Multistage Fault-Related Dolomitisation of the Middle Cambrian Mount Whyte and Cathedral Formations: Insights into the Tectonic and Diagenetic History of the Western Canada Sedimentary Basin*

Jack Stacey[1], Ardiansyah Koeshidayatullah[1], Cathy Hollis[1], and Hilary Corlett[2]

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[1]School of Earth and Environmental Sciences, University of Manchester, United Kingdom (jack.stacey@postgrad.manchester.ac.uk)
[2]Alberta Geological Survey, Edmonton, Alberta, Canada

Abstract

Dolomitisation of carbonate rocks can significantly modify rock petrophysical properties, and hence hydrocarbon reservoir potential, yet the shape, size and termination of such bodies is often poorly described. This project considers the basin-scale controls on fault-controlled hydrothermal dolomitisation within the Western Canada Sedimentary Basin (WCSB), a mature petroleum province in which dolomitized limestone is one of the most important reservoir-types. This study focuses on Cambrian sections exposed in the Canadian Rocky Mountains to the southwest of Alberta. In this region, the Middle Cambrian carbonate platform is characterised by a series of shallowing-upward cycles known as Grand Cycles (Aitken, 1997; Jeary, 2002). The Cathedral Formation comprises the upper carbonate section of the lowest Grand Cycle, overlying the shales and carbonates of the Mount Whyte Formation. The Mount Whyte and Cathedral formations overlie the coarse-grained clastics of the Gog Group and are capped by the Stephen Formation shales (Jeary, 2002). Outcrops of the Mount Whyte and Cathedral formations are located near Whirlpool Point, northwest of Banff National Park, Alberta, and contain both stratabound and non-stratabound dolostone bodies, tens of metres or more in diameter. Faulting, fracturing, brecciation and zebra dolomite textures are commonly observed features.

Geological Framework

The Western Canada Sedimentary Basin (WCSB) is a large sedimentary basin underlying most of western Canada. It is a mature hydrocarbon province that comprises both conventional and unconventional resources. The basin is situated within a complex tectonic region, influenced by the Foreland Fold and Thrust Belt of the Canadian Rocky Mountains to the west and several transform faults. The sedimentation history of this basin can be divided into two phases associated with distinct tectonic settings (Wright et al., 1994; Ross et al., 1994). The Palaeozoic to Jurassic was mostly dominated by a succession of carbonate platforms with minor siliciclastic incursions, deposited in a relatively stable cratonic setting. The basin originally developed as a passive margin (Price, 1994), persisting from the Precambrian to Late Devonian (Bradley, 2008), when the Antler Orogeny is thought to have changed the basin configuration to that of a back-arc setting (Nelson et al., 2002). Root

(2001) proposed that the WCSB was a distal foreland basin during the Devonian and Mississippian, and used sedimentological and structural evidence to support the existence of this event. Although the exact impact of the Antler Orogeny on the WCSB is poorly understood, certain fault-related dolomites have been dated as Devonian in age using 87Sr/86Sr data (Duggan et al., 2001; Lonnee and Machel, 2006; Machel and Buschkuehle, 2008), suggesting that fault reactivation and hydrothermal fluid flux occurred from the Late Devonian to Mississippian. The back-arc setting established in the Late Devonian persisted until the Middle Jurassic, when a foreland basin stage was initiated by the Columbian and Laramide Orogenies (Pana et al., 2001).

The Mount Whyte Formation (Figure 1) represents the first carbonate unit deposited during the first cratonic transgression in the WCSB (Slind et al., 1994). It predominantly consists of interbedded limestone-dolostone and shale, which in places, can be up to 176 m thick. Aitken (1989) concluded that the Mount Whyte Formation comprises the earliest part and base of the first Grand Cycle, with the Cathedral Formation representing the 'cap carbonate unit'. The Cathedral Formation represents the first major cliff forming carbonate unit in the Canadian Rockies and is comprised of limestone and dolostone with a maximum thickness of ~360 m in the Main Ranges.

Methodology

A total 105.9 m section was logged and described in the field and 78 representative carbonate samples were collected from both the Mount Whyte and Cathedral formations at the Whirlpool Point locality, northwest of Banff National Park. Thin sections were studied using standard petrographic techniques and stained with Alizarin Red S (Dickson, 1966) to qualitatively discriminate between calcite and dolomite. Cathodoluminescence (CL) analysis was performed to determine different dolomite phases and cements. In situ XRF analysis was also conducted along the logged section.

Results

Macroscopic Features of Dolomite

The discrimination between dolostone and limestone in the field was facilitated by the contrast of their colour: dolostone has a brownish-yellow colour, while limestone is predominantly grey-beige and confirmed by in situ XRF analysis. The dolostone successions also exhibit more fracturing than the limestone. The dolostone bodies in the study area occur as both stratabound and non-stratabound geometries. While stratabound dolomite bodies can extend for > 6 km, non-stratabound bodies only occur on a scale of tens of metres, proximal to faults. They sometimes form extremely irregular masses, which enclose remnants of undolomitised limestone 'rafts' as relict bodies. The Mount Whyte and Cathedral formations both contain zebra dolomite textures, along with well-developed brecciated zones, most commonly observed in the Cathedral Formation.

Dolostone-Limestone Transition

The termination of dolostone in the host limestone occurs in various geometries in the study area (Figure 2). A gradual transition is the most common, where the dolomitisation fronts form a finger-like geometry. This type of termination can occur across a few centimeters to meters and is rarely concordant with the stratification. Sharp transitions with irregular contacts are also observed and are mostly associated with the stratabound-type dolomite bodies. These are bounded by more mud-dominated limestone lithologies.

Diagenetic Features

Integration of petrography, cathodoluminescence (CL) and secondary electron microcopy (SEM) identified different calcite and dolomite calcite phases based on their characteristics in both the Mount Whyte and Cathedral formations (Figure 3). These include a primary phase of void filling calcite cement, replacive dolomite, dolomite cement, saddle dolomite, "slurry" dolomite, and a late fracture-filling calcite phase.

Pre-Dolomitisation Diagenesis

The initial limestone fabrics of the studied Cambrian strata are commonly bioturbated with horizontal burrows. Microbial micritisation of skeletal and non-skeletal grains is observed in the majority of samples, with both skeletal and non-skeletal grains affected. Micrite forms as envelopes on grains and replaces the relict marine isopachous cement within the host limestone.

Calcite Cement 1 (CC1)

CC1 is characterised by non-ferroan, blocky to drusy crystals (<200 μm). This phase occurs as a pore filling cement occluding intra- and intergranular voids of dissolved precursor skeletal and non-skeletal grains. Under CL, this phase appears dull red to dull orange, with no distinct zonation. In the Cathedral Formation this is expressed as void filling calcite cement.

Replacive Dolomite (RD)

Replacive dolomite was observed in both formations. It is strongly fabric destructive, with a polymodal size distribution. Dolomite crystals exhibit a non-planar texture and closely packed mosaic of subhedral to anhedral crystals (sensu Sibley and Gregg, 1987), ranging in size from 100-1000 μm. In some examples, the coarsest RD crystals (~1000 μm) exhibit curved faces and sweeping extinction commonly observed in saddle dolomite cement (Radke and Mathis 1980; Spötl and Pitman 1998). Observations from the Mount Whyte Formation suggest that RD is closely associated with small, euhedral dolomite crystals. Under CL, the RD phases in the Mount Whyte luminesce dull red, with no zonation and occasional mottled brighter orange-yellow sections in the centre of crystals. In the Cathedral Formation, all replacive phases appear dull purple/dark blue, indicating ferroan dolomite. In both formations only slight variations in CL colour and intensity were observed for RD. In the Cathedral Formation, moderate-amplitude, inclined stylolites form boundaries between replacement and saddle dolomite phases.

Fine Dolomite Cement (FDC)

The void filling FDC phase comprises white-yellowish sparry dolomite. It is not common and only comprises <5% by volume of the Mount Whyte Formation dolostone. The crystals of FDC are interlocked, and have a finer crystal size (50-200 μm) compared to RD. The crystal size is relatively unimodal and exhibits planar-e to -s textures (sensu Sibley and Gregg (1987). Under plane-polarized light, the FDC phase shows cloudy, inclusion-rich cores and clear crystal rims. FDC has a distinct dull red luminescent crystal cores and thick, bright orange luminescent zones in outer crystal rims. This dolomite cement phase occludes pores and significantly reduces both intercrystalline and mouldic porosity.

Saddle Dolomite (SD)

This type of dolomite can be easily distinguished from the previous phases by its undulose extinction, curved crystal cleavage/faces, and megacrystal size (up to >2 mm). SD exhibits a non-planar and mosaic texture of anhedral crystals, which are replacive, and completely fabric destructive. Under CL, SD in the Mount Whyte Formation has alternating bright to dull red and thin bright orange luminescent zones. In the Cathedral Formation, SD appears to be more euhedral, exhibiting a high degree of zonation, which alternates between dull red to bright orange. In certain sections the crystal faces of the final zone are highly irregular, suggesting some corrosion has occurred. This partial dissolution generated minor intercrystalline porosity in both the Mount Whyte and Cathedral formations, but overall SD generally occludes pore space. Dolomite 'veinlets' (~10 μm across) are observed in the Cathedral Formation, and are present within coarse saddle textured dolomite crystals. These veinlets are similar in luminescence to the outer zones of well-developed saddle dolomite crystals. High amplitude horizontal stylolites are commonly found to postdate SD, and microsized dolomite inclusions are associated with this phase in the Mount Whyte Formation.

<u>"Slurry" Dolomite (SLD)</u>
The "slurry" dolomite is mainly characterised by micrite and microspar-sized dolomite crystals (10-30 μm), floating in a black matrix. In some cases, SLD is associated with stylolites. SLD crystals have a planar-e to -s texture. This dolomite phase is recognized in almost all dolostone and limestone samples in both the Mount Whyte and Cathedral formations. Under plane-polarized light, crystals shows cloudy, inclusion rich cores, and appear dark to bright purple luminescent under CL. The black matrix observed in PPL is also found lining vugs in both formations and fractures in the Cathedral.

<u>Calcite Cement 2 (CC2)</u>
CC2 is associated with fractures and is characterised by blocky, non-planar crystals (20-350 μm). This calcite phase is present in both the Mount Whyte and Cathedral formations, and crosscuts all the previously described diagenetic phases, including replacive dolomite. Under CL, this phase appears dull red-orange to bright orange, with some zonation in larger crystals.

<u>Authigenic Quartz</u>
In the Cathedral Formation, authigenic quartz is found within vugs bordered by well-developed saddle dolomite cement. This is absent in the Mount Whyte Formation.

Paragenetic Sequence

An interpretation of the relative timing and paragenetic relationship between the different diagenetic features is summarised below.

<u>Surface to Early Burial</u>
In the Mount Whyte Formation, the marine realm is characterised by the presence of microbial micritisation on both skeletal and non-skeletal grains, relics of marine isopachous cement and blocky calcite cement that overprint the isopachous cement and occludes pore space. Planar, euhedral dolomite crystals in the Mount Whyte Formation, which may indicate a low temperature, near surface environment (Gregg and Sibley, 1984) are the earliest phases to form. This phase is not present in the Cathedral Formation. Unimodal, nonplanar matrix-replacive calcite (~25 μm) comprises ~80% of the single limestone sample analysed in the Cathedral Formation. Within this phase, peloid ghosts are present, suggesting neomorphism of the original limestone matrix from micrite to microspar. Void filling calcite cement formed after the matrix

developed, and has a lenticular morphology with coarser, more equant crystals than the preceding matrix calcite. Both are thought to have formed prior to the onset of chemical compaction as they are cross-cut by stylolites.

Deeper Burial Diagenesis

The deep burial environment is considered to begin when a formation becomes isolated from circulating surface (marine or meteoric) fluids, which in the study area could have occurred from the late Middle Cambrian onwards. Burial is evidenced by mechanical compaction (concavo-convex grain contacts) and multistage dolomitisation (replacive, saddle and dolomite cements). Maximum burial was reached prior to the initiation of the Laramide Orogeny, with a maximum burial depth of ~3 km (Wright et al., 1994; Jeary, 2002). This latest stage of burial diagenesis is represented by the appearance of high amplitude stylolites in mud-dominated facies as a product of chemical compaction. The occurrence of 'slurry' dolomite is closely associated with dark organic material in both formations, and lines vugs in the Cathedral Formation. This suggests that this was the last diagenetic phase to form. The dark material is interpreted to be organic based on a previous study by Vandeginste et al. (2005), who analysed the total organic carbon content (TOC) of the dark bands and matrix from a dolomite type similar to "slurry dolomite" in the Cathedral Formation (typical range 0.14- 0.27% TOC). This organic material potentially represents biodegraded hydrocarbons. Given that hydrocarbon migration in the deep WCSB occurred from the Columbian to Laramide Orogenies (Duggan et al., 2001; Lonnee and Al-Aasm, 2000; Lonnee and Machel, 2006; Machel and Buschkuehle, 2008), it is reasonable to suggest that the sections in the Canadian Rockies were charged at this time. In the deep WCSB, saddle dolomite forms over a range of 80-180° C (Mountjoy and Halim-Dihardja, 1991). This suggests that significant cooling took place prior to the precipitation of 'slurry' dolomite, possibly related to uplift during the Palaeogene. The presence of organic material in Cathedral Formation fractures also supports this. The later stage fracture lining calcite cements seen in both formations postdate all previous phases. The CL characteristics (bright orange colour) suggest a meteoric origin, related to telogenesis (uplift).

Termination of Dolomite Bodies

Stratabound bodies typically display sharp terminations on their upper and lower boundaries. This suggests a petrophysical variation across strata that led to dolomitisation along specific permeable beds (aquifers), bounded by lower permeability aquitards. Conversely, the lateral margins of stratabound boundaries display a gradual diffuse termination, suggesting either a more irregular and diffuse change in petrophysical properties and/or a decrease in the dolomitising potential of the fluids. Stratabound dolomite is facies selective, and is more pervasive within mud-dominated bioturbated limestone facies. Non-stratabound dolomite is non-facies selective, and is only observed in the Cathedral Formation. Dolomite bodies are highly irregular in shape, primarily due to intense brecciation. Non-stratabound bodies are also localised on the hanging wall of faults, suggesting that fluids were preferentially focused along fault damage zones, unconstrained by the petrophysical properties of the host strata. Although this is effective in producing brecciated textures proximal to the fault, this process has limited lateral dolomitising potential.

Timing of Dolomitisation

The timing of dolomitisation is hard to delineate because of the complex tectonic history of the Western Canada Sedimentary Basin. Based on these preliminary results, dolomitisation could have occurred during fault-reactivation during post-rift thermal subsidence, although the extent of fault-reactivation at this time is unknown. This potentially occurred in the Upper Precambrian (Bond et al., 1989) and/or back-arc basin creation during the mid-late Devonian associated with the Antler Orogeny (based on indirect evidence). This latter model would facilitate large-scale fluid flow and circulation along and away from faults. The two tectonic events represent extensional-transtensional faulting systems, which are commonly linked with hydrothermal dolomitisation (Davies and Smith, 2006; Martin et al., 2015). While no direct evidence can be deduced from these preliminary results, the potential of fault-controlled dolomitisation during later tectonic reactivation in the Cretaceous to Tertiary (Laramide Orogeny) cannot be ruled out. Furthermore, a long-term period of relatively quiescent tectonic conditions persisted from the Late Devonian to Mid-Cretaceous where the Middle Cambrian successions were buried to ~1.5 km. This may also hold important information on the evolution of dolomite within the Mount Whyte and Cathedral formations as well as the Devonian strata of the deep WCSB.

Conclusions

The preliminary results of this study indicate that there are two distinct dolomite geobodies which are stratabound and non-stratabound in these formations, with the stratabound type more commonly observed in the field. Combined petrography and CL studies have identified four different phases of dolomite: (a) replacive dolomite; (b) fine dolomite cement; (c) saddle dolomite; (d) 'slurry' dolomite. These dolomite phases are broadly similar in character in the Mount Whyte and Cathedral formations, with the exception of more well-developed saddle dolomite cements in the latter. Three different diagenetic realms (marine, burial and telogenetic meteoric) have been recognised based on the different diagenetic features present and their relationships to one another. Burial diagenesis (Upper Cambrian-Cretaceous) is suggested as the most dominant diagenetic process in both the Mount Whyte and Cathedral formations carbonate sequences and was also responsible for the formation of the different dolomite phases observed.

The main dolomitisation model for both the Mount Whyte and Cathedral formations is hypothesised as fault-controlled hydrothermal dolomitisation with the main source of magnesium possibly provided by circulation of seawater, which interacted with deeper basal aquifers below the carbonate sequences. The timing of this hydrothermal dolomitisation is thought to be associated with post-rift thermal subsidence in the Upper Cambrian and/or the development of the backarc basin during the Mid-Devonian. However, the influence of the Columbian and Laramide orogenies cannot be ruled out, due to the meteoric signature of fracture-lining calcite found in both formations.

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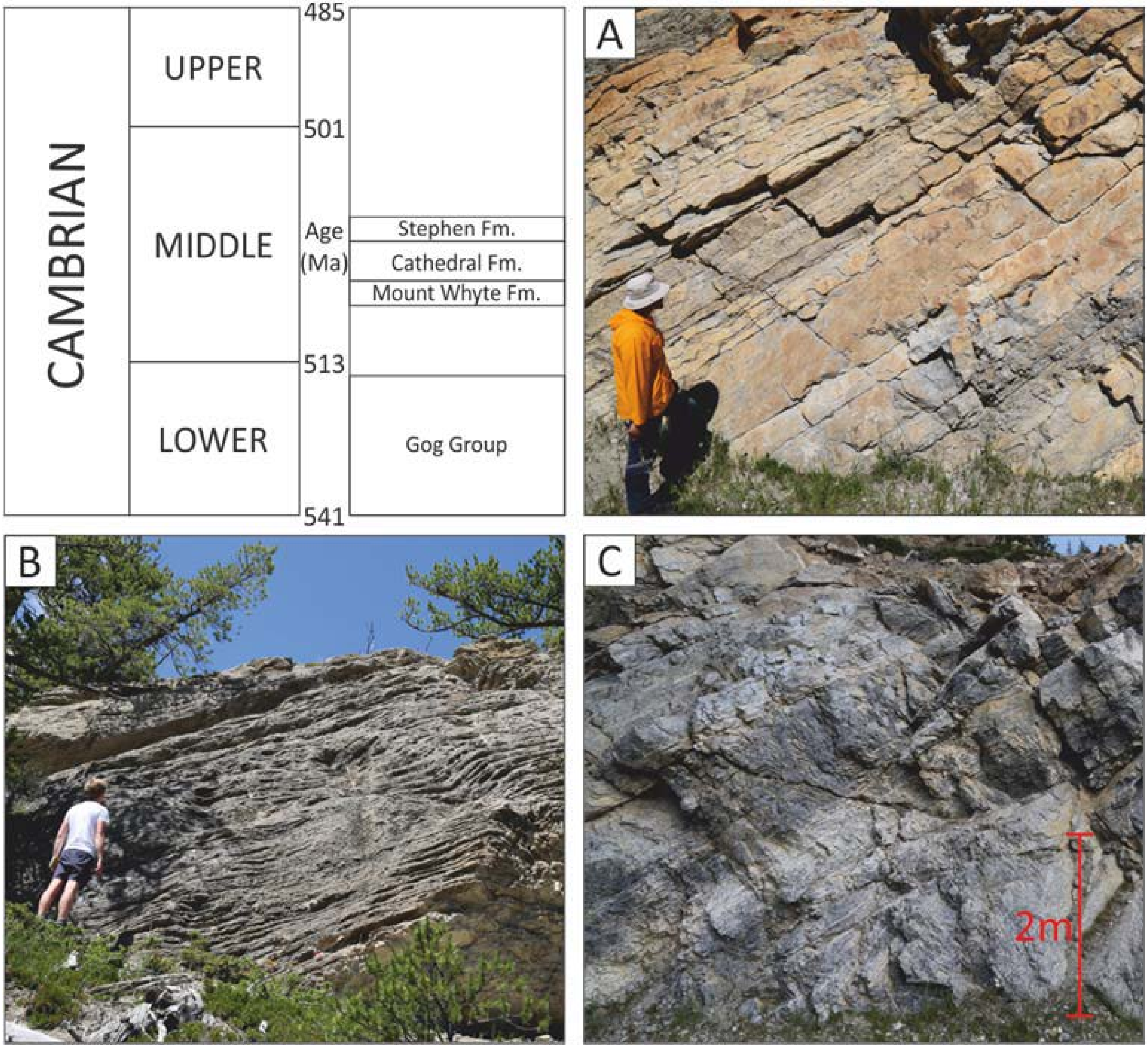

Figure 1. Representative field images. (A) Gog Group sandstone, (B) Mount Whyte Formation limestone, (C) Cathedral Formation dolostone.

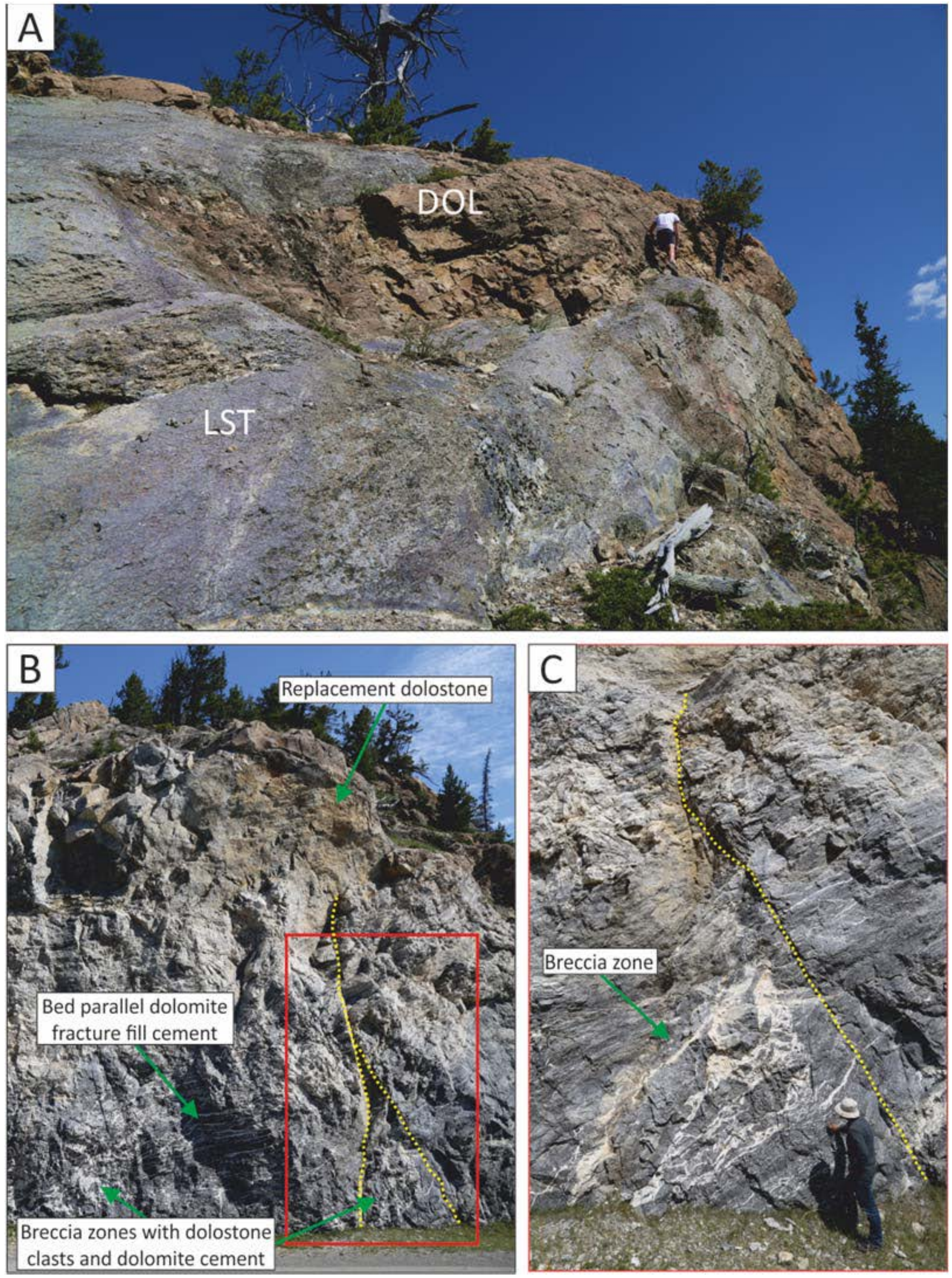

Figure 2. Dolostone bodies observed in the field. (A) Stratabound dolostone in the Mount Whyte Formation, (B) Non-stratabound dolostone in the Cathedral Formation (yellow dashed line indicates fracture), (C) Close-up view of a breccia zone (the red rectangle shown in B).

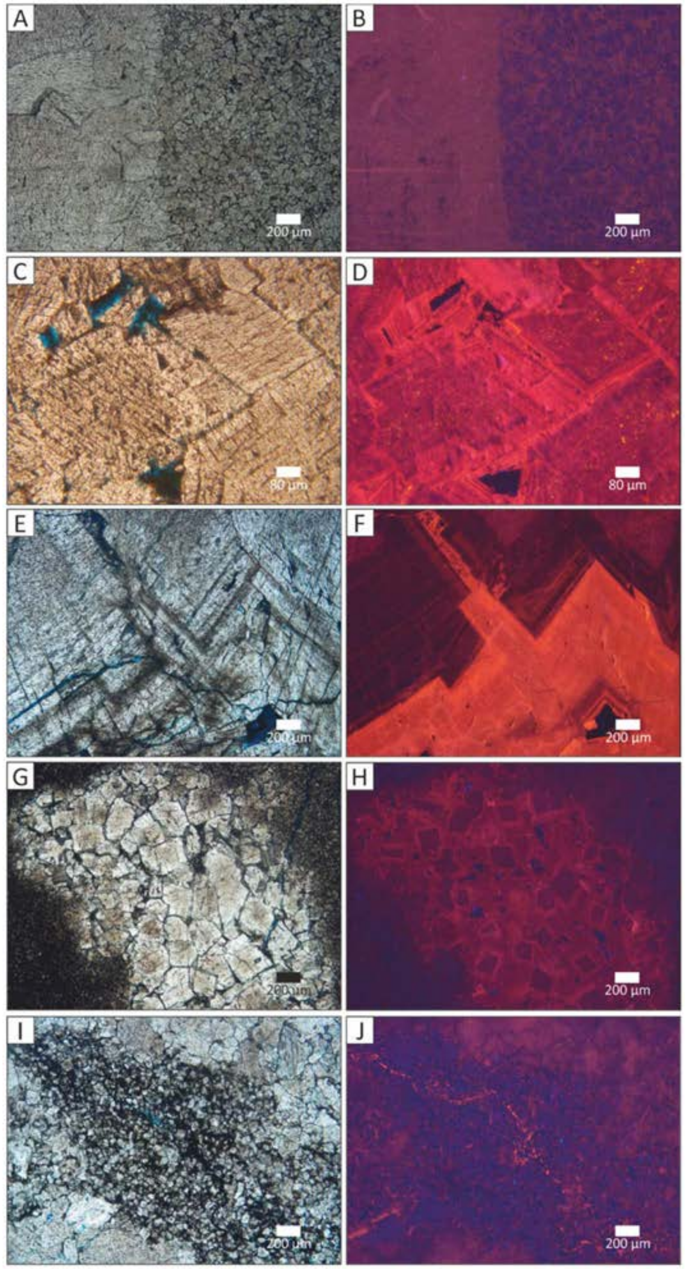

Figure 3. PPL and CL images of the Mount Whyte (MWF) and Cathedral formations (CF). (A-B) Replacement dolomite exhibiting a sharp contact with saddle dolomite (CF). (C-D) Typical saddle dolomite with multiple thin luminescent zones (MWF). (E-F) Typical saddle dolomite with multiple thick luminescent zones (CF). (G-H) Euhedral dolomite cement (MWF). (I-J) "Slurry" dolomite hosted within stylolite (MWF).