

New evidence of carbonate cementation in the Hibernia Formation, Hibernia field, offshore Newfoundland: implications for reservoir quality

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Summary

Carbonate cements are one of the most common authigenic minerals in clastic reservoirs and impact reservoir quality and performance. When cementation is extensive, it can reduce porosity and permeability, leading to tight reservoirs. The sandstones of the Cretaceous Hibernia Formation form the major oil-bearing reservoir in the Hibernia field, located in the Jeanne d'Arc Basin. The Hibernia formation is stratigraphically divided into the Lower Zone and Upper Zone. The Lower Hibernia Zone is also subdivided into five informal units from bottom to top: Layer 4, Layer 3, Medial Shale, Layer 2 and Layer 1. The main reservoir strata occur in Layers 3 and 2. Calcite, ferroan calcite, dolomite, ferroan dolomite and siderite cements were found in various intervals of the Hibernia Formation based on core, well log and petrographic observations. Calcite and ferroan calcite occur mainly in the fluvial channel facies of Layer 3. Dolomite and ferroan dolomite are relatively minor carbonate cements in the Hibernia reservoir that occlude intragranular and intergranular porosity in mainly in fine-grained shallow marine strata. Siderite cements are widespread stratigraphically, showing different morphologies and textures in the Lower Hibernia Zone. Calcite and dolomite cements precipitated throughout much of the Hibernia Formation during early diagenesis prior to a significant carbonate dissolution event evidenced by elongated and oversized pores and corroded grain boundaries in non-cemented sandstones. Ferroan calcite is most likely to have precipitated in a reducing setting much later during burial diagenesis based on depleted oxygen and carbon isotopic signatures. Locally, sandstone intervals with no effective porosity are cemented mainly by calcite and ferroan calcite in Layers 1 and 3, respectively. However, dolomite and ferroan dolomite cements are restricted in the shallow marine strata of the Medial Shale and Layer 4, demonstrating a stratigraphic control on carbonate cementation that potentially links sedimentary environments to precipitating fluids.

Theory

The Hibernia Formation is an important Cretaceous reservoir in the Jeanne d'Arc Basin, which is a significant hydrocarbon-production region in Newfoundland (Enachescu, 2005). Sinclair et al. (2005) divided the Hibernia Formation into two stratigraphic members: the Lower Zone, where the primary reservoir strata occur, and the Upper Zone. Brown et al. (1989) interpreted the sedimentary environments of the Lower and Upper Zone as delta plain and delta front environments, respectively. Well-sorted, medium to very coarse-grained quartz arenite defines approximately three-fourths of the Lower Zone, and the remainder consists of mudstone and siltstone (Brown et al., 1998). The field operator divided the Lower zone into four subdivisions from bottom to top stratigraphically (Figure 1): A thin heterolithic interval composed of sandstone and siltstone known as Layer 4; this is overlain by Layer 3, comprising incised valley fluvial

channel facies at the bottom of the member; the Medial Shale, consisting of shallow marine mudstone; the sand-rich Layer 2 consisting of fluvial sheet sandstone; and Layer 1, characterized by marine delta front strata (Sinclair et al., 2005).

Carbonate minerals are one of the most common cements in clastic oil reservoirs and play an essential role in developing porosity and permeability (Macaulay et al., 2009). They can act as fluid flow barriers during hydrocarbon migration or production and effectively compartmentalize reservoirs (Morad, 1998). Furthermore, the chemical composition of carbonate cements have considerable implications for enhanced oil recovery (EOR) because carbonates may react with injected acid fluids and precipitate iron oxides and oxyhydroxides (Morad, 1998; Graham et al., 2020). Pore-filling calcite cements were initially reported by Brown et al. (1985) in the Hibernia formation. A petrography and SEM study corroborated the presence of calcite, dolomite and siderite in the four reservoir intervals of the Hibernia field, including the Hibernia Formation (Hesse and Abid, 1995). However, the genesis and distribution of authigenic carbonates through the reservoir remain elusive. This comprehensive study combines core and well logs data, optical and analytical petrography, stable isotopes, and trace elements analyses to understand the diagenetic history of the Hibernia reservoir, and in particular, links between early carbonate precipitating fluids and sedimentary facies that could be used to link carbonate cement distribution to reservoir stratigraphy.

Method / Workflow

Seven hundred and sixty meters of core from ten wellbores from different locations across the Hibernia field were logged in the Lower Zone interval. Forty-four samples were selected and cut into polished thin sections of 35 microns, and seven samples were further selected for MLA-SEM analysis. Percentages of framework grains and authigenic cement were estimated by MLA analyses and petrography observations. Thin sections were analyzed under a Zeiss axioScope 5 polarizing microscope with 5x, 10x, 20x and 40x lenses to identify mineral phases and diagenetic features. Seven samples were selected for quantitative mineral liberation analysis (MLA) using an FEI MLA 650F and a FEI Quanta 400 scanning electron microscope equipped with an energy dispersive X-ray (EDS) microanalytical system (Bruker AXS, XFlash Detector 4010) at Memorial University of Newfoundland. The EDS and element mapping techniques were helpful in recognizing carbonate mineral phases, cement percentages and microtextures.

$\delta^{18}\text{O}$ -values of carbonate cements are useful to constrain the influence of marine or meteoric water in diagenetic fluids, and the ^{13}C signatures constrain the carbon sources of the carbonate-bearing fluids and subsequent diagenetic processes (e.g., microbial methanogenesis, microbial sulphate reduction and decarboxylation of organic matter). Trace elements measured in representative carbonate crystals function as proxies of the origin of parent fluids (e.g., Sr) and redox conditions of precipitation during diagenesis (e.g., Mn, Mg, Fe, U and Y) (Xiong et al., 2016; Olanipekun and Azmy, 2022). Therefore, stable isotope analyses were performed on 75 μg of micro-drilled carbonate cements. Sample CO_2 was generated by a reaction of phosphoric acid using a Thermo Scientific Kiel IV Carbonate Device interfaced to the inlet of a ThermoFinnigan MAT 253 dual inlet mass spectrometer for stable isotope analysis. Lastly, Minor and trace elements were analyzed using LA-ICP-MS. Laser sampling was performed using a GEOLAS 193 nm laser system. Sampling spots (20 – 40 μm) on carbonate cements were selected under SEM.

Results

Carbonate-cemented layers were found in various intervals of the Hibernia reservoir strata by core examinations. Cemented sandstones up 2 meters thick have irregular boundaries, no concordant to bedding and low bitumen saturation because of porosity reduction. Moreover, density (RHOZ) and photoelectric factor (PEFZ) value increment and porosity reduction (TNPH) in thick sandstone bodies reflect the presence of carbonated cemented layers (Beds A-D; Figure 2). These wellbore log responses correlate with carbonate-cemented sandstones examined and sampled in core. Scattered patches of calcite of approximately 5 to 10 mm are relatively scarce and can be distinguished from carbonate-cemented layers.

Five carbonate mineral phases were identified in the Lower Hibernia Zone by petrography and SEM examinations: calcite, ferroan calcite, dolomite, ferroan dolomite, and siderite. Calcite and ferroan calcite occur in Layer 1, the Medial Shale and Layer 3, forming scattered patches and continuous cemented layers. Both types of cement have poikilotopic textures engulfing the majority of detrital grains (Figures 3a and 3b). Ferroan calcite is more abundant than non-ferroan calcite in fluvial channel facies of Layer 3, and it occasionally shows a radial fabric or plumose texture in photomicrographs. A distinctive type of ferroan calcite found in Layer 3 exhibits various rhombic morphologies and encloses organic matter (Figure 3e).

Dolomite fills intergranular spaces in Layer 4 and the Medial Shale, forming continuous cemented layers mainly in sandstone and siltstone in places where calcite cement is not pervasive. Ferroan dolomite fills intragranular pores within bioclasts in intervals where dolomite fills intergranular space (Figure 3d). Siderite occurs as nodules, concretions and scattered patches in mainly in fine-grained lithologies of the Layer 1, the Medial Shale and Layer 3 (Figure 1f). MLA and EDS examination reveal microcrystalline rhombs of siderite, filling intergranular space and occasionally shell fragments (Figure 3g and 3h). Quartz overgrowths are more common in sandstones that have no pervasive calcite cement. Lastly, pyrite cements form euhedral to subhedral microcubes occluding intergranular and intragranular porosity.

The absence of compaction fabrics in non-ferroan calcite-cemented sandstone and the paucity of contacts among cemented grains demonstrates that calcite precipitated during early diagenesis soon after deposition and prior to compaction. The relative depletion of $\delta^{18}\text{O}$ values of non-ferroan calcite (-7,65 to -1,40 ‰ VPDB, mean -5,34 ‰ VPDB Figure 2) indicates that calcite may have precipitated from diagenetic fluids influenced by mixed marine and meteoric water. Moreover, higher Y concentrations (87 ppm) compared to marine carbonates (<1 ppm, Olanipekum and Azmy, 2022) and low Sr concentrations (<1000 ppm, Xiong et al., 2016) indicate that calcite cement were not sourced from the dissolution of marine shells or directly from marine pore water. Interactions between the meteoric wedge and infiltrated pore marine waters occurred during sea-level rising after channel deposition.

Similarly, detrital grains are typically floating in dolomite cements as well, and no compaction fabric is evident, suggesting they also precipitated during early diagenesis. The oxygen signatures of dolomite cements indicate a strong influence of marine water in the precipitating fluids ($\delta^{18}\text{O}$: -4,10 to -1,59 ‰ VPDB, mean -2,92 ‰ VPDB). The $\delta^{13}\text{C}$ -values of dolomite (-11,77 to 0,58 ‰

VPDB, mean $-2,26\text{‰}$ VPDB) suggest that dolomite formed in the microbial methanogenesis zone, where ferroan dolomite also tends to precipitate (Morad, 1998). Moreover, dolomite cementation only occurs in shallow marine strata corresponding to Layer 4 and the Medial Shale, demonstrating a stratigraphic control on dolomite cementation linked to marine environments. Siderite may have precipitated during early diagenesis due to the less depleted oxygen and carbon signatures $-8,21$ to $-1,20\text{‰}$ VPDB (mean $-4,14\text{‰}$ VPDB) and $-13,43$ to $-1,61\text{‰}$ VPDB (mean $-6,36\text{‰}$ VPDB), respectively. The higher concentrations of Mn, Fe and lower Sr values indicate that siderite precipitated from reduced pore waters that usually evolve in the microbial methanogenesis zone (Morad, 1998). Widespread early carbonate dissolution by low pH fluids postdates calcite, dolomite, and siderite cementation, supported by dissolution textures such as corroded detrital grains boundaries, oversized pores and remnants of partly-dissolved feldspar grains found in sandstones where carbonate cements are absent. Based on the present evidence, early carbonate cementation in the Lower Hibernia zone is linked to the sedimentary environment of deposition.

Ferroan calcite cements then precipitated after compaction and dissolution, as evidenced by the lack of fractures in ferroan calcite cement and the presence of fractures in detrital grains. Moreover, ferroan calcite precipitated in reducing environments such as those related to burial settings, based on the enriched Mn and Fe values and low U concentrations (Olanipekum and Azmy 2022, Figure 3). The relative low Mg concentration of ferroan calcite in comparison to dolomite and non-ferroan calcite also supports the minimal influence of marine water in the precipitating fluids. The depleted oxygen ($-10,21$ to $-6,78\text{‰}$ VPDB, mean $-9,34\text{‰}$ VPDB) and carbon ($-13,11$ to $-4,91\text{‰}$ VPDB, mean: $-8,25\text{‰}$ VPDB) isotopic signatures measured in ferroan calcite evidence that this precipitated from late diagenetic fluids influenced by thermal decarboxylation processes of organic matter (Morad, 1998). The coexistence of bitumen and ferroan calcite could indicate the co-taneity of calcite precipitation and hydrocarbon migration. Further investigations will establish if late carbonated-cemented sandstones are associated with folds or fault of the Hibernia field. No carbonate cements were found in sandstones of Layer 2.

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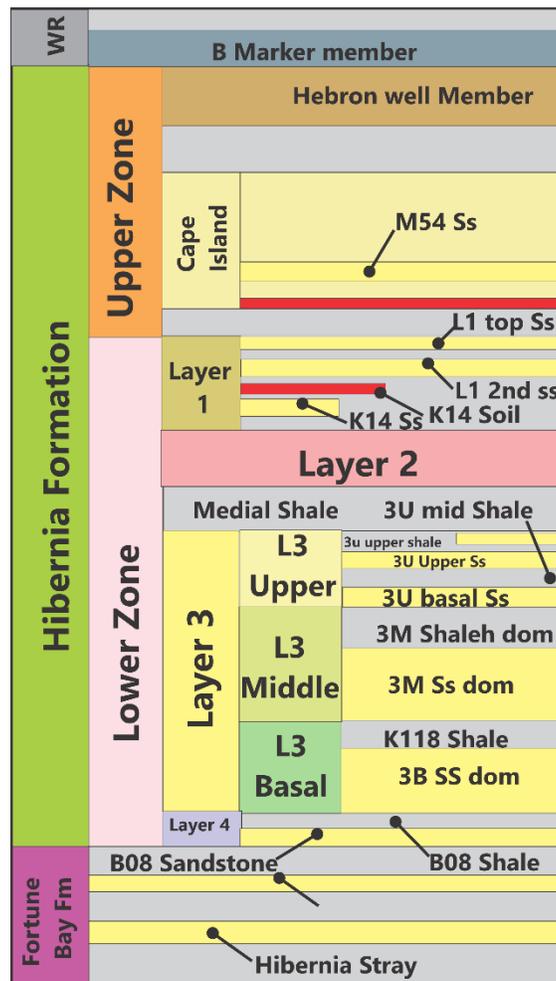


Figure 1. Lithostratigraphy of the Hibernia Formation. Modified after Sinclair et al., 2005.

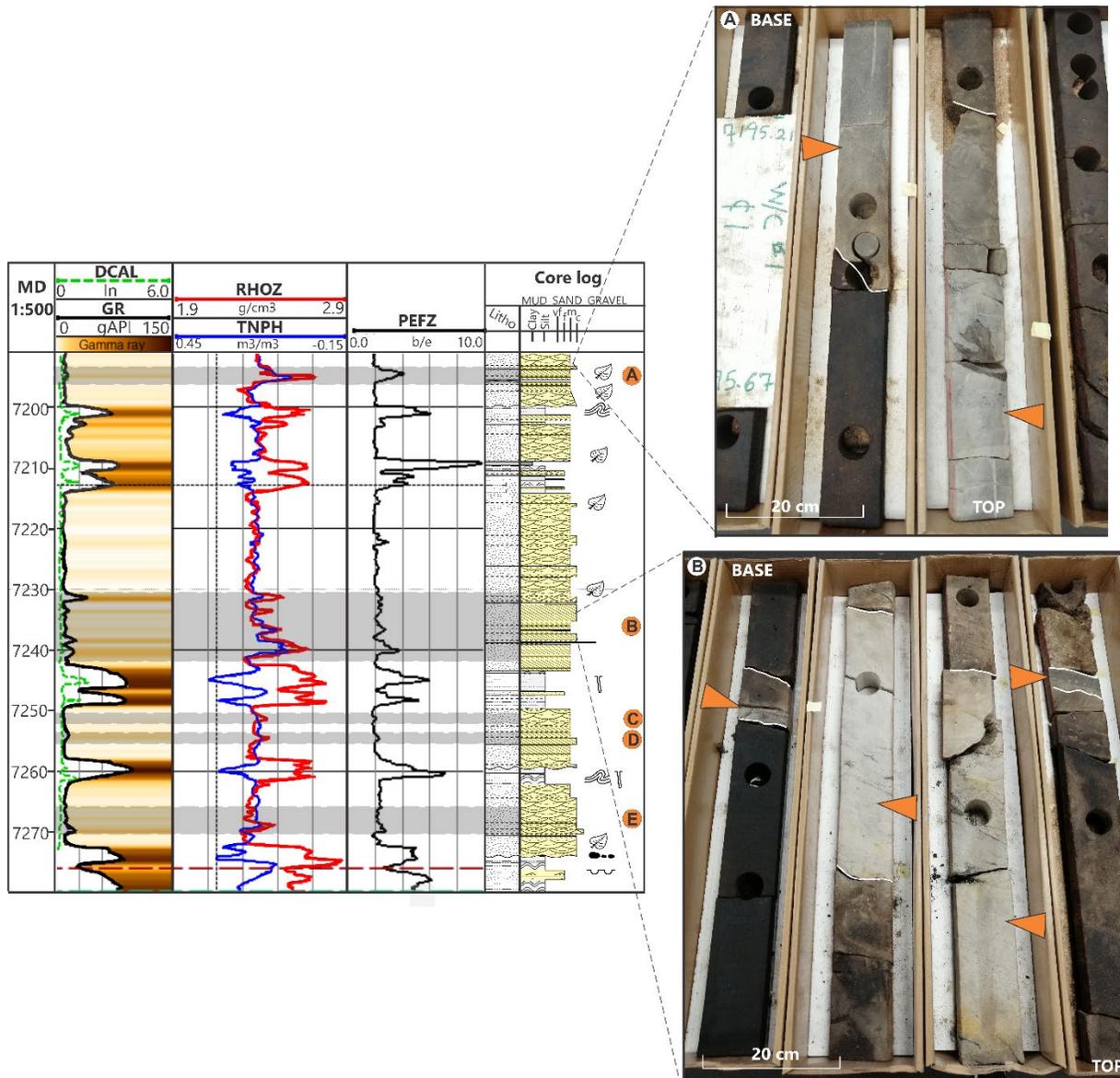


Figure 2. Wellbore logs response of carbonate-cemented sandstones in Layer 3, Hibernia B-16-55. (A) and (B) shows the carbonate cemented layers observed in cores. Note the low bitumen saturation and irregular boundaries. (GR) Gamma-ray, (RHOZ) Standard Resolution Formation Density, (TNPH) Thermal Neutron Porosity, (PEFZ) Standard Resolution Formation Photoelectric Factor.

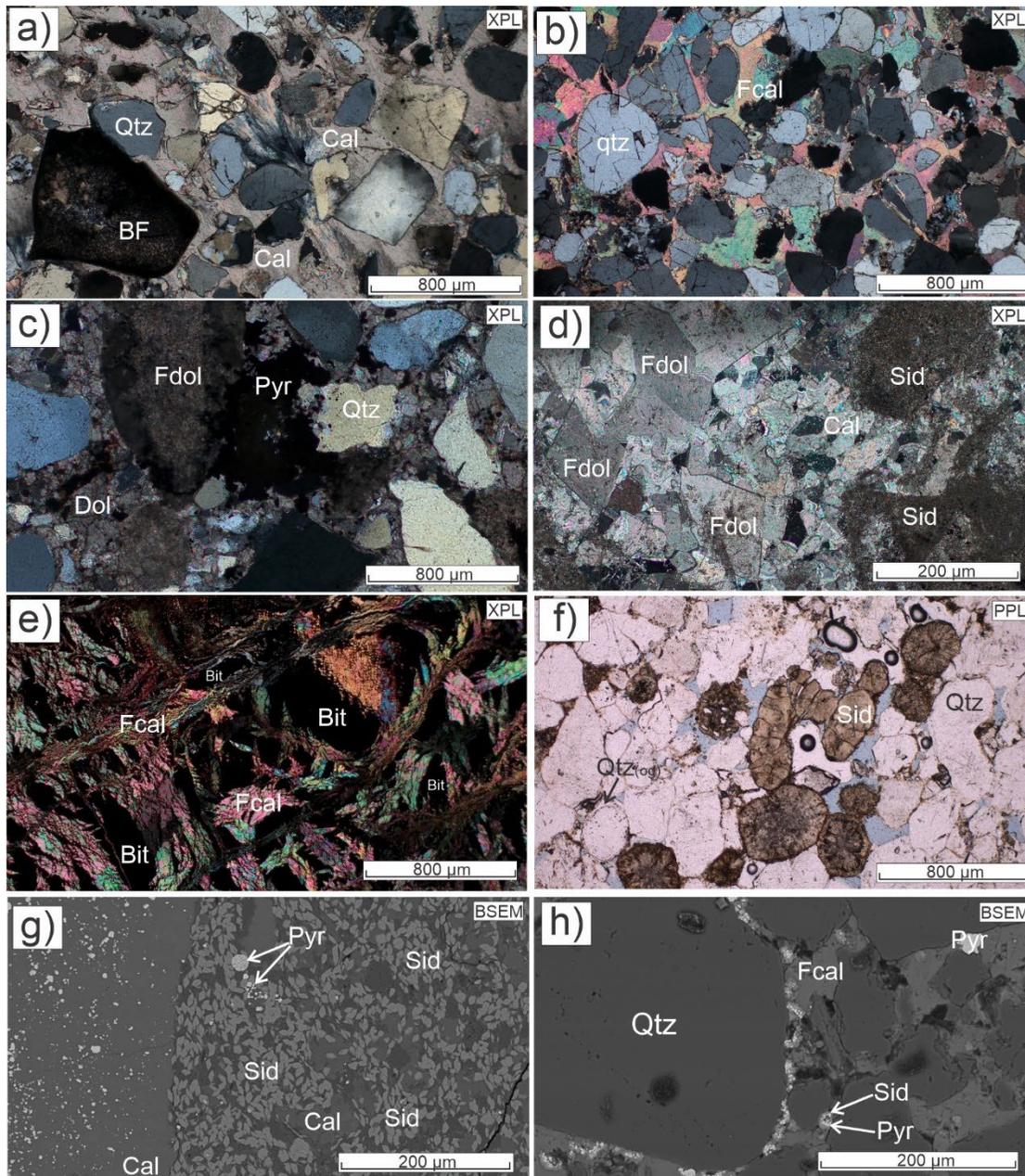


Figure 3. Photomicrograph of sandstones showing detrital grains with effective porosity occluded by a) non-ferroan calcite and b) ferroan calcite. Note in (b) the presence of fractured grains and the absence of fractures in the ferroan calcite cement. c) Dolomite engulfing detrital grains and bioclasts; d) Euhedral rhombs of ferroan dolomite filling a bioclast fragment; e) Extensive ferroan calcite and bitumen; f) Nodular aggregates of siderite partially occluding effective porosity in medium-grained sandstone. BSEM images of polished thin sections showing g) microcrystalline siderite and pyrite; h) and pyrite growing in grain-rimming siderite. Calcite (Cal), ferroan calcite (Fcal), dolomite (D), ferroan dolomite (Fdol), Siderite (Sid), Pyrite (Pyr), Quartz overgrowth (Qtz(og)) and bioclast fragments (BF).

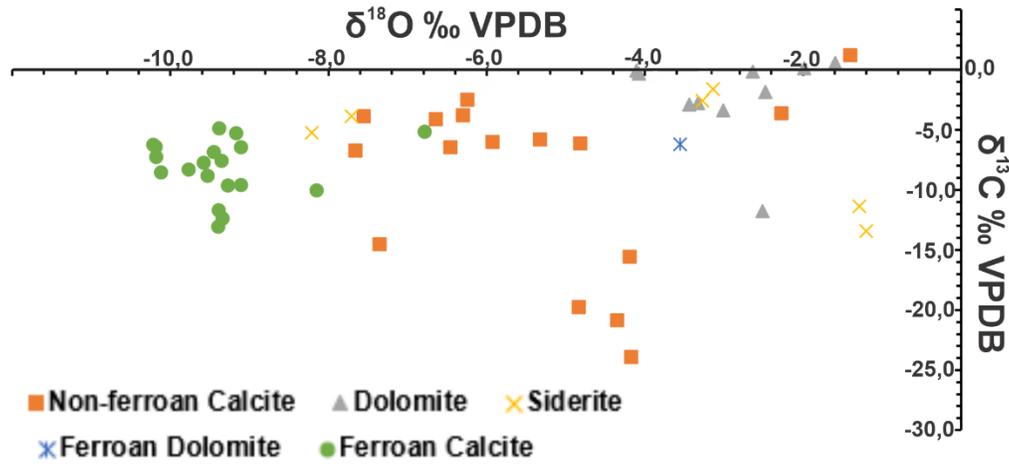


Figure 4. Scatter diagram of $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ for non-ferroan calcite, dolomite, ferroan dolomite, siderite and ferroan calcite.

		Fe (ppm)	Mg (ppm)	Mn (ppm)	Sr (ppm)	Y (ppm)	U (ppm)
Ferroan Calcite n=15	Mean	14424	3001	2150	938	4,994	0,015457
	Min	12560	2118	1874	619	1,62	0,002
	Max	16190	3519	2312	1703	13,86	0,041
Non-ferroan calcite n=15	Mean	141	17667	2954	599	87,96056	0,026853
	Min	23	16670	2379	538	0,427	0,0021
	Max	450	19040	3713	687	1560	0,049
Dolomite n=11	Mean	6931	94790	1778	332,6	15,79636	217,3215
	Min	2970	93700	1602	323,3	8,11	0,335
	Max	15800	96500	1920	338,8	21,75	1330
Ferroan Dolomite n=11	Mean	49145	71418	2277	464	12,48818	0,737727
	Min	38500	38000	1343	321,2	9,31	0,459
	Max	71200	83700	2620	590	20,3	1,66
Siderite n=15	Mean	380400	19216	3662,2	178,86	9,363333	3,534667
	Min	289000	17400	3460	136,2	7,9	2,67
	Max	408000	20240	3920	338	12,25	4,89

Table 1. Trace element concentrations for ferroan calcite, non-ferroan calcite, dolomite, ferroan dolomite and siderite.