Ichnology Applied to the Pronghorn Member, Bakken Formation (Mississippian-Devonian)

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The Pronghorn Member of the Bakken Formation was formally proposed in 2011 by LeFever and others for the strata underlying the Lower Member and overlying the Three Forks Formation. These strata had previously been included in the Three Forks and referred to as the "Sanish sand." Examination of these rocks revealed a significant basinwide unconformity at the top of the Three Forks section. Also in support of its placement in the Bakken Formation, lithologies within the Pronghorn section are mappable and are consistent with those observed within the Middle Member.

The continued development of the oilfields has increased the information and available cores for this section. It appears that there are some constraints placed on production by the lithofacies present. Ichnofauna can be used in this case to further define the depositional environments of the proximal section and potentially explain why some areas produce better than others. Further examination of the Pronghorn may result in adjustments to completion techniques enabling better production.

The Pronghorn Member is located throughout the Williston Basin. It divides easily into proximal and distal beds. The proximal beds occur primarily in the southwestern portion of the basin whereas the distal portion is more centrally located (fig. 1). The proximal beds are the ones that are associated with production.

The Section

Three Forks Formation

The uppermost portion of the Three Forks Formation consists of an alternating sequence of apple green and tan dolomudstones and claystones with uni- and bi-directional ripples, parallel laminations, flaser beds, scours, fluid escape structures, and rip-ups clasts (Dumonceaux, 1984; Berwick, 2008; LeFever and Nordeng, 2009; Berwick and Hendricks, 2011; Bottjer and others, 2011). These beds reflect a shallowing-upward sequence of rocks representing subtidal to supratidal environments. A significant regional unconformity occurs at the top of this section indicating a major erosional event (fig. 2).

Pronghorn Member

Bakken Formation

The Pronghorn Member of the Bakken Formation can be divided into 5 lithofacies described here, in ascending order from A-E. The focus of this paper is to look at the ichnofauna present in the middle section B of the member.

<u>A. Basal Sandstone</u>

The lowermost sandstone lithofacies is described as a thin, fine- to very fine-grained quartz sandstone that is characterized by abundant *Skolithus* burrows. A lesser amount of dolomite is also present (fig. 3; Sesack, 2011). The distribution of the basal sandstone

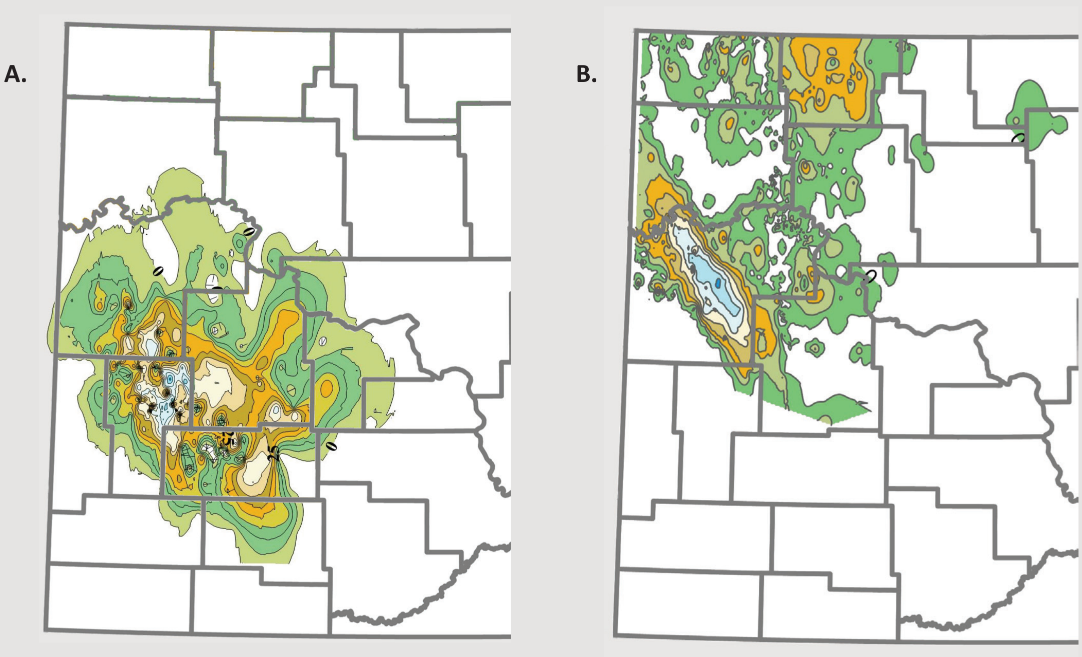


Figure 1. (A) Isopach of the proximal beds of the Pronghorn Member. (B) Isopach of the distal beds of the Pronghorn Member.

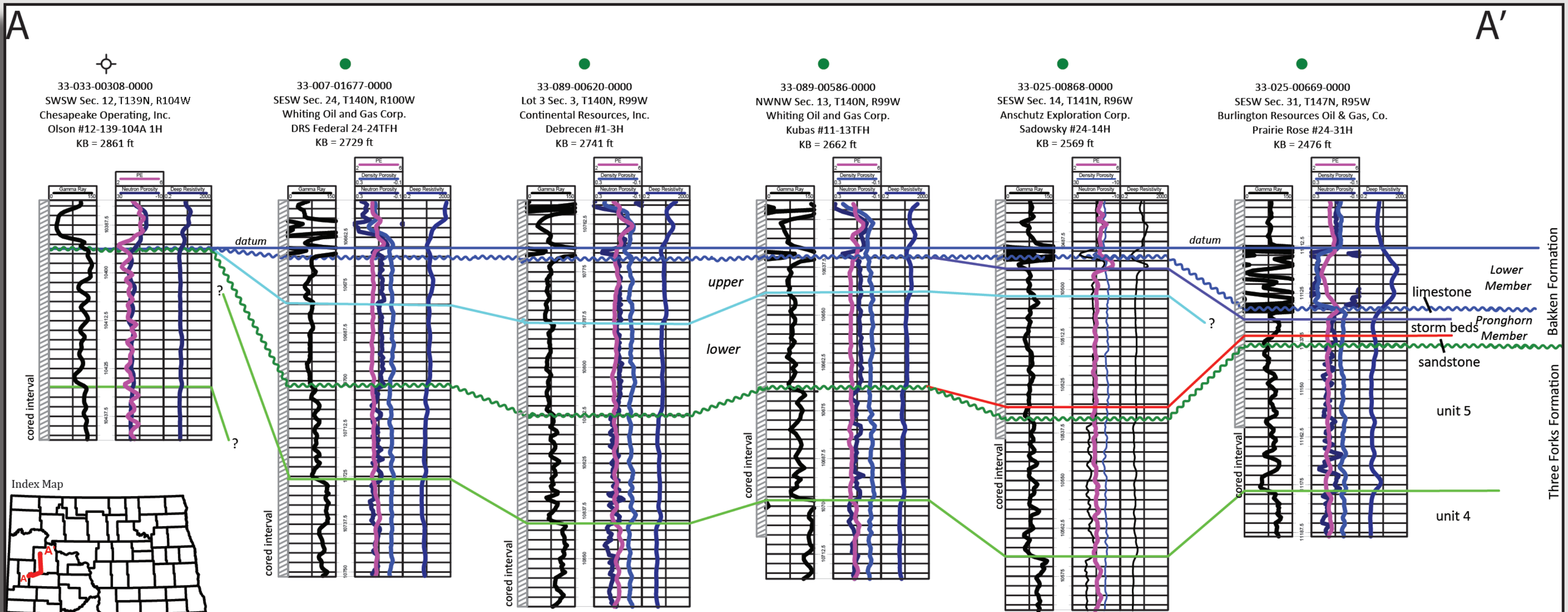


Figure 2. Cross-section A-A′ across the area of interest showing the breakdown and distribution of the intervals within the Pronghorn Member of the Bakken Formation and their relationships with the underlying Three Forks Formation and overlying Lower Member.

Figure 3. Basal lithofacies of the Pronghorn Member showing the extensive *Skolithus* burrowing and bioturbation. From the Raymond T. Duncan-#1 Rose (SENE Sec. 33, T152N, R94W) at a depth of 10,601 ft. Penny for scale.

is varied across the basin and is difficult to identify with certainty on wireline logs so that good core control is necessary (figs. 2 and 3). Depositionally, the basal sandstone (A) is probably lower to middle shoreface based on the extensive *Skolithus* ichnofacies. Note the number of cross-cutting burrows in these core photos.

B. Dolomitic Mudstones with Storm Beds

The upper portion of the interval consists of a dolomitic mudstone with thicker storm beds (HCS beds) of very fine- to fine-grained quartz. Minor amounts of calcite and illite are present (Sesack, 2011). Burrows include *Chondrites, Asteroma, Teichichnus, Planolites*, and *Thalassinoides*. Also, the mudstone interbeds are highly bioturbated with numerous cross-cutting burrows making burrow identification difficult.

The environment of deposition for this portion is lower to middle shoreface. There appears to be a surface, perhaps a minor unconformity, in the middle of the section related to a shift in environments. The lower portion consists of dolomitic mudstones with tan, very fine-grained, sandstone, thinner storm beds representing an upper offshore environment.

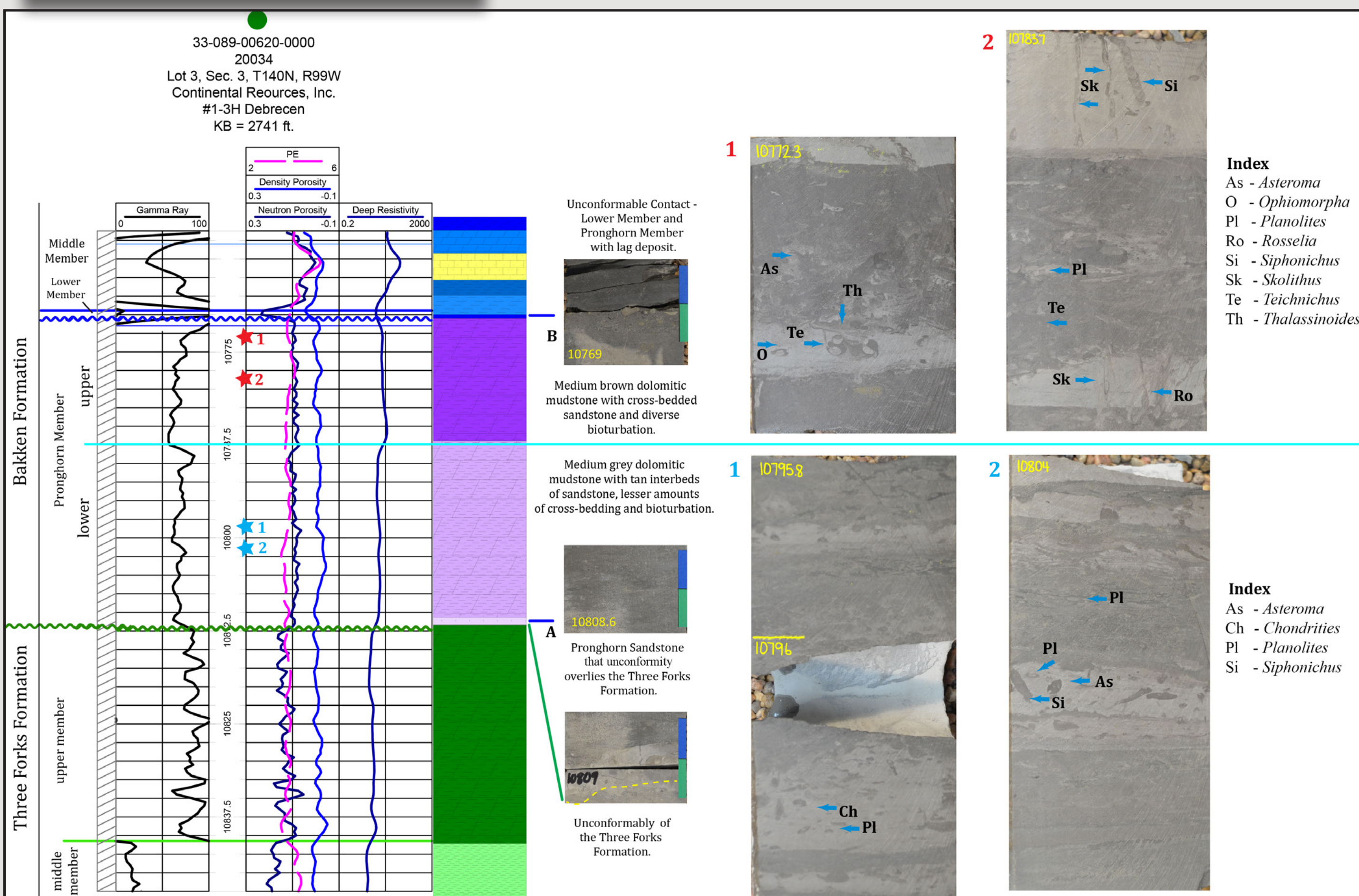


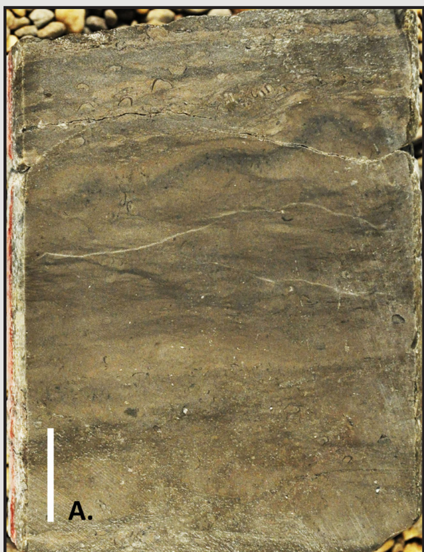
Figure 4. Continental Resources, Inc. - #1-3H Debrecen (Lot 3, Sec. 3, T140N, R99W) is used to illustrate the breakdown of the Bakken Pronghorn Member. In this area, limestone and the shale of the member are absent. The identifiable ichnofauna within the middle section containing the storm beds can be subdivided (light blue line). The upper portion has a more diverse ichnofauna and a lower to middle shoreface environment, whereas the lower portion is less diverse and can be assigned to the lower shoreface-upper offshore environment. Letter A corresponds to the basal sandstone and B to the dolomitic mudstone with storm beds. Not all facies of the Pronghorn are present in this well. The four core photographs on the far right were taken from the rocker set and the photos on the Oil and Gas Subscription site were taken from the curator set.

The upper portion of the interval becomes significant when examining production. Although the porosities are similar throughout the interval, the upper portion of the lithofacies appears to have better permeability than the underlying portion, probably due to burrowing and the lithologies involved.

C. Lime Mudstone

The third lithofacies is a thin, medium brown-grey mudstone to siltstone with brachiopods (fig. 5). The lithofacies is unconformable with the Three Forks and upwardly conformable in the central portion of the basin with the Lower Member (LeFever and others, 2011).

Contact with the underlying storm beds is conformable. The contact with overlying limestone is irregular. Distribution is difficult to determine without core control owing to lack of definition on wireline logs.



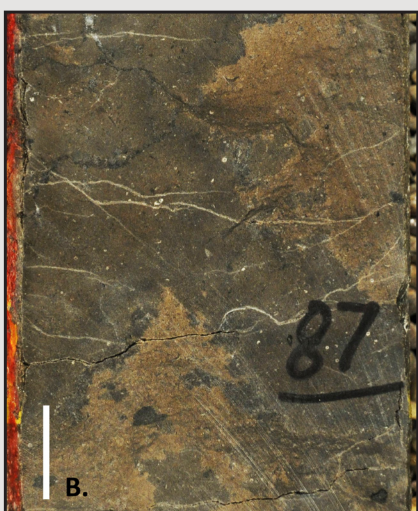


Figure 5. (A) Core photograph of the lime mudstone lithofacies from Anschutz Exploration Corp.-Sadowsky #24-14H (SESW Sec. 14, T141N, R96W) at a depth of 10,488.5 ft. White bar represents 1 inch. (B) Core photograph of limestone lithofacies from the Raymond T. Duncan-#1 Rose (SENE Sec. 33, T152N, R94W) at a depth of 10,601 ft. White bar is 1 inch.

D. Limestone

The fourth lithofacies consists of a medium grey, nodular-bedded limestone with crinoids, brachiopods and other skeletal fragments. This lithofacies represents an open marine environment. The contact with the overlying Lower Member of the Bakken is generally unconformable where present. Difficulties occur in mapping this interval on wireline logs, its signature is similar to that of the sandstone lithofacies and requires careful core to log control.

E. Silt

The uppermost lithofacies has been previously referred to as the "Bakken silt" and is possibly the distal equivalent to the proximal lithofacies – the sandstone, storm beds, lime mudstone, and limestone. It is described as medium dark brown to brown-black mudstone with thin laminae of fine-grained sand (fig. 6). Burrowing becomes prevalent towards the lower contact. Organic values (TOCs) are significantly less than the overlying Lower Member of the Bakken Formation. The environment of deposition is lower offshore.

Lower Member

The Lower Member of the Bakken Formation consists of a dark brown to black organic-rich shale. Pyrite is abundant as thin wispy laminae, lenses, nodules, or is disseminated throughout. Fossils present include tasmanites, condonts, brachiopods, and fish teeth, scales, and bones. Minor amounts of calcite occur as fracture fill.

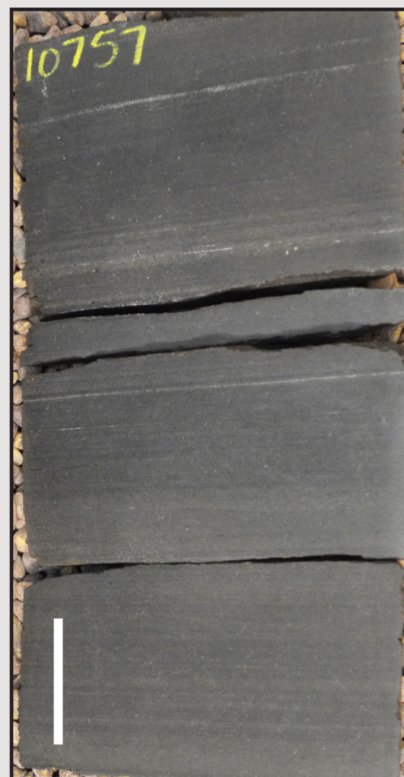


Figure 6. Core photograph of the silt lithofacies at 10,757 ft. From the Continental Resources, Inc. Debrecen #1-3H (Lot 3, Sec. 3, T140N, R99W). White bar is 1 inch. Map showing the distribution of this facies is shown in figure 1.

The Lower Member was deposited in a restricted marine setting allowing for the stratification of the water column and the development of anoxic bottom waters.

Relationship of Facies to Production

Minor changes in the depositional environment of the "B" beds appear to have an effect on production. Although porosity over the section is consistent, the permeability decreases from the upper section to the lower section (fig. 7). This decrease is probably due to an increase in the amount of dolomitic mud present resulting from deposition in a slightly deeper, more offshore environment. The silt interval of the Pronghorn should negatively affect production. However, it performs better as

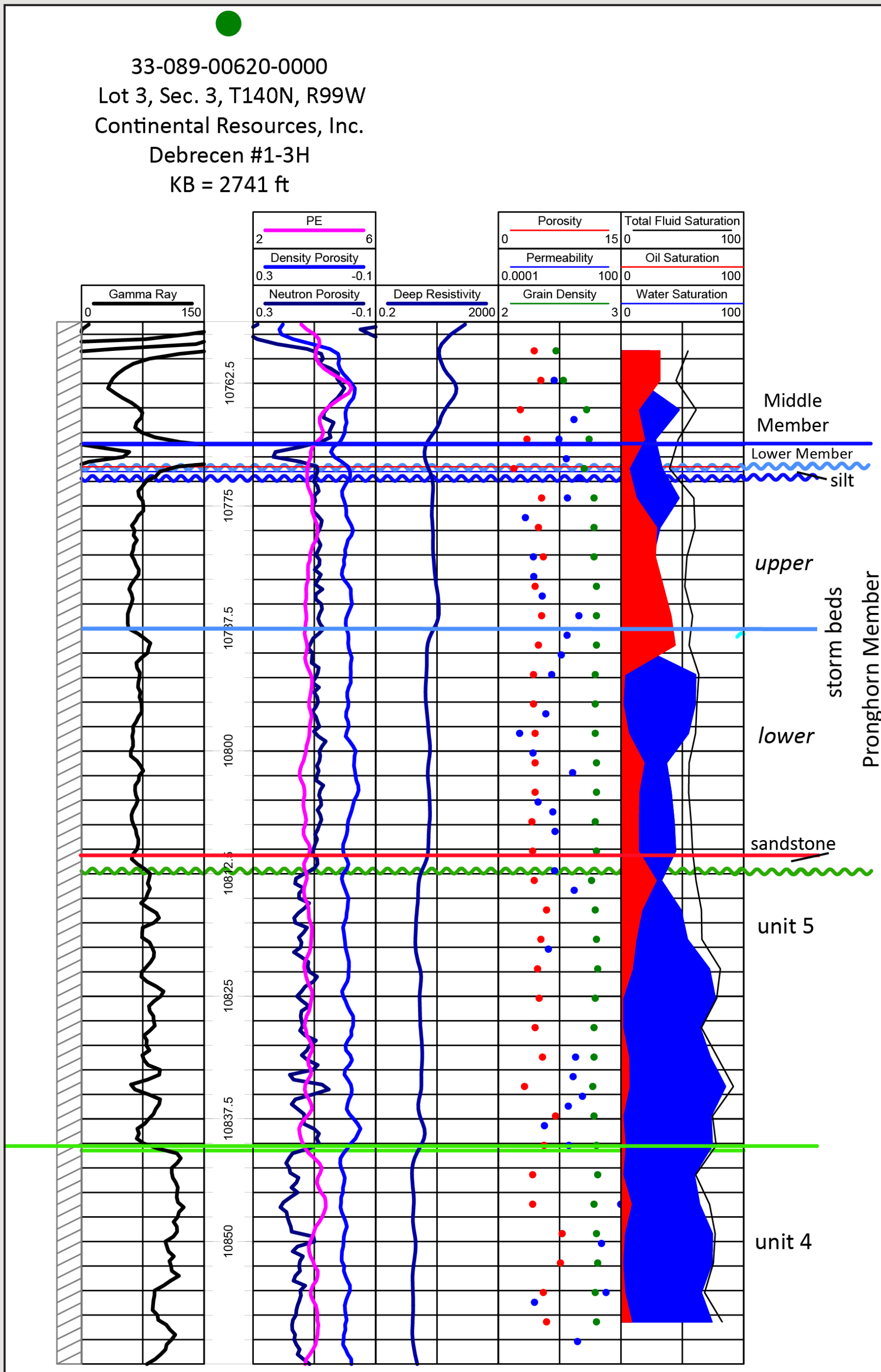


Figure 7. Core analyses show the variation of oil-water saturations between the upper and lower HCS beds within the Pronghorn Member in the Continental Resouces-Debrecen #1-3H (Lot 3, Sec. 3, T140N, R99W).

a reservoir because of the higher percentage of oil saturation to total fluids and therefore produces less water.

Ichnofacies Impact

The Pronghorn Member of the Bakken Formation overlies the sequence boundary at the top of the Three Forks Formation. The section represents an overall transgressive sequence culminating with the deposition of the Lower Member. The lower portion of the storm beds probably represents rapid change in accommodation space due to salt collapse resulting in deeper water conditions and a slight change in environment. The ability to determine subtle changes in the depositional environments are greatly enhanced by the use of ichnofauna. These identifiable changes may lead to adjustments in potential targets or completion methods thereby enhancing production.

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