GEOCHEMISTRY OF THE FRACTURE-FILLING DOLOMITE AND CALCITE CEMENTS IN MIDDLE DEVONIAN DUNEDIN FORMATION: IMPLICATION FOR THE STRATA DOLOMITIZATION MODEL

Sze-Shan Yip[1], Hairuo Qing[1] and Osman Salad Hersi[1]

ABSTRACT

Coarsely crystalline saddle dolomite and blocky calcite cements in the dolomitized reservoir of the Dunedin and Stone formations of northeast British Columbia have been studied over the last two decades. Vitrinite reflectance study, and isotopic composition and fluid inclusion geochemical analyses supported that these two crystalline phases were precipitated during the Latest Devonian to Early Carboniferous from modified Devonian seawater. Coarsely crystalline saddle dolomite has been interpreted to be the product of hydrothermal dolomitization. Hydrothermal dolomitization and secondary porosity creation are therefore interpreted to have occurred during the Latest Devonian to Early Carboniferous.

Recent core investigation identified three sets of fractures within the strata that cross-cut the two coarsely crystalline cement phases. Some of the fractures are filled with dolomite, some are filled with calcite and others remain open. Geochemical analyses have shown similarities between coarsely crystalline saddle dolomite and fracture-filling dolomite. Similarities were also found between coarsely crystalline calcite and fracture-filling calcite. Petrological observation and geochemical analytical results suggest the fracturing-filling dolomite was precipitated at the same time as or immediately after its void-filling, coarsely crystalline saddle dolomite counterpart, and that fracture-filling calcite was precipitated at the same time as or immediately after its void-filling, coarsely crystalline blocky calcite counterpart. High dip angles measured from both dolomite and calcite-filled fractures indicate that the dominant compression direction was from top to bottom. These findings help to put an additional and essential time constraint on the relative timing of hydrothermal dolomitization.

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[1]Department of Geology, University of Regina. Regina, Saskatchewan S4S 0A2, Canada

INTRODUCTION

The Middle Devonian carbonate play type has upwards of 2.35 trillion cubic feet (Tcf) of remaining undiscovered gas in place within northeastern British Columbia (National Energy Board 2000). Investigating the sedimentology, diagenetic evolution, fractures, and geochemical and fluid inclusion attributes of the strata provides a renewed opportunity for expanding our knowledge of the dolomite reservoirs in northeastern British Columbia. Coarsely crystalline saddle dolomite, calcite, and cemented-filled fractures in the Middle Devonian Stone and Dunedin formations are the focus of this study (Figures 1 and 2).

GEOLOGICAL MODEL AND PROBLEMS

A development model for dolomite reservoirs in the study area has been proposed by Morrow et al. (1990). Maturation of organic-rich Devonian Besa River shale occurred during the Late Paleozoic to Early Mesozoic. Hydrocarbons were expelled and migrated laterally and downward into the permeable dolomitized strata. Intense deformation during the Tertiary Laramide orogeny has resulted in further fracturing and additional permeability development; anticlinal folding and thrust faulting also occurred during that time. Fluid inclusion microthermometric analysis by Aulstead (1987) showed that the homogenization temperatures of primary inclusions in saddle dolomite are between 150 and 215 °C with a mean of around 185 °C, which corresponds to the geothermal temperature during the Late Devonian to Carboniferous in southernmost Yukon (adjacent to 94N map area; Morrow and Aulstead 1995). Fractures that are filled with dolomite cement were found by Davies and Smith (2006). The fractures were interpreted to be shear microfractures.

Collaborative diagenesis studies on the Stone and Dunedin formations were initiated in 2007 by the British Columbia Ministry of Energy, Mines and Petroleum Resources (MEMPR) and the University of Regina. Nineteen diagenetic phases have been identified from core and petrological investigation (Figure 3). Core investigation in Janu-

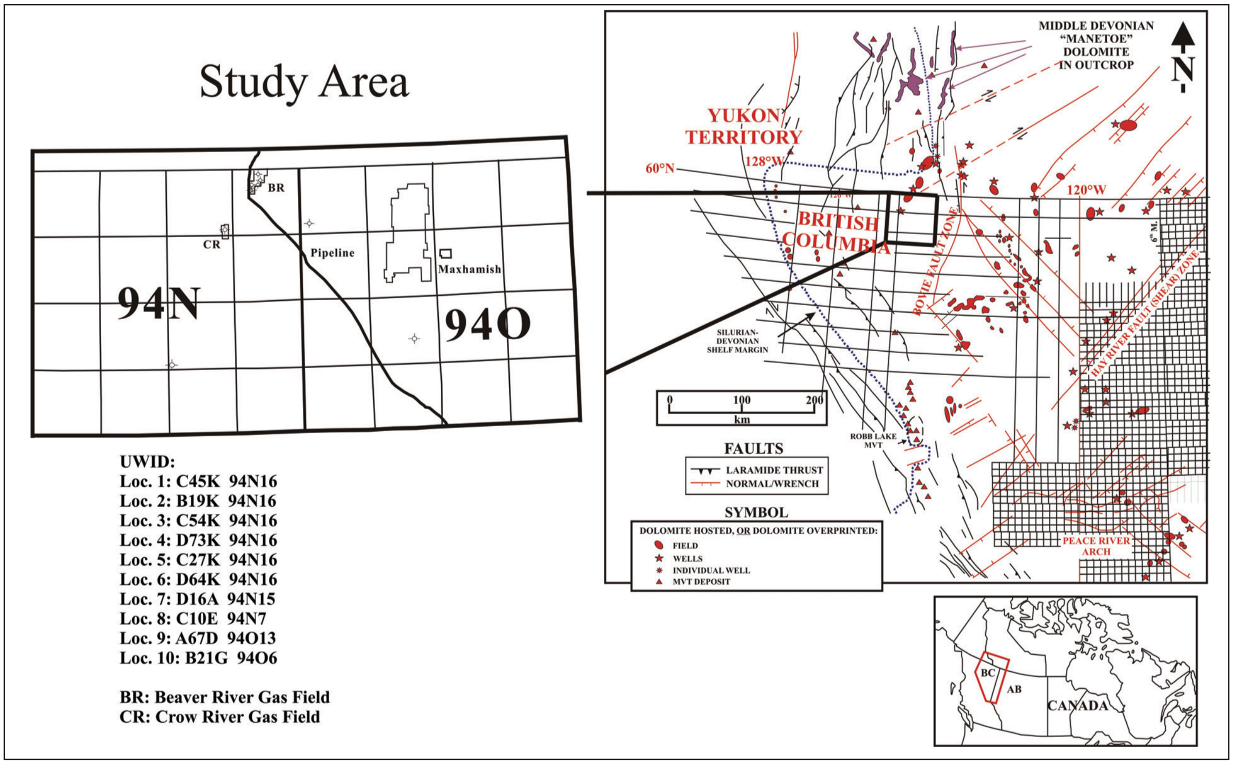

Figure 1. Geographic map of northeast British Columbia and the study area and list of studied wells.Geographic map modified from Davies and Smith (2006).

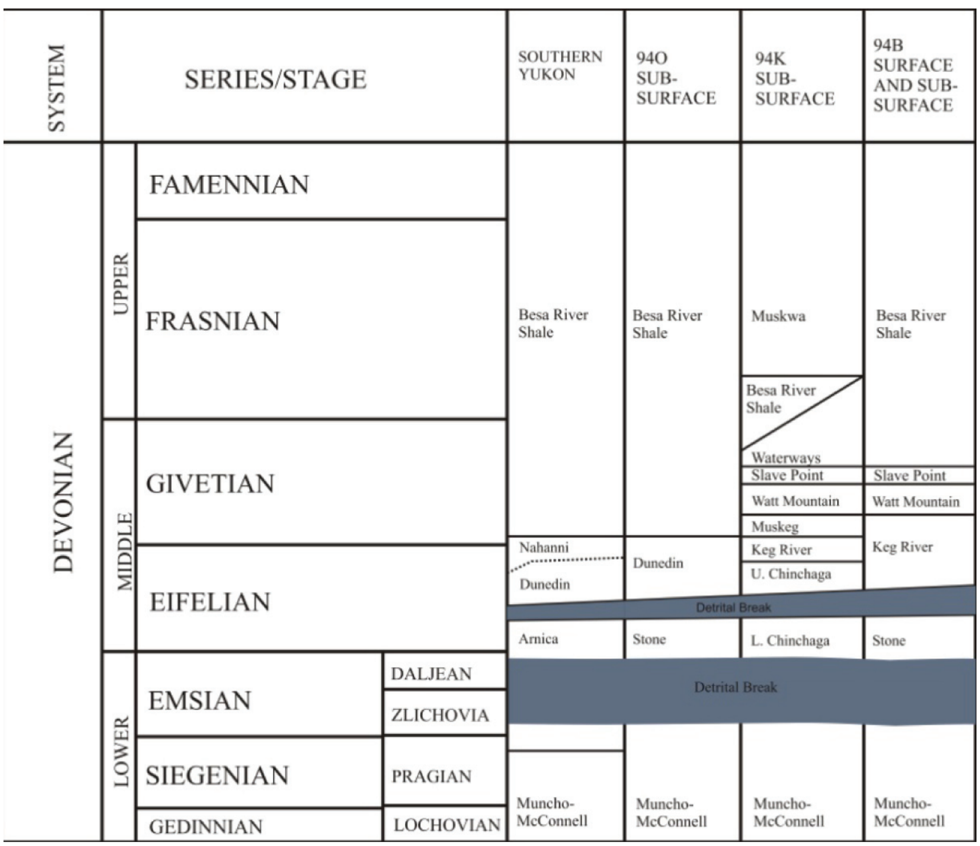

Figure. 2. Stratigraphic chart of the Middle Devonian strata in northeast British Columbia and adjacent Yukon subsurface (Modified from Nadjiwon 2001).

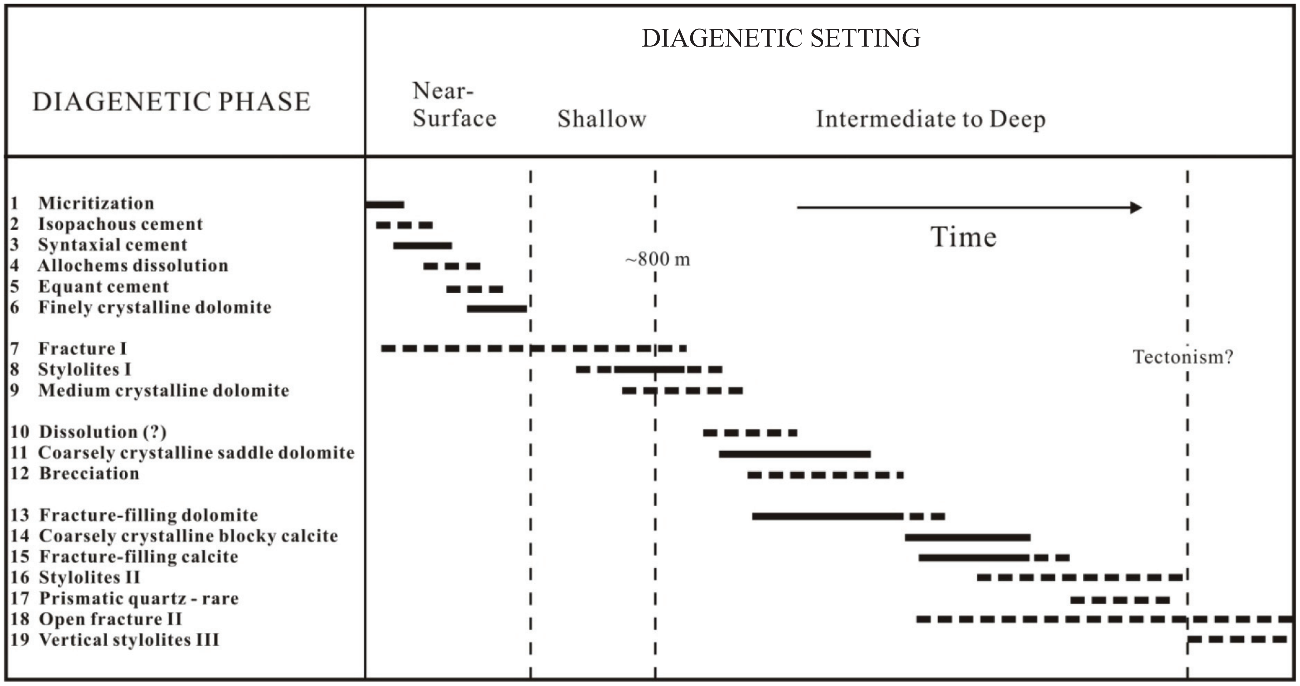

Figure 3. Summary of diagenetic paragenesis of the Middle Devonian Stone and Dunedin formations. Diagenetic phases were identified from petrological and petrographic investigation. They were record by their first appearance and cross-cutting relationship with other phases. Diagenetic phase 1 being the first phase that precipitated or formed immediately after sedimentation. Diagenetic phase 11 – Coarsely crystalline saddle dolomite, 13 – Fracture-filling dolomite, 14 – Coarsely crystalline blocky calcite, 15 – Fracture-filling calcite and 18 – Open fracture II are discussed in this report. Diagenetic phase 1 to 9 and other phases are described and interpreted in the first author's thesis-in-preparation.

ary 2009 has identified three sets of fractures in the strata (Figure 4). The fractures are filled with dolomite, filled with calcite, or remain open. Dolomite-filled fractures appear to have developed before coarsely crystalline saddle dolomite precipitation (Davies and Smith 2006). Calcite-filled fractures have not been reported in the literature. These fractures are crucial geological records in studying dolomitized carbonate reservoirs, because they are the diagenetic phases that directly cross-cut saddle dolomite. They provide important information on the fluid temperature and isotopic composition of the diagenetic fluid that flowed through the strata, which constrain the relative timing of dolomitization, allowing stratal dolomitization models to be further refined.

RESULTS

Structure

Structural measurements of dolomite- and calcite-filled fractures were plotted in Figures 5 and 6. Dolomite-filled fractures show bimodal strike orientation towards east and west. Dip directions are oriented north and south. Dip angles are dominantly 60° to 90°. Calcite-filled fractures show diffused to bimodal strike orientation towards northeast and southwest. Dip directions are oriented northwest and southeast. Dip angles are predominantly from 50° to 90°. The core axis was assumed to be vertical because no record was available.

Oxygen and Carbon Isotopes

Stable oxygen and carbon isotope results are summarized in Table 1. $\delta^{18}O$ and $\delta^{13}C$ cross-plots are presented in Figure 7. Coarsely crystalline, nonplanar-e, saddle dolomites show oxygen isotope ratios from -10.01 to -16.63 ‰ V-PDB and carbon isotope ratios from -1.51 to -9.02 ‰ V-PDB. Medium crystalline, fracturing-filling dolomite shows oxygen isotope ratios from -9.09 to -14.28 ‰ V-PDB and carbon isotope ratios from +1.05 to -7.71 ‰ V-PDB. Coarsely crystalline, blocky calcites show oxygen isotope ratios from -9.80 to -15.50 ‰ V-PDB and carbon isotope ratios from -1.71 to -11.23 ‰ V-PDB. Medium crystalline, fracture-filling calcites show oxygen isotope ratios from -11.61 to -13.49 ‰ V-PDB and carbon isotope ratios from -1.74 to -10.63 ‰ V-PDB.

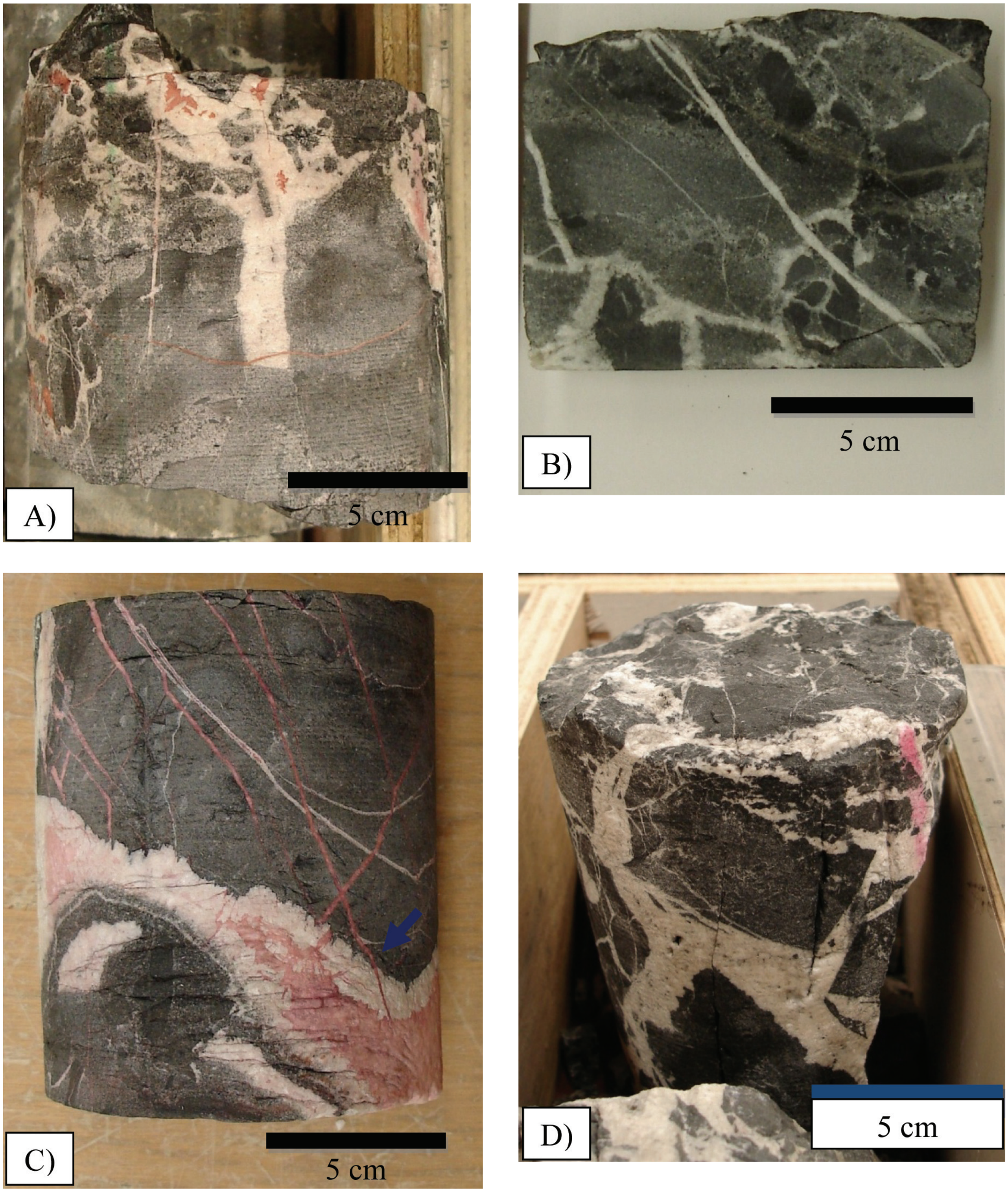

Figure 4. Core photos from D-16-A/94-N-15. A) Stained core photo showing the cross-cutting relationship between coarsely crystalline saddle dolomite, coarsely crystalline blocky calcite, dolomite-filled fracture, and calcite-filled fracture. 3798.0 m. B) Dolomite-filled fracture. 3810.9 m. C) Dolomite- and calcite-filled fractures as shown by Alizarin Red S staining. Notice calcite-filled fractures cut into saddle dolomite at the lower right corner (arrow). 3815.0 m. D) Open to partially open fracture post-dating coarsely crystalline saddle dolomite and blocky calcite. 3783.7 m.

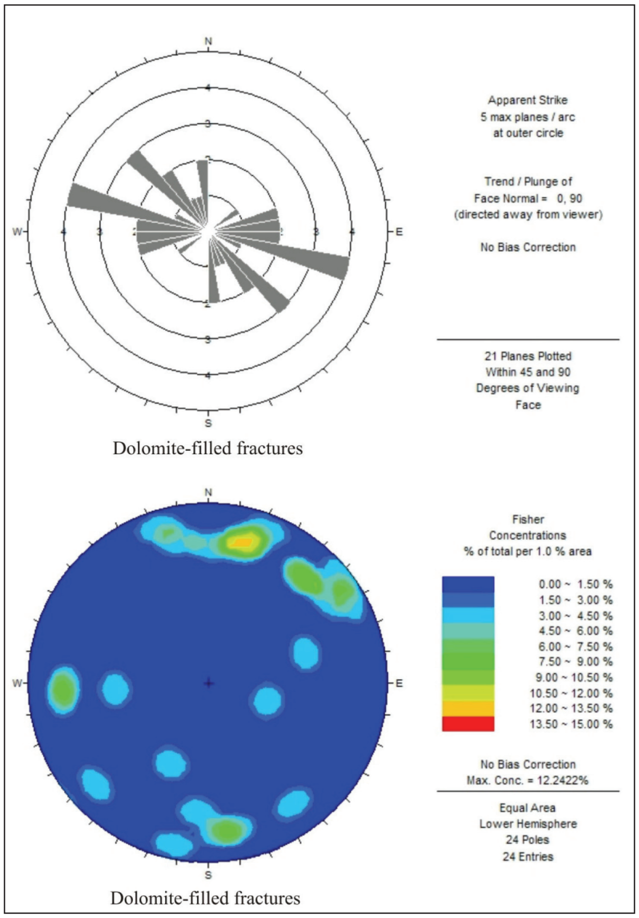

Figure 5. Structural data measured from well D-16-A/94-N-15, 3764.0 to 3818.0 m. Top: Strike orientation of dolomite-filled fractures. Bottom: Lower hemisphere stereoplots of structural data showing bimodal dipping directions towards SW and NE.

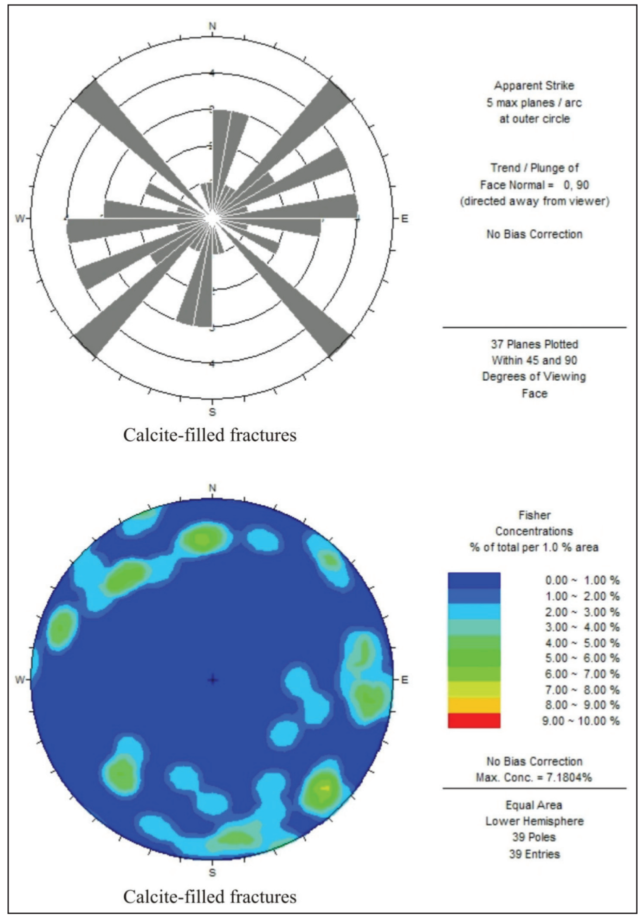

Figure 6. Structural data measured from well D-16-A/94-N-15, 3764.0 to 3818.0 m. Top: Strike orientation of calcite-filled fractures. Bottom: Lower hemisphere stereoplots of structural data showing bimodal dipping directions towards SE and NW.

TABLE 1. SUMMARY OF STABLE OXYGEN AND CARBON ISOTOPE ANALYTICAL RESULTS FOR SAMPLES FROM THE STONE AND DUNEDIN FORMATIONS.

Diagenetic Phase (Number of Samples)	$\delta^{18}O$ (Mean; ‰, V-PDB)	$\delta^{13}C$ (Mean; ‰, V-PDB)
Coarsely crystalline, nonplanar-e, saddle dolomite (n=13)	-12.47	-3.25
Medium crystalline, fracture-filling dolomite (n=19)	-11.54	-2.53
Coarsely crystalline, blocky calcite (n=10)	-13.26	-6.95
Medium crystalline, fracture-filling calcite (n=11)	-12.87	-6.58

Fluid Inclusion Microthermometry

Fluid inclusion microthermometric data of two samples collected from the Dunedin Formation in well D-16-A/94-N-15 are presented in Table 2. Homogenization temperatures (T_h) measured from coarsely crystalline saddle dolomite are from 191 to 228 °C (mean = 209 °C; n = 7); melting temperatures (T_m) are from -17.0 to -16.8 °C (mean = 16.9; n = 2). Homogenization temperatures measured from coarsely crystalline calcite are from 165 to 196 °C (mean = 186 °C; n = 19); melting temperatures are from -18.5 to -13.2 °C (mean = 16.0; n = 8). Homogenization temperatures measured from fracturing-filling dolomites are from 185 to 208 °C (mean = 199 °C; n = 21); melting temperatures are from -16.0 to -16.1 °C (mean = -16.1; n = 2). Homogenization temperatures measured from fracturing-filling calcites are from 176 to 195 °C (mean = 188 °C; n = 9); melting temperatures are from -20.8 to -15.1 °C (mean = -17.8; n = 5).

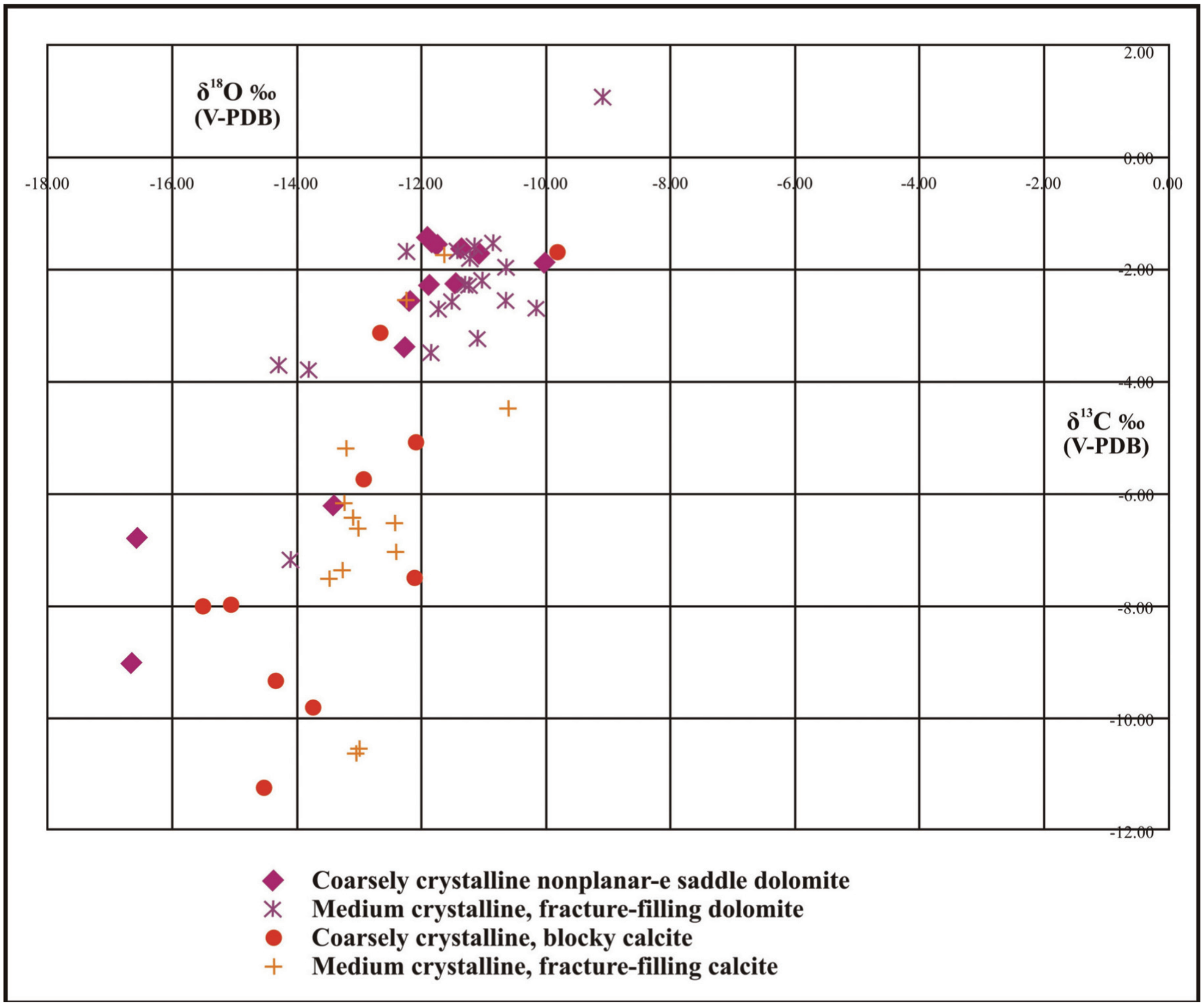

Figure 7. Oxygen and carbon isotope cross-plot for saddle dolomite, fracture-filling dolomite, blocky calcite, and fracture-filling calcite.

SUMMARY

This report summarizes the recent geochemical analysis of an ongoing graduate research project. Three sets of fractures have been identified. One fracture set is filled with dolomite, one fracture set is filled with calcite and one set is open. Coarsely crystalline saddle dolomite in the matrix is being compared with fracture-filling dolomite, and coarsely crystalline calcite in the matrix is being compared with fracture-filling calcite. Oxygen isotope analyses and fluid inclusion microthermometric studies have shown similarities between the coarsely crystalline saddle dolomite and the fracture-filling dolomite. Both phases are depleted in $\delta^{18}O$, and the majority of the values are from -10 to -13 ‰ V-PDB. Homogenization temperatures are predominantly from 195 to 205 °C. These indicate that the two dolomite phases were precipitated under similar conditions. Similarities were also found between the coarsely crystalline calcite and fracture-filling calcite. $\delta^{18}O$ analytical results of both phases are from -12 to -16 ‰ V-PDB (Figure 7). Homogenization temperatures are predominantly from 174 to 195 °C. These suggest that the two calcite phases were precipitated under similar conditions.

Petrological observation and geochemical analytical results suggest that 1) the fracture-filling dolomites were precipitated at the same time as or immediately after their void-filling, coarsely crystalline saddle dolomite counterparts; 2) fracture-filling calcites were precipitated at the same time as or immediately after their void-filling, coarsely crystalline calcite counterparts.

High dip angles (70° to 90°) measured from both dolomite- and calcite-filled fractures indicate that the dominant compression direction was from top to bottom. The preliminary interpretation is that these fractures were developed in deep burial settings. Ongoing fracture mapping will help to determine whether these fractures were developed by tectonic activity or by hydrostatic pressure during massive fluid flow (Davies and Smith 2006).

TABLE 2. SUMMARY OF FLUID INCLUSION MICROTHERMOMETRIC DATA FOR TWO SAMPLES FROM WELL D-16-A/94-N-15.

Well ID (Depth)	Diagenetic Phase	Occurrence (inclusions measured)	Size (µm)	Vapor (%)	Tm-first (range °C; n)	Tm-HH (range °C; n)	Tm-H_2O (range °C)	Tm-H_2O (mean °C; n)	Th-final (range °C)	Th-final (mean °C; n)
D16A 94N15 3764.3 m	Coarsely-crystalline saddle dolomite	Random (7)	1 – 3	5 – 7	-55 (1)	-25 (2)	-16.8 – -17.0	-16.9 (2)	191 – 228	209 (7)
D16A 94N15 3764.3 m	Coarsely-crystalline blocky calcite	Random (2)	3 – 5	5 – 6	-53 (1)	-23 (2)	-15.1 – -14.8	-15.0 (2)	188 – 191	190 (2)
		Random (1)	9	5	<-49 (1)	-24 (1)	-14.0	-14.0 (1)	196	196 (1)
		Cluster (5)	4 – 13	6 – 10	-	-25 (2)	-18.5 – -16.0	-17.5 (5)	188 – 199	193 (5)
		Random (2)	8 – 14	5 – 6	-	-22 (1)	-15.5 – -13.2	-14.4 (2)	186 – 191	189 (2)
		Random (3)	9 – 20	6	<-46 (1)	-23 (1)	-14.8 – -14.5	-14.7 (3)	165 – 166	166 (3)
		Random (3)	5 – 6	6	-52 (1)	-23 (1)	-16.3 – -15.3	-15.8 (3)	174 – 193	182 (3)
		Random (3)	4 – 9	5 – 6	<-46 (1)	-23 (2)	-18.5 – -18.2	-18.4 (2)	184 – 194	188 (3)
D16A 94N15 3816.8 m	Fracture-filling dolomite	Random (3)	2 – 3	5	-56 (1)	-25 (1)	-16.0	-16.0 (1)	202 – 207	205 (3)
		Random (2)	2	5	-	-	-	-	206 – 208	207 (2)
		Random (3)	2	5	-	-	-16.1	-16.1 (1)	197 – 198	198 (3)
		Random (7)	2 – 4	5	-55 (3)	-24 (1)	-	-	185 – 212	200 (7)
		Random (3)	2 – 3	5 – 6	-	-	-	-	186 – 194	189 (3)
		Cluster (3)	3 – 4	5 – 6	-56 (1)	-26 (2)	-	-	194 – 204	197 (3)
D16A 94N15 3816.8 m	Fracture-filling calcite	Random (1)	10	5	-53 (1)	-24 (1)	-17.3	-17.3 (1)	187	187 (1)
		Random (1)	4	5	-54 (1)	-25 (1)	-20.8	-20.8 (1)	179	179 (1)
		Random (2)	6	5	-53 (1)	-24 (1)	-19.3	-19.3 (1)	193 – 195	194 (2)
		Random (1)	5	6	-53 (1)	-24 (1)	-16.3	-16.3 (1)	176	176 (1)
		Random (2)	5	6	-53 (1)	-24 (2)	-15.1	-15.1 (1)	191 – 193	192 (2)
		Random (1)	7	6	-52 (1)	-23 (1)	-	-	189	189 (1)
		Random (1)	7	6	-	-23 (1)	-16.6	-16.6 (1)	192	192 (1)

Tm-first: first (antarcticite) melting temperature (observed antarcticite melting temperature).
Tm-HH: hydrohalite melting temperature (observed hydrohalite melting temperature).
Tm-H_2O: ice melting temperature (observed ice melting temperature).
Th-final: final homogenization temperature (from liquid + vapor → liquid)

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