Subsurface Core and Analogous Outcrop Characterization of the Muddy/Newcastle Formation for the Bell Creek Oil Field, Powder River County, Montana

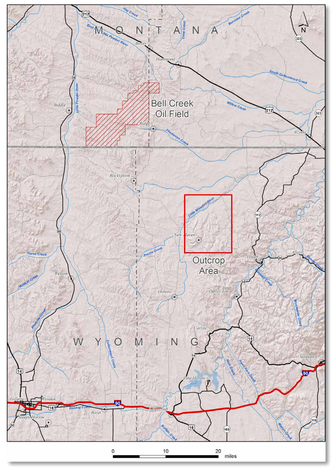
Jason R. Braunberger, Wesley D. Peck, Terry P. Bailey, Jordan M. Bremer, Benjamin W. Huffman, and Charles D. Gorecki
Energy & Environmental Research Center (EERC)
University of North Dakota (UND)
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

Abstract

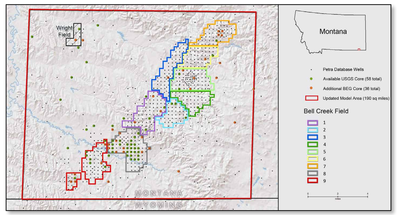
The Plains CO_2 Reduction (PCOR) Partnership led by the Energy & Environmental Research Center (EERC) conducted several field trips to a Cretaceous Muddy (Newcastle) Formation outcrop in Wyoming which is analogous to the nearby Bell Creek oil field reservoir. Regional uplift in the area of the Black Hills during Tertiary time, and subsequent erosion, has exposed significant outcrops of the Muddy Formation in northeastern Wyoming. The proximity of these outcrops to their deeply buried (~4500 ft) equivalents in the Bell Creek oil field provides an excellent opportunity to understand the potential heterogeneities in the reservoir system. Ongoing work to prepare for a carbon dioxide (CO_2) enhanced oil recovery project includes characterizing 61 subsurface cores, analyzing whole core and sidewall plugs collected from an observation well, and exploring additional miles of analogous outcrop.

Although numerous wells and core are available in the field, many cores had poor recovery; thus only 25 cores were available to interpret vertical and horizontal variations in facies and internal structure. Because of the reduced number of core, there are subtleties in the 3-D geologic model framework that occur at a finer resolution than the well control. Outcrop examination provides a source of extensive geologic data in the X, Y, and Z directions. This assists in gaining an understanding of regional structure, facies, and heterogeneities that can be correlated back to core and the 3-D geologic models.

The investigation has shown good sedimentological correlation between outcrop and subsurface core. Three formations and five facies have been described from the subsurface core, and the same three formations and four of the five facies are seen in the outcrop. The similarities between the corresponding surface and subsurface facies allow further lab testing to take place on analogous outcrop rock, when sufficient subsurface core is unavailable. Thus describing and sampling the outcrop has provided a valuable visualization tool when the nature of reservoir rocks in the oil field is observed. Data collected from the outcrop provide insight for major variogram ranges, porosity-to-permeability transforms, geomechanical variables, and flow zones and barriers and help minimize uncertainty while developing the associated 3-D geologic models.



Regional map depicting the location of the Bell Creek oil field in southeastern Montana and the nearby Muddy/Newcastle outcrop in the Bear Lodge Mountains in northeastern Wyoming.



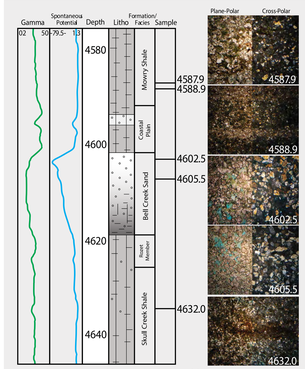
Fieldwide study area for an updated 3-D geologic model, with all wells and those with core available highlighted.

Depth	To	Formation/Facies	Lithology
4446	4495.6	Shell Creek	Shale
4495.6	4496.7	Coastal Plain	Fluvial sandstone
4496.7	4497.2	Coastal Plain	Burrowed sandstone
4497.2	4507	Coastal Plain	Fluvial sandstone
4507	4518	Bell Creek	Crossbedded sandstone
4518	4529	Bell Creek	Massive sandstone
4529	4532	Bell Creek	Burrowed sandstone
4532	4518	Bell Creek	Massive sandstone
4518	4545	Bell Creek	Burrowed sandstone
4545	4552	Skull Creek	Shale
4552	4553	Skull Creek	Fluvial sandstone
4553	4577	Skull Creek	Shale

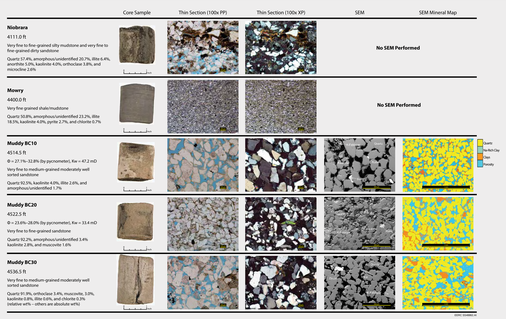
110 feet of full-diameter core and 47 rotary sidewall cores were taken from the observation well for further reservoir characterization.

Core with oil present from observation well.

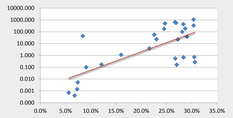
Sidewall core barrel containing rotary cores collected from observation well.



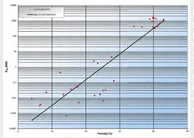
74 samples were acquired from 23 U.S. Geological Survey Core Research Center (USGS CRC) cores for petrographic analysis. Shown are thin sections in both plain- and cross-polar from the TAACK A1 well.



A representative summary of each interval tested from the rotary sidewall cores collected from the observation well, illustrating the differences in lithological character based on petrographic analysis.



Results of porosity and permeability testing on 27 samples acquired from eight USGS CRC cores.



Results of porosity and permeability testing on 33 samples aquired from the plugs taken out of observation well core.

Regional Subsurface Stratigraphy

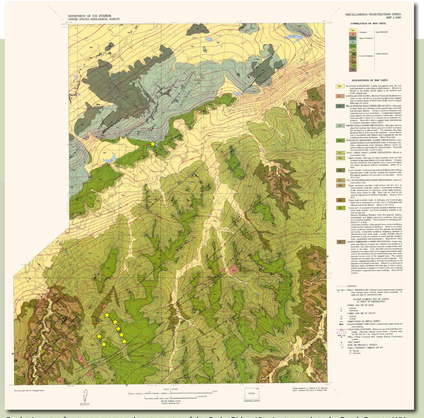
Period	Age	Central Wyoming	Southwestern Montana	Western North Dakota		Bell Creek Study Area
Lower Cretaceous	Albian	Mowry Shale	Mowry Shale	Mowry Fm	Mowry Shale	Mowry Shale
		Shell Creek Shale	Muddy Sandstone		Dynneson Sandstone	Muddy Sandstone
		Muddy Sandstone			Newcastle Sandstone	Rozet Member
		Thermopolis Shale	Thermopolis Fm: Thermopolis Shale		Skull Creek Shale	Skull Creek Shale
		Greybull Sandstone	Thermopolis Fm: Rusty Beds		Fall River Sandstone	Fall River Sandstone
	Aptian	Cloverly Group	Gastropod Limestone; Kootenai Formation		Lakota Formation	Lakota Formation
	Neocomian					

Stratigraphic column of Lower Cretaceous Period. The Bell Creek Area column is the nomenclature used for the subsurface of the Bell Creek Field for this poster.

Maximum transgression of the Early Cretaceous seaway depositing the Skull Creek Shale (modified from Vuke, 1984).

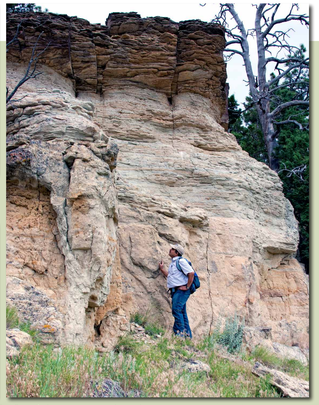
Regression of the Early Cretaceous seaway depositing the Muddy Sandstone (modified from Vuke, 1984).

Transgression of the Early Cretaceous seaway, depositing the Mowry Shale (modified from Vuke, 1984).



Geologic map of outcrop area: southeast quarter of the Cedar Ridge 15-minute quadrangle, Crook County, WY (by C.H. Maxwell and C.S. Robinson, 1978). Stars indicate the outcrops that have been visited thus far.

View of Muddy/Newcastle outcrop capping a bluff across a valley. The Bell Creek oil field lies behind the furthest trees seen on the horizon, approximately 35 miles to the northwest.



Muddy/Newcastle outcrops showing the massive Bell Creek and laminated Bell Creek facies capped by erosion-resistant, well-cemented sandstones and the Mowry Shale. The transition from massive to laminated is gradational, and no restriction to flow is expected between the two units. Approximately 22 vertical feet (6.5 meters) of outcrop is exposed at these locations.

Massive Bell Creek sandstone overlain by laminated sandstone.

Newcastle/Muddy Sandstone as the cliff-forming outcrop rock, near New Haven, WY.

Bell Creek Outcrop Stratigraphy

Mowry Shale		Thick gray shale, waxy texture, with thin silty laminations.
Muddy Formation	Laminated and Bedded Bell Creek Sand	White, massive, with laminations; weathers to blocky structure; minor effervescence with acid; some nodules strongly calcareous, up to 15 feet thick, easily eroded.
	Massive Bell Creek Sand	Yellow to orange from local iron oxidation; massive, with burrowing from several organisms; 10–20 feet thick.
	Bioturbated Bell Creek Sand	White, gray, orange, burrowed, mottled, bioturbated, with some iron staining and laminations; 1–3 feet thick.
	Rozet Member	Locally interbedded silt, sand, and shale with fine laminations and organic matter; undetermined thickness; poorly defined contact.
Skull Creek Shale		Thick gray shale, waxy texture, with distinct aragonite nodules.

Stratigraphic column of rock described in the Muddy/Newcastle outcrop near New Haven, WY, from several field trips to the area.

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Mowry Shale

Slabbed whole core from well 05-06 OW, depths shown 4451–4461 ft, representing the Mowry Shale.

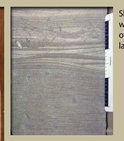
Slabbed whole core from well TAACK A-1, depth of 4587 feet shown, contact between the Mowry Formation and Muddy Formation.

Six plugs were drilled from Mowry Shale outcrop rock to be tested for triaxial and dynamic geomechanical properties.

Drilling a 1-inch plug from Mowry Shale outcrop rock collected in the field for further lab analysis.

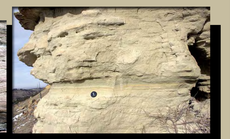
Mowry Shale outcrop near New Haven, WY.

Laminated Bell Creek Sand



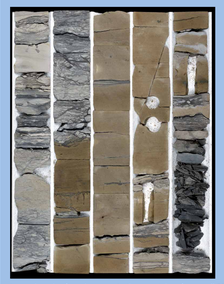
Slabbed whole core from well 31 TAACK, depth of 4156.5 feet shown, laminated Bell Creek sand.

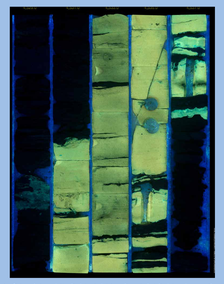
Slabbed whole core from well TAACK A-1, depth of 4589 feet shown, laminated Bell Creek sand.



Laminated Bell Creek sand as seen in outcrop section near New Haven, WY.

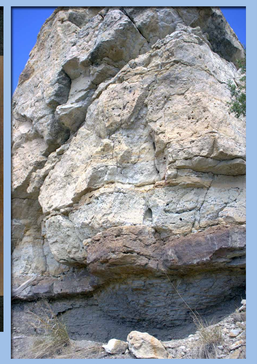
Massive Bell Creek Sand





Lower bench of sand as seen in the core taken from well 05-06 OW. Left in plain white light, right in ultraviolet light, where oil fluorescence highlights the leftover hydrocarbon after primary and secondary recovery.

Slabbed whole core from well TAACK A-1, depth of 4605–4614 feet shown, massive Bell Creek sand with some interbedded bioturbated sand.



Massive Bell Creek sand as seen in outcrop section, near New Haven, WY. The Rozet submember can be seen at the base of the outcrop under the iron-stained base of the massive sand.

A laterally extensive outcrop of massive Bell Creek sand. In this location, the massive sand is capped directly by the Mowry Formation. Outcrops such as this suggest a large major variogram distance.

Bioturbated Bell Creek Sand

Slabbed whole core from well 4-4 Tanner, depth of 4404 feet shown, bioturbated Bell Creek sand.

Slabbed whole core from well 1 Woodson Federal, depth of 4840 feet shown, bioturbated Bell Creek sand.

Slabbed whole core from well 1-31 Biddle, depth of 4602 feet shown, bioturbated Bell Creek sand.

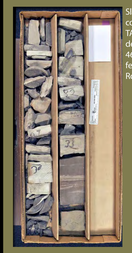
Bioturbated Bell Creek sand as seen on a horizontal bedding plane of the outcrop, near New Haven, WY.

Trace fossils and animal burrows found in the bioturbated Bell Creek sand outcrop near New Haven, WY.

Bioturbated Bell Creek sand as seen in outcrop section near New Haven, WY. The Rozet Member can be seen at the base of the outcrop as gray in color with small lenses of iron-stained sandstone.

Bioturbated Bell Creek sand as seen on a horizontal bedding plane of the outcrop, near New Haven, WY.

Rozet Member and Skull Creek Shale



Slabbed whole core from well TAACK A-1, depth of 4628–4635 feet shown, Rozet Member.

Skull Creek Shale as seen cropping out from a large landslide, near New Haven, WY.

Rozet Member as seen cropping out below the Bell Creek sand, near New Haven, WY.

Rozet Member outcrop, near New Haven, WY.

Skull Creek Shale outcrop forming the hillside slopes under the cliff forming Muddy Sandstone, near New Haven, WY.

Observations

Outcrop

- Features observed in outcrop correlate well to those present in field core; three formations and four facies.
- No extensive lateral or vertical barriers to flow were recognized; all facies described in outcrop were conformable with one another.
- Massive (shoreface) and laminated (foreshore) Bell Creek sands will act as one flow unit. These thick sands are present throughout the outcrop, are well to moderately sorted, and should have high porosity and permeability in the reservoir.
- Based on the outcrop extents, sands have major variogram ranges greater than 3000 feet (880 m).
- The Coastal Plain facies was not observed in outcrop, but has been identified in field core. However, the tidal channels observed in outcrop may have been deposited subsequently to the Coastal Plain.
- Tidal channels are not laterally extensive. These deposits are less porous and permeable but will not behave as flow barriers as they are only present at the top of the Bell Creek sedimentary package.
- Although the unit is silty and contains sandy lenses, the Rozet Member is primarily shale/mudstone and is expected to behave as a bottom seal along with the Skull Creek Formation.

Subsurface Core

- Three formation and five facies of the Muddy Formationwere described in core. Four of the facies correlated nicely to outcrop facies.
- Small clay lenses acting as permeability barriers are seen often in core but absent in outcrop.
- X-ray diffraction (XRD) clay typing analysis has shown the primary clay types to be illite with small amounts of kaolinite.
- Porosity–permeability crossplots are similar when comparing new measurements made on historic core with those measurements made on newly acquired core from the observation well. Previous historic porosity and permeability data on cores have been erroneously high; thus this work has provided some resolve in understanding these reservoir properties.
- Thin-section analysis has concluded the majority of samples are quartz-rich.
- Scanning electron microscopy (SEM) analysis has confirmed XRD and thin-section analysis with displaying images of clay infill between quartz grains and mapping siderite, which is unique to the type of environment in which the sand benches were deposited.

PCOR Partnership

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