Brecciation and hydrothermal dolomitization of the Middle Devonian Dunedin, Keg River, and Slave Point formations of northeastern British Columbia.

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INTRODUCTION

The Devonian paleogeography of northeast British Columbia was influenced by several rifting events, forming a miogeocline with deep troughs and marginal platforms (Cecile *et al*. 1997). One of these platforms, the Macdonald Shelf, was the site of deposition for some of the largest carbonate reservoirs in the Devonian of the Western Canadian Sedimentary Basin (Moore 1989). Most petroleum in northeastern British Columbia is found in hydrothermally dolomitized reservoirs associated with the Keg River-Slave Point barrier. Middle Devonian strata in northeast British Columbia include the platform deposits of the Dunedin and lower Keg River formations and the reefs of the upper Keg River and Slave Point formations. These formations were examined from seventeen localities in the Rocky Mountains and twenty cores from the adjacent subsurface to the east of the outcrop belt (Figure 1).

Hydrothermal saddle dolomite is the host of numerous sulphide and petroleum deposits worldwide. Saddle dolomite generally occurs in a complex mineralogical and fabric association (the hydrothermal dolomite reservoir facies, or HTD) including host limestone, matrix dolomitization, brecciation and fracturing with saddle dolomite cementation, bitumen, sulphide minerals, and late calcite and quartz cements. Fluid inclusion data indicate that globally saddle dolomites precipitate from highly saline brines at high temperature, and have a characteristic stable isotope signature for oxygen and carbon (Berger and Davies 2000).

There are currently three models in use to explain the genesis of extensive subsurface hydrothermal dolomite reservoir facies. The first model, topographic recharge and regional subsurface dolomitization, proposed by Garven and Freeze (1984), utilizes the hydrodynamic potential of elevated topography within thrust belts to drive deep groundwater circulation, creating stratabound HTD's. The second model was first proposed by Oliver (1986), and is currently known as the tectonically driven compaction flow model. In this model, tectonic compression and loading during orogenies act as a squeegee, pushing formational fluids into the foreland basins and creating stratabound HTD's. The third model, hydrothermal convection, (e.g. Morrow *et al*. (1986)) requires a critical basal heat flow to initiate subsurface fluid convection.

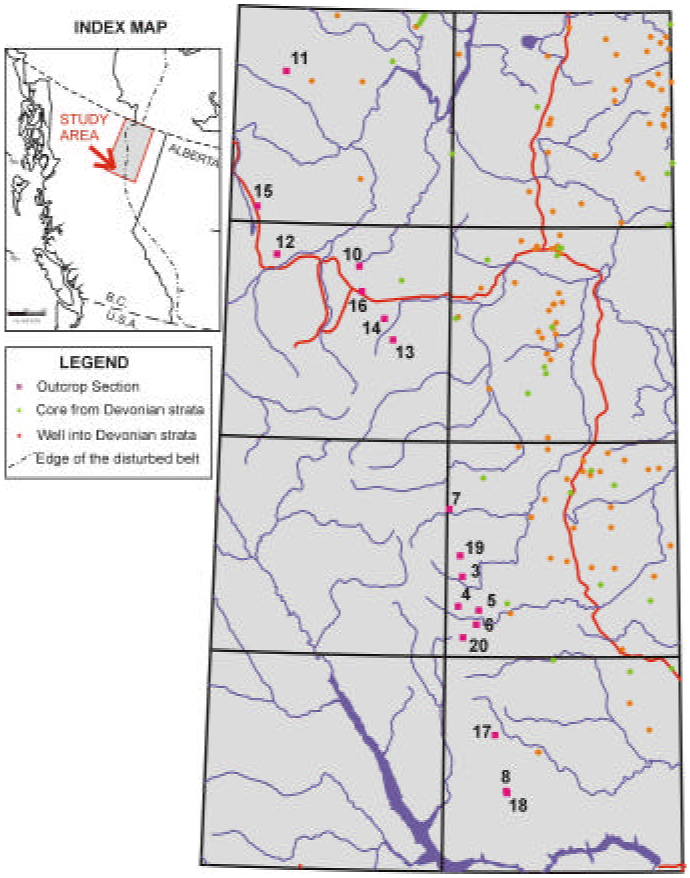

Figure 1. Location of research area, indicating locations of sections and examined core.

STUDY RESULTS

This study involved the examination of the Dunedin and Keg River formations in the outcrop belt of the Rocky Mountains, and the Dunedin, Keg River and Slave Point formations in the subsurface to the east of the outcrop belt. Similar hydrothermal dolomite textures were seen in all formations in the subsurface and in the Keg River Formation in outcrop.

The most common dolomitization is replacement of the matrix by non-planar dolomite, referred to as saddlerization (Figure 3). The dolomite is generally non-ferroan, and varies in crystal size from 50 to 800 µm. Crystal size differences produce a mottled appearance in some rocks (Figure 3B), and in general replaced bioclasts are composed of the coarser crystals. Crystals are dark due to high concentrations of inclusions. Bioclasts are at times replaced by finer crystalline dolomite with some retention of internal fabrics (Figure 3A), totally replaced by coarse white saddle dolomite (size <1 mm), or dissolved to form vugs, generally lined with coarse (1-3 mm) saddle dolomite crystals.

The other dolomite type is coarse saddle dolomite cement which occurs as vug linings and fillings (Figure 4A), cement in breccias (Figure 4B), and fracture cement in unbrecciated areas. The crystals are generally white, have a relatively low inclusion content, and can range in size from 500 µm to several millimeters.

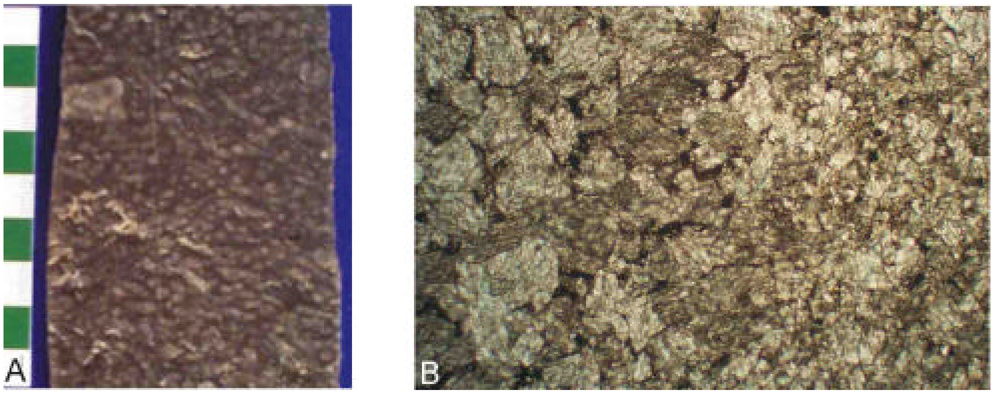

Figure 3. Replacement dolomite. A) fabric-retentive dolomitization in amphiporid floatstone, slab from Section 20, Keg River Formation, scale in centimeters; B) plane light thin section photomicrograph of saddlerization, with anhedral to subhedral crystals ranging from fine to coarse in size, field of view 3.5 mm, Well R7, Slave Point Formation.

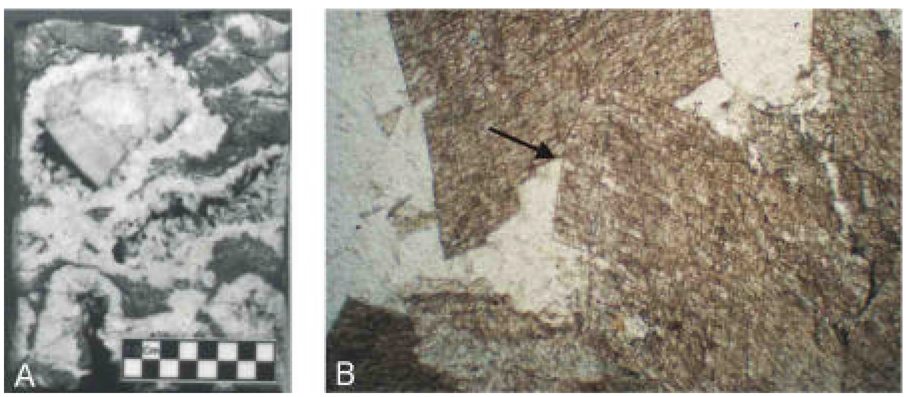

Figure 4. Saddle dolomite cement. A) core photograph of saddle dolomite lining vugs, Well L4, Dunedin Formation; B) plane light thin section photomicrograph showing the curved spear form (arrow) of saddle dolomite cement lining a void that was subsequently filled with late quartz cement, Well R7, Slave Point Formation.

The two dolomite types recognized are associated with several different dolomitization textures. One common texture is “salt and pepper”, named for the marked contrast between the white euhedral saddle dolomite crystals and the black residual bitumen matrix (Figure 5A). This texture is commonly associated closely with the more general replaced saddlerized dolomites. Zebroid texture (Figure 5B, C) consists of white saddle dolomite cement lining sheet cavity networks within a saddlerized host rock. These cavities can extend for tens of centimeters (Figure 5B), and are commonly joined by vertical veins cemented by white saddle dolomite. A feature of this texure is the common abutment of the zebroid textures against a vertical to sub-vertical fractures or joints (Figure 5C).

The most common texture associated with hydrothermal dolomitization is brecciation, which resulted in the formation of crackle packbreccia to rubble floatbreccia with more than 50% cement (Figure 6). The cement is always coarse white saddle dolomite, but clasts can be saddlerized to salt and pepper texture, or ghosts within the cement, indicating partial digestion during cementation (Figure 6A). Brecciation can occur as a single phase of saddlerized clasts and cement, or as several stages of brecciation where older brecciated fabric occurs as clasts within younger breccias. Brecciation can be found within single beds or extensively within formations (Figure 6B).

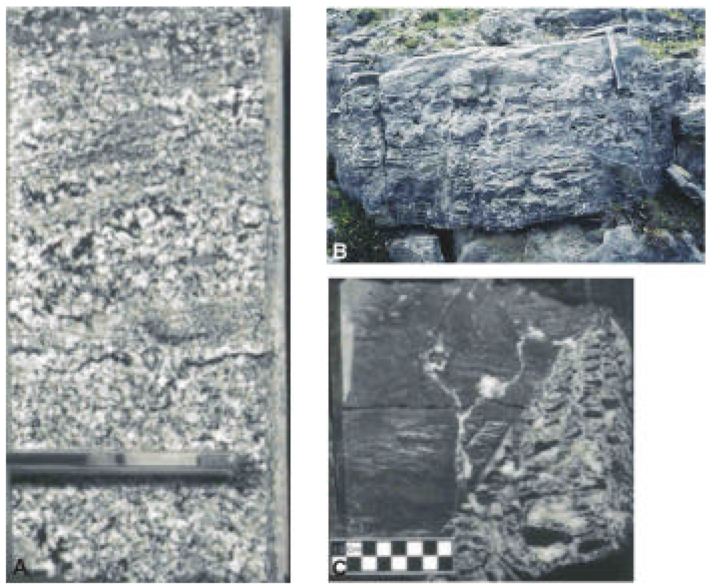

Figure 5. Dolomitization textures. A) core sample showing salt and pepper fabric, Well R7, Keg River Formation; B) field photograph of zebroid dolomitization texture showing extent of the sheet cavity networks and vertical interconnections between them, Section 5, Keg River Formation; C) core photograph of zebroid dolomitization fabric (right side of photograph), which is truncated abruptly against a sub-vertical fracture, Well L9, Keg River Formation.

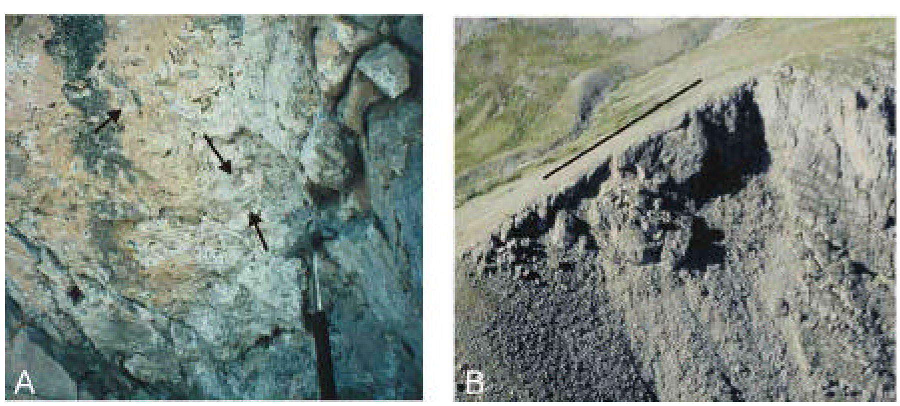

Figure 6. Brecciation textures. A) outcrop photograph of highly altered and replaced breccia, with nearly total digestion of the clasts (arrows) by

the white and pink saddle dolomite cement, Section 17, Keg River Formation; B) outcrop photo of breccia mass extending more than 200 m stratigraphically (below the black line), Section 5, Keg River Formation.

Associated with the dolomitization fabrics are late-stage cements and other features. Coarse calcite cement and euhedral quartz prisms are common post-dolomitization void linings and fillings (Figure 8). Both post-date bitumen residues left in the voids (Figure 8A), and sulphides if present, including sphalerite and pyrite. The calcite and quartz cements are generally mutually exclusive, and whereas calcite typically fills completely the vugs in which it occurs, quartz cement generally only lines its saddle dolomite substrate (Figure 8B). The isotopic signature of the late-stage calcites ($\delta^{18}O$ = -13.5‰ to -11.4‰; $\delta^{13}C$ = -5.3‰ to –2.3‰) indicate precipitation from hydrothermal fluids with composition very different from Devonian seawater ($\delta^{18}O$ = -5.8‰ to –3.7‰, $\delta^{13}C$ = 0‰ to 4‰). Fluid inclusion analysis on the same samples indicate precipitation from highly saline brines at temperatures above 110°C. Both the calcite and quartz cements contained hydrocarbon inclusions. Other late diagenetic features that post-date dolomitization include bitumen emplacement, which pre-dates the calcite and quartz cement; stylolitization, which also pre-dates the late cements; and sulphide precipitation, which may be contemporaneous with or post-date the dolomitization. Pyrite and sphalerite may occur as disseminated patches within breccia clasts, as breccia cement, and as late-stage filling of voids within a saddlerized host. More rarely sulphides occur as clasts within the breccia.

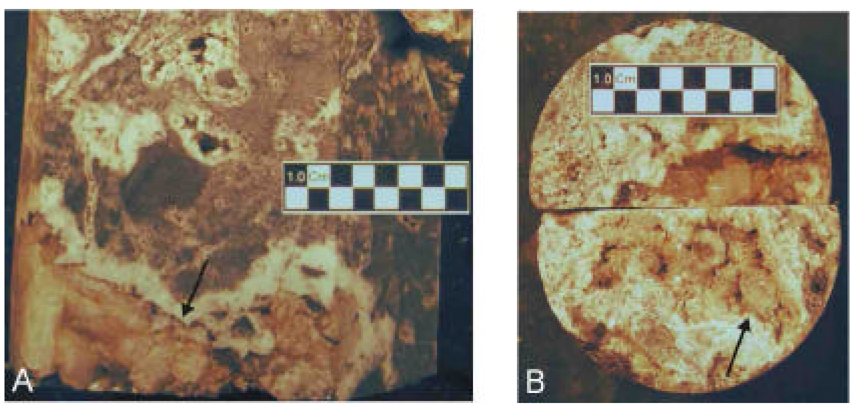

Figure 8. Late stage cements. A) core photograph of coarse calcite cement which fills a saddle dolomite-lined vug. The black arrow indicates bitumen emplacement between the two cements, Well L11, Slave Point Formation; B) core photograph of euhedral quartz crystals overlying a saddle dolomite cement in a vug, Well L12, Keg River Formation.

Carbon and oxygen isotopic analyses of replacement dolomite and the saddle dolomite cements from the surface and subsurface show both dolomite types have similar ranges of isotopic values for $\delta^{18}O$ (-15.1‰ to -8.9‰) and $\delta^{13}C$ (-4.9‰ to 1.0‰). The oxygen isotope values all fall within the characteristic range for hydrothermal dolomites (Figure 5), whereas the carbon isotopic values are depleted from the range of Devonian seawater ($\delta^{13}C$ = 0‰ to 4‰, from Lohmann (1988)), indicating contributions from organic reactions such as oxidation, sulphate reduction, oil degradation and decarboxylation. Initial fluid inclusion results conducted on the two dolomite types indicate that they formed at high temperature (greater than 110°C) and from highly saline fluids, and they do not contain hydrocarbon inclusions.

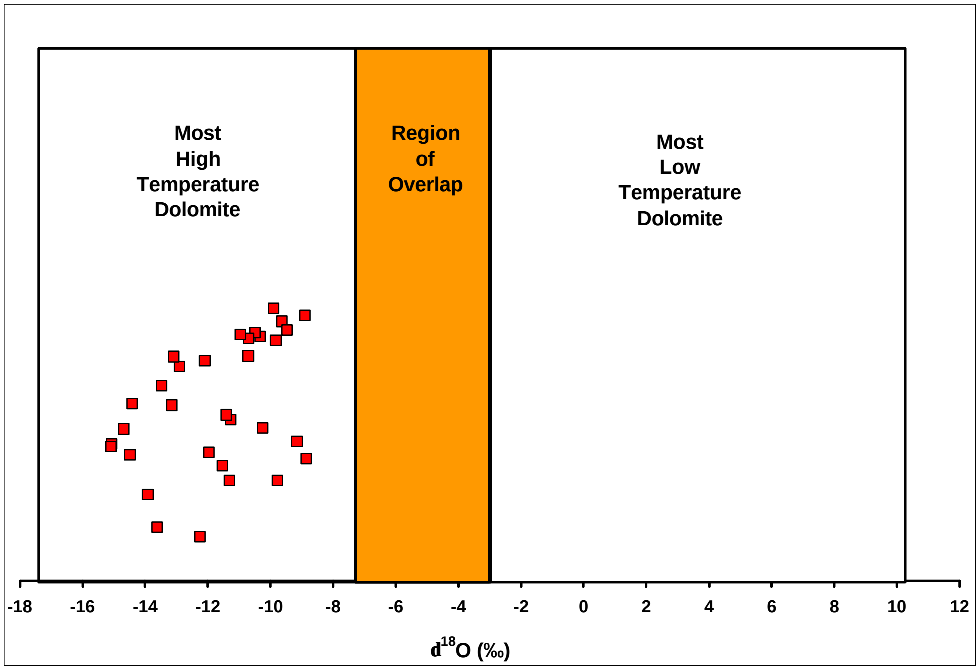

Figure 5. Stable oxygen isotopic values for the two dolomite types recognized in this study (red squares). They fall within the values for high temperature dolomite. Dolomite regions from Allan and Wiggins (1993)

Hydrothermal dolomite reservoir facies are not found in outcrop sections of the Dunedin Formation, though different breccia types do occur. In the far north of the study area (Section 11), a thick calcite-cemented rubble to mosaic floatbreccia was encountered. The host limestone had been silicified, and the breccia cement was coarsely crystalline anhedral calcite. Brecciation appeared to be solution collapse, due to downward displacement of breccia clasts (Figure 9A). Another breccia occurs in Sections 10 and 13, which is cemented by barite with some minor calcite. The barite forms bed-parallel veins in both sections, and also occurs as cement of a rubble packbreccia to floatbreccia in Section 10. Both breccia types in the Dunedin Formation are associated with similar breccia occurrences in northeast British Columbia within Lower and Middle Devonian strata.

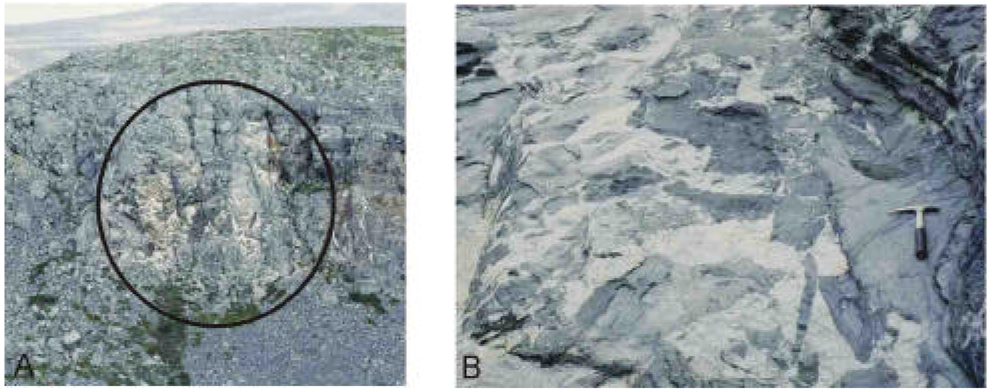

Figure 9. A) outcrop photo of calcite cemented breccia pillar (height of cliff approximately 100 m), where blocks of host rock have been displaced downward indicating solution collapse, Section 11, Dunedin Formation. B) outcrop photo of barite cemented rubble floatbreccia, Section 10, Dunedin Formation.

CONCLUSIONS

Dolomites in the Middle Devonian of northeast British Columbia are hydrothermal in origin, as indicated by their mineralogy, textures, stable carbon and oxygen isotope values and fluid inclusion homogenization temperatures. These data closely resemble hydrothermal dolomite reservoir facies worldwide. Formation of the HTD occurred at shallow burial depths, before extensive stylolitization, and occurs in all three formations within thick packages of strata. The model which best explains the formation of these dolomites is the hydrothermal convection model, in which dolomitization by hydrothermal fluids can occur at shallow depths and can extend upward through many formations. The first orogeny to affect the west coast of North America occurred after Middle Devonian strata were buried to at least 3000 meters below sea level. Since both the topographic recharge and tectonically driven compaction flow models require deep burial and mountain building before dolomitization can occur, they are not adequate to explain the dolomitization of the Middle Devonian of northeastern British Columbia. Understanding the dolomitization mechanism for such coarsely crystalline dolomites has important implications for predicting the geometry and extent of potential reservoir rocks.

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