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DIAGENESIS OF WABISKAW MEMBER (LOWER CLEARWATER FORMATION)
RESERVOIR SANDS, PRIMROSE BLOCK, ALBERTA

by

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feldspar occurs as overgrowths on partially dissolved detrital K-feldspar (Fig. 2.4a) and as discrete crystals (Fig. 2.4b). Minor dissolution of diagenetic K-feldspar has occurred (Fig. 2.4c). The composition of diagenetic K-feldspar is variable (Table 2.2).

Calcite: Five types of diagenetic calcite have been identified: (i) early grain-coating (Fig. 2.4d), (ii) pore-filling (Figs. 2.4d, e, f), (iii) replacement (Figs. 2.2c, d), (iv) late pore-lining to pore-filling (Figs. 2.5a, b, c), and (v) veinlette (Fig. 2.5d). Early grain-coating calcite occurs in some bitumen-free cemented sands and is $<5 \mu\text{m}$ thick. Because of this calcite's thin nature, only one reliable (not contaminated by other carbonate minerals) electron microprobe analysis is available; it is Fe-poor and has an XRD d_{104} of 3.026 to 3.028Å (Tables 2.3, 2.4). Early grain-coating calcite only occurs in association with Fe-rich, pore-filling calcite.

Pore-filling calcite is the dominant diagenetic phase in bitumen-free cemented zones (up to 55%, Table 2.1) and occludes all porosity in these zones. The chemical composition of the pore-filling calcite is variable; both Fe-rich and Fe-poor varieties were identified (Table 2.3). XRD d_{104} values vary from 2.999 to 3.026 (Table 2.4). Detrital plagioclase and volcanic rock fragments are commonly replaced by calcite in bitumen-free cemented zones. The chemical composition of that replaces framework grains is variable but it is similar in composition (although sometimes lower in Fe) to associated pore-filling calcite (Fig. 2.6, Table 2.3).

Late pore-lining to pore-filling calcite occurs in bitumen-saturated cemented zones (up to 38%, Table 2.1). This generation of calcite has undergone dissolution; the resulting secondary porosity has been filled by hydrocarbons. Calcite from bitumen-saturated cemented sands is Fe-poor. The chemical composition of this calcite is not as variable as obtained for calcite from bitumen-free cemented sands: XRD d_{104} varies from 3.023 to 3.029 (Table 2.4). In general, pore-lining to pore-filling calcite from bitumen-saturated cemented sands contain less Fe than pore-filling calcite from bitumen-free cemented sands

(Fig. 2.7). Veinlettes of calcite cross-cut pore-filling calcite. Vein calcite is similar in composition to calcite from bitumen-saturated cemented sands (Table 2.3).

While chemical data are not available for all calcite cements examined during this study, bulk XRD data have been obtained. The d_{104} diffraction and mole % FeCO_3 and MgCO_3 exhibit an inverse relationship in the samples for which both chemical and XRD data are available (Fig. 2.8). From this relationship, the Fe + Mg content of calcite can be inferred for all samples. XRD data show that with few exceptions, calcite from bitumen-free, cemented sands are richer in Fe and Mg than calcite from bitumen-saturated, cemented sands (Fig. 2.8).

Stable isotope data are available for calcite from bitumen-free and bitumen-saturated cemented sands and for veinlette calcite. A large range in stable isotope values exists for calcite from bitumen-free cemented sands: $\delta^{13}\text{C}$, -4.78 to 11.22‰ (PDB) and $\delta^{18}\text{O}$, 13.51 to 22.15‰ (SMOW) (Table 2.4). Stable isotopic compositions of calcite from bitumen-saturated cemented sands are less variable: $\delta^{13}\text{C}$, 9.81 to 12.55‰ (PDB) and $\delta^{18}\text{O}$, 14.77 to 16.87‰ (SMOW) (Table 2.4). In general, calcite from bitumen-free cemented sands has lower $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values than calcite from bitumen-saturated cemented sands (Fig. 2.9). Veinlette calcite (one sample) has a similar isotopic composition to calcite from bitumen-saturated, cemented sands or high $\delta^{13}\text{C}$ calcite from bitumen-free, cemented sands, $\delta^{13}\text{C}=11.45\text{‰}$ (PDB), $\delta^{18}\text{O}=17.13\text{‰}$ (SMOW) (Fig. 2.9, Table 2.4).

Siderite: Diagenetic siderite is present in all lithologies as discrete rhombs (Figs. 2.3f, 2.5b, e, f) or as aggregates comprised of rhombs (Fig. 2.5f, 2.10a). Siderite rhombs occur as a minor phase in association with pore-filling calcite in bitumen-free, cemented sands, and together with or without calcite in bitumen-saturated, cemented sands. Some shale and mud beds/clasts have been sideritized (Fig. 2.10b).

As for calcite, siderite from bitumen-saturated cemented sands is chemically less

on diagenetic mineralogy and the saturating fluid (water, gas or bitumen) (Fig. 2.13):

Bitumen-free cemented sands: Pore-filling calcite (including replacement calcite) is the dominant diagenetic phase in bitumen-free, cemented sands. Lesser amounts of pyrite, chlorite/smectite, fluorite, grain-coating calcite, siderite (Fe-rich), K-feldspar, veinlet calcite and kaolinite also precipitated in bitumen-free cemented sands.

Bitumen-saturated cemented zones: Fe-poor, pore-lining to pore-filling calcite and/or Fe-poor siderite are the typical diagenetic phases in bitumen-saturated, cemented sands. Kaolinite is abundant with lesser amounts of pyrite and K-feldspar.

Bitumen-saturated sands: Bitumen-saturated sands are generally clay cemented and unconsolidated (hardness = 1 to 3). Kaolinite dominates the diagenetic mineral assemblage with lesser amounts of pyrite, chlorite/smectite, siderite and K-feldspar.

Gas-saturated sands: The diagenetic mineral assemblage of gas-saturated sands is similar to that of bitumen-saturated sands: pore-filling kaolinite dominates with lesser amounts of pyrite, chlorite/smectite and K-feldspar.

Water-saturated sands: The diagenetic mineral assemblage of water-saturated sands is similar to that of bitumen-saturated sands: pore-filling kaolinite dominates with lesser amounts of pyrite, chlorite/smectite and K-feldspar.

2.6 Bulk Sample Mineralogy: X-ray Diffraction Results

XRD analysis of sands is an effective means of establishing mineralogical variations over a large area. Bulk XRD data for 115 samples of sands, silts, shales and mud clasts are listed in Table 2.7. Average XRD mineralogy for each lithology is presented

Table 2.8a. Average bulk XRD mineralogy of sands, silts, shales and mud clasts

Description	n	Qtz	Plag	KF	SW	14A	10A	7A	Cal	Dol	Sid	Py	%
oil sands 1	26	74	12	5	1	1	4	4	0	0	1	0	
oil sands 2	30	63	9	4	1	1	4	4	6	0	7	0	
gas sands	5	75	11	4	1	1	4	4	0	0	1	0	
water sands	4	73	9	3	1	1	5	5	0	1	1	0	
ccz	28	38	9	3	1	1	3	3	38	1	3	0	
mud clasts	11	56	7	4	3	2	7	6	0	0	15	0	
shale	9	68	4	1	3	1	12	7	1	1	1	0	
silt	1	81	2	0	0	0	8	3	1	6	0	0	

2.7 Clay Mineral Assemblage

To characterize the detrital and diagenetic clay mineral assemblages, the clay (< 2 μ m) size fraction was separated from 52 sand, silt, shale and mud clast samples (Table 2.9, Appendix II). The clay mineral assemblage of reservoir sands provides information on both the detrital and diagenetic clay minerals; the detrital clay mineral assemblage was inferred by examining the shales, mud clasts and silts interbedded with Wabiskaw Member sands.

2.7.1 Identification of clay minerals

XRD of the <2 μ m size-fraction was used to identify 7Å (kaolinite), 10Å (illite + glauconite), 14Å and 17Å (illite/smectite and chlorite/smectite) in the detrital and/or diagenetic clay mineral assemblages (Figs. 2.14, 2.15, 2.16). Differentiation among these minerals was achieved using six different humidity/organic solvent and heat treatments followed by XRD. Humidity and heat treatments and associated XRD scan conditions are described in Appendix I. A complete set of XRD charts is provided in figures 2.14 through 2.16 for samples containing chlorite/smectite and/or illite/smectite in addition to 7Å and 10Å clay minerals. An interpretation of the diffractograms is provided in the caption of each figure.

2.7.2 Detrital clay mineral assemblage

With the exception of one sample (WS-90-1-28) that is rich in 7Å clay, the clay mineral assemblage of shales interbedded with Wabiskaw Member reservoir sands is dominated by 17Å and 10Å clays (Table 2.9). Randomly interstratified illite/smectite is the only mixed-layer clay mineral detected in shales, mud clasts and silts (Table 2.9). Using the method of Inoue et al. (1989), the percent of smectite layers in I/S was calculated to be 51 to 75%; however, the error of this method (10 to 15%, Inoue et al., 1989) could account for much of the apparent variation.

2.7.3 Wabiskaw Member sands, clay mineral assemblage

The $<2\ \mu\text{m}$ size fraction of Wabiskaw Member sands was dominated by 7\AA clay. Lesser amounts of 10\AA (glauconite + illite, 7 to 39%), 17\AA (including illite/smectite and chlorite/smectite, 3 to 24%) and 14\AA (3 to 15%) clay minerals were also present (Table 2.9). In general, sands are richer in 7\AA clay and poorer in 17\AA and 10\AA clays than silts, shales and mud clasts (Fig. 2.17). This behaviour suggests that 7\AA clays are diagenetic whereas 17\AA and 10\AA clays are detrital. Diffractions at 1.489\AA on high angle (58 to 78° , 2θ , $\text{Co K}\alpha$) XRD patterns and petrographic (optical microscopy, SEM and BSE) observations indicate that the 7\AA clay is kaolinite. Berthierine, which is common in the Clearwater Formation at the Cold Lake area to the south (Racki, 1991; Longstaffe et al. 1989a, b, c, 1990, 1991a, 1992a,b), was not observed in Wabiskaw Member sands, silts, shales or mud clasts. XRD and petrographic observations indicate that 17\AA clays are mostly mixed-layer chlorite/smectite (C/S) and illite/smectite (I/S) with C/S being diagenetic and I/S being detrital.

2.8. Fines and Bitumen Content

Bitumen-saturated (poorly cemented) sands have the highest bitumen content and the lowest $<2\ \mu\text{m}$ (2.01 weight %) content of all sands (Table 2.10). Bitumen-saturated cemented sands contain approximately 6 weight % bitumen and have approximately the same $<2\ \mu\text{m}$ content as bitumen-saturated sands (Table 2.10). Water saturated sands have higher $<2\ \mu\text{m}$ content (Table 2.10) than bitumen-saturated sands and are also richer in 10\AA clays, suggesting the dominance of detrital clays over diagenetic clays (Table 2.9). Gas-saturated sands have approximately the same $<2\ \mu\text{m}$ content as bitumen-saturated (poorly cemented) sands (Tables 2.8).

Bitumen and $<2\ \mu\text{m}$ content are inversely related on both a regional (Fig. 2.18a) and local (Figs. 2.18b, c) scale. This trend suggests that hydrocarbon emplacement was

inhibited in samples with abundant fine particles.

2.8.1 Relationship between fines content and clay mineralogy

Comparison of clay mineral data with fines and bitumen content (Tables 2.7 and 2.8) shows that with few exceptions, bitumen-saturated sands which are high in 10Å and 17Å clays are also relatively rich in fines and poor in kaolinite and bitumen (Fig. 2.19a, b). High fines content most likely represents a high abundance of detrital (17Å and 10Å) clay. Detrital clays filled pore space during deposition and inhibited the formation of diagenetic minerals and emplacement of hydrocarbons.

2.8.2 Relationship between carbonate and bitumen contents

Occlusion of porosity by diagenetic minerals hindered hydrocarbon emplacement. Carbonate (calcite + siderite) contents greater than 10 to 15% result in lower bitumen contents (Fig. 2.20). At lower carbonate contents, bitumen content is controlled by the abundance of detrital clay minerals.

2.9 Implications for Enhanced *In Situ* Recovery of Bitumen

Five mineralogical facies have been identified (section 2.5). Bitumen-saturated sands, bitumen-saturated cemented sands and bitumen-free cemented sands occur most frequently throughout reservoir sands and their mineralogical differences affect *in situ* production strategies. Water-, and gas-saturated sands do not occur frequently throughout Wabiskaw Member reservoir sands. Swelling of smectitic clays and migration of illitic and smectitic clay from water-saturated sands should not hamper production of hydrocarbons.

In general, kaolinite is the dominant clay mineral in bitumen-saturated sands although illitic and smectitic clays can also be abundant (Fig. 2.17). Migration of fines can be expected in bitumen-saturated sands regardless of whether 7Å, 10Å or 17Å clays are dominant resulting in the reduction of permeability (Leone and Scott, 1987). However, for

sands in which 17Å (detrital) clays are abundant, clay mineral swelling may occur. Therefore, fines migration and brine sensitivity must be considered when planning production strategies.

In addition to clay minerals, diagenetic carbonates (calcite+siderite) play an important role during *in situ* recovery. Calcite and/or siderite occlude porosity in bitumen-free cemented sands and partially occlude porosity in bitumen-saturated cemented sands. Bitumen-free cemented sands may act as barriers to steam, and steam can be channelled along them to increase sweep efficiency and hydrocarbon production. Differentiation between bitumen-free and bitumen-saturated cemented sands is essential (section 1.4.1). Bitumen-saturated cemented sands contain approximately 15% porosity; if they are misidentified from geophysical logs as bitumen-free cemented sands for the purpose of steam channelling, steam will be lost to surrounding sands. Misidentification would result in decreased sweep efficiency and hydrocarbon production. Proper identification would avoid steam loss; moreover, since bitumen is present in these sands (Table 2.10), the potential exists to remove hydrocarbons from these zones.