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Research paper

Statistical modeling of biogenically enhanced permeability in tight reservoir rock

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ABSTRACT

Bioturbation is generally perceived to be detrimental to bulk permeability by reducing primary grain sorting, homogenizing sediment, and introducing mud as burrow linings and feces. Recent studies show, however, that some ichnogenera and biogenic fabrics serves to increase porosity and permeability. In tight hydrocarbon reservoirs, subtle changes in sand and silt distributions, such as may be generated by bioturbation, can greatly affect the resulting porosity and permeability distribution. Despite this, permeability across unfractured sedimentary reservoirs is commonly assessed solely on the basis of average grain size. This study of the Lower Cretaceous Viking Fm integrates sedimentary and ichnologic features to define recurring "hydrofacies" that possess distinct permeability grades. Grain size, lithology, bioturbation index, and trace fossil suites were described from a cored section of well 14-30-22-16W4. The k_{max} values from small plugs and full-diameter core samples were used to represent each hydrofacies. Hydrofacies were qualitatively defined at the bed/bedset scale, based on sedimentary, ichnological and permeability attributes, all of which affect flow pathways in heterolithic facies. The Markov chain method was employed to compare the vertical transitions of permeability (k_{max}) within a borehole against grain size and hydrofacies at the bed to bedset scale. This provided an intuitive framework for interpreting facies relationships such as coarsening-upwards successions. The results show that in the studied core, grain size only correlates to permeability in homogeneous rock units. The transiograms show that the volumetric proportions of different k_{max} classes show a 15% correlation with grain size, compared to a 97% correlation with the hydrofacies, indicating that variations in permeability down the well are strongly related to variations in the hydrofacies. The hydrofacies approach potentially can be used as a conceptual framework for the spatial modeling of permeability in tight hydrocarbon reservoirs, where grain size may not be the primary factor on permeability distributions.

1. Introduction

The storage capacity and productivity of a reservoir are determined by its porosity and permeability. Permeability is also an important factor that controls reservoir response during enhanced recovery. Correspondingly, understanding and projecting variations in porosity and permeability within a reservoir are vital to maximizing the acquisition of the resource. Recently, there has been considerable interest in recovering hydrocarbons from marginal (generally lower-quality) reservoirs using horizontal drilling techniques and fracturing, particularly in areas prone to light oil. The so-called "Tight Oil" play of the Viking Formation in east-central Alberta and west-central Saskatchewan is one example. "Tight" reservoirs are characterized by permeabilities that range from 0.01 to 0.1 mD (Spencer, 1989; Holditch, 2006; Clarkson and Pedersen, 2010). In such reservoirs, subtle changes in the distribution of sedimentary media, such as are generated by bioturbation, can greatly affect the porosity and permeability distribution of the facies.

Bioturbation remains an under-appreciated mechanism by which porosity and permeability of a sedimentary facies are

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modified (cf. Pemberton and Gingras, 2005). Even when considered, bioturbation is generally perceived to be detrimental to bulk permeability, through reduction of primary grain sorting, homogenization of the sediment, and introduction of mud through linings, biogenic deposits, and feces (Qi, 1998; Dornbos et al., 2000; Qi et al., 2000; McDowell et al., 2001; Pemberton and Gingras, 2005; Tonkin et al., 2010; Lemiski et al., 2011; La Croix et al., 2013). Recent studies have shown, however, that several ichnogenera and their associated biogenic fabrics are capable of increasing a reservoir rock's porosity and permeability (Gingras et al., 2004; Pemberton and Gingras, 2005; Hovikoski et al., 2007; Volkenborn et al., 2007; Cunningham et al., 2009; Tonkin et al., 2010; Lemiski et al., 2011; Gingras et al., 2012; La Croix et al., 2013; Knaust, 2014). Ichnogenera that form branching burrow networks can create flow pathways in otherwise less permeable units where the burrow fills consist of coarser grains and better-connected intergranular pore space relative to the surrounding matrix (Fig. 1; Gingras et al., 2004; Pemberton and Gingras, 2005; Lemiski et al., 2011; Gingras et al., 2012; La Croix et al., 2013). Additionally, burrows are capable of increasing vertical permeability in laminated sedimentary rocks, where horizontal permeability otherwise tends to dominate (Gingras et al., 2012). Burrow fills also may undergo diagenetic changes that may lead to higher permeability than that of the surrounding matrix (Pemberton and Gingras, 2005; Tonkin et al., 2010; Gingras et al., 2012).

Despite this, permeability across unfractured sedimentary reservoirs is commonly assessed solely on the basis of grain size (e.g. lithostratigraphic units). By contrast, this paper proposes the use of "hydrofacies" (HF) in reservoir characterization. A hydrofacies is defined herein as a recurring sedimentary facies possessing a distinct permeability grade generated by a combination of sedimentological and ichnological characteristics. Such a hydrofacies takes into account the lithology, textural characteristics, physical and biogenic fabric, the presence and distribution of trace fossils, and the expression of burrow fill(s), all of which serve to affect permeable flow pathways (vertically and laterally) in heterolithic facies. The Markov chain approach proposed in this paper is used to compare vertical transitions in permeability within a borehole with transitions in a) grain size, and b) hydrofacies at the bed to bedset scale, in order to determine which variable best reflects the observed permeability variations.

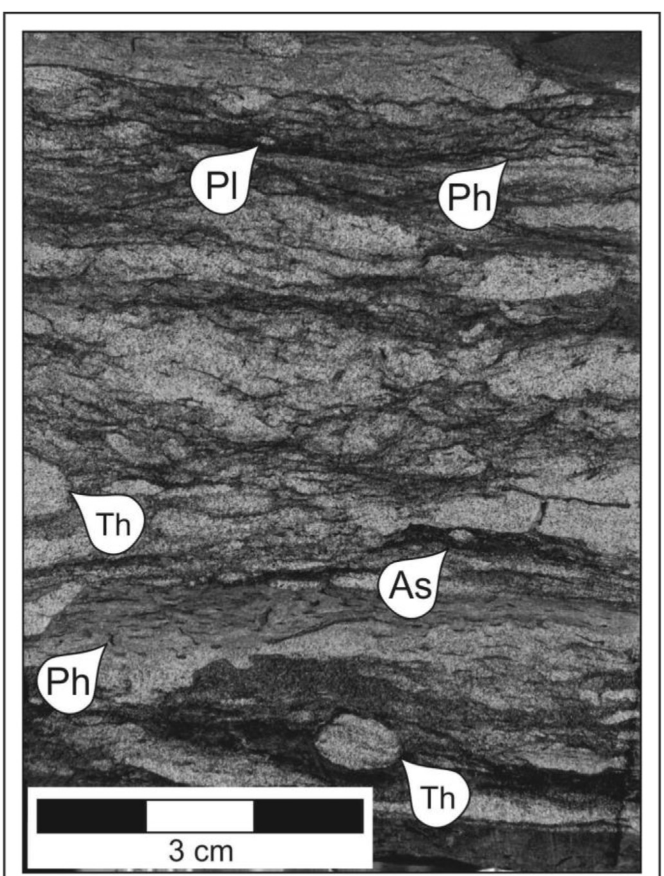

Figure 1. Sand-filled trace fossils, such as *Thalassinoides* (Th) and *Planolites* (Pl) create potential flow paths in an otherwise low-permeability unit. Mud-filled traces are dominated by *Phycosiphon* (Ph).

2. Geologic setting

The Lower Cretaceous (Upper Albian) Viking Formation is a prolific oil- and gas-producing interval that was deposited in the Western Canada foreland basin during a period of active tectonism and eustatic sea level fluctuations. During Viking deposition, a shallow epicontinental seaway extended from the Arctic Ocean to the Gulf of Mexico (Fig. 2; Williams and Stelck, 1975; Caldwell, 1984; Walker, 1990; Reinson et al., 1994), into which was deposited a complex succession of siliciclastics, dominated by mudstones, heterolithic bedsets of sandstone and shale, and sandstones, with minor conglomerates.

The Viking Formation stratigraphically overlies the Joli Fou Formation and underlies the Westgate Formation (Fig. 3; Stelck, 1958). It is generally regarded to be roughly equivalent to the Paddy Member of the Peace River Formation of northwestern Alberta (Leckie et al., 1990), and the Bow Island Formation of southern Alberta and southwestern Saskatchewan (Fig. 3; Stelck and Koke, 1987; Raychaudhuri and Pemberton, 1992). While the Viking sediments only range from 15 to 30 m in thickness, they are discontinuity-bound and depositionally complex, resulting in sedimentary successions, facies, and geometries that are challenging to characterize and correlate (e.g. Pattison, 1991; Reinson et al., 1994; Walker, 1995; Burton and Walker, 1999).

The Late Albian (Lower Cretaceous) Viking Formation comprises a siliciclastic succession consisting of interstratified mudstones, sandstones and rare conglomerates, mainly reflecting shoreface, delta and estuarine valley deposits. These clastics were supplied from the rising Cordillera in the west and reflect northward and eastward progradation of environments into the Alberta foreland basin. The Viking Formation overlies marine shale of the Joli Fou Formation and is capped by marine shale of the Westgate Formation (Fig. 3). The stratigraphic relationships were addressed by the work of Stelck (1958), Glaister (1959), McGookey et al. (1972), Weimer (1984), Cobban and Kennedy (1989), Stelck and Leckie (1990), Bloch et al. (1993), Caldwell et al. (1993), and Obradovich (1993).

The Viking Formation is internally complex stratigraphically, and characterized by numerous internal discontinuities. Beaumont (1984), Boreen and Walker (1991), Pattison (1991), Posamentier and Chamberlain (1993), Reinson et al. (1994), Walker (1995), Burton and Walker (1999), and MacEachern et al. (1999), among others, have attempted to provide allostratigraphic and sequence stratigraphic assessments of the Viking, with varying levels of success. Viking Formation discontinuities have been linked to the global changes of sea level outlined in Kauffman (1977), Vail et al. (1977), Weimer (1984), and Haq et al. (1987). A cored interval of the Viking Formation from the Verger Field was selected for this study because it exhibits stacked parasequences characterized by the interstratification of impermeable and permeable beds with variable but locally pervasive bioturbation.