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NOVEMBER 10 & 11, 2022

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FALL 2022 SPONSOR MEETING

Meeting: Thursday, November 10, 2022

– Via ZOOM Invite & In-Person CSM Student Center

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Origin and Stratigraphy of Enigmatic Sandstones of the Cretaceous Western Interior Seaway: the Late Turonian Wall Creek-Turner System, Powder River Basin, WY

Patrick Sullivan, PhD. Student, Department of Geology and Geological Engineering, CSM

Abstract

Relatively thin, laterally extensive sandstones bounded by marine shales are common features in late Cretaceous strata of the U.S. western interior, and are responsible for the majority of recent unconventional hydrocarbon production and development in the region. One such unit is the Wall Creek-Turner system, consisting of the upper Turonian Wall Creek Member of the Frontier Formation and the coeval Turner Sandy Member of the Carlile Shale, which is one of the most prolific reservoirs of the Powder River Basin in Wyoming, responsible for nearly 70% of gas and 50% of oil production in the past 20 years. Regional studies of the Wall Creek-Turner system are sparse, and most analyses of the units consist of isolated studies within a single outcrop belt or producing field. As such, the nature of regional stratigraphic relationships, sediment provenance, and the evolution of depositional environments within the system remain largely unresolved.

The objective of this study is to characterize the facies distribution, provenance and chronostratigraphic relationships of the Wall Creek-Turner system across the Powder River Basin. Detailed core and outcrop descriptions tied to well logs across the nearly 150-mile-wide basin, in tandem with newly acquired CA-IDTIMS U-Pb geochronology data on ash beds and LA-ICPMS analysis on detrital zircons, will resolve long-standing uncertainties surrounding the paleogeographic evolution of the Turonian Western Interior Seaway and provide insight into the distribution and depositional controls of productive sandstone reservoirs in the western U.S.

Reservoir Characterization of the Shannon Sandstone, Southwestern Powder River Basin, Wyoming

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Abstract

The Upper Cretaceous (Campanian) Shannon Sandstone is an unconventional stratigraphic play in the southwest Powder River Basin in Wyoming. The Shannon has a long history of petroleum production, as well as varied proposed depositional models. Interpretations include deposition by a shelf sand ridge complex, a prograding shoreface, or an incised valley fill. Understanding the depositional framework of the Shannon is crucial for characterizing reservoir heterogeneity and the distribution of productive facies, yet regional studies that integrate facies relationships and lateral heterogeneity are rare.

A detailed sedimentary investigation of the Shannon Sandstone using multiple cores in Johnson and Campbell Counties as well as outcrops in Natrona County yielded five facies: 1) moderately bioturbated silty sand, 2) planar to low angle cross-stratified heterolithic sandstone, 3) glauconitic planar to cross-stratified heterolithic sandstone, 4) heavily bioturbated silty sand, and 5) laminated silty shale. Core analysis and cumulative flow and storage capacity plots indicate multiple flow bins are present. Flow bins classified as "excellent" have permeabilities above 10 mD and upper meso pore throat size. A conservative mineral model was constructed using XRF-derived elemental values and ratios and plotted against depth to compare with the core description, facies, and flow bins. Changes in minerology supports qualitative observations and helps further delineate facies.

Machine learning image segmentation on thin section photomicrographs was used to quickly assess changes in sedimentary characteristics in Shannon Sandstone facies. Ongoing work to improve model accuracy includes using higher resolution images, tailored brightness gradient bins, paired plane-polarized with cross-polarized photos, and specific mineral labels for the training images. This method supports the larger multi-scale study of the Shannon and evolves previous depositional interpretations by rapidly delineating lateral facies heterogeneity. These depositional insights help not only reconstruct the geologic evolution of the basin but also maximize future successful development.

Muddy Sandstone EOR (CCUS), Bell Creek Field, Montana

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Abstract

Bell Creek Oil Field is located in southwestern Montana within the Powder River Basin and is a major oil producer that is currently going through enhanced oil recovery (EOR). The field was discovered in 1967 and the Muddy Sandstone is the primary producing reservoir. This reservoir has produced 147 million barrels of oil throughout its lifetime with the help of water flooding and carbon dioxide injection. Major carbon dioxide injection began in 2012 which caused a notable increase in oil production. In conjunction with the carbon dioxide injection, a 4D seismic survey was collected over part of the field to show where the carbon dioxide was migrating to within the formation. This study will include detailed core analysis, log interpretation, and petrography to understand the differing porosities and permeabilities throughout the field.

Muddy Sandstone depths range between 4,300 to 4,600 feet across the field and has an average porosity of 28.5% with ranges of 6% between 35% while permeability ranges from 0.1 mD to 13,000 mD. The Muddy Sandstone divided into two separate sections, the Bell Creek Sandstone and the Valley Fill Sandstone. Both sections are divided by a low stand erosional surface where above the surface is the Valley Fill Member and below is the quartz-arenite sandstone Bell Creek member. Bell Creek field is divided into nine different injection units based on how the incised valley split up the field for the purpose of water flooding. Deposition of the Muddy Sandstone is a combination of an incised valley with tidal flats that make up the valley fill in the Valley Fill member. The Bell Creek Section is mostly quartz-arenite sandstone with excellent reservoir quality characteristics while the upper section, the Valley Fill member is a mixture of reworked Bell Creek Sandstones, siltstones and shales. Stratigraphic pinchout are the main trapping mechanism for the field and make it very desirable for oil and gas production. Understanding the depositional environments throughout the field will help to understand the compartmentalization of the field and where best to inject carbon dioxide for further increase in oil production.

"The Little Shale That Could": Looking Back on Two Decades of Unconventional Mowry Shale Development in the Powder River Basin

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Abstract

Attempts at extracting oil directly from the Mowry Shale began as early as 1917 when Spokane Wyoming Oil drilled the Tribal 7 (API: 49013059540000) to a depth of 700 ft in Plunkett field in the Wind River Basin. By 1923 geologists recognized that many of the oil fields producing from Lower Cretaceous reservoirs were located in areas where the Mowry Shale entered the oil-generative window (Geis, 1923; Forgotson and Stark, 1972; Burtner and Warner, 1984). Several decades of vertical drilling ensued and fewer than 200 vertical wells were completed in the Mowry. Interest renewed in the 1960's following the discovery of Muddy Sandstone reserves in the Powder River Basin, spurring studies of stratigraphically adjacent organic-rich shale units (Mowry, Shell Creek, Skull Creek, and Thermopolis shales).

Horizontal exploration was first attempted in late 1994 when Exxon drilled the first Mowry Shale lateral wellbore, the Wyoming State D Federal 1H, in Amos Draw Field but it was never produced and was subsequently plugged and abandoned. Since then, approximately 70 Mowry Shale horizontal wells have been drilled in the Powder River Basin. Initial attempts at unconventional production struggled in their early stages, but recent well results prove the existence of a viable Mowry Shale unconventional play. This presentation will review the history of the Mowry Shale in the Powder River Basin through a discussion of early failures, lessons learned along the way, a review of current drilling/completions trends, and a future outlook for this unconventional resource.

CCUS Potential for the Niobrara A and B Intervals at Redtail Field, Weld County

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Abstract

Carbon capture, utilization, and storage (CCUS) is the process of capturing carbon dioxide (CO_2), injecting it into reservoirs to enhance oil and gas production, and safely and permanently storing it in the subsurface. This process has become more common in the oil and gas industry both as a technology to enhance production, and for companies to work towards carbon neutrality. While carbon capture and storage (CCS) has sometimes garnered more attention, carbon capture, utilization and storage (CCUS) is more attractive as it offers the additional economic incentive of increased hydrocarbon production as primary and secondary oil and gas recovery methods can leave up to ~80% of the oil in the reservoir. CCUS is a type of enhanced oil recovery (EOR) and can be a more effective technology for recovering additional hydrocarbons with the added benefit of safely sequestering CO_2 in the subsurface. CCUS is continuing to expand and has the potential to capture ~6GtCO_2 per year by 2050.

The Niobrara System was deposited in the Western Interior Seaway (WIS) during the Late Cretaceous by a series of sea-level transgressions and regressions. Carbonate deposition in the WIS was controlled by cooler, oxygen rich water from the north, mixing with warmer, oxygen poor water from the south. In the Denver-Julesburg Basin, the carbonate rich Niobrara A and B exhibit favorable petrophysical properties for hydrocarbon production with increased resistivity and porosity. Consequently, they have both been extensively produced from in recent years, and it is important to evaluate their potential as CCUS targets.

Core data from the Razor 25-2514H well in Redtail Field is being evaluated to determine if the Niobrara A and B could be viable CCUS targets. Porosity and permeability measurements combined with production flow and injection treatments of CO_2 and methane acting on the core plugs will help to determine if the reservoir properties in the Niobrara A and B are favorable for CCUS. Additional work will compare results from Redtail Field to analogous CCUS projects in the Eagle Ford of South Texas, which has similar petrophysical properties to the Niobrara reservoirs. Results from the Redtail Field study area can then be applied to other fields in the Denver Basin leading to increased hydrocarbon recovery and the safe storage of CO_2.

The Geological Reservoir Characterization and Assessment of Reservoir Deliverability for Unconventional Niobrara and Codell Reservoir Targets within the Hereford Field Area, Weld County, Colorado

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Abstract

The Hereford Field lies in the north-central Colorado portion of the Denver Basin, approximately sixty miles northeast of the prolific Wattenberg Field. Hereford gained notoriety in 2009 when the 18-stage Niobrara completion of the EOG Resources Jake #2-01H averaged more than 49 MBO during the first three months of production. Such a large volume of oil production in a short period proved that chalk lithofacies within the Niobrara Formation had significant potential as a viable unconventional resource play in the Denver Basin.

Drilling and completion methodologies employed in the Hereford Field have quickly evolved since the completion of the Jake well in 2009. The post-2015 redevelopment operations incorporate cemented pad-drilled laterals (XRL and SRL) utilizing high-volume plug and perf completions, mirroring designs employed in the contemporary generation of unconventional Niobrara and Codell wells drilled and completed with great success in the Wattenberg Field.

Niobrara and Codell reservoir quality within the Hereford Field appears regulated by the abundant fracturing associated with the adjacent E / NE trending paleo structure, the Morrill County High, which bounds the northern extent of the Hereford Field area. Fracture development and reservoir fluid dynamics appear linked to episodic reactivation of sheer-driven faults and the extensive layer-bound normal fault system formed during the deposition of the overlying Pierre Shale. Furthermore, the structural complexity combined with Hereford's complicated depositional and compactional histories has added an extra layer of reservoir fluid heterogeneity observed in wells throughout the Hereford field.

As of October 2020, cumulative production from all unconventional wells within the Hereford Field study area exceeded 13.3 MMBO, 18.6 BCF, and 12.7 MMBW. The Niobrara B Chalk lithofacies and the Codell Sandstone are the primary reservoir targets within the Hereford area; however, additional secondary reservoir potential exists in the b1 chalk and c marl lithofacies of the Niobrara Formation.

This study incorporates petrophysical data, fluid / sample geochemistry, laterally acquired formation image logs, thin sections and SEM analysis, and legacy well / production data located throughout the greater Hereford Field area to facilitate an integrated characterization of properties that control overall unconventional reservoir quality and deliverability from targets in the Hereford Field.

Organic matter enrichment and preservation during Ocean Anoxic Event 2 in the Cretaceous Western Interior Sea

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Abstract

The Late Cretaceous presents an ideal time to study the relationship between carbon burial, ocean biogeochemistry, water column anoxia, and sedimentary processes. High global sea-level and enhanced ocean connectivity due to an increase in tectonism and eruptions of Large Igneous Provinces occurred amid persistent global hothouse conditions. The result was a ~600 ka perturbation in the global carbon cycle referred to as Ocean Anoxic Event 2. However, marine sediments deposited during this interval were not uniformly anoxic, especially in the relatively shallow, epeiric ocean of the Western Interior Sea of North America. This investigation provides a new synthesis and interpretation of organic enrichment combining unpublished MUDTOC Consortium and publicly available organic geochemical data from thousands of analyses spanning the Upper Cretaceous Graneros, Greenhorn, and Carlile Shale formations (collectively the Greenhorn Cyclothem). New regional models generated from these investigations confirm that organic enrichment increases distally in the basin and during transgression. Organic matter enrichment was controlled by water depth, marine productivity, and water column stratification. Water depth may be especially prescient where basin geometry and circulation patterns between normal marine Boreal waters in the north and the warm, dysoxic Gulfian waters to the south combined to influence bottom water anoxia. Biomarker proxies suggest broad and prolonged water column stratification during transgression when organic enrichment was favored by increasing depth tipping biogeochemical systems more readily in favor stratification. By peak highstand at the Cenomanian-Turonian Boundary, transient oxygenation and water column turnover are suggested by elemental, biomarker, and sedimentary proxy evidence including extensive bioturbation in the carbonate-rich facies of the Bridge Creek Limestone Member of the Greenhorn Formation. Yet, the underlying marls record some of the highest TOC values in the Greenhorn Cyclothem. Facies-level investigations to determine the relationship between the timing of volcanic influences, stacking patterns, and subsequent diagenesis remain ongoing. Defining the relevance and sequence of first-order controls on organic matter enrichment provides a window into how ancient marine environments responded to profound carbon perturbations and better predicts how modern ecosystems will behave.

Reservoir Characterization of the Codell & Niobrara Formations, Postle Area, Wattenberg Field

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Abstract

Late Cretaceous Codell Sandstone of the Wattenberg field were derived from a major deltaic source and was deposited on the seafloor of the Western Interior Seaway (WIS) by waxing and waning shelf currents. Above the Codell Sandstone, the Niobrara Formation lithologies represent periods of fluctuating sea-level conditions that resulted in depositing cycles of chalks, marls, sandstones, and shales. The Wattenberg Field is located in the Denver-Julesburg (DJ) Basin in the northeast Colorado, north of Denver across the axis of the Denver Basin and covers approximately 81 townships.

The Wattenberg field development and production started in 1970, with the majority of production coming from vertical drilling of the Niobrara and Codell Formations. In addition, the production in the Wattenberg is found in the Dakota, J Sandstone, D Sandstone, Greenhorn, Codell and Niobrara. The continuous gas accumulations are common throughout the field. The Wattenberg gas field is one of the largest natural gas fields in the United States, with resource estimates from the Niobrara being approximately 3-4 billion barrels equivalent (BBOE).

Faulting in the Wattenberg field is primarily basement controlled, right lateral wrench fault zones with secondary faulting in between the wrench fault zones. Originally the basin axis was oriented north-south (N-S), but the Denver Basin axis was shifted because of the wrench fault zones that crosscut the Wattenberg field. The wrench fault zones of the Wattenberg Field can be associated with maximum compressional stress-oriented east-west (E-W) on a horizontal plane. The wrench fault zones will be a key driver of fracture formation, and potentially oil and gas migration within the Wattenberg field. In this study, detailed fracture characterization of the Codell and Niobrara Formations will be performed, which will help characterize both natural and induced fractures within these formations. Formation microresistivity image (FMI) log interpretation indicates a strong orientation preference created through hydraulic stimulation and can assume that the present-day stress orientation is not a result of reorientation due to production and stimulations. Interpretation of the image log data can establish the spatial geometry of the natural fractures within the wells and will help characterize the fractures that help produce hydrocarbons by hydraulic stimulation.

Reservoir Characterization and Quality of the Codell Sandstone, NE Silo Field Area

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Abstract

The Turonian-aged Codell Sandstone member of the Carlile Shale Formation is a hydrocarbon bearing shaley sandstone that has been interpreted as a regressive, shelf sand deposit that has been reworked by storm waves in the Cretaceous Western Interior Seaway. The Codell Sandstone behaves as a low resistivity pay zone suppressed by the presence of clays and pyrite. Production out of the Codell Sandstone began in northeastern Colorado out of Wattenberg Field in the early 1980's and has expanded north into southeast Wyoming. The Codell Sandstone is an unconventional tight sand reservoir that has been targeted in Silo Field approximately 20 miles northeast of Cheyenne, Wyoming within Laramie County and is the focus of this study. Structure maps indicate that the Codell Sandstone is approximately 7500 – 9000 feet TVD in the field, whereas isopach maps indicate a thickness of approximately 25 – 35 feet. The Codell Sandstone is 38 feet thick from a core taken from the Helis Cain 16-63-2-11-1CH well and was the targeted formation.

Geochemical analysis of produced oils from the Codell Sandstone and extracted hydrocarbons from the Niobrara C Marl and Greenhorn Limestone indicates a marine shale source from the Graneros Shale, Greenhorn Limestone, or Pierre Shale (Sharon Springs equivalent) formations. Core analysis from the Cain 16-63-2-11-1CH well indicated average permeability to air values of 0.019 millidarcys and average porosities of 12 – 13%. XRD analysis from core indicated clay percent by weight through the Codell interval in the Cain 16-63-2-11-1CH well to be between 16 – 20%. Porosity vs. permeability cross plots indicate a nano pore structure. A Modified Lorenz Plot was constructed along with cumulative storage capacity and cumulative flow capacity vs. depth plots. The Modified Lorenz Plot reveals seven distinct flow units. Flow units one and seven being "poor" while also showing no oil staining in the core under UV light. Flow units two through seven were considered "good" flow units and showed oil staining in the core. A cumulative storage capacity vs. depth plot showed consistent porosity through the section. Cumulative flow capacity vs. depth plot showed variable permeability that was affecting the quality of the flow units. Trace fossils include *Teichichnus*, *Planolites*, and *Skolithos*, indicating a mostly *Cuziana* ichnofacies. The *Cruziana* ichnofacies is consistent with a sublittoral zone of deposition between the fair-weather wave base and storm wave base. Future work includes thin section and FESEM analysis based on interpreted facies in the Cain 16-63-2-11-1CH core, detailed core descriptions from the Cirque V.O. Child #30-9 and Cirque Berry Unit 13-9 wells, and detailed resistivity mapping to help delineate the edge of production in NE Silo Field.

Evaluating Production Performance of Permian Basin Wells to Improve Hydrocarbon Recovery

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Abstract

The Permian Basin is one of the most prolific oil and gas producing geologic basins in the United States. Permian Basin spans West Texas and Southeastern New Mexico. It has supplied more than 33.4 billion barrels of oil and 118 Tcf of natural gas during a 100-year period (EIA 2018). The ever-increasing water production and usage in the Permian Basin require produced water management by the operators. Classical waterflooding or gas flooding in unconventional reservoirs is not plausible because of the shale matrix's small pore size and low permeability. Therefore, creative approaches are needed to increase oil production without relying on large quantities of water injection to displace oil favorably. The practical alternative is a cyclic gas injection which is an objective of my research to increase oil production.

I reviewed and organized the production data for the wells that have been drilled into the Wolfcamp Formation of the Delaware Basin from 2012 to 2020. I prepared bubble maps to identify the changes in cumulative oil, gas, and water production. The maps show the maturity of the basin where gas-prone wells are the majority in the North and North-Western part, and the South is more oil-prone. The wells drilled in Lea, Loving, and East-Reeves counties show the most oil production in one year of production. The gas production is highest at Culberson, North Reeves, and Loving counties. Furthermore, water production is large throughout the region regardless of the produced fluid type.

I performed production decline and Rate Transient Analyses (RTA) on several wells from the Delaware Basin to determine the stimulated formation permeability to determine stimulation effectiveness, the behavior of the flow types, and production of the individual wells in the region. The wells show diverse behaviors, where wells with the same linear flow period have significantly different cumulative production. This portion of the work will continue as a routine matter as new data become available.

Unconventional reservoirs are heterogeneous and show strong velocity anisotropy. Quantifying velocity anisotropy and geomechanical properties are important for reservoir characterization. Thus, I conducted experiments on selected cores from two wells in the Delaware basin to determine permeability, porosity, and pore compressibility. Siliceous mudstone samples show higher permeability values compared to calcareous silty mudstone facies. The mineralogical content was correlated to permeability. Furthermore, laboratory experiments indicated that the pore compressibility decreases with increasing quartz content.

Using data from four different wells, static and dynamic elastic properties, Young’s Modulus (E), Bulk Modulus (K), and Poisson’s Ratio (v), were compared. The core data and log

data were used to obtain a correlation between static and dynamic stiffness coefficients. The data also indicate that the wells in Delaware Basin exhibit vertical transverse isotropy (VTI).

In searching for the mechanism of huff-n-puff gas injection oil recovery in unconventional shale reservoirs, I came across convincing experimental results that indicate molecular diffusion is the main mechanism for improving oil recovery through micro-fracture-matrix interface.

Wettability is a crucial property of the interactions between the reservoir rock and the pore fluids which strongly affects the distribution of fluids in the reservoir pores and multiphase flow in porous in the reservoir. Consequently, I have conducted contact angle experiments on five different unconventional reservoir formations around the US and measured interfacial tension (IFT) between oil and brine from the formation.

I built a conceptual compositional dual-porosity reservoir model using CMG-GEM commercial reservoir modeling software in conjunction with the experiments. Next, I built a hydraulic fracturing model using Halliburton's GOHFER commercial software to simulate the actual hydraulic fracture propagation. The well completions and stimulation reports on actual well stimulation operations were used to build this model. This model provides conductivity and hydraulic fracture properties for each stage used in further reservoir simulation models. Finally, PVT reports from a Wolfcamp reservoir were used to build a fluid model for a reservoir using the CMG-Winprop module. Then, I used the production data from a well to get an idea about the reservoir production behavior. A sensitivity analysis will follow this effort to identify the parameters which impact the reservoir performance most. The ultimate goal is to combine geology, fluid flow theory, experimental observations, and reservoir simulation to evaluate production performance and improve Permian basin hydrocarbon recovery.

Finally, I will evaluate the current machine learning models using data from hydraulic fracture treatments and the associated production data to arrive at an optimal hydraulic fracture design. To accomplish this, I collaborated with GOHFER software development team. We are building a workflow to be used in GOHFER to arrive at more accurate model interpretations using statistically quantified inputs from many treatments. To be able to accomplish this goal I first cross correlated the formation tops using digital logs from Ward County, TX. And then I created subsurface maps. The next step in this effort (the petrophysics analysis) is to create synthetic logs for the wells when they are not available. Afterwards, the created synthetic logs will be verified on the geologic model. This machine-learning process will include cycles of training and verification where the accuracy of the model will increase with each cycle.

Sedimentary Lithofacies Classification in Wolfcamp A and B in Midland Basin from Supervised Machine Learning

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Abstract

Interbedded organic-rich siliciclastic, mixed carbonate-siliciclastic gravity flows, and carbonate gravity flows dominate accommodation during the evolution of the Midland Basin, west Texas, USA. The carbonate gravity flows originated from the reefs along the basin margins. The mixed carbonate-siliciclastic gravity flows originated from mixing of reef-sourced carbonate and terrestrial siliciclastic sediments. Carbonate and mixed lithology gravity flows periodically reached into the depocenter in response to changes in accommodation due to tectonic activity and fluctuating sea level that repeatedly exposed and covered the reef systems. Carbonate and mixed lithology gravity flows are abundant in the Wolfcamp A and B members and the higher their carbonate content, the greater their hazard to successfully drilling and completing a well. They also act as top and lateral seals, can suppress the oil maturity window and, where significant secondary dissolution occurs, can be reservoirs. Targeting how and where lithologies vary improves selection of well targets, paths, and completion strategies, increasing overall rate of return.

XRD mineralogy from core plugs, core plug descriptions and thin section photomicrographs from two vertical wells in Midland and Martin County of west Texas are interpreted to create rock-based lithofacies labels of siltstone, mudrock, carbonate, calcareous siltstone/mudrock, and silty/muddy carbonate. These vertical lithofacies labels are used with wireline data from the two vertical well sections to train a multilayer perceptron machine learning algorithm. The resulting trained model predicts the five rock-types of siltstone, mudrock, carbonate, calcareous siltstone/mudrock, and silty/muddy carbonate in the Wolfcamp A and B. The lithofacies model is applied to horizontal wells, where they predict the facies over the length of each lateral. Future work with predicted well lithofacies involves stratigraphically mapping the extent and thicknesses of carbonate gravity flows to better understand the facies variability in the Wolfcamp A and B. Stratigraphic maps highlighting carbonate gravity flows and facies heterogeneity would ultimately aid operators by avoiding hazardous drilling conditions and enhancing completion economics.

Geochemistry of the Niobrara Formation and Oceanic Anoxic Event III (OAE III): A Regional Study in the Western Interior Seaway

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Abstract

The Coniacian – Santonian (C – S) time interval displays positive enrichment of stable carbon isotopes (CIE) globally, and elevated organic carbon burial under oxygen depleted conditions in the Western Interior Seaway (WIS) and proto-equatorial Atlantic regions. The CIE associated with C – S has been described as the Oceanic Anoxic Event III (OAE III) with a duration of approximately 3 my and high organic carbon potential. The OAE III in the WIS correlates to the Niobrara Formation C marl and C chalk intervals and *Scaphites Depressus* biozone in the Denver Basin and is represented by the Razor 25-2514H core (Redtail Field) in this study. Redox sensitive trace elements (molybdenum (Mo), vanadium (V), and iron (Fe)) indicate a range of redox conditions from dysoxia to persistent euxinia were present during the regional OAE III in the Denver Basin. Water-column stratification and deep-water mass restriction were established and displayed varying degrees at the onset and during the event. The OAE III is continuous across the WIS based on redox sensitive Mo trends indicating positive enrichment, except in the Piceance Basin. The analysis of the high-resolution bulk sedimentary XRF results indicate three distinct anoxic phases which are informally named OAE IIIa, OAE IIIb, and OAEIIIc. OAE IIIa and OAE IIIb displays the strongest anoxic conditions, while OAE IIIc marks the waning period of anoxia in the WIS. Each of the subdivisions are separated by intervals that display low enrichments of redox sensitive trace elements that indicate periodic oxygenation of the water column in between anoxic phases.

Based on the acyclic, saturates, and aromatics biomarkers results of the Niobrara Formation, the organic matter (OM) is primarily composed of algae remains and terrestrial woody material. The relative concentration of the algal and woody organic matter depends on the paleogeography where western margins display more woody organic matter content whereas eastern parts show more algal input. The OM in the Niobrara Formation was deposited in epeiric seaway conditions. Ocean salinity levels in the WIS differed from the Gulfian Regions based on the distribution of Oleanane (Ol/H) and Moretane (Mo/H). Gammacerane (Ga/H) index indicates anoxic conditions were stronger in the Powder River Basin than the Cañon City Embayment and the Piceance Basin. The presence of tricyclic terpanes is either related to presence of Tasmanites algae or formation of tricyclic terpanes through cracking of tetracyclic terpanes. Dinosterane index readings from the Cañon City Embayment and Piceance Basin indicate that dinoflagellates were not present in the western parts. In the OAE III, trends in the relative abundances of n-alkanes, pristane and phytane indicate the organic matter composition changed and became more algal compared to the Fort Hays member. Source rock analysis (SRA) results show substantial increase in hydrogen index (HI) and decrease in oxygen index (OI) values at the onset of the OAE III supporting an increase in algal contribution to the OM composition as well as formation of oxygen depleted conditions.

During the OAE III, phosphorus (P), barium (Ba), cadmium (Cd), nickel (Ni) and copper (Cu) were recycled and led elevated production rates. Ni and Cu trends with low values in the OAE IIIa and OAE IIIb, indicate lack of free hydrogen-sulfide (H_2S) in the water column. Elevated amounts of Ni and Cu deposition took place during the OAE IIIc. A sharp positive increase in the concentrations of redox sensitive trace

elements that correlate to the B chalk, A marl, and A chalk intervals indicate another episode of oxygen depletion during the deposition of Smoky Hill Member under high marine productivity rates. Silicon (Si) and titanium (Ti) indicate major changes in the paleoclimate that occurred with the onset of OAE III. Dry climate conditions transitioned to more wet/humid climate promoting elevated continental weathering rates and subsequently larger quantities of nutrient transportation to the WIS. Potassium (K) and magnesium (Mg) show a period of steady stream influx followed by quiescence at the onset of the OAE III. The low riverine influx rates are due to the initial deepening of the WIS which is followed by an increase in the stream influx rates during the deposition of the C marl interval. Paleoproductivity, nutrient recycling, paleoclimate, and riverine influx trends across the WIS show drastic changes associated with the paleogeography. In the western margins, trends are cyclic due to the proximity to sediment source areas whereas in deeper parts of the WIS, the trends better show influence of anoxia on trace metal sequestration.

Overall, the results from this study indicate that the OAE III in the Denver Basin include three discrete anoxic intervals and was initially formed during the deepening of the WIS above the Fort Hays member, and was prolonged due to the elevated production rates that took place under wet/humid climate conditions and varying degrees of riverine influx during the C marl and C chalk intervals. The OM composition changed from more terrestrial to more marine algal at the onset of the OAE III and persisted throughout the Niobrara Formation. Biomarker results provided important knowledge on the WIS-wide changes in the OM composition. The regional correlation of the OAE III shows the paleogeography of the study sites were the determining factors in terms of anoxia versus oxygen rich conditions. The paleoproductivity, nutrient recycling, riverine influx rates, and paleoclimate varied across the WIS.

The Identification and Characterization of Sedimentary Geothermal Play Types on the Texas Gulf Coast for Power Generation

Eric Stautberg, PhD Student, Department of Geology and Geological Engineering, CSM

Abstract

Sedimentary geothermal is an emerging energy sector with the potential to provide renewable baseload electricity to residential, commercial, and industrial markets above sedimentary basins. The Texas Gulf Coast contains the necessary reservoir temperatures required for electrical power generation (>250^{o} F), and Texas is the largest consumer of electricity in the United States with a high demand for dispatchable baseload electricity. Identifying and characterizing the major geothermal play types in this basin will help to reduce the exploration and development risks associated with these geothermal resources.

Currently, the main sedimentary geothermal play type identified on the Texas Gulf Coast is the Tertiary geopressured-geothermal sandstones of the Wilcox, Vicksburg, and Frio formations. In addition to these geopressured-geothermal systems, other sedimentary geothermal play types have yet to be identified. Cretaceous and Jurassic formations in south and east Texas have the necessary reservoir properties to be used for power generation but have not yet been investigated thoroughly. Additionally, salt diapirs across the Gulf Coast are a potential source of geothermal energy because of their high thermal conductivity and thermal anomalies associated with reservoirs above and adjacent to them.

Preliminary results show that south Texas is optimal for sedimentary geothermal exploration. Eocene Wilcox geopressured-geothermal sandstones are in relatively close proximity to multiple salt diapirs and Cretaceous formations with reservoir temperatures greater than 250^{o} F. The proximity of multiple potential geothermal play types here provides an ideal location to compare the characteristics of each reservoir and resulting resource potential. 596 wells with Quad Combo log suites below the depth of 8,000 ft were selected for stratigraphic, petrophysical, and temperature analysis across the research area. This dataset will be used to identify the depth to 250^{o} F and what reservoirs are below this isothermal surface, as 250^{o} F is currently the lowest temperature required for producing electricity from brines. Combining the temperature at depth mapping with stratigraphic correlations will identify the major sedimentary play types across the research area and be used to generate reservoir models, resource estimates, and techno-economic evaluations for each play type.

Reservoir Characterization of the Deadwood Sandstone, Williston Basin

Gabrielle Bennett, MS Student, Department of Geology and Geological Engineering, CSM

Abstract

The Deadwood Formation is the deepest sedimentary unit in the Williston Basin; it is present in North and South Dakota, Montana, parts of Alberta, Saskatchewan, and Manitoba, Canada. It represents the earliest documented Paleozoic deposition in the Williston basin. The siliciclastic-rich unit has an economic history that is not as extensive as other formations in the Williston Basin, such as the Three Forks or the Bakken. The Deadwood is a minor producer of hydrocarbons; with about 15 wells drilled, the Deadwood has produced ~500,000 mmboe and ~59,000,000 mcf of gas. Other energy potentials that are currently being researched include geothermal production by the Canadian company Deep Earth Energy Production (DEEP). Carbon Capture Sequestration is also being explored by the Aquisitore Project in Saskatchewan, led by SaskPower Boundary Dam Carbon Capture Facility. The goal of Gabrielle's project will be to incorporate multiple full core analyses, outcrop data from the Black Hills of South Dakota, thin sections, and well logs in order to discover the total energy potential of the Deadwood Formation.

About Gabrielle:

Gabrielle is a first-year Masters' Student in the MUDTOC Consortium, working under Dr. Stephen Sonnenberg. She has a background in Igneous Petrology from Texas A&M University-College Station under Dr. J Brian Balta, where she graduated in 2019 with a Bachelor of Science in Geology accompanied by minors in Geographic Information Systems Technology and Spanish. Upon graduation, Gabrielle worked for EOG Resources in Midland, Texas, as a Geological Technician for three years. She collaborated on various geological projects with several geological advisors across EOG Resources. Gabrielle has two cats named Clay and Mica. She loves to hike, scuba dive, and play golf. Gabrielle's focus will be a Reservoir Characterization of the late Cambrian/early Ordovician Deadwood Sandstone.

The Cause of Geothermal Temperature Anomalies in the Denver Basin: An Application to Petroleum and Geothermal Energy

Melia Eaton, MS Student, Department of Geology and Geological Engineering, CSM

Abstract

Geothermal gradients and reservoir temperatures are critical components of the exploration process for petroleum and geothermal energy resources. Hydrocarbon maturity and generation within a source rock is largely controlled by temperature, a function of the local geothermal gradient. Likewise, reservoir temperature is a key component of potential geothermal energy resources - the hotter the reservoir, the better the geothermal energy potential.

The effect of subsurface temperature anomalies on hydrocarbon and geothermal energy resources is well known. The Wattenberg Field thermal anomaly exemplifies a positive correlation between locally higher subsurface temperatures and hydrocarbon production. In producing Niobrara wells, locations of thermal anomaly coincide with higher oil gravity, higher gas-oil ratios, and better productivity. Within Peoria Field, anomalously high geothermal gradients coincide with productive areas of the Muddy “J” Sandstone. Similarly, productive areas of the Muddy “D” Sandstone within the Bennett Field coincide with anomalously high geothermal gradients. Geothermal exploration is also affected by subsurface temperature anomalies. Higher reservoir temperatures are required for electrical power generation which can be distributed to larger areas, but lower temperature reservoirs can only be used locally for direct use applications.

While there has been significant research published about the importance of subsurface temperatures anomalies in sedimentary basins, there is a lack of research detailing why these anomalies occur. This project is focused on identifying the source of geothermal temperature anomalies and their effect on hydrocarbon and geothermal resources within the Denver Basin. If temperature anomalies within the Denver Basin can be explained, findings could be applied to sedimentary basins worldwide to assist in hydrocarbon and geothermal energy exploration.

About Melia:

Melia Eaton is a first-generation college student pursuing a MS Geology at Colorado School of Mines, working under Dr. Stephen Sonnenberg in the MUDTOC consortium. She was born and raised in Charlotte, North Carolina and attained a BS Geology at the University of North Carolina-Wilmington. Through her undergraduate education she completed a BS Geology with a geospatial technologies minor and a professional GEOINT certificate. While completing her BS Geology in three years, she conducted a variety of different research initiatives. Beginning her first year, she worked under Dr. Till Wagner in his physical oceanography research group to complete a project titled *“Flow Vector Analysis of Icebergs and Sea Ice”*. Her GEOINT capstone project united ArcGIS, remote sensing software, and multiple data sources to characterize Hurricane Irma damage throughout the Florida Keys. She completed a geothermal energy exploration Honors thesis working under Mr. Roger Shew titled *“Analysis of the Deep Direct-Use Geothermal Potential of the Upper Atlantic Coastal Plain, NC”*. Her thesis research confirmed the geothermal potential of two Supergroups underlying the NC Coastal Plain. She will be continuing her pioneering geothermal research through her MS Geology investigating the source of geothermal anomalies within the Denver Basin.

FMI and Facies Analyses of the Codell Sandstone in the Redtail Field, North-Central Denver Basin

Sean Rascoe, MS Student, Department of Geology and Geological Engineering, CSM

Abstract

The middle Turonian (Upper Cretaceous) Codell Sandstone Member of the Carlile Shale is one of many lucrative sedimentary units within the Denver Julesburg Basin. Unlike adjacent limestone and shale formations, the Codell is comprised of more porous, very fine- to upper medium grained silt and sandstones that can behave more similarly to a hybrid reservoir. The Codell was deposited around the storm weather wave base along the western margin of the Western Interior Seaway. Storm events are recorded as discrete sequences of hummocky cross-stratified sands that grade vertically into planar to low angle cross-stratified laminations followed by a return to normal sedimentation in the form of shale deposition.

Within this study, seven cores penetrating the Codell will be described and analyzed to identify storm sequences within the Redtail Field in North-Central Colorado, USA. Core descriptions and analysis will be compared to downhole FMI image logs to create a comprehensive understanding of the nature of these storm units and potentially correlate them across the Field.

About Sean:

I was born in New Jersey and raised in Saratoga Springs, a small town in Upstate New York. I had an affinity for geology, and the outside in general, from a young age. In 2016, I was accepted to State University of New York (SUNY) Oneonta to obtain a bachelor's degree in Geology. After graduation in 2020, I was accepted to Colorado School of Mines to get a Professional Master's degree in Petroleum Reservoir Systems, which was completed in the fall of 2021. After a semester off in the spring of 2022, I returned to CSM to join MUDTOC and complete a thesis-based Master's degree in Geology.

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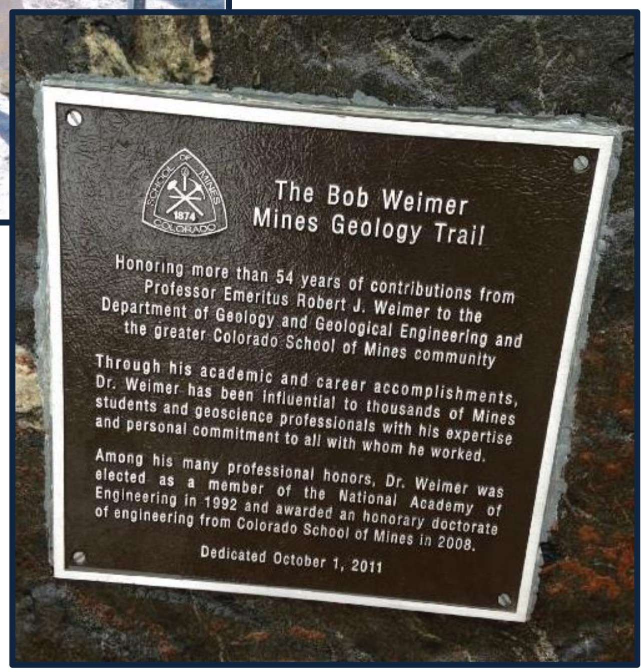

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FOR MORE INFORMATION, PLEASE CONTACT CHRIS MATSON: MATSON@MINES.EDU