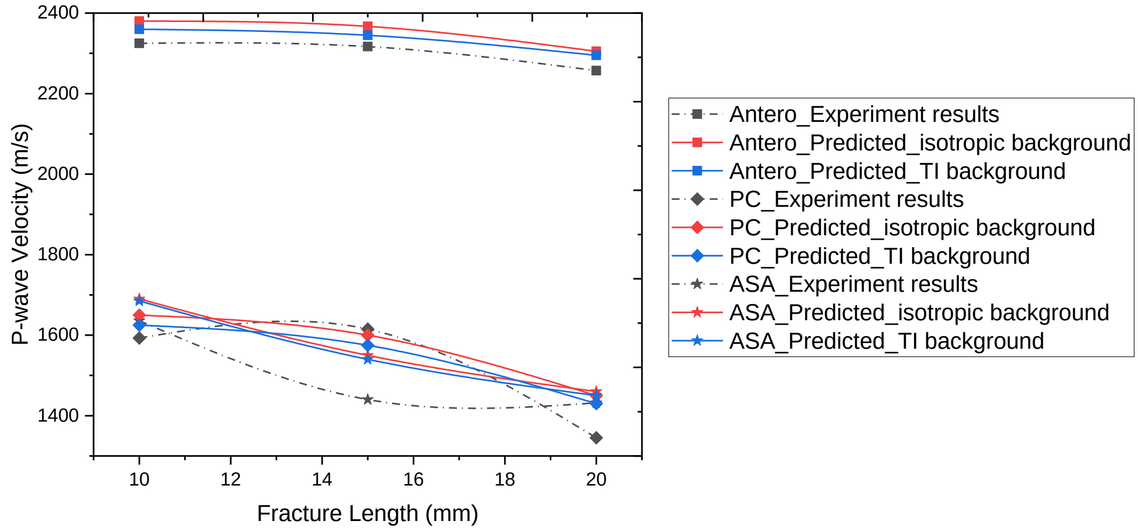


Figure 6 Validating the experimental results using two rock physics models, one of which is isotropic background and another is TI background.

All the results and conclusions have been published or submitted to peer-reviewed journals and given presentations in world-class conferences. Please see below the list of my publication pertaining to this research topic.

Reference

1. **Kong, L.**, Ostadhassan, M., Liu, B., Li, C., Liu, K., 2019. Multifractal Characteristics of MIP-Based Pore Size Distribution of 3D-Printed Powder-Based Rocks: A Study of Post-Processing Effect. *Transport in Porous Media.* DOI: 10.1007/s11242-018-1152-9 (IF: 2.211)

2. **Kong, L.,** Ostadhassan, M., Hou, X., Mann, M., Li, C., 2019. Microstructure Characteristics and Fractal Analysis of 3D-printed Sandstone Using Micro-CT and SEM-EDS. *Journal of Petroleum Science & Engineering*. DOI: 10.1016/j.petrol.2019.01.050 (IF: 2.382)

3. **Kong, L.,** Ostadhassan, M., Zamiran, S., Liu, B., Marino, G., Sakhaee-Pour, A., Li, C., 2019. Geomechanical Upscaling Methods: Comparison and Verification via 3D Printing. *Energies*. DOI:10.3390/en12030382 (IF: 2.676)

4. **Kong, L.,** Ostadhassan, M., Lin, R., Li, C., 2019. Nanoscale Mechanical Properties of 3D Printed Gypsum-Powder Based Rocks by Nanoindentation and Numerical Modeling. *Rapid Prototyping Journal*. （IF: 2.346）

5. **Kong, L.,** Ostadhassan, M., Liu, B., Eshraghi, M., Li, C., Navarro, M., Zhang, Y., Wei, H., 2019. A Comparison of 3D Printed Porous Rocks with Nano X-ray Computed Tomography: Silica Sand, Gypsum Powder and Resin. *AAPG Bulletin.* (Accept pending revision) (IF: 3.208)

Multi-Scale Organic Material Characterization of the Bakken Source Rock

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Project advancement:

Samples from the Bakken Formation Shale members retrieved from fourteen different wells and corresponding depths and thermal maturity levels were studied in order to characterize the organic matter and type of organofacies (Figure 1). This study was carried out by a combination of analytical techniques including Rock-Eval 6 pyrolysis, X-ray fluorescence, vitrinite reflection, and organic petrography. First and foremost, pyrolysis results showed that the Bakken Formation has a very high TOC, 9.08-24.71 (wt%). The diagram of S_2 versus TOC, S_1+S_2 versus TOC and HI versus TOC denoted that the Bakken Formation is a very good to excellent source rock. Cross-plots of HI versus T_{max} showed that marine type II kerogen is the dominant organic matter. Vitrinite reflectance of the samples exhibited a range from 0.95% to 0.99% and from 0.88% to 0.92% in two of the wells from the deeper part of the basin, thus supporting maturity results obtained by Rock-Eval pyrolysis T_{max}. In order to identify the Bakken organofacies based on the Jones (1987), BP (Pepper and Corvi, 1995), and Tyson (1995) models, present-day values of HI, S_2, and TOC restored to original values using various approaches. Based on these models, all the samples studied represent mainly organofacies B with a minor contribution from organofacies AB.

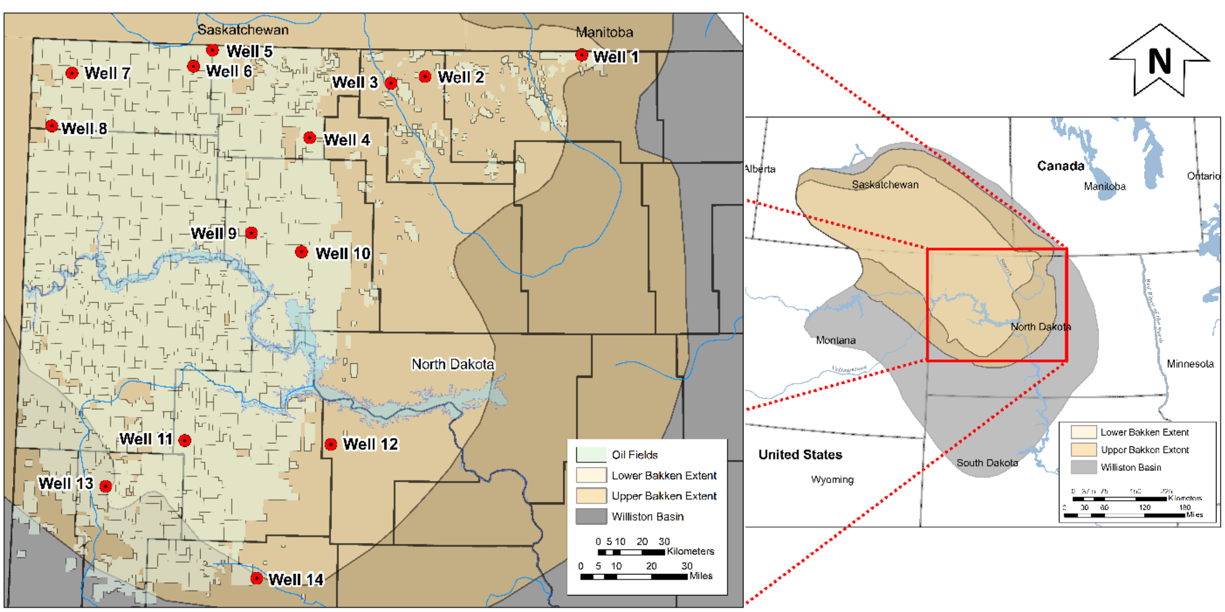


Figure 1. Williston Basin and the extent of the Bakken Formation in the United States and Canada. The image displays the limits of the upper and lower shale members in North Dakota also with the location of the studied well.

The Bakken Formation as a major unconventional shale play in North America, lacks an independent calibration for accurately correlate thermal maturity from programmed pyrolysis (via temperature of maximum pyrolysis yield, T_{max}) with optical methods (e.g., bitumen reflectance).

For establishing an equation specific to the Bakken Shale, several samples were investigated for thermal maturity trends using extensive organic petrography, bitumen reflectance and Rock-Eval pyrolysis derived T_{max} analysis. Organic petrography results showed that various types of bitumen with different optical properties, amorphous bituminite (hebamorphinite), liptinite, acanthomorphic acritarch, marine-derived alginite, fusinite, and inertinite comprise the organic matter in the samples. In the scarcity/absence of primary vitrinite, the various bitumen types were examined, and the appropriate bitumen population was selected for BR_O% measurements. The measured BRO% values then were converted to vitrinite reflectance equivalent ($VR_{O\text{-}Eq}$%) using Liu et al. (2017) equation. When comparing the Bakken Shale members' proposed linear trend with that of the Barnett and the Duvernay shales, major differences were observed. Although each member of the Bakken represents variations in organic matter type and concentrations, both members display very similar geochemical variations. This made us accept to define the same conversion equation for both members. However, the Bakken Shale's conversion SLR equation was developed with a high degree of confidence, it is believed that unless kinetics of kerogen conversion and underlying chemistry that define the relationship between T_{max} and TR through thermal advance is considered, such models cannot be accurate. Thus, to better satisfy these conditions a non-linear model, which also presented a better fit to the data, was proposed (Figure 2).

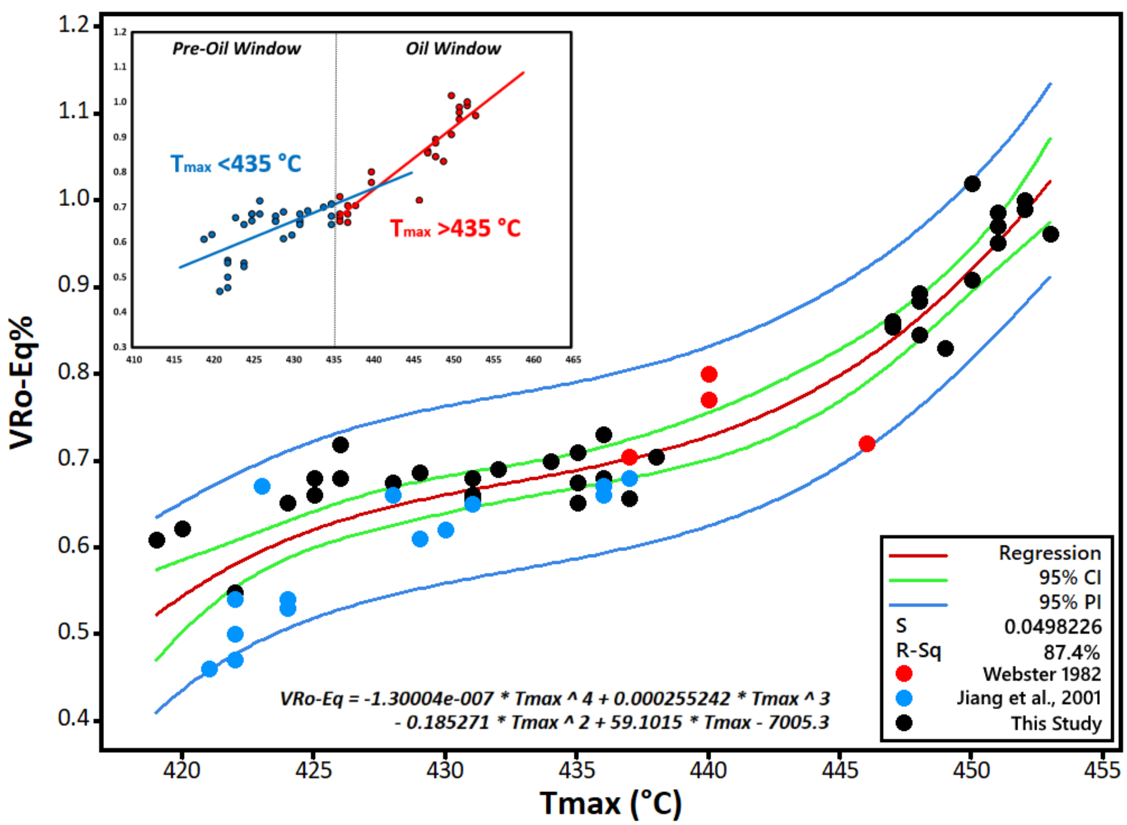


Figure 2. The polynomial correlation between $VR_{O\text{-}Eq}$ and T_{max}. The clear discrepancy was observed on fitted linear regressions for the samples with T_{max} smaller/greater than 435 °C (The boundary between the pre-oil and oil windows) in the small picture in the upper left corner.

Furthermore, we used the shear and compressional sonic logs and formation density log to calculate dynamic Young's modulus (E_d). Using experimental relationship developed for other major shale plays such as the Barnett, Collingwood, Eagle Ford, Haynesville, Kimmeridge, Wolfcamp and Woodford shales (Figure 3), calculated E_d values were converted to equivalent indentation Young's modulus (E_i). Continuous TOC logs were generated based on the relationship between E_i and core samples Rock-Eval 6 pyrolysis derived TOC values. Solid bitumen reflectance measurement as a reliable thermal maturity indicator was carried out on all core samples. Relationships between BR_O% and GR/NPHI/RHOZ wireline logs were investigated and based on the strength in the relationship between each log and BR_O% values; a new empirical parameter "Ʈ" was defined. Continuous BR_O% logs for the whole length of the Upper and Lower members of the Bakken Formation were created based on the empirical relationship between our newly defined parameter and measured BR_O%. Resulted logs are in good agreement with true measured BR_O% values and could be used directly for thermal maturity interpretation or conversion to T_{max} values. This was done through the correlation that was obtained between these two parameters for the Bakken core samples. Finally, this enables us to perform thermal maturity interpretation based on estimated T_{max} values. Using this new technique, it is possible to utilize continuous BR_O% or T_{max} data in generating thermal maturity 3D models and provide a better insight of the source rock in the basin scale.

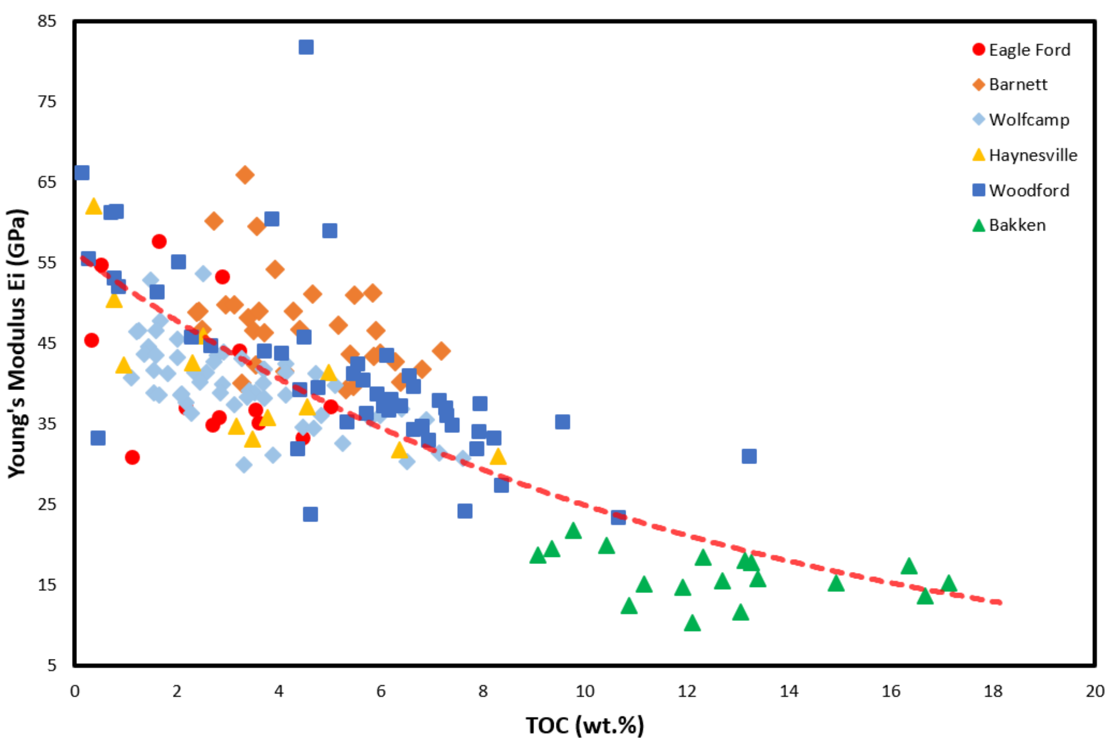
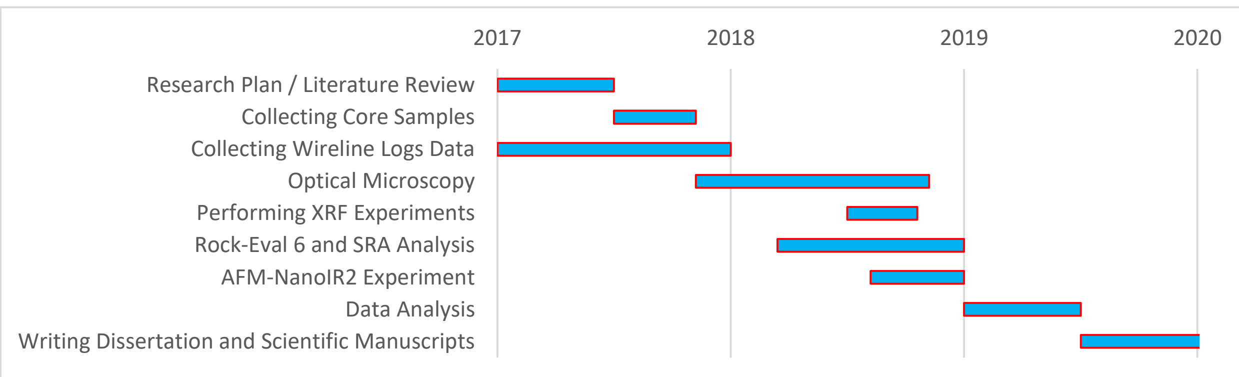


Figure 3. Indentation Young's modulus (E_i) versus TOC for the Bakken samples and other major shale plays (modified after Shukla et al., 2013). Note that, the Bakken samples exhibit higher values of TOC and smaller Young's modulus compared to other shale plays.

In the next stage, the newly introduced method in the geosciences of the AFM based NanoIR was carried out on the samples especially in the interface zone between alginite and in-situ produced bitumen to find out the effect of thermal maturity advancement in the geochemical and geomechanical properties variation of the organic matter. Outcomes show that the organic matter heterogeneity is decreased with increasing of thermal maturity in the micro and Nano scales which reflected on the IR spectra and Young's modulus of samples. Thermal maturity also has a considerable effect on the samples Young's modulus. In the early mature sample, AFM revealed a large variation in modulus across the bitumen particle due to the high amounts of the original alginite remnants while in the peak sample modulus have shown more homogeneity.
Currently, this project is continuing by analyzing the AFM based NanoIR data, interpretation of organic matter heterogeneity at nanoscale and also investigation of the effect of thermal maturity on the trace metals distribution across the basin employing different indicators including solid bitumen reflectance, liptinite maceral groups fluorescence emission intensity, Rock-Eval derived T_{max}, and NMR spectroscopy.

Project Milestone and Timing:



Progress to date:

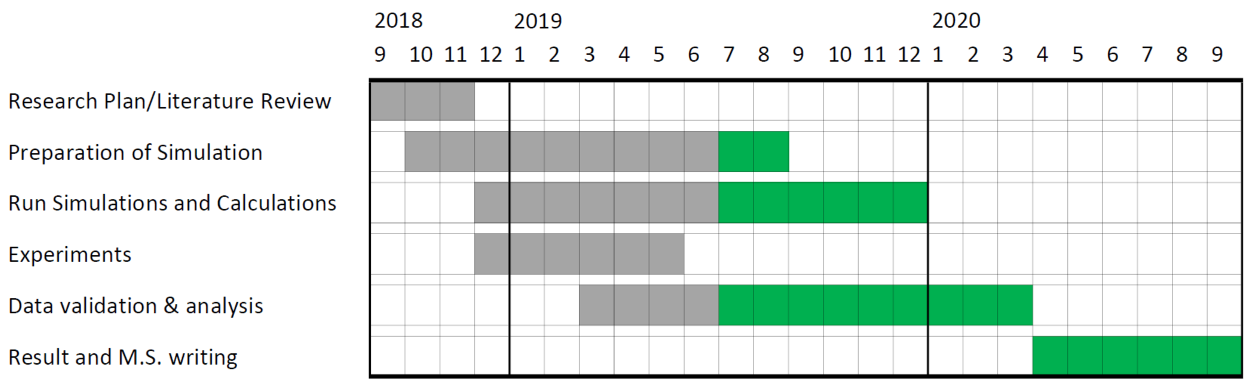
I have carried out various analysis and researches simultaneously to keep the project progress moving forward. Most experiments have been done on the samples including organic petrology, vitrinite reflectance, XRF, AFM-based NanoIR analysis. Some others are planned to be done. Some results were already published in the peer-reviewed journals, and some are under review.

CO_2 sequestration and EOR capacity of the Bakken Formation through Molecular Simulation & Characterization

Hyeon Seok Lee

Ph.D. student, Department of Petroleum Engineering, UND

Project Milestone and Timing:



Results:

1) The initial computational kerogen 3D molecular structure models for the Bakken were developed by using molecular simulation and quantum mechanics calculation in figure 1. The models have a good overall agreement with real Bakken sample in the adsorption isotherm from previous laboratory experiments.

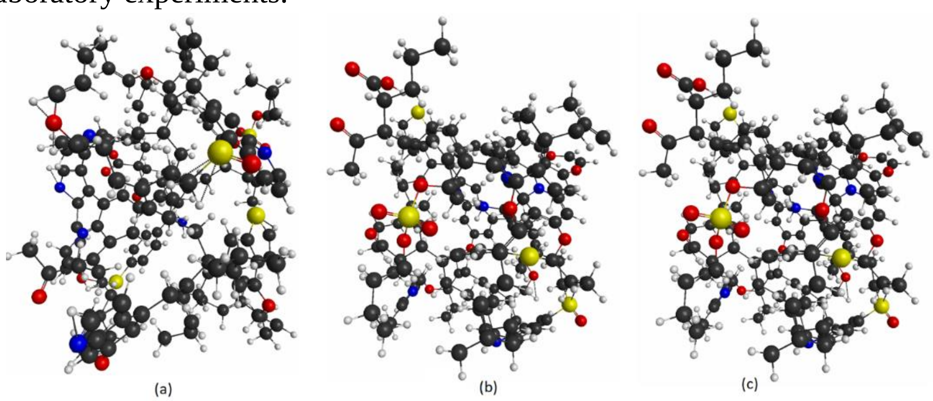


Figure 1. Different geometric configuration and chemical compositions with the color code: Carbon: Black; Hydrogen: white; Oxygen: red; Sulfur: yellow and Nitrogen: blue.

2) The simulation models have been conducted in terms of the selectivity between CH_4/CO_2/Brines and their mixtures for further analysis of EOR and sequestration capacity of the formation in figure 2.

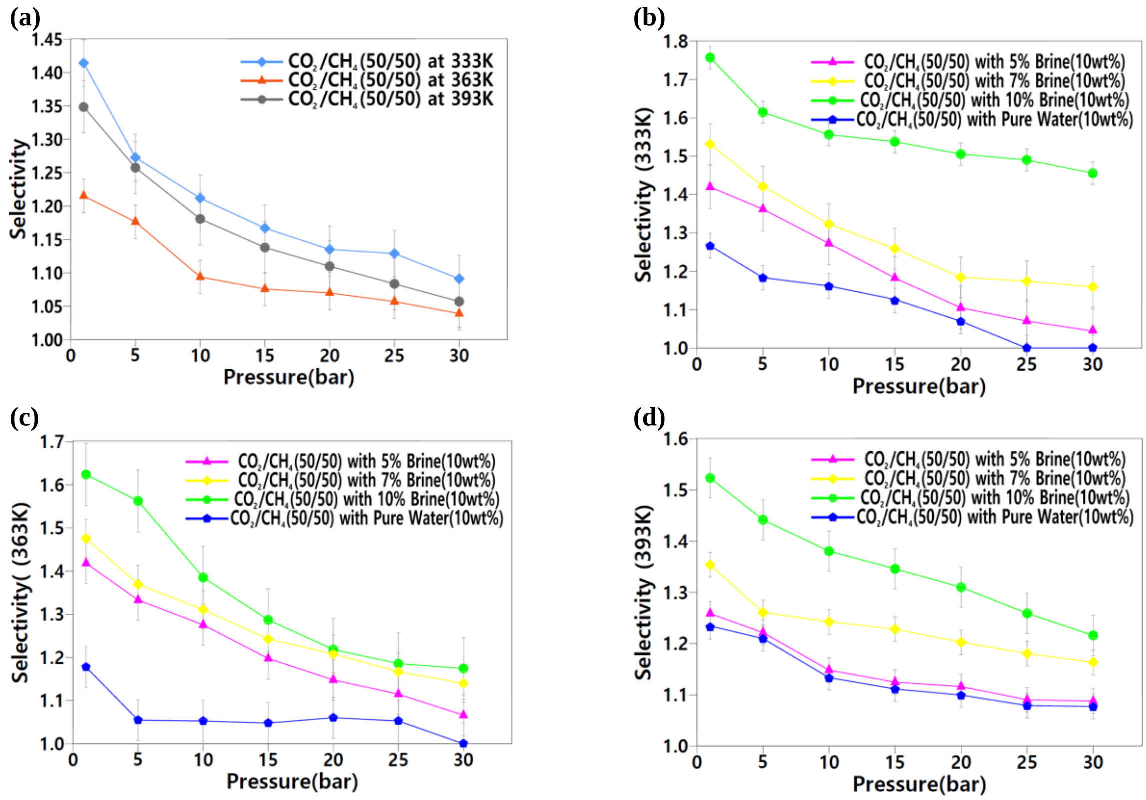


Figure. 2. (a) Estimated CO2/CH4 selectivity for binary mixture (CO2/CH4:50/50 mol%) on the kerogen model. Estimated CO2/CH4 selectivity for the mixture of CO2/CH4/Brine on the kerogen model at (b) 333K, (c) 363K, and (d) 393K.

3) MALDI-TOF and FTIR experiments of organic materials have been conducted and analyzed. The result will be discussed and establish the characteristic of structure in terms of the degree of maturity of samples in figure 3.

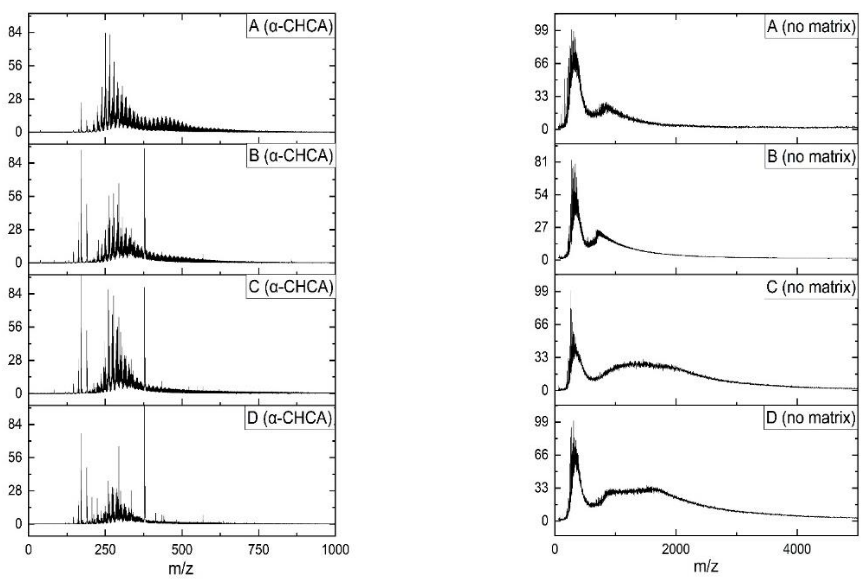


Figure 3 Normalized MALDI-TOF spectra of kerogens in the order of increasing maturity (Left) in the presence of the matrix (α-CHCA) and (Right) in the absence of the matrix.

4) XPS and NMR experiments are being conducted and physical Bakken samples which are at different maturity levels that are estimated from Rock-Eval pyrolysis. NMR results are shown in figure 4. Then, molecular Bakken kerogen models are going to be upgraded and corrected iteratively.

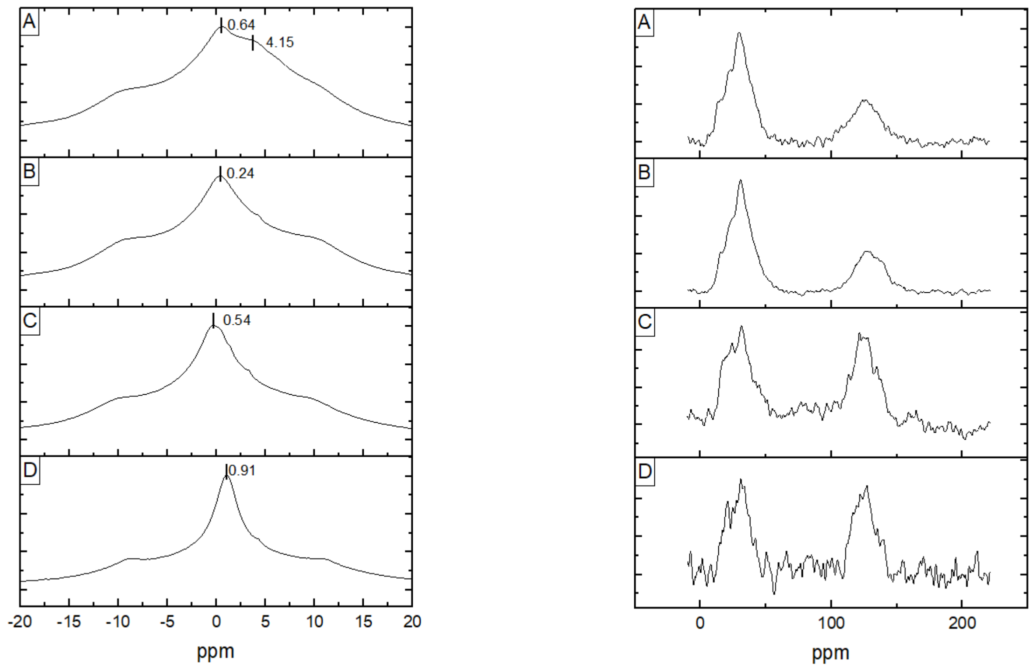


Figure 4 1H NMR (left) and 13C NMR (right) spectrum of kerogen sample of: (A) Vro-eq: 0.6, (B) Vro-eq: 0.7, (C) Vro-eq: 0.88, (D) Vro-eq: 0.98.

Fine scale characterization of organic matter using analytical methods: Raman and NMR spectroscopies

Seyedalireza Khatibi

Ph.D. student, Department of Petroleum Engineering, UND

Progress to date

I have performed preliminary and final lab experiments and established the correlations between Raman/NMR spectroscopies with organic matter geochemical properties obtained from Rock Eval pyrolysis. In addition to my previous publications, I have also published and submitted new journal papers.

Summary of the results

Samples from the source rock of the Bakken Formation varying in depth and maturity were retrieved. One of the samples was then artificially matured through various stages of hydrous pyrolysis (HP). Solid bitumen reflectance, programmed pyrolysis and Raman spectroscopy were performed on all samples to obtain general maturity, bulk geochemistry and chemical fingerprinting, Figure 1. Results showed that, HP procedures are not necessarily following the natural maturation rate of organic matter, Figure 2.

In the next step, Raman signals were acquired on solid bitumen particles on HP samples (at each stage) to show the heterogeneity of organic matter more possibly due to chemical composition which can causes heterogeneity in geomechanical properties of the organic matter as well. It was found as maturity increases, heterogeneity of organic matter decreases, and Raman map of solid bitumen particle shows more uniform distribution of G-D band characteristics, Figure 3.

We understood that various parameters are affecting the path that leads OM towards higher maturity levels, however, the overall impact of all of them would be on the chemical structure of the remaining OM. This structural evolution can be detected by Raman spectroscopy as a whole at different maturity levels regardless to the dominant underlying reason. Therefore, the proposed method can be used to establish protocols and adjust experimental parameters for HP in a way to mimic the natural maturation conditions.

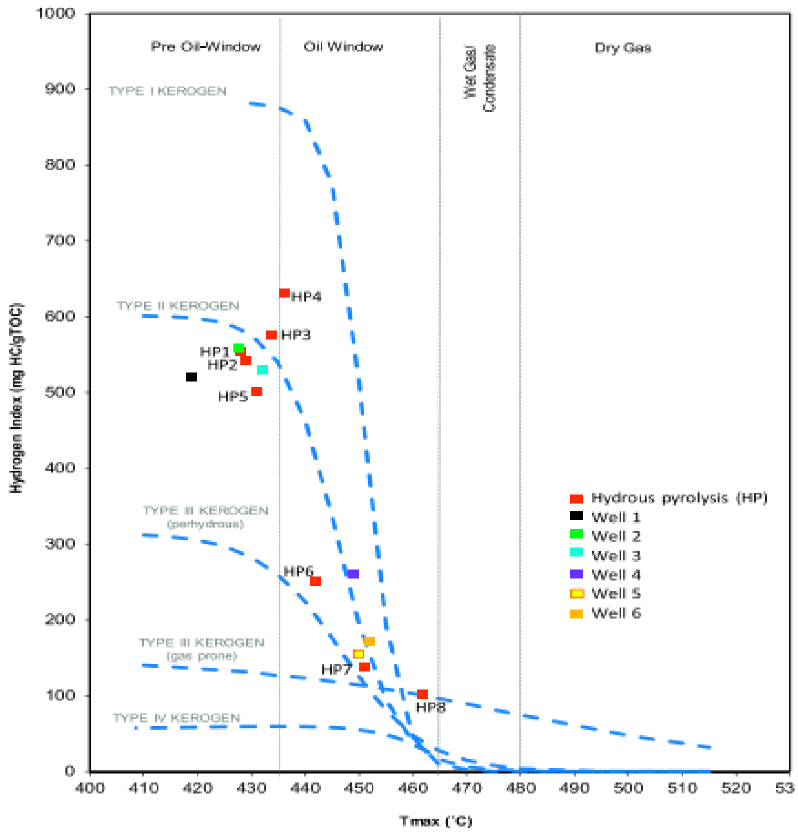


Figure 1 Hydrogen index vs. Tmax for kerogen typing. As seen all samples including naturally an artificially matured samples are approximately in type II kerogen.

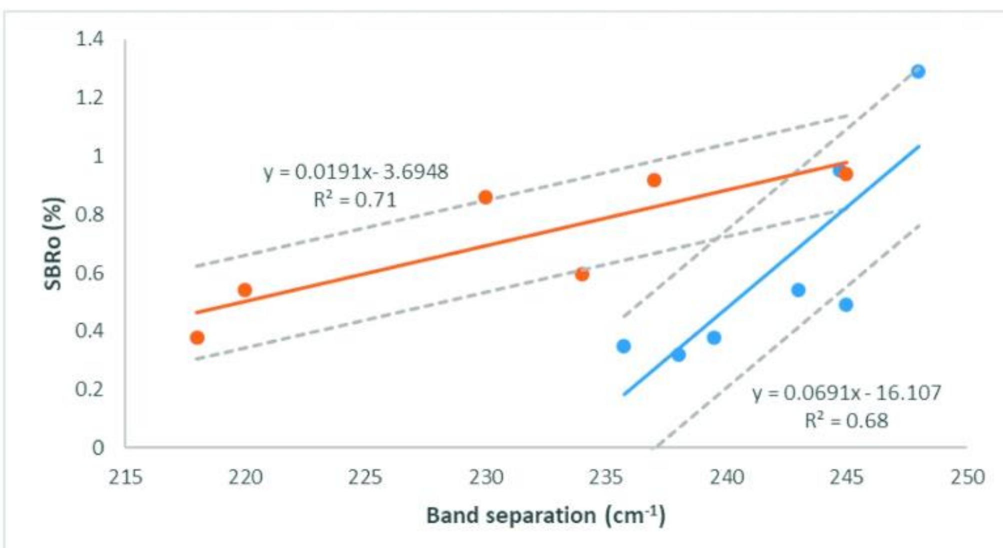


Figure 2 SBRo and Tmax (as maturity indicators) vs. band separation along with 95% confidence interval of regression and residual error profile for each sample set. Trendlines for HP and naturally matured samples along with their corresponding correlation coefficients are shown on each plot. Orange represents naturally matured samples and blue represents HP samples.

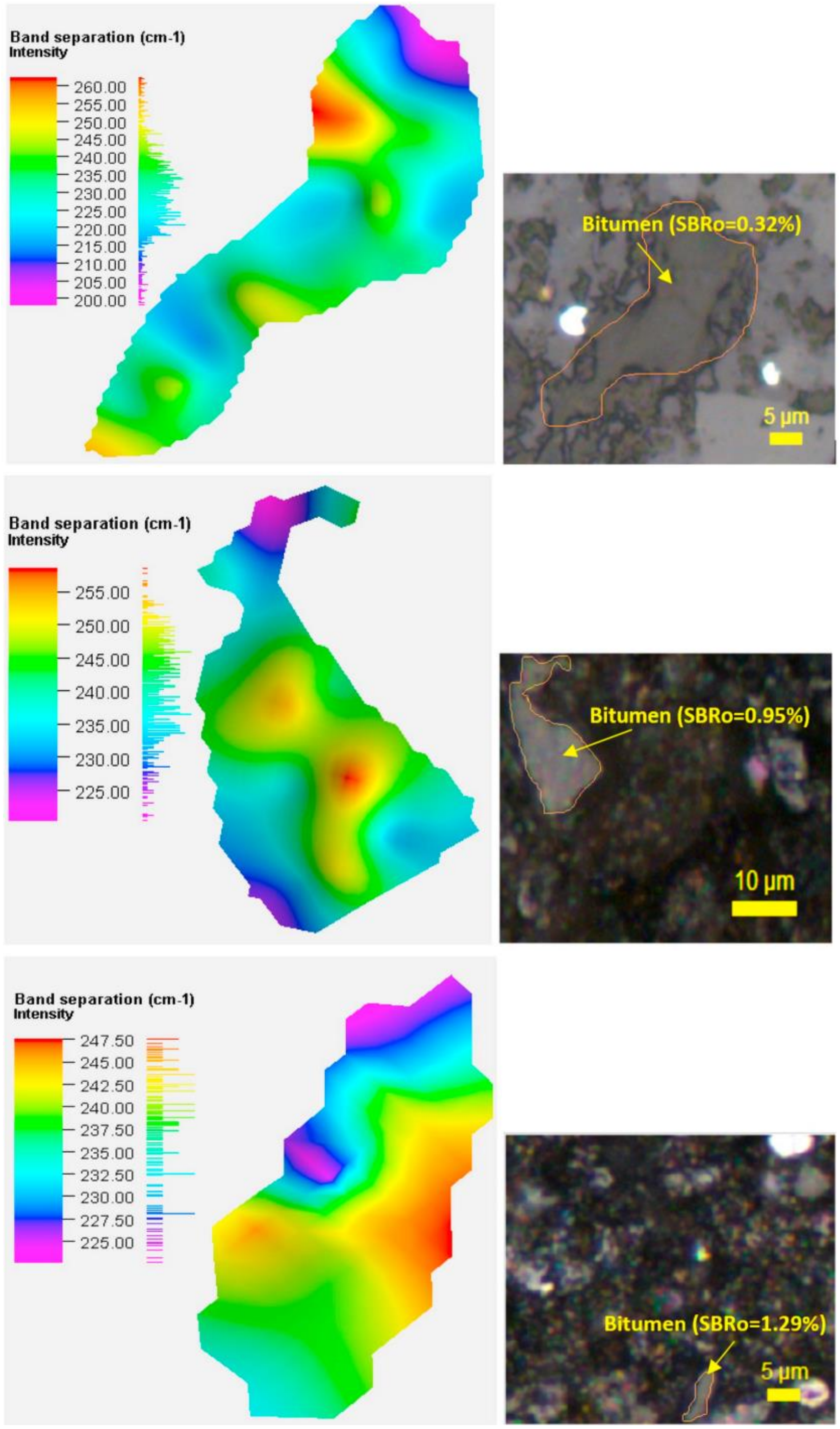
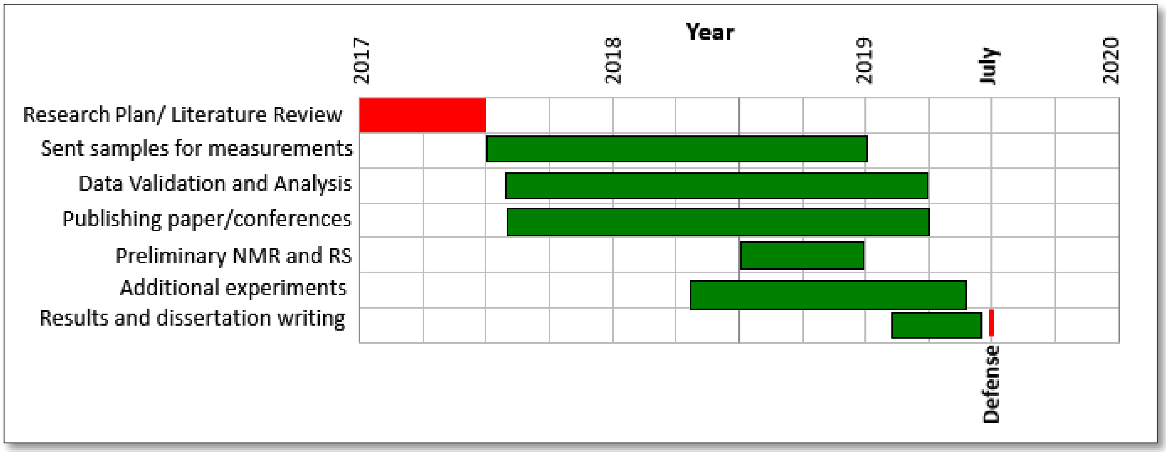


Figure 3 Raman map of a bitumen corresponding to three different samples with different maturity levels. Note the changes of band separation indicating changes of chemical composition of the solid bitumen. As seen, variation of band separation is reducing by increasing maturity.

Project Milestone and Timing:



FRACTURE DETECTION AND PREDICTION IN UNCONVENTIONAL RESERVOIRS FOR FINDING SWEET SPOT

Sofiane Djezzar

Ph.D. student, Department of Petroleum Engineering, UND

Gravity, Seismic Data, and Structural Analysis

Firstly, the gravity data is used to determine the different positive and negative axes in the Mouydir basin. A comparison between the gravity data and geological maps is made to verify if there is an analogy between the two types of data. Secondly, the fault network that affect the Mouydir basin is analyzed by determining the different fault sets, their length, their fractal dimension which help to generate a 3D fault model. The latter is merged with the outcrops fracture model to generate a unique 3D faults model that help to understand the origin and the extension of this fault network from the subsurface to the surface. Thirdly, the major fault sets that affect the area of study are analyzed by using the geological maps to determine the age and the kinematics of these faults. In addition, the 2D seismic profiles that cross these faults we used in order to interpret their kinematics in the subsurface. Fourthly, a 3D seismic survey located in the Ahnet basin and close to the area of study is used to illustrate the dense fracture network that affect the reservoir Ordovician and could be used as a reference analog for the future wells in the Mouydir basin. 3D seismic survey is used to enhance the reservoir's fracture network at different scale by using several seismic attributes such curvature and Ant Tracking. The latter help to extract a fracture network, its orientations, lengths, and density.

Fracture Intensity, Density, and Connectivity

Circular scan window method of Mauldon was used to calculate an estimate of fracture density and intensity of the area of study by generating 'Estimated Density, P20' and 'Estimated Intensity, P21' maps of the fracture in the area of study. The estimated fracture intensity map shows high intensity that is defined as the larger length of fractures per unit area in border of the zone of interest, which correspond to the edges of the Mouydir basin. This pattern of fracture abundance is consistent with the through-going strike slip fractures oriented N-S and NW-SE. The density map show 2 main trends oriented in the same direction of the major faults N000 and N150. The ternary plot, shows the relative proportions of isolated (I), splay or abutment (Y), and intersection

(X) nodes in the fracture network. The fracture network in the area of study shows that 2% of fractures are slay, 13% have intersection with each other, and 85 % of fractures are isolated.

Core Fracture Analysis

The core's analysis goals are to determine the distribution and typology of fractures in Ordovician reservoir in the Mouydir basin. Three (3) wells, namely GM-1, ME-1, and EA-1 were described for this purpose. The cores were described based on their lithologic variations, grain-size distribution, mineralogical composition, fossils, sedimentary structures, and the presence of faults and fractures. Several types of fractures and faults characterize the Cambro-Ordovician formations in Mouydir basin. Some of them are related to the sediment compaction and other to the basin tectonic evolution. They are represented by several fracture sets, parallel or secant to each other and their dip could be horizontal, vertical or oblique. The closed fractures are characterized by a dip that varies from 0 to 90 degrees and they are filled essentially with quartz. The partially open fractures have a dip that varies between 0 to 90 degrees and they are filled by the quartz and sometimes with pyrite. They are parallel or oblique to the stratification. The opened fractures are rare and we can detect them in all the Cambro-Ordovician formation. In addition, the presence of normal and reverse micro-scale faults is highlighted and they are located only in the Ordovician formation.

Borehole Imagery Analysis

The wells in the Mouydir basin were drilled the fifties and no borehole imagery were recorded on them. For this purpose, three (3) vertical wells located in the eastern edge of Ahnet basin and close to the area of study were chosen for this study. Their analysis help to identify the stratification, the fracture types, the Dip-Azimuth, the dip, the fracture density, as well as the maximum horizontal stress deduced from the analysis of the breakouts. The breakouts have an orientation NE-SW, the conductive fracture are oriented NW-SE parallel to the maximum horizontal stress.

Reservoirs Quality

The Cambrian reservoir, although compact, could be considered as a secondary objective in the Mouydir basin, especially to the southern part of the basin where it is at shallow depths. The sandstone units of the Ordovician are the main objective although their quality reservoir are average to low. The two formations show a tight sand reservoir characteristic where the fracture have a huge impact in improving the permeability.

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE	2019											
						13	14	15	16	17	18	19	20	21	22	23	24
Phase II : Subsurface Studies																	
- Gravity, Seismic Data, and Structural Analysis	13	4	13	4	100%												
- Fracture Intensity, Density, and Connectivity	14	1	14	1	100%												
- Core Fracture Analysis	15	1	15	1	100%												
- Borehole Imagery Analysis	16	1	16	1	100%												
-Reservoirs Quality	17	1	17	1	100%												
- Thesis fulfillment	13	6	13	6	100%												

Lab Experiments Using a Two-phase Flow Loop Unit and Numerical Simulations

Yanbo Wang
Ph.D. student, Department of Petroleum Engineering, UND

Flow Loop Unit

Figure 1 shows a view of the multi-phase flow loop that was built at UND Petroleum Engineering department.

Figure 1 Overall view of Flow loop

Selecting and installing pressure and flow transmitter

The Pressure Transmitter we selected is Model 628 made by Dwyer instrument, ranging from 0 to 400 psi. I change the T-joint to the Cross one so that we could monitor the pressure change both manually and automatically as it shows in Figure 2.

Figure 2 Pressure transmitter

Water flow meter is Model FDT7032 (Figure 3) ranging from 0.7 to 73 LPM, because of this flow meter using ultrasonic devices to detect flow rate, so the test section of our pipe is made by copper to get a more accurate result.

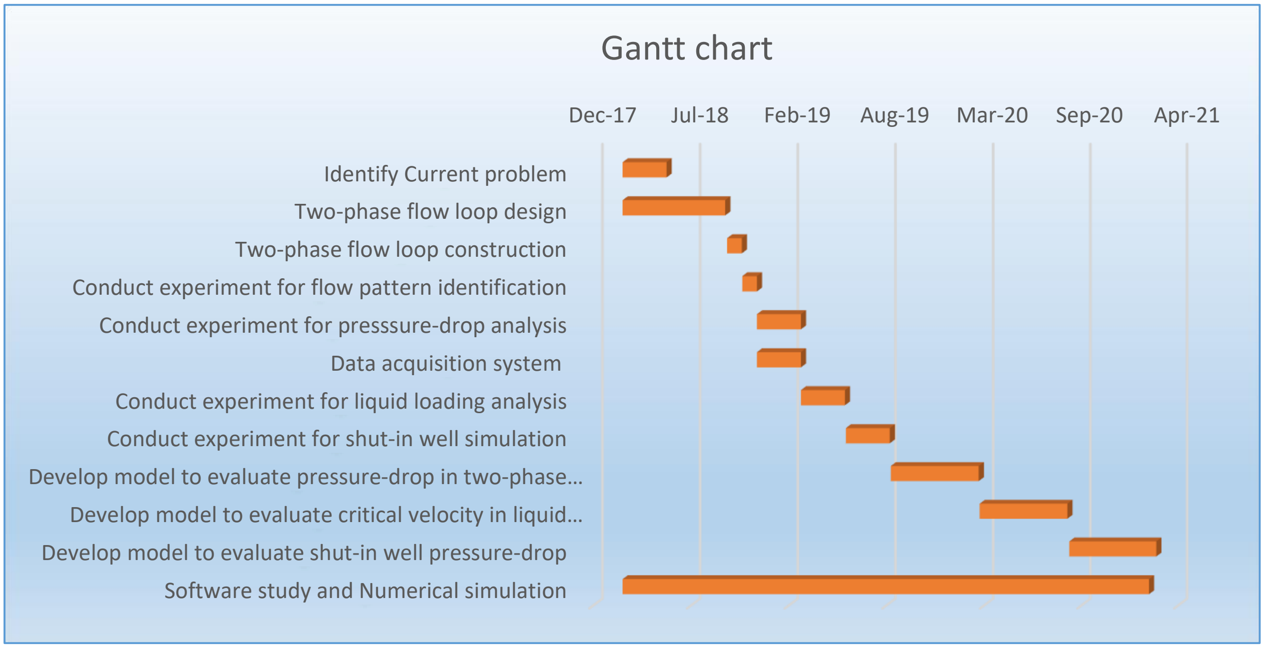
Figure 3 Water flow transmitter

Air flow transmitter is FMA1845A (Figure 4) which could detect flow rate up to 1000 SLM, and accuracy is ±1% of full scale.

Figure 4 Air flow transmitter

We are setting up the data acquisition part which including: 8- Slot Chassis, Module for Analog Inputs (4-20mA), 24vdc Power Supply, 120V AC Power Cord and do the programming on the computer.

Project Milestone and Timing:



Progress to date:

- Flow meter for the data acquisition system has been set up, and we are programming on the computer for the data acquisition system.
- Literature review is being carried out on flow pattern map in different size pipe and liquid loading.
- Continue learning Ansys-fluent software and try to generate simple models to simulate experiment.

Cuttings Transportation Optimization: Lab Experiments Using a Large Scale Slurry Loop Unit and Numerical Simulations

Foued, Badrouchi
Ph.D. student, Department of Petroleum Engineering, UND

Progress to date:

- The slurry loop was fully commissioned during the past few months and is ready for simulations.
- SLP Modifications:

In the past period we worked on fixing major and minor items including:

- Changing the inlet and outlet hose to a better flexible PVC hoses.
- We added a stretching mechanism to the inlet hose to prevent any problems during lifting of releasing the wellbore (changing the angle)
- A digital and gravitational proctoring systems were placed
- Lights were ordered to be fixed on the wellbore wall for more clear vision
- A camera with a stand was placed for filming and photo capturing
- A new cleaning and flashing system (used to clean the tank and the system from the liquid and solid parts) was used. This solution helped us temporary to avoid extra expenses on connecting a new tank for cleaning purposes.

- Literature review is being carried out on different cuttings transportation experimental and modelling studies:
  - Studying the advances in this field
  - Studying the shortage of previous studies
  - Looking for solutions to overcome these shortages
- Communicated with Halliburton and Baker Hughes drilling team who indicated great interest in collaborating in this project and provide support to this study.
  - Halliburton showed interest in studying the effect of centralizers on cuttings transportation in deviated wellbores
  - Halliburton promised to provide us with real cuttings from the field
  - Halliburton promised to provide us with their fluids for further studies

- Also Baker Hughes promised to provide us with some real cuttings
- Both companies also showed interest on giving us access to their cuttings transportation modeling software to compare results for accuracy and validation

• In the past couple of months till today we started working in the drilling fluid lab in order to understand our viscosifier CHP polymer
  - Rheology lab tests are in progress to study the effect of the CHP Polymer on the fluid rheology, the effect of shearing with time (**Figure 1**)
  - Study the suspension criteria of our different solid particles: Sand and proppants in our slurry (**Figure 2**)

• First experimental results were carried out and more experiences are coming: different fluid rheological properties, different cutting sizes and different injection rates for different angles 0-90 degrees). (**Figure 3**)
  - The experiment consists on shearing the CHP Polymer in the water for several days until reaching a constant fluid rheological behavior
  - After shearing the polymer in the water we start adding the cuttings in different quantities, mixing then start the circulation
  - 10 stations of measurement are considered (Different wellbore deviation: 0 horizontal, 10, 20, 30, 40, 50, 60, 70, 80, 90 Vertical)
  - For each measurement station we start increasing the flow rate slowly and noting the observation and the cuttings transportation regime and rate instantaneously.

• Different types of cuttings are used until receiving real field cuttings:
  - We received some proppant samples to use them as cuttings and currently after the first experiments, it seemed that we need more collaboration with Carbo Ceramics Company to better study the dispersion of solids in our slurry (**Figure 4a**)
  - Sand (plus clay) particles seemed to show more dispersion in the fluid, but needs strict and hard cleaning to prevent dust particles to form murky slurries (Which will lead to improper vision through the PCV) (**Figure 4b**)

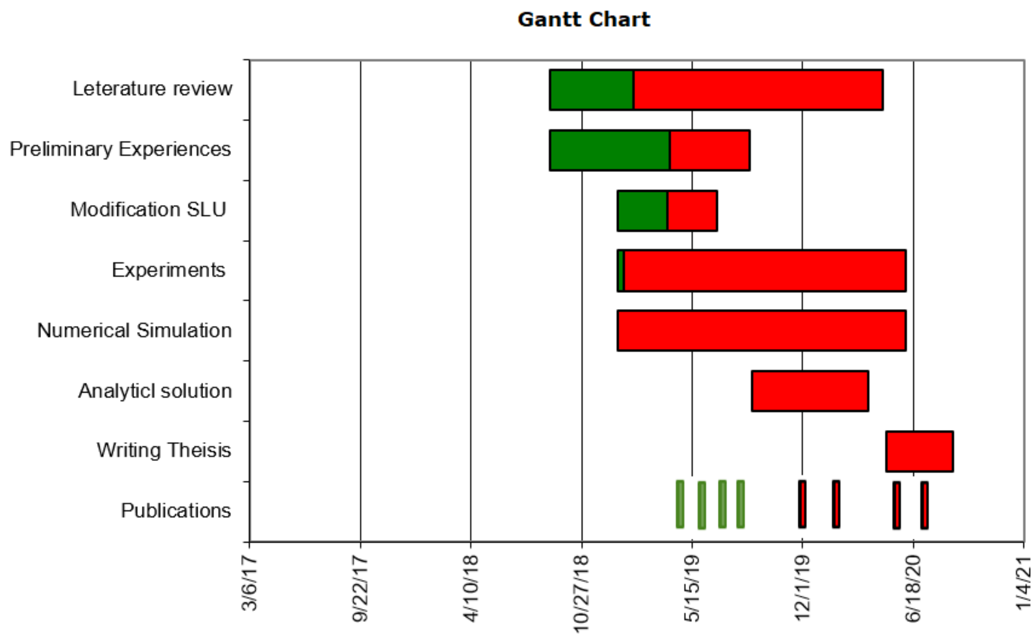
• Future modifications

Some modifications are postponed due to budget lack

- Auto cleaning system
- Link the mixer to our LabView and control it from distance and in different speeds
- Install a second mixing blade

- Currently working on a Journal paper to be published as soon as we finish from all first experiments

Project Milestone and Timing:



2019 Publications:

1- Lattice Simulation of Fracture Containment in Middle Bakken Formation F. Badrouchi, I. Bouchakour, N. Djabelkhir, N. Badrouchi and V. Rasouli
2- Estimation of Elastic Properties of Bakken Formation Using an Artificial Neural Network Model

   F. Badrouchi, M. Rabiei, N. Badrouchi and V. Rasouli
3- Comparison of Unsteady-State Permeability Measurement methods for Middle-Bakken Core Samples

   N. Badrouchi, H. Jabbari and F. Badrouchi
4- Lattice Simulations of Hydraulic Fracture Reorientation from Perforations. O. Akash, R. Vamegh, B. Damjanac, F. Zhang and F. Badrouchi

Future Publications (Current Work):

1- A Large Scale Slurry Loop Unit Used to Study the Effects of Cuttings Geometry and Wellbore Deviation on Hole Cleaning Efficiency.

2- Review of the effect of cuttings and fluid properties on cuttings transportation in deviated wellbores.

Appendix

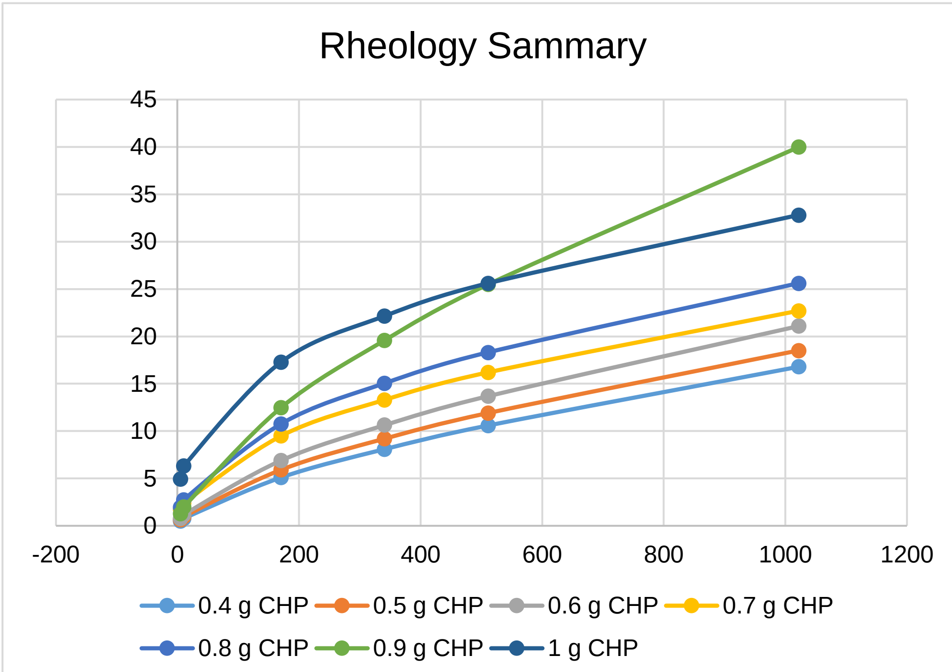


Figure 1 - Some Rheology Tests Results

Figure 2 – Different Solids Dispersion and Suspension Evaluation

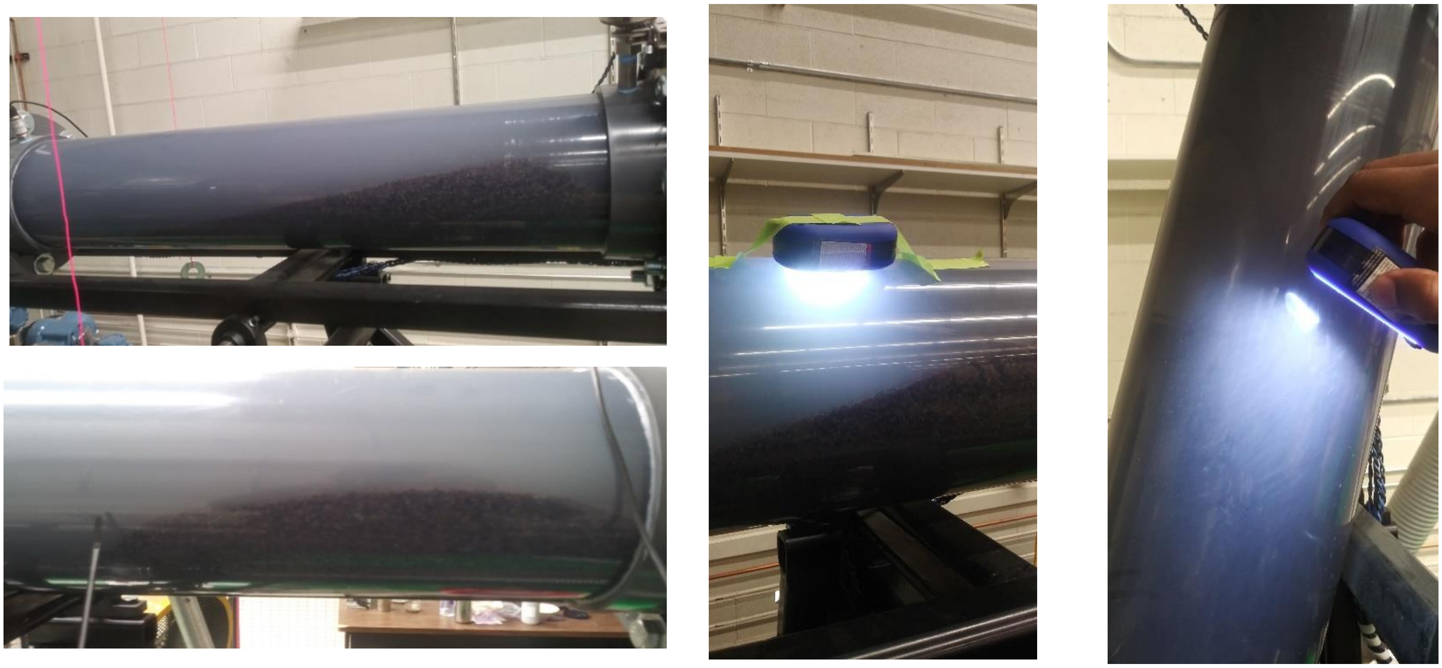
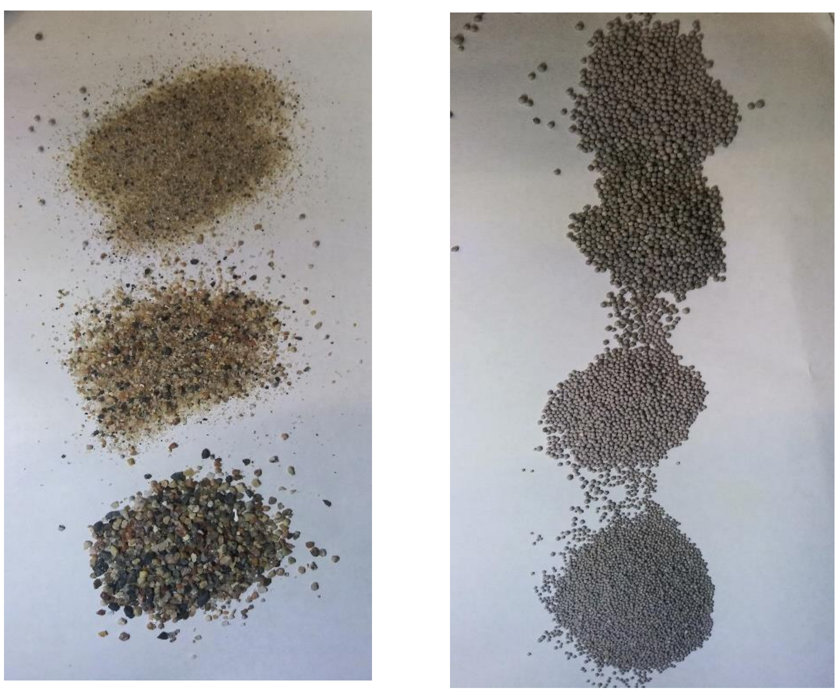


Figure 3 – Visual Observation of Solids Transport Regime



(a) (b)

Figure 4 – Different Cuttings Used for Experimental Simulation: Sand samples to the left (a) and Proppants to the right (b)

Automated Directional Drilling: Lab Experiments and Numerical Simulations

Ahmed Ismail

Ph.D. student, Department of Petroleum Engineering, UND

Problem Statement:

Directional drilling can be the only feasible option available for many applications such as unconventional reservoirs and offshore drilling from a platform. Complex well trajectories and the number of hyper parameters in drilling unconventional reservoirs make directional drilling a big challenge. Automation of the drilling process with such a challenge is a very complex process. The complexity of the process is from design and operational perspectives. Optimization of the drilling process through the hyper parameters affects cost, energy and time. Finding the appropriate techniques and technologies to optimize this complex process is quite challenging. The Petroleum Engineering Department at UND is working on building an automated lab scale rig that is capable of drilling directional wells. This lab scaled rig is the first step of the study, where upscaling the automated directional drilling process is planned to reach the field scale. This type of lab work would help examining to see the effect of different parameters through sensitivity studies. These studies would let us simulate the drilling process and compare the results to the available analytical and numerical models. Lab simulations, where the rock specimen can be visually inspected after drilling, will allow us to visualize what happens during real drilling operations. This will help us to expand our knowledge about different aspects of directional drilling and optimize the solutions. Feeding these information and learning experiences while applying Machine Learning Techniques will be used later on to design a more efficient automated drilling systems.

Figure 3: Lab-scale Automated drill Rig initially used for drilling a vertical

Objectives:

- Design and built an automated drilling rig that is capable of controlled directional drilling;
- Studying the effect of changing the drilling parameters (weigh on bit, torque and drag, rate of penetration, mud density and rheology, drilling fluid flow rate, and others) on the directional drilling quality;
- Studying the effect of changing the directional drilling parameters on maintaining the hole quality;
- Studying the effect of the lithology on build and hold the angle;
- Visualizing the effect of changing various directional drilling parameters by visual inspection of the rock sample post drilling and during drilling using automated data acquisition system;
- Optimizing the bit selection;
- Optimizing directional drilling process based on mechanical specific energy (MSE), rate of penetration (ROP) and cost;
- Selecting the most fit-for-purpose directional drilling technique;
- Feeding the results obtained to ensure a quality automated system;
- Upscaling the results to field scale.

Methodology:

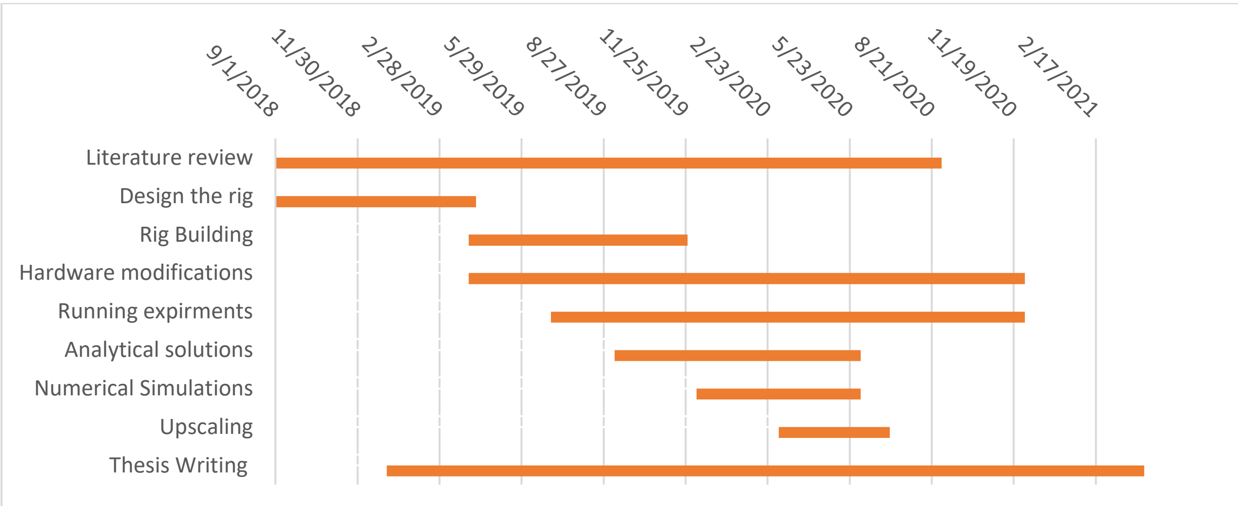
- Use the lab scale directional drilling rig being built to conduct several experiments;
- Analytical models and numerical simulation will be used to simulate the lab experiments and calibrate the results;
- Sensitivity analysis of various parameters affecting drilling operation;
- Upscaling the lab results to field scale.

Significance:

- To the best of our knowledge, this is one of the first attempt to design a directional drilling rig where the directional tools will be used to build the trajectory;
- Most of North Dakota wells and other unconventional reservoirs nowadays are drilled horizontally making the outcome of proposed study of a wide application in oil field industry;

- Generating large volume of data from the lab experiments will allow us to do big data analytics to optimize drilling parameters. This may not be readily possible in real operations due to limited amount of data and uncertainty in data quality;
- The optimization process can result in saving millions of dollars/ year.

Project Milestone and Timing:



Progress up to date:

- Literature review is continued;
- The rig has been tested for drilling vertical holes;
- The rig is being redesigned for directional drilling;
- The hardware is being tested.
- Presented the design concept at the SPE drillbotics competition held in May 2019 in Houston.

Publications

1. Cenk Temizel, Karthik Balaji, Celal Hakan Canbaz, Yildiray Palabiyik, Raul Moreno, Minou nRabiei, Zifu Zhou, Rahul Ranjith, Data-Driven Analysis of Natural Gas ROE in Unconventional

Shale Oils, SPE Oklahoma City Oil and Gas Symposium as co-author, 9-10 April, Oklahoma City, Oklahoma, USA

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