

Regional fault-controlled shallow dolomitization of the Middle Cambrian Cathedral Formation by hydrothermal fluids fluxed through a basal clastic aquifer

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ABSTRACT

This study evaluates examples of hydrothermal dolomitization in the Middle Cambrian Cathedral Formation of the Western Canadian Sedimentary Basin. Kilometer-scale dolomite bodies within the Cathedral Formation carbonate platform are composed of replacement dolomite (RD), with saddle dolomite-cemented (SDC) breccias occurring along faults. These are overlain by the Stephen Formation (Burgess Shale equivalent) shale. RD is crosscut by low-amplitude stylolites cemented by SDC, indicating that dolomitization occurred at very shallow depths (<1 km) during the Middle Cambrian. Clumped isotope data from RD and SDC indicate that dolomitizing fluid temperatures were >230 °C, which demonstrates that dolomitization occurred from hydrothermal fluids. Assuming a geothermal gradient of 40 °C/km, due to rift-related basin extension, fluids likely convected along faults that extended to ~6 km depth. The negative cerium anomalies of RD indicate that seawater was involved in the earliest phases of replacement dolomitization. ⁸⁴Kr/³⁶Ar and ¹³²Xe/³⁶Ar data are consistent with serpentinite-derived fluids, which became more dominant during later phases of replacement dolomitization/SDC precipitation. The elevated ⁸⁷Sr/⁸⁶Sr of dolomite phases, and its co-occurrence with authigenic quartz and albite, likely reflects fluid interaction with K-feldspar in the underlying Gog Group before ascending faults to regionally

dolomitize the Cathedral Formation. In summary, these results demonstrate the important role of a basal clastic aquifer in regional-scale fluid circulation during hydrothermal dolomitization. Furthermore, the presence of the Stephen Formation shale above the platform facilitated the build-up of fluid pressure during the final phase of dolomitization, leading to the formation of saddle dolomite-cemented breccias at much shallower depths than previously realized.

INTRODUCTION

Structurally controlled hydrothermal dolomitization (HTD) (Machel and Lonnee, 2002; Davies and Smith, 2006) has been widely described (e.g., Sharp et al., 2010; Barale et al., 2016), partly due to the economic importance of HTD bodies as hydrocarbon reservoirs (e.g., Davies and Smith, 2006) and as hosts of Mississippi Valley-type (MVT) lead-zinc mineralization (e.g., Vandeginste et al., 2007). Common features of HTD bodies include faulting, fracturing, brecciation, and zebra dolomite textures, world-renowned examples of which are found in the Paleozoic carbonates of the Western Canadian Sedimentary Basin (Davies and Smith, 2006). One of the key uncertainties with the HTD model is the ultimate source of dolomitizing fluids, which are often interpreted to be “evolved crustal fluids” based on highly saline, high temperature fluid inclusions within dolomite crystals (e.g., Wendte et al., 1998; Lonnee and Al-Aasm, 2000; Nelson et al., 2002; Al-Aasm, 2003; Morrow, 2014). However, recent work (Gomez-Rivas et al., 2014; Hollis et al., 2017; Rustichelli et al., 2017; Hirani et al., 2018a; Hirani et al., 2018b; Benjakul et al., 2020) has shown that HTD can occur from the convection of seawater along

fault planes, facilitated by basal clastic aquifers (e.g., Martín-Martín et al., 2015; Lukoczki et al., 2019), indicating that fault-controlled dolomitization can occur from fluids that are heated at shallow depths. As such, this study will evaluate recently recognized components of the HTD model on the pervasively dolomitized carbonates of the Middle Cambrian (509–497 Ma; Miaolingian Epoch) Cathedral Formation and determine whether this example of HTD is more complex than previously thought. As the HTD of the Cathedral Formation has been considered analogous to many examples of HTD worldwide (e.g., Davies and Smith, 2006; Sharp et al., 2010), this has significant implications for our understanding of these systems, particularly for the timing and depth of saddle dolomite-cemented breccia formation.

Fault-controlled dolomite bodies in the Cathedral Formation are well exposed in the thrust sheets of the southern Canadian Rocky Mountains and provide an opportunity to study and sample their vertical and lateral extent. Previous studies have primarily focused on the Kicking Horse Rim, a fault-controlled, linear paleo-topographic feature (Aitken, 1971) that coincides with the trend of the Cathedral Escarpment, the gravity-collapsed margin of the Cathedral carbonate platform (Johnston et al., 2009). In this area, talc and magnesite are present (Powell et al., 2006), and MVT mineralization (Vandeginste et al., 2007) is hosted in saddle dolomite-cemented breccias within replacement dolomite bodies. To the northeast, talc, magnesite, and MVT mineralization are absent, but examples of zebra dolomite textures are present in the Beauty Creek and Mistaya Canyon areas (Vandeginste et al., 2005). Additionally, zebra dolomite and saddle dolomite-cemented breccias occur at Whirlpool Point (Jeary, 2002).

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The earliest timing proposed for dolomitization is during the Middle Cambrian by thermal convection of brines (Jeary, 2002; Powell et al., 2006). Yao and Demicco (1997) suggested a later event in the Middle Silurian to Late Devonian, involving topographically induced flow of basinal brines and mixing with meteoric water. Conversely, Nesbitt and Prochaska (1998) concluded that dolomitization occurred from residual evapo-concentrated brines derived from Middle Devonian sediments that flowed westward during the Late Devonian to Mississippian Antler Orogeny. Vandeginste et al. (2005) also suggested that dolomitization was related to the Antler Orogeny but favored the expulsion of hot basinal brines from underlying Lower Cambrian strata, and Symons et al. (1998) concluded that dolomitization was related to regional fluid flow induced by the Laramide Orogeny (Cretaceous to Paleocene). Additionally, recent work (Koeshidayatullah et al., 2020) on the underlying Mount Whyte Formation suggested that dolomitization occurred from fluids that were partially sourced from, or interacted with, Proterozoic serpentinite during the Middle Cambrian. In summary, it is clear from previous research that hydrothermal fluids were involved in dolomitizing the Middle Cambrian succession, but their timing of emplacement, flow mechanisms, and ultimate origin remain uncertain.

This study focuses on the vertically and laterally extensive outcrops of the Cathedral Formation at Whirlpool Point (Fig. 1), which include replacement dolomite bodies containing saddle dolomite-cemented breccias that overlie the mudstones and carbonates of the Mount Whyte Formation and the sandstones of the Gog Group. This offers a unique opportunity to examine an ancient and complex hydrothermal dolomite system and to evaluate the potential role of basal clastic aquifers in dolomitization and the formation of “classic” HTD features in a shallow burial setting. This study integrates existing geochemical data from across the dolomitized Cathedral platform (Jeary, 2002; Vandeginste et al., 2005) with new data from Whirlpool Point to address the following objectives:

- (1) Determine the timing and diagenetic environment of dolomitization using petrographical, sedimentological, and geochemical evidence.
- (2) Evaluate the source of dolomitizing fluids and their migration pathways.
- (3) Assess existing classic dolomitization models to determine their validity.

GEOLOGICAL SETTING

The Western Canadian Sedimentary Basin is a large sedimentary basin that extends from north-east British Columbia and the southern edge of

the Northwest Territories, underlies most of Alberta, and continues into southwestern Saskatchewan and the north-central United States. The Western Canadian Sedimentary Basin has experienced a complex tectonic history that began with Neoproterozoic rifting (780–570 Ma), during which the deep-water, turbidite-dominated Miette Group was deposited (Slind and Perkins, 1966). Following a period (ca. 700–635 Ma) of declining tectonic activity (Collom et al., 2009, and references therein), renewed rifting occurred during the Early Cambrian (541–509 Ma; Terreneuvian Epoch–Stage 2) (Bond and Kominz, 1984), when the quartz arenites of the Gog Group were deposited in a subtidal setting (Desjardins et al., 2012). This final rifting episode ended with regional subsidence during the Middle Cambrian (Bond and Kominz, 1984), although heat flow and tectonic activity potentially remained high (Powell et al., 2006). During this time, the Cathedral carbonate platform developed, with the platform margin located in the vicinity of the Kicking Horse Rim (Aitken, 1971). This paleo-topographic feature likely formed through the syn-depositional activation of deep-rooted basement faults (Powell et al., 2006) and was responsible for the formation of the Cathedral Escarpment, which is the gravity-collapsed margin of the Cathedral platform (Stewart et al., 1993; Johnston et al., 2009). In the Kicking Horse Rim area, the Cathedral Formation directly overlies the Gog Group (Aitken, 1997), whereas in the Whirlpool Point region, the Gog and Cathedral are separated by carbonates and shales of the Mount Whyte Formation. In both areas, the Cathedral Formation is unconformably overlain by the shales of the Stephen Formation (host to the Burgess Shale lagerstätte; Collom et al., 2009).

Subsequent tectonic events that affected Cambrian strata include the Antler Orogeny (Devonian to Mississippian) (Hauck et al., 2017), Columbian Orogeny (Middle Jurassic to Early Cretaceous) and the Laramide Orogeny (Late Cretaceous to Paleocene) (Pana et al., 2001). The Columbian and Laramide Orogenies caused the Western Canadian Sedimentary Basin to develop into a foreland basin due to the loading of the Cordilleran deformation front, which also uplifted and exposed Cambrian strata in the thrust sheets of the Canadian Rocky Mountains.

In the Whirlpool Point area of southwestern Alberta, the Cathedral Formation is well exposed as part of the Bourgeau Thrust (Fig. 1A). Although the diagenetic features in the Whirlpool Point and Kicking Horse Rim areas are similar, their depositional facies are markedly different. The Cathedral Formation at the Kicking Horse Rim is dominated by microbial boundstones and ooid grainstones that grade upward into tepee-

bearing grainstones that are indicative of platform margin facies, whereas Whirlpool Point is characterized by the occurrence of peritidal/microbially laminated mudstones and bioturbated lagoonal mudstones that are interpreted to represent platform interior facies (Pratt, 2002).

Early (pre-Laramide) structural elements at Whirlpool Point are NE-SW-trending normal faults that intersect the Cathedral Formation. Non-stratabound dolomite bodies are sub-parallel to bedding and have stratabound (bedding-parallel) terminations that extend up to 6.5 km in length away from the faults. Non-stratabound dolomite bodies are only found within 16 m of the normal faults (3 m and 13 m in the footwall and hanging wall, respectively) and are characterized by the occurrence of saddle dolomite-cemented breccias, fractures, and zebra dolomite textures. This study focuses in detail on one brecciated dolomite body that is exposed in a road cut along the David Thompson Highway at Whirlpool Point and also incorporates field mapping of other bodies in the Bourgeau Thrust (Fig. 1).

METHODOLOGY

Petrographic analysis was undertaken on 72 representative carbonate samples from the Cathedral Formation (52°00′07.46″N, 116°28′13.54″W), 35 of which were taken systematically every 2 m along a 62 m logged section. Eleven samples were also taken along a 32 m logged section of the Gog Group (52°00′16.04″N, 116°27′47.72″W), which included samples of the sandstone matrix and dolomite-cemented fractures. Polished thin sections of these samples were stained with alizarin Red-S and potassium ferricyanide (Dickson, 1966) and impregnated with blue-dye resin to identify porosity. Polished sections were examined under plane-polarized light and cross-polarized light using a Nikon Eclipse LV100N POL microscope. Calcite and dolomite crystal textures were described based on the respective classifications of Flügel (2013) and Sibley and Gregg (1987). Polished sections were also examined using a CITL Mk5 cold cathodoluminescence system (operating conditions 10–15 kV and 350–400 μ A) mounted on a Nikon Eclipse LV100N POL microscope.

Thirty-five bulk rock samples from the logged section of the Cathedral Formation were analyzed for mineralogical composition through standard powder X-ray diffraction (XRD) using a Bruker D8 Advance diffractometer (operating conditions 40 kV and 30 mA, sample scans in the 2θ range from 5° to 70° in increments of 0.02°). Mineral identifications were made using standard peak-fitting software,

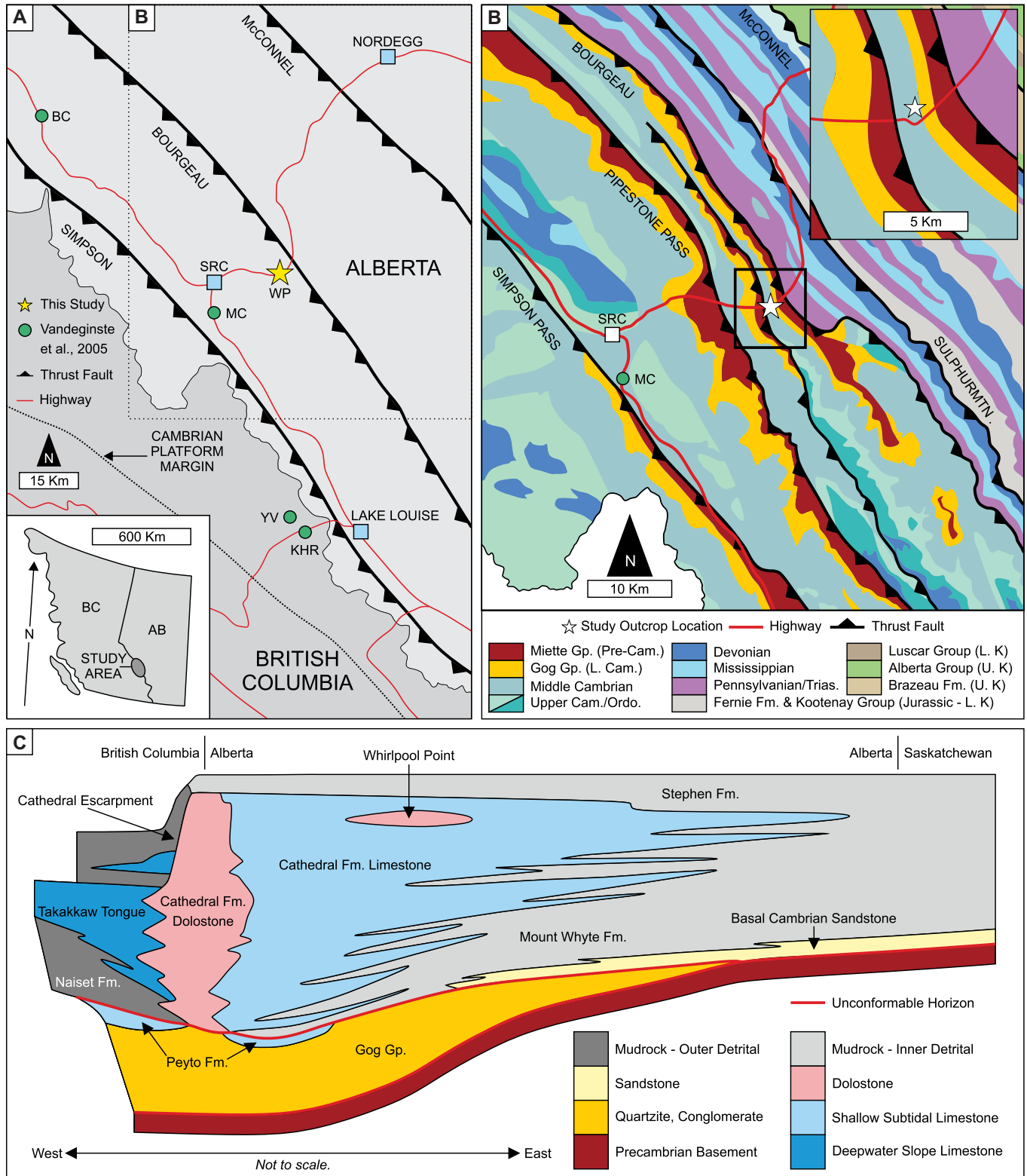


Figure 1. (A) Location of the study area in British Columbia and Alberta with major thrust faults shown (modified after Vandeginste et al., 2005). The outcrop location of this study is indicated by the white star (WP—Whirlpool Point). The outcrop locations of Vandeginste et al. (2005) are shown as green circles (BC—Beauty Creek; MC—Mistaya Canyon; YV—Yoho Valley; KHR—Kicking Horse Rim). SRC—Saskatchewan River Crossing. (B) Geological and structural map of the study area (modified from the Alberta Geological Survey Alberta Interactive Minerals Map). (C) Schematic cross-section of the Cathedral carbonate lithosome in the Canadian Rocky Mountains (modified from Slind et al., 1994; Aitken, 1989).

and peak displacement corrections were made using a quartz internal standard. Dolomite stoichiometry was calculated based on the method of Lumsden (1979) with the degree of ordering based on Goldsmith and Graf (1958), and quantitative Rietveld analyses were conducted using TOPAS XRD software.

Thirty-eight representative calcite and dolomite powder samples from the Cathedral Formation and two from dolomite-cemented fractures in the Gog Group were micro-drilled from thin section counterparts with individual phases drilled to ensure that the subsequent geochemical analyses were not influenced by contamination of additional phases. The resulting powder underwent conventional phosphoric acid digestion (McCrea, 1950). Gases were measured by dual-inlet, stable isotope ratio ($\delta^{13}\text{C}_{\text{VPDB}}$, $\delta^{18}\text{O}_{\text{VPDB}}$) mass spectrometry using a VG SIRA10 mass spectrometer at the Liverpool Isotope Facility for Environmental Research at the University of Liverpool. All stable isotope values are reported per mil (‰) relative to the Vienna Pee Dee Belemnite (VPDB) standard. Average analytical precision of repeat analyses was better than $\pm 0.1\text{‰}$ for $\delta^{13}\text{C}_{\text{VPDB}}$ and $\delta^{18}\text{O}_{\text{VPDB}}$.

Twenty-nine samples (Cathedral Formation = 27, Gog Group = 2) used for stable isotope analysis were analyzed for rare earth elements (REE) and trace elements ($n = 6$) using an Agilent 7700 $\times$ inductively coupled plasma mass spectrometer (ICP-MS) at the Advanced Isotope Geochemistry and Cosmochemistry Suite at the University of Manchester. REE concentrations were normalized to the post-Archean Australian Shales (PAAS) (Taylor and McLennan, 1985) and to chondrite values (Anders and Grevesse, 1989).

Clumped isotopes were measured from one limestone sample and five dolomite samples from the Cathedral Formation at the Stable Isotope Laboratory, University of Miami, on a dual inlet Thermo Fisher MAT 235 isotope ratio mass spectrometer following the methodology of Murray et al. (2016) and Swart et al. (2016). The Δ_{47} values were adjusted and converted to temperature values by using the equation of Staudigel et al. (2018) and are reported in $^{\circ}\text{C}$. The $\delta^{18}\text{O}$ values of the parent fluids were calculated using the fractionation calibration of Horita (2014) and are reported relative to Vienna Standard Mean Ocean Water ($\delta^{18}\text{O}_{\text{VSMOW}}$). Dolomite crystallization temperatures were only determined using this method, as it allows a direct comparison between finely crystalline replacement dolomite phases and coarsely crystalline saddle dolomite cement. However, to check their reliability, clumped isotope temperatures were compared with the fluid inclusion homogenization temperatures of Jeary (2002).

Noble gas analysis (He, Ne, Ar, Kr, and Xe) was conducted on four representative replacement dolomite and saddle dolomite samples from the Cathedral Formation in the noble gas laboratories at Lancaster University and the University of Manchester. Gas was extracted by manual crushing of samples under ultra-high vacuum ($<2 \times 10^{-7}$ mbar) using modified Swagelok valves with rounded steel tips. Samples were first partially crushed until the sample was heard to fragment and then fully crushed when the valve tip was fully extended. Samples were purified and analyzed following the procedures of Li et al. (2020). A blank and an air standard were analyzed for each sample (see Supplemental Material¹).

RESULTS

Geometries and Dimensions of Dolomite Bodies

The Cathedral Formation at Whirlpool Point contains variably continuous dolomite bodies up to 100 m in width and 20 m in height that extend in length for ~ 6.5 km. Dolomite bodies are typically non-stratabound (perpendicular to bedding) with stratabound margins (bedding parallel) and appear brown/orange in color compared to gray host limestone (Figs. 2A–2B). The southern end of the exposed dolomite bodies is bisected by the David Thompson Highway, where saddle dolomite-cemented, non-stratabound dolomite is crosscut by a normal fault (Fig. 2C). Although the middle section of dolomite bodies exhibits non-stratabound dolomite-limestone contacts (Fig. 2D), contacts at the northern end become increasingly bed-parallel and stratabound (Fig. 2E).

Sedimentology and Stratigraphy

Gog Group

A 32 m section of the Gog Group was logged at Whirlpool Point (Fig. 3A), which is ~ 250 m below the base of the Cathedral Formation. The lower section of the Gog Group contains ~ 1.5 -m-thick, coarse- to medium grained cross-bedded sandstones that are orange and gray in

color (Fig. 3H) and contain common dolomite-cemented vertical fractures (Fig. 3G). The middle section contains ~ 1 -m-thick, medium- to fine-grained crinkly laminated sandstones that appear orange and contain light gray burrows (Fig. 3F). Planar laminated to massive sandstones are also present in the middle section (Fig. 3D) and are interbedded with shales up to 1.5 m thick (Fig. 3E). The top of the section is composed of gray to green siltstone (Fig. 3C) that is possibly part of the Peyto Formation (Aitken, 1997).

Mount Whyte Formation

Aitken (1997) and Jeary (2002) concluded that the interval overlying the Gog Group at Whirlpool Point was part of the Peyto Formation. However, Koeshidayatullah et al. (2020) found that the thickness of this interval (~ 80 m) was far greater than expected for the Peyto Formation (7.6 m) and the upper ~ 70 m of this should therefore be assigned to the Mount Whyte Formation. Koeshidayatullah et al. (2020) identified five lithologies, which include a lower section of shaley limestone and microbial laminites, a middle section of crinkly laminated dolostone and bedding-parallel dolostone bodies with dolomite-cemented fractures, and an upper section with partially dolomitized lime mudrocks and undolomitized ooidal to oncolitic grainstones. Dolostone bodies with rare zebra fabrics comprise over half of the total thickness of the Mount Whyte Formation and are distinguished by their orange-brown color as compared to the gray color of limestone.

Cathedral Formation

Directly overlying the Mount Whyte Formation are the light to dark gray bioturbated peloidal packstones and microbial boundstones of the lower Cathedral Formation. A dolomite-limestone contact occurs 2 m above this (Figs. 4A and 4H) with no observed change in primary facies across the contact. The Cathedral Formation is characterized by 35-cm-thick, medium crystalline, dark gray variably fabric retentive dolomitized packstone beds. Peloidal packstones commonly contain irregular light gray, bedding-parallel mottling (Fig. 4G), and bedding-parallel, bedding-inclined, and bedding-perpendicular fractures cemented by saddle dolomite (Fig. 4F). Zebra dolomite textures are typically parallel or slightly inclined relative to bedding surfaces and are cemented by saddle dolomite (Fig. 4E). The middle section of the Cathedral Formation is marked by the occurrence of highly irregular mosaic and chaotic breccias up to 18 m in height and 16 m in width (relative to ground surface) (Fig. 4B). Breccias are characterized by large (up to 20 cm) dilational fractures and

¹Supplemental Material. Geochemical data for dolomite and limestone (trace element, rare earth element, carbon and oxygen stable isotope, clumped oxygen isotope, noble gas, fluid inclusion and bulk rock XRD) of the Middle Cambrian Cathedral Formation, Southern Canadian Rocky Mountains. Please visit <https://doi.org/10.1130/GSAB.S.13653017> to access the supplemental material, and contact editing@geosociety.org with any questions.

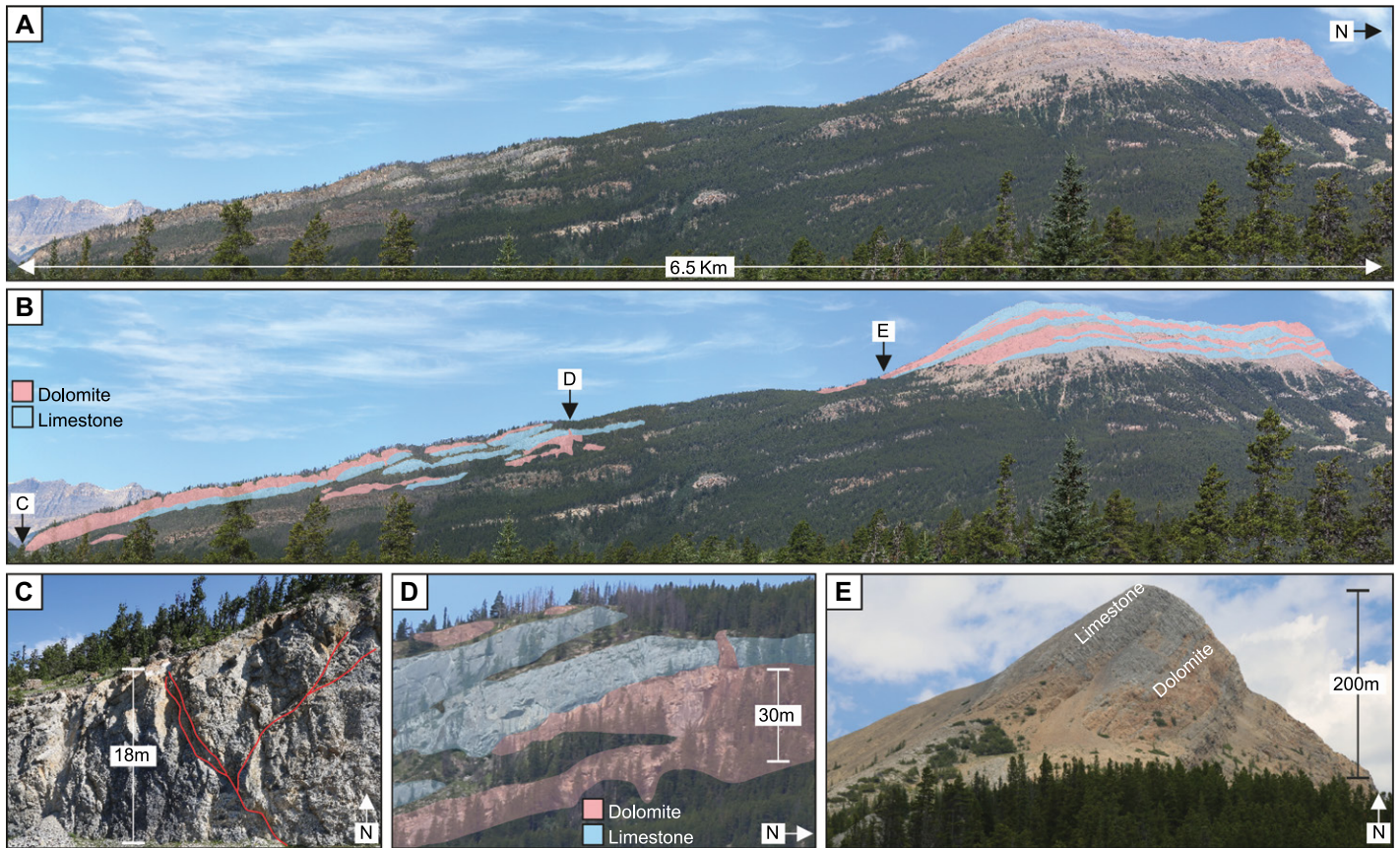


Figure 2. (A) Panorama of the Cathedral Formation at Whirlpool Point is shown. (B) Interpreted limestone units (blue) and dolostone bodies (pink). (C) Fault with saddle dolomite cemented, non-stratabound dolostone. (D) Example of dolostone body contact with host limestone. (E) Sub-bedding parallel dolostone bodies within host limestone.

floating clasts of dolostone cemented by saddle dolomite (Fig. 4D). Dolostone clasts are either light or dark gray (or occasionally both) with microbial laminations uncommonly preserved. Light gray clasts are sub-rounded in comparison to angular dark gray clasts. Light gray clasts occasionally contain fragments of dark gray dolomitized microbial laminations that contain tepee structures and saddle dolomite cement. A normal fault crosscuts this brecciated zone and offsets it by ~30 cm (Fig. 4C). The upper Cathedral Formation is similar to the lower section and is characterized by the occurrence of dark gray dolomitized, bioturbated packstones, intervals of zebra dolomite, and an absence of breccias (Fig. 4A).

Petrography

Cathedral Formation

Petrographic analysis of outcrop samples from the Cathedral Formation identified diagenetic phases based on crystal size, crystal shape, variability of crystal fluid inclusions, and cathodoluminescence (CL) properties.

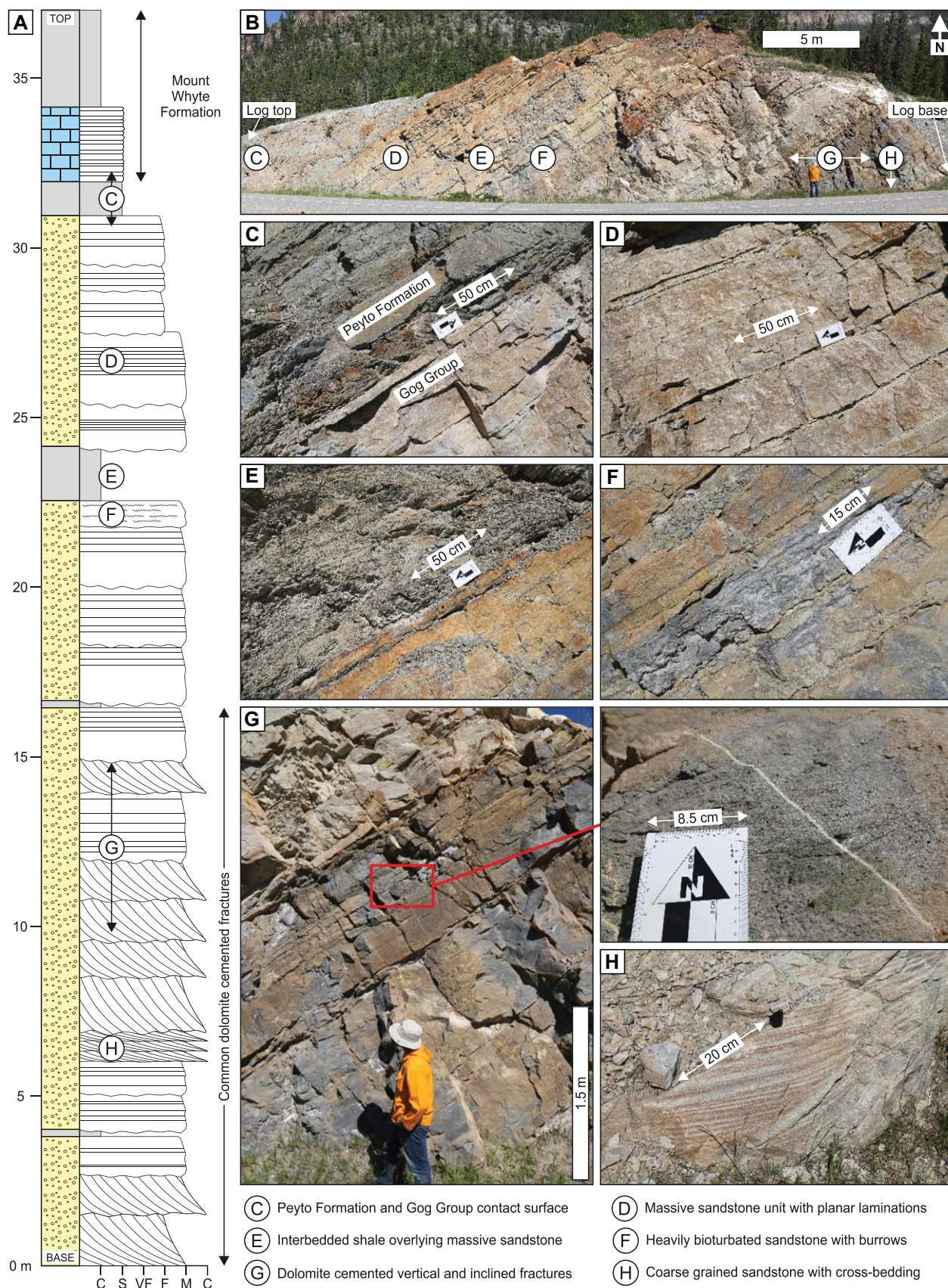
Four calcite phases were identified: matrix calcite (MC), calcite cement 1 (CC1), calcite cement 2 (CC2), and calcite cement 3 (CC3). Four replacement dolomite (RD) phases were also identified (RD1, RD2, RD3, and RD4) in addition to saddle dolomite cement (SDC), which is petrographically similar to a fracture- and stylolite-filling dolomite cement (DC1) phase. Authigenic quartz was also observed within vugs lined with SDC crystals that have irregular crystal faces. Low-amplitude stylolites are the dominant observed pressure solution feature and commonly contain insoluble organic material. Stylolites crosscut all replacement dolomite phases and contain DC1. Quartz is the only diagenetic phase to fully postdate stylolite formation.

Gog Group

Well-rounded to sub-rounded quartz grains are predominantly well-sorted and monocrystalline. Quartz comprises the majority of the matrix, which also contains ~15% K-feldspar. The majority of quartz grains are not in contact with one another and are supported by dolomite ce-

ment. The luminescence of this dolomite phase is similar to SDC and DC1. For full descriptions and the petrographic appearance of the diagenetic phases in the Cathedral Formation and Gog Group; see Table 1 and Figures 5, 6, and 7.

Figure 3. (A) Sedimentary log of the Gog Group at Whirlpool Point is shown. (B) Photograph panorama of the Gog Group outcrop at Whirlpool Point with the base and top of the logged section and photograph locations indicated. (C) Contact of the carbonates of the Peyto Formation with the underlying Gog Group sandstones. (D) Massive sandstone with planar laminations. (E) Interbedded shale overlying massive sandstone. (F) Heavily bioturbated sandstone with burrows (light gray). (G) Dolomite-cemented vertical and inclined fractures within cross-bedded and massive sandstones (inset photograph shows the scale of individual fractures). (H) Coarse-grained sandstone with cross-bedding.



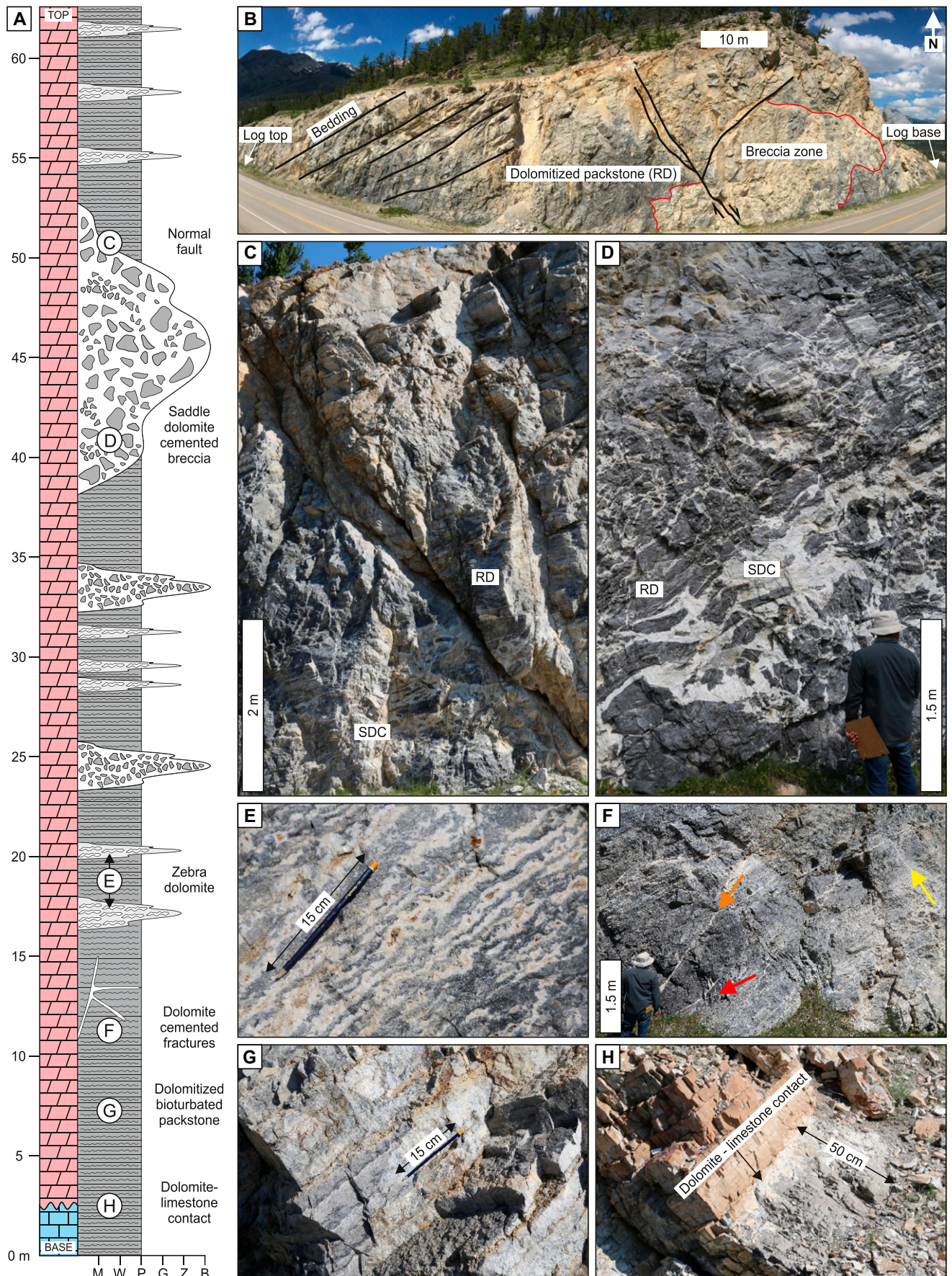


Figure 4. (A) Sedimentary log of the Cathedral Formation at Whirlpool Point is shown. (B) Photograph panorama of the Cathedral Formation outcrop at Whirlpool Point with the base and top of the logged section, fault occurrence, and key features indicated. (C) Normal fault with associated saddle dolomite-cemented (SDC) breccia within replacement dolomite (RD). (D) Saddle dolomite-cemented (SDC) breccia within replacement dolomite (RD). (E) Bedding-parallel zebra fabric within replacement dolomite (gray), cemented by saddle dolomite (white/cream). (F) Bed-parallel (red arrow), bed-inclined (orange arrow), and bed-perpendicular (yellow arrow) fractures cemented by saddle dolomite. (G) Dolomitized packstones (light gray) with horizontal burrows (dark gray). (H) Gradational dolomite (orange)–limestone (gray) contact.

X-Ray Diffraction

Based on bulk rock XRD analyses, all 35 carbonate samples taken along the Cathedral Formation road cut are composed of dolomite with minor calcite (except for two partially dolomitized limestone samples). Eighty-eight percent of dolomite phases are stoichiometric (49–51 mol% CaCO_3), ranging from 49.2 to 52.2 mol% (mean 50.3 ± 0.73 mol%). Dolomite phases are mostly well ordered, ranging from 0.69 to 1.24 (mean 0.98 ± 0.14). Trace quartz and albite are present in partially dolomitized limestone (mean 0.48 wt% and 0.29 wt%, respectively), but these phases are more abundant in pervasively dolomitized intervals (mean 0.99 wt% and 0.41 wt%, respectively). This is corroborated by the presence of authigenic quartz (1–5 mm) in saddle dolomite-cemented vugs.

Trace Elements

Trace element concentrations (Fe, Mn, Sr, Ba, Zn, and Pb) were analyzed by ICP-MS for limestone, replacement dolomite (RD), and saddle dolomite cement (SDC). Concentrations are mean values with standard deviations ($\pm$); see Table 2 for the mean, standard deviation, and range of specific phases.

The mean Fe and Mn concentrations of limestone are 494 ± 99 ppm and 11 ± 0.6 ppm, respectively. Compared to this, RD phases are significantly enriched in Fe and Mn (4475 ± 3430 ppm and 248 ± 222 ppm, re-

spectively). Similarly, SDC phases in the Cathedral Formation and Gog Group are significantly enriched compared to limestone, and certain phases (Table 2) have higher Fe and Mn concentrations than RD (5092 ± 6083 ppm and 399 ± 239 ppm, respectively). The Sr concentrations of RD are depleted (179 ± 107 ppm) compared to limestone (727 ± 61 ppm). SDC Sr concentrations are also depleted (20 ± 5 ppm) compared to limestone and RD. Concentrations of Ba and Pb in RD (1.3 ± 0.4 ppm and 1.9 ± 4.2 ppm, respectively) and SDC (1.6 ± 0.6 ppm and 0.8 ± 1 ppm, respectively) are similar to limestone (2.3 ± 0.2 ppm and 1.1 ± 0.1 ppm). Conversely, the Zn concentrations of RD and SDC are similar (6.7 ± 9.3 ppm and 6.9 ± 3.6 ppm) and are slightly elevated compared to limestone (3.73 ± 0.6 ppm).

Rare Earth Elements

Rare earth element and yttrium (REE + Y) concentrations in limestone, replacement dolomite (RD), and saddle dolomite cement (SDC) are presented in Figure 8; mean values with standard deviations ($\pm$) and the ranges of specific phases are shown in Table 3.

Limestone: The total REE content (ΣREE) of host limestone is 2.74 ± 0.34 ppm, and there is no enrichment of light REE (ΣLREE) (2.38 ± 0.29 ppm) relative to PAAS (Fig. 8A). The mean ratio of Y and Ho (Y/Ho) is 37.35. Calculated Ce anomalies ($\text{Ce}/\text{Ce}^* = [\text{Ce}/(0.5 \text{ La} + 0.5 \text{ Pr})]_{\text{SN}}$) and Pr anomalies ($\text{Pr}/\text{Pr}^* = [\text{Pr}/$

$(0.5 \text{ Ce} + 0.5 \text{ Nd})_{\text{SN}}$) are positive, as values are greater (mean 1.39) than 1 (Fig. 8C). Calculated Eu ($\text{Eu}/\text{Eu}^* = [\text{Eu}/(0.67\text{Sm} + 0.33\text{Tb})]_{\text{SN}}$) anomalies are positive, as values are greater (mean 1.09) than 1. No correlation exists between Eu and Ba, which indicates the absence of Ba interference during REE analysis (Fig. 8D).

Replacement Dolomite: Relative to limestone, RD1 has lower Y/Ho (mean 31.80), Ce/Ce* and Pr/Pr* (mean 1.32) but higher Eu/Eu* (mean 1.16). Compared to RD1, RD2 has lower Y/Ho (mean 30.01) but higher Ce/Ce* and Pr/Pr* (mean 1.26) and Eu/Eu* (mean 1.25). Relative to RD2, RD3 has lower Y/Ho (mean 27.45), Ce/Ce* and Pr/Pr* (mean 1.09), and Eu/Eu* (mean 1.01). Compared to RD3, RD4 has lower Y/Ho (mean 26.79) and Ce/Ce* and Pr/Pr* (mean 1.01).

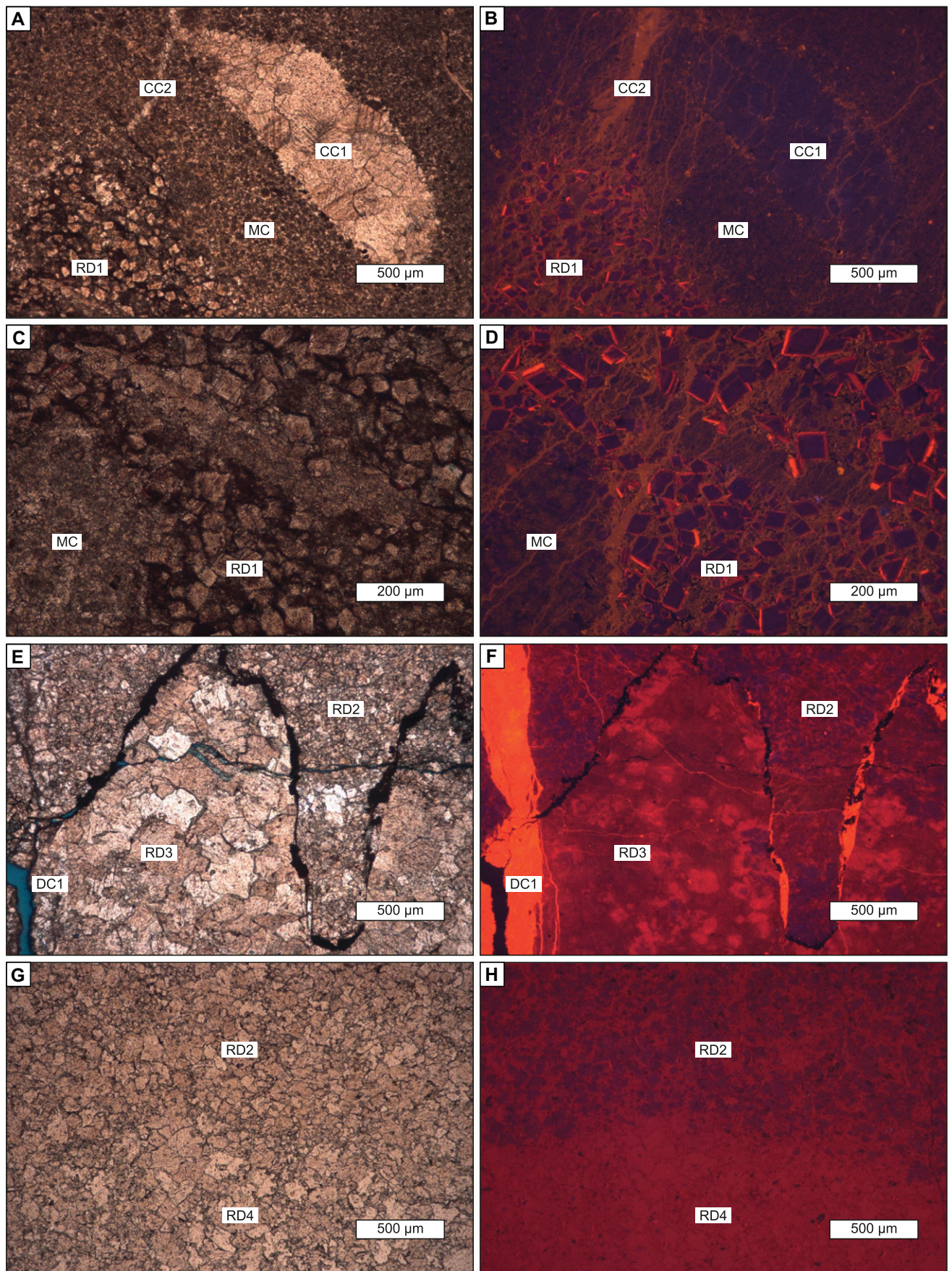
Figure 5. Plane polarized light (PPL) (left) and cathodoluminescence (right) photomicrographs of the Cathedral Formation at the Whirlpool Point locality are shown. (A, B) Partially dolomitized limestone with matrix calcite (MC), pore filling (CC1), and fracture filling (CC2) calcite cements and replacement dolomite (RD1). (C, D) Replacement dolomite (RD1) within matrix calcite (MC). (E, F) Replacement dolomite above (RD2) and below (RD3) stylolites. Dolomite cement (DC1) filling stylolite and vertical fracture. (G, H) Two phases of replacement dolomite above (RD2) and below (RD4) a stylolite.

TABLE 1. PETROGRAPHY OF DIAGENETIC PHASES

Diagenetic Phase	Size (μm)	Morphology*	Extinction	Inclusions	Cathodoluminescence	Distribution
Matrix Calcite (MC)	~25	Blocky	Straight	Turbid	Mottled dark purple–dull orange (no zoning)	Limestone matrix
Calcite Cement 1 (CC1)	30–100	Blocky	Straight	Limpid	Homogenous dull purple (no zoning)	Pore fill in limestone
Calcite Cement 2 (CC2)	25–75	Blocky	Straight	Limpid	Homogenous dull orange (no zoning)	Fracture fill in limestone
Replacement Dolomite 1 (RD1)	20–150	P-e	Straight	Turbid	Simple concentric zoning: dull purple cores, bright orange rims	Dolostone matrix
Replacement Dolomite 2 (RD2)	50–100	P-s / Np	Straight	Turbid	Blotchy zoning: dull purple cores, dull red rims	Dolostone matrix
Replacement Dolomite 3 (RD3)	100–350	Np	Straight	Limpid	Blotchy zoning: light red cores, darker red rims	Dolostone matrix
Replacement Dolomite 4 (RD4)	~15–400	P-s / Np	Straight	Limpid	Blotchy zoning: dull red cores, darker red rims	Dolostone matrix
Saddle Dolomite Cement (SDC)	400–5 mm	Np	Sweeping	Limpid	Simple concentric/oscillatory zoning: dull/dark red, dull/bright orange	Breccia and fracture fill
Calcite Cement 3 (CC3)	600–2 mm	Blocky	Straight	Limpid	Simple concentric zoning: dull purple core, light purple rim	Fracture fill in dolostone
Dolomite Cement 1 (DC1)	250–400	Np / P-e	Sweeping	Limpid	Bright orange (similar to SDC)	Fracture fill in dolostone
Authigenic Quartz (Qtz)	2–4 mm	An	Undulatory	Limpid	Homogenous very dark red	Breccia fill in dolostone
Detrital Quartz†	75–1 mm	An	Undulatory	Limpid	Dull purple/blue	Gog Group matrix
K-Feldspar†	500–4 mm	An	Undulatory	Limpid	Complex bright blue and orange	Gog Group matrix
Dolomite Cement†	30–450	P-e / Np	Straight	Limpid	Simple concentric zoning: dull orange cores, bright orange rims	Gog Group porosity

*Morphology: P-e—planar-e; P-s—planar-s; Np—nonplanar; An—Anhedra.

†Indicates samples from the Gog Group at Whirlpool Point.



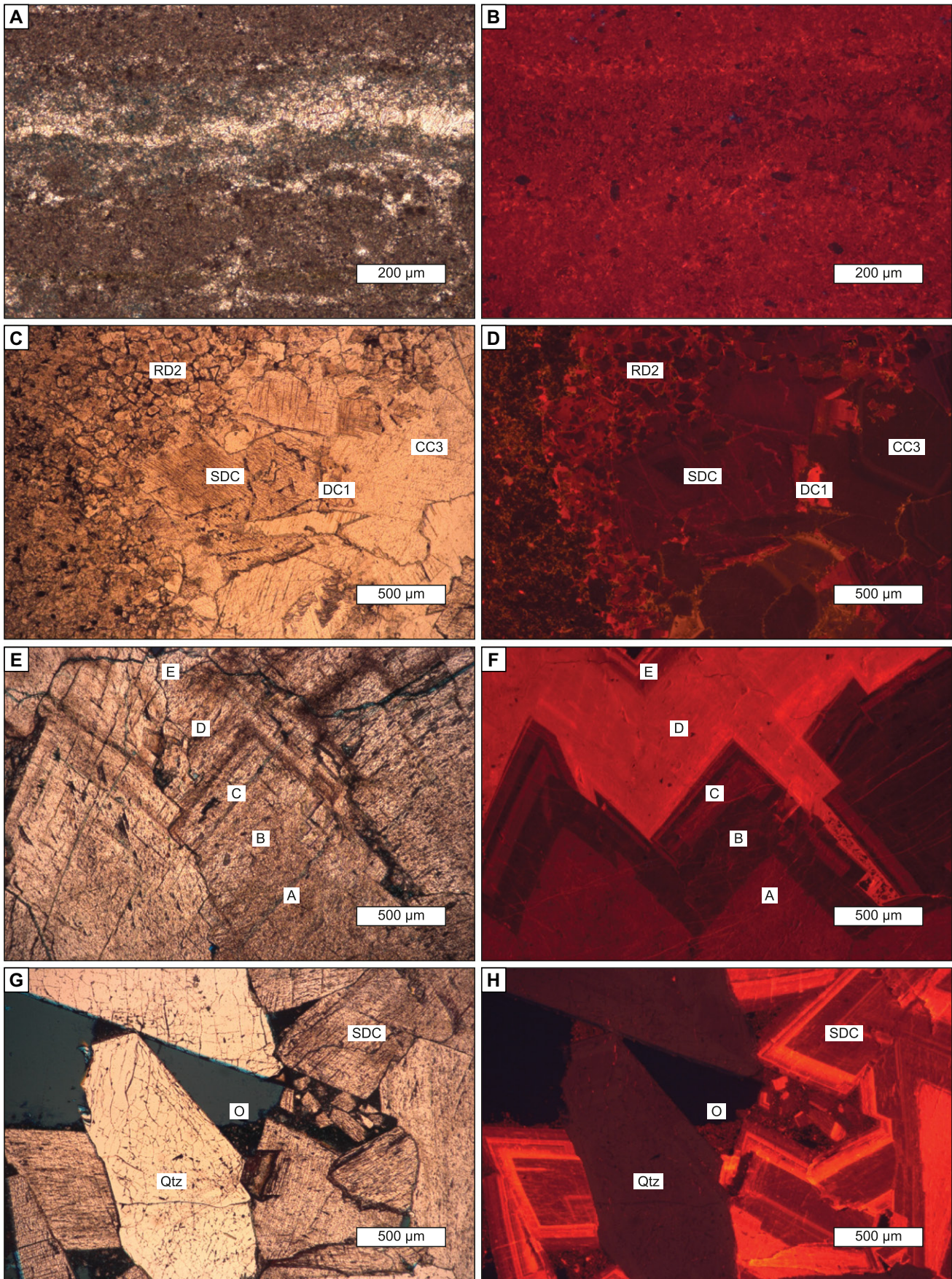


Figure 6. PPL (left) and cathodoluminescence (right) photomicrographs of the Cathedral Formation at the Whirlpool Point locality are shown. (A, B) Depositional laminations replaced by replacement dolomite 4 (RD4). (C, D) Pore infilled by replacement dolomite (RD2), saddle dolomite cement (SDC), calcite cement (CC3), and dolomite cement (DC1). (E, F) Saddle dolomite cement (SDC) with multiple zoning: A. homogenous dull red, B. homogenous dark red, C. alternating zones of dull red and dark red, D. homogenous bright orange, E. alternating zones of dull red and bright orange. (G, H) Vuggy pore partially filled with saddle dolomite cement (SDC), quartz (Qtz), and organics (O).

Pr* (mean 1.07) but higher Eu/Eu* (mean 1.16). All replacement dolomite phases plot within the marine quadrant of the (Pr/Pr*)_{SN} versus (Ce/Ce*)_{SN} cerium anomaly plot (Fig. 8C).

Saddle Dolomite Cement (SDC): Relative to RD4, Road SDC has higher Y/Ho (mean 27.90), Ce/Ce* and Pr/Pr* (mean 1.15), and Eu/Eu* (mean 1.21) (Figs. 8C–8D). Compared to Road SDC, River SDC has higher Y/Ho (34.15) but lower Ce/Ce* and Pr/Pr* and Eu/Eu* anomalies (1.05 and 1.05, respectively). Relative to River SDC, Fault 2 SDC has lower Y/Ho (mean

27.83), whereas Ce/Ce* and Pr/Pr* and Eu/Eu* are higher (1.10 and 1.34, respectively). Gog Group SDC has the lowest mean Y/Ho (22.59) and Ce/Ce* and Pr/Pr* anomalies (1.04) of all samples but high mean Eu/Eu* (1.28). With the exception of one Road SDC sample, all saddle dolomite phases plot outside the marine quadrant of the (Pr/Pr*)_{SN} versus (Ce/Ce*)_{SN} cerium anomaly plot (Fig. 8C).

Stable Isotopes

Stable isotopes of carbon ($\delta^{13}\text{C}_{\text{VPDB}}$) and oxygen ($\delta^{18}\text{O}_{\text{VPDB}}$) are plotted in Figure 9 and shown in Table 4. The mean $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of limestone are -11.6‰ and -0.6‰ , respectively. $\delta^{18}\text{O}$ values of RD phases are progressively more depleted than this (RD1 = -12.3‰ , RD2 = -13.1‰ , RD3 = -13.3‰ , RD4 = -14.1‰). Mean $\delta^{18}\text{O}_{\text{SDC}}$ are also significantly depleted compared to limestone, with River and Road samples also overlapping with RD values (-12.7‰ and -13.9‰ , respectively). Fault 2 and Gog Group SDC are more $\delta^{18}\text{O}$ depleted than these phases (-15.2‰ and -17.7‰ , respectively; Fig. 9). The mean $\delta^{13}\text{C}$ value of RD3 (-0.5‰) is most similar to host limestone. Other RD phases exhibit mean values that are less similar to limestone (RD1 = -0.3‰ , RD2 = 0.4‰ , RD4 = -0.7‰). Similarly, certain SDC phases

exhibit mean $\delta^{13}\text{C}$ values similar to limestone (River SDC = -0.7‰ , Road SDC = -0.7‰), whereas others are more depleted (Fault 2 SDC = -0.8‰ , Gog Group SDC = -2.6‰).

Clumped Isotopes

Precipitation temperatures (Fig. 10A) and the $\delta^{18}\text{O}_{\text{water}}$ (Fig. 10B) of limestone and dolomite samples from the Cathedral Formation were calculated from clumped isotope (Δ_{47}) data (Table 4). The Δ_{47} values of limestone range from 0.329‰ to 0.347‰ , corresponding to $182\text{--}205\text{ °C}$. Replaced (dolomitized) limestone clasts (RLC) have Δ_{47} values of 0.365‰ to 0.398‰ ($130\text{--}162\text{ °C}$). Replacement dolomite (RD) was sampled proximal and distal to the normal fault at Whirlpool Point to determine any spatial variation in temperature. Proximal RD has Δ_{47} values of 0.323‰ to 0.371‰ ($155\text{--}213\text{ °C}$), and distal RD has Δ_{47} values of 0.325‰ to 0.353‰ ($175\text{--}210\text{ °C}$). Saddle dolomite cement (SDC) was also sampled proximal and distal to the fault and has Δ_{47} values of 0.307‰ to 0.344‰ and 0.332‰ to 0.336‰ , respectively ($185\text{--}238\text{ °C}$ and $195\text{--}201\text{ °C}$). The calculated mean $\delta^{18}\text{O}_{\text{water}}$ (‰VSMOW) of limestone is $+8.1\text{‰}$, which is more positive than RLC ($+5.5\text{‰}$). Proximal RD is more positive ($+8.5\text{‰}$) than distal RD ($+7.5\text{‰}$). Similarly, proximal SDC is also more positive ($+9.9\text{‰}$) than distal SDC ($+6.5\text{‰}$).

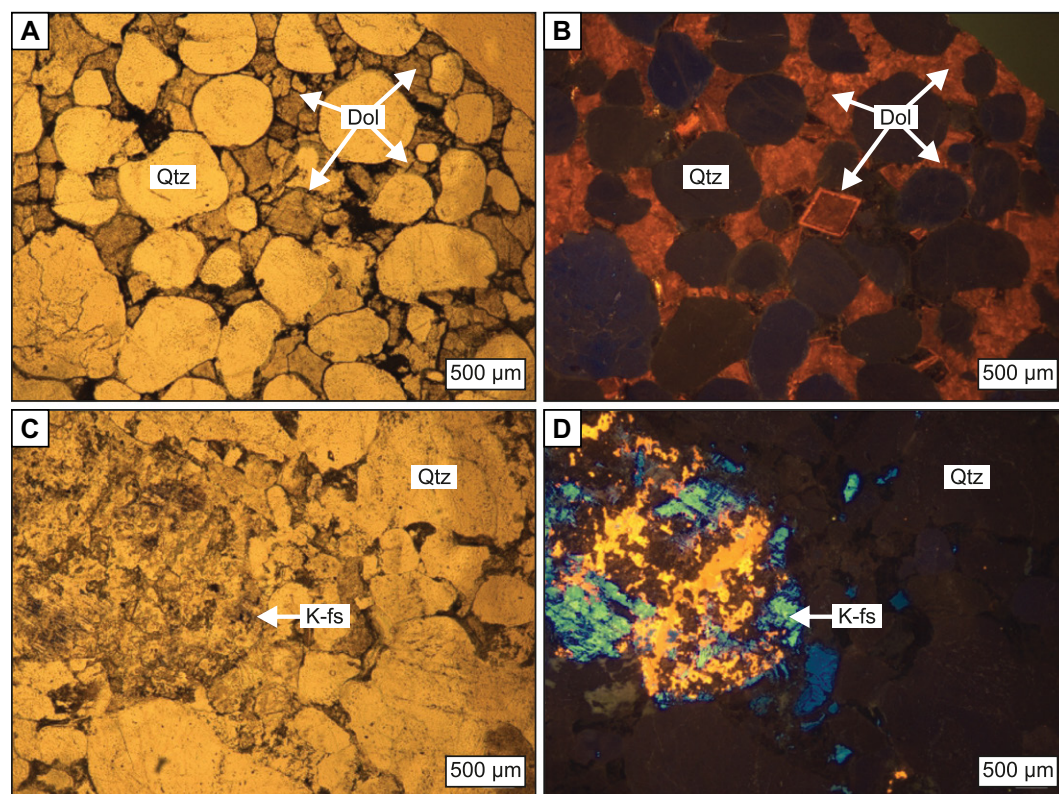


Figure 7. PPL (left) and cathodoluminescence (right) photomicrographs of the Gog Group at Whirlpool Point are shown. (A) Quartz (Qtz) grains with minor concavo-convex contacts cemented by dolomite (dol). (B) Image shows the dull blue luminescence of quartz compared to the bright orange zoned luminescence of dolomite. (C) Quartz (Qtz) grains surround albitized K-feldspar (K-fs). (D) Image shows the complex luminescence of albitized K-feldspar.

TABLE 2. TRACE ELEMENT AND STABLE ISOTOPE DATA

Diagenetic phase	Fe (ppm)	Mn (ppm)	Sr (ppm)	Ba (ppm)	Zn (ppm)	Pb (ppm)	$\delta^{13}\text{C}_{\text{VPDB}}$ (‰)	$\delta^{18}\text{O}_{\text{VPDB}}$ (‰)
Host Limestone								
n	3	3	3	3	3	3	2	2
Min	420	11	662	2.1	3.1	1.0	-0.68	-12.18
Mean	494	11.58	727	2.3	3.73	1.1	-0.66	-11.66
Max	608	12	786	2.5	4.43	1.2	-0.64	-11.15
S.D.	99	0.62	61	0.2	0.6	0.1	0.03	0.72
Replacement Dolomite 1 (RD1)								
n	3	3	3	3	3	3	4	4
Min	958	195	92	1.4	0.8	0.5	-0.72	-13.21
Mean	1353	93	265	1.7	3.5	0.8	-0.30	-12.28
Max	2038	195	377	1.9	5.9	1.0	0.34	-10.76
S.D.	595	88	151	0.3	2.5	0.2	0.48	1.06
Replacement Dolomite 2 (RD2)								
n	2	2	2	2	2	2	2	2
Min	1917	86	24	1.3	1.5	0.5	0.20	-14.27
Mean	3987	316	30	1.5	2.5	0.8	0.42	-13.08
Max	6057	546	35	1.6	3.4	1.0	0.64	-11.89
S.D.	2927	324	7	0.2	1.3	0.2	0.31	1.68
Replacement Dolomite 3 (RD3)								
n	2	2	2	2	2	2	3	3
Min	2893	219	11	0.9	6.3	0.4	-0.68	-14.66
Mean	3914	268	14	1.6	6.5	0.6	-0.54	-13.32
Max	4935	317	17	2.2	6.8	0.7	-0.28	-12.07
S.D.	1444	68	4	0.9	0.3	0.2	0.21	1.29
Replacement Dolomite 4 (RD4)								
n	11	11	11	11	11	11	9	9
Min	1444	101	12	0.6	0.7	0.4	-1.13	-15.32
Mean	5087	353	18	1.3	8.0	2.3	-0.78	-14.11
Max	11,005	813	37	1.7	42.6	18.5	-0.45	-11.90
S.D.	3942	235	6	0.4	11.7	5.3	0.21	1.06
Road Saddle Dolomite Cement								
n	2	2	2	2	2	2	8	8
Min	2026	183	11	0.7	4.4	0.1	-0.97	-15.13
Mean	6171	481	14	0.8	4.8	0.1	-0.74	-13.97
Max	10,317	779	17	0.9	5.2	0.1	-0.52	-12.03
S.D.	5862	421	4	0.1	0.5	0.01	0.17	0.95
River Saddle Dolomite Cement								
n	1	1	1	1	1	1	1	1
Range	3354	346	26	0.9	1.3	0.05	-0.71	-12.75
Fault 2 Saddle Dolomite Cement								
n	2	2	2	2	2	2	2	2
Min	10,991	803	19	0.7	5.7	0.9	-1.02	-15.29
Mean	11,640	808	22	1.6	6.1	1.1	-0.89	-15.26
Max	12,289	813	26	2.6	6.5	1.2	-0.75	-15.23
S.D.	918	7	5	1.4	0.5	0.1	0.19	0.03
Gog Group Saddle Dolomite Cement								
n	2	2	2	2	2	2	2	2
Min	14,572	582	20	0.3	1.9	0.4	-2.64	-17.82
Mean	17,565	629	22	0.7	5.9	0.7	-2.62	-17.76
Max	20,558	677	23	1.2	9.8	0.9	-2.59	-17.71
S.D.	4232	67	2	0.6	5.5	0.3	0.03	0.07

Note: VPDB—Vienna Pee Dee Belemnite; S.D.—standard deviation.

Noble Gases

Helium ($^3\text{He}/^4\text{He}$) and argon ($^{40}\text{Ar}/^{36}\text{Ar}$) isotope ratios were measured for two replacement dolomite (RD) samples (Road and Fault 2) and two saddle dolomite cement (SDC) samples (Road and Fault 2) (Table 5). $^3\text{He}/^4\text{He}$ was normalized to atmospheric values ($R_a = 1.4 \times 10^{-6}$) to produce R/R_a values of 0.077 (± 0.019) (Road SDC) and 0.065 (± 0.065) (Fault 2 SDC). Due to high analytical error, no He data were collected for the RD samples. SDC samples are significantly below the atmospheric $^3\text{He}/^4\text{He}$ ratio of 1 R_a (Farley and Neroda, 1998) and are slightly elevated compared to radiogenic crustal fluids (0.01–0.05 R_a ; Tolstikhin, 1978). The $^{40}\text{Ar}/^{36}\text{Ar}$ values of Road RD and Fault 2 RD are 650 (± 5.34) and 477 (± 8.75), respectively, and the values of Road

SDC and Fault 2 SDC are 556 (± 3.38) and 391 (± 1.72), respectively. All samples have $^{40}\text{Ar}/^{36}\text{Ar}$ values that significantly exceed the atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ value of 298 (Lee et al., 2006). Non-radiogenic heavy noble gases ($\text{Ar}/\text{Kr}/\text{Xe}$) are consistent with a water-derived source.

INTERPRETATION AND DISCUSSION

Timing and Depth of Dolomitization

Petrographical observations were used to determine the paragenesis of the Cathedral Formation at Whirlpool Point (Fig. 11). The earliest diagenetic process to occur was the micritization of skeletal and non-skeletal grains. As very few concavo-convex grain contacts are observed, and blocky calcite cement (CC1) occludes pores

in matrix calcite (MC), significant compaction appears not to have occurred prior to the precipitation of these phases. This is consistent with calcite cementation at or just below the seafloor in the Middle Cambrian.

All RD phases in the Cathedral Formation are crosscut by low amplitude, bedding-parallel stylolites, which suggests that they formed prior to significant burial. Bedding-parallel stylolites have been interpreted to form at depths of 300–800 m (Martín-Martín et al., 2018, and references therein), which suggests that replacement dolomitization of the Cathedral Formation could have occurred at a maximum depth of 800 m and perhaps as shallow as 300 m during early burial. RD crystal textures range from planar-e (RD1) to planar-s and nonplanar (RD2, RD3, and RD4), and increasing crystal sizes result in the reduction of porosity (*sensu* Kaczmarek and Sibley, 2014). Additionally, porosity was likely decreased by pressure solution (stylolitization) during burial (Fig. 11).

As SDC occurs as a cement along stylolites, it must have precipitated during or after stylolitization. Evidence for post-stylolite SDC includes the occurrence of highly brecciated intervals, which are characterized by “exploded” clasts typical of volume expansion associated with hydrobrecciation (*sensu* Jébrak, 1997). This suggests high pore fluid pressures at the time of saddle dolomite cementation. In these intervals, RD inter-clast porosity is fully cemented by SDC (Fig. 4D), which indicates that this phase postdates replacement dolomitization. Certain SDC crystals exhibit irregular faces and cross-cutting of zones in CL (Fig. 6H), which suggests corrosion. One possible explanation for this is that fluids were acidic, perhaps CO_2 bearing (the origin of CO_2 will be discussed in the following section, “Sources of Dolomitizing Fluids”). This is supported by Nesbitt and Muehlenbachs (1994), who found CO_2 in magnesite fluid inclusions from the Cathedral Formation in the Mount Brussilof area. The last diagenetic phase to form was quartz (Fig. 11), as it is observed within vugs cemented by SDC.

The majority of quartz grains in the Gog Group are not in contact, and less than ~20% of grains exhibit concavo-convex contacts. As intergranular volumes are filled with dolomite cement, this suggests that the dolomite was precipitated within interparticle porosity prior to significant burial. This is consistent with the interpreted dolomitization of the Cathedral Formation at a shallow depth, likely through the Middle Cambrian and possibly into the Late Cambrian (497–485.4 Ma; Furongian Epoch) (Fig. 11). This is significantly earlier than previously proposed timings of dolomitization, specifically the middle Silurian to Late Devonian

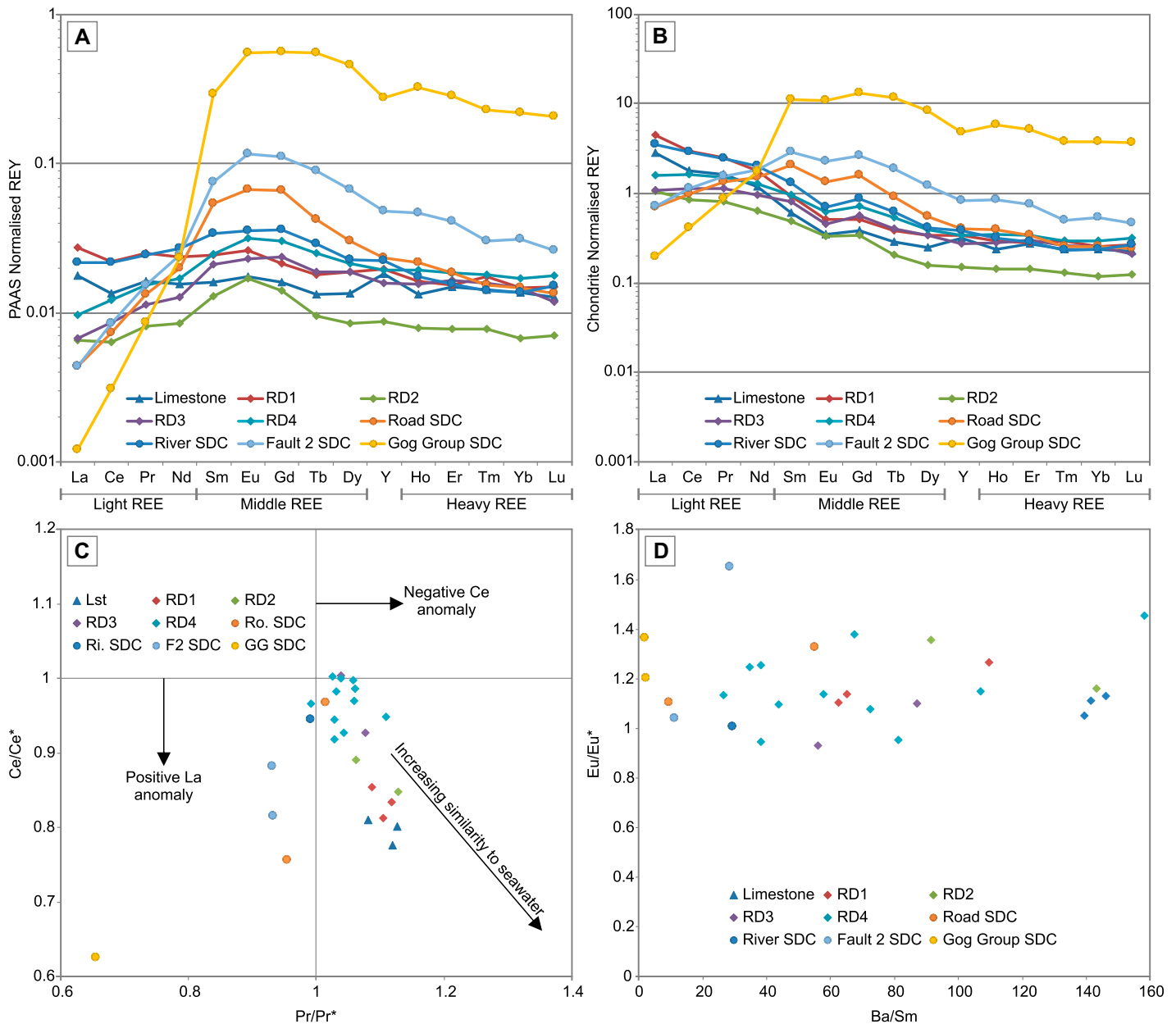


Figure 8. (A) Post Archean Australian Shale- (PAAS) normalized (Taylor and McLennan, 1985) and (B) chondrite-normalized (Anders and Grevesse, 1989) rare earth element (REE) concentrations for limestone and dolomite samples are shown. RD—replacement dolomite; SDC—saddle dolomite cement. Displayed REE profiles are averaged with the exception of River SDC and Gog Group SDC (limestone = 3, RD1 = 3, RD2 = 2, RD3 = 2, RD4 = 11, Road SDC = 2, Fault 2 SDC = 2). (C) $(Pr/Pr^*)_{SN}$ versus $(Ce/Ce^*)_{SN}$ cerium anomaly plot (Webb and Kamber, 2000) shows the clustering of the majority of samples in the marine field of negative Ce and positive La anomalies. (D) (Ba/Sm) versus (Eu/Eu^*) plot demonstrates that no correlation exists between Ba content and Eu anomalies.

(Yao and Demicco, 1997), Late Devonian to Mississippian (Nesbitt and Prochaska, 1998; Vandeginste et al., 2005) and Cretaceous to Paleocene (Symons et al., 1998). A Middle Cambrian timing of dolomitization agrees with other studies of the Cathedral Formation in the Southern Rocky Mountains (Jeary, 2002; Powell et al., 2006; Johnston et al., 2009; Powell, 2009; Collom et al., 2009; Koeshidayatullah et al., 2020). Johnston et al. (2009) found that

a dolomitized megabreccia in the vicinity of the Kicking Horse Rim is crosscut by a mega-truncation event that marked the collapse of the Cathedral platform margin, which suggests that dolomitizing brines were active since the deposition of the Takakkaw Tongue (early *Glossopleura* trilobite zone, ca. 509 Ma) and throughout the deposition of the Burgess Shale (mid *Bathyriscus* trilobite zone, ca. 503 Ma, age-equivalent to the Stephen Formation, which

overlies the Cathedral Formation) during the Middle Cambrian (Collom et al., 2009).

Temperature of Dolomitization

Calculation of $\delta^{18}O_{water}$ (‰VSMOW) using the fractionation calibration of Horita (2014) suggests that limestone precipitated at 40 °C from $\delta^{18}O_{water}$ of −6‰, which agrees with the estimated $\delta^{18}O_{water}$ of Middle Cambrian seawater

TABLE 3. RARE EARTH ELEMENT DATA

Phase	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Y (ppm)	Y/Ho (ppm)	Σ REE (ppm)	Σ LREE (ppm)	Σ HREE (ppm)
Lst	0.748	1.234	0.167	0.576	0.097	0.022	0.085	0.011	0.069	0.016	0.055	0.007	0.046	0.006	0.597	37.346	3.143	2.727	0.130
	0.625	1.002	0.128	0.542	0.083	0.017	0.072	0.009	0.056	0.011	0.039	0.006	0.036	0.005	0.438	38.786	2.545	2.209	0.096
Mean	0.633	0.988	0.135	0.471	0.086	0.018	0.075	0.009	0.054	0.012	0.043	0.005	0.033	0.005	0.449	35.942	2.555	2.228	0.091
RD1	0.669	1.075	0.143	0.500	0.089	0.019	0.075	0.010	0.060	0.013	0.043	0.006	0.038	0.005	0.495	37.358	2.748	2.388	0.106
	1.188	2.048	0.255	0.868	0.156	0.032	0.113	0.016	0.094	0.019	0.048	0.008	0.046	0.008	0.611	32.897	4.903	4.360	0.129
	1.366	2.326	0.300	1.001	0.179	0.036	0.133	0.017	0.104	0.021	0.060	0.009	0.059	0.008	0.705	33.893	5.623	4.995	0.156
Mean	0.575	0.920	0.117	0.393	0.071	0.016	0.054	0.007	0.049	0.009	0.025	0.004	0.019	0.003	0.261	38.630	2.266	2.007	0.060
RD2	1.043	1.765	0.224	0.754	0.135	0.028	0.100	0.013	0.082	0.016	0.044	0.007	0.041	0.006	0.526	31.807	4.264	3.787	0.115
	0.274	0.578	0.080	0.311	0.079	0.021	0.070	0.007	0.034	0.007	0.021	0.003	0.018	0.002	0.239	32.323	1.509	1.245	0.052
Mean	0.218	0.439	0.064	0.233	0.063	0.015	0.061	0.007	0.041	0.008	0.024	0.003	0.020	0.004	0.230	27.700	1.205	0.956	0.059
RD3	0.246	0.509	0.072	0.272	0.071	0.018	0.065	0.007	0.038	0.008	0.023	0.003	0.019	0.003	0.235	30.012	1.357	1.100	0.055
	0.174	0.490	0.067	0.273	0.091	0.017	0.079	0.009	0.063	0.012	0.042	0.005	0.033	0.004	0.330	27.014	1.364	1.006	0.097
Mean	0.333	0.883	0.133	0.541	0.144	0.033	0.141	0.019	0.102	0.019	0.053	0.007	0.049	0.006	0.524	27.889	2.469	1.893	0.135
RD4	0.253	0.687	0.100	0.407	0.118	0.025	0.110	0.014	0.082	0.016	0.048	0.006	0.041	0.005	0.427	27.452	1.916	1.449	0.116
	0.276	0.719	0.107	0.455	0.112	0.021	0.103	0.014	0.067	0.015	0.041	0.006	0.042	0.007	0.423	28.483	1.989	1.559	0.111
Mean	0.252	0.739	0.108	0.459	0.143	0.032	0.130	0.020	0.110	0.024	0.072	0.009	0.064	0.012	0.585	24.786	2.177	1.559	0.181
	0.463	1.129	0.142	0.535	0.116	0.027	0.120	0.015	0.073	0.017	0.045	0.006	0.045	0.006	0.424	25.248	2.742	2.271	0.119
	0.239	0.507	0.066	0.264	0.060	0.021	0.076	0.009	0.047	0.010	0.030	0.003	0.022	0.005	0.254	26.328	1.361	1.077	0.069
	0.214	0.635	0.069	0.442	0.147	0.038	0.170	0.021	0.113	0.024	0.066	0.010	0.050	0.011	0.634	25.977	2.042	1.389	0.162
	1.279	3.225	0.419	1.560	0.310	0.071	0.280	0.033	0.167	0.030	0.079	0.010	0.073	0.010	0.951	31.543	7.552	6.485	0.203
	0.348	1.102	0.167	0.691	0.261	0.074	0.297	0.034	0.172	0.031	0.080	0.011	0.077	0.010	0.898	29.330	3.361	2.311	0.209
Mean	0.325	0.850	0.123	0.458	0.104	0.021	0.105	0.018	0.087	0.022	0.051	0.006	0.034	0.004	0.435	19.821	2.212	1.758	0.116
RoSDC	0.170	0.554	0.082	0.337	0.088	0.026	0.087	0.014	0.063	0.015	0.049	0.007	0.044	0.006	0.393	26.046	1.567	1.165	0.121
	0.207	0.630	0.091	0.388	0.091	0.023	0.098	0.015	0.073	0.014	0.044	0.005	0.039	0.008	0.405	28.735	1.729	1.318	0.110
	0.249	0.623	0.088	0.368	0.090	0.023	0.086	0.012	0.062	0.012	0.035	0.005	0.032	0.008	0.342	28.406	1.693	1.330	0.089
	0.367	0.974	0.135	0.542	0.138	0.034	0.141	0.019	0.094	0.019	0.054	0.007	0.047	0.008	0.522	26.791	2.584	2.020	0.135
Mean	0.182	0.444	0.059	0.243	0.063	0.017	0.056	0.007	0.045	0.009	0.030	0.004	0.029	0.004	0.235	25.429	1.198	0.930	0.077
	0.111	0.648	0.164	0.980	0.527	0.127	0.550	0.056	0.213	0.032	0.072	0.007	0.046	0.006	0.976	30.381	3.544	1.906	0.164
Mean	0.147	0.546	0.112	0.611	0.295	0.072	0.303	0.031	0.129	0.021	0.051	0.006	0.038	0.005	0.605	27.905	2.371	1.418	0.121
FiSDC	0.829	1.739	0.215	0.866	0.190	0.038	0.169	0.022	0.099	0.018	0.045	0.006	0.036	0.007	0.600	34.159	4.285	3.651	0.113
F2SDC	0.103	0.480	0.107	0.633	0.328	0.122	0.365	0.045	0.192	0.029	0.079	0.009	0.065	0.008	0.834	28.430	2.569	1.324	0.191
	0.228	0.868	0.165	0.929	0.513	0.131	0.677	0.091	0.396	0.064	0.161	0.015	0.109	0.014	1.750	27.244	4.365	2.192	0.364
Mean	0.165	0.674	0.136	0.781	0.420	0.127	0.521	0.068	0.294	0.047	0.120	0.012	0.087	0.011	1.292	27.637	3.467	1.758	0.277
GGSDC	0.045	0.245	0.076	0.741	1.639	0.607	2.623	0.424	2.007	0.325	0.824	0.091	0.612	0.089	7.510	23.085	10.354	1.109	1.942
	0.030	0.363	0.157	1.91	4.529	1.45	7.041	1.067	4.997	0.833	2.008	0.229	1.625	0.159	18.416	22.114	26.503	2.486	4.923
Mean	0.038	0.314	0.116	1.32	3.084	1.03	4.832	0.746	3.502	0.579	1.416	0.160	1.119	0.159	12.963	22.600	18.249	1.798	3.432

Note: Lst—limestone; RD—replacement dolomite; SDC—saddle dolomite cement; Fo—road sample; Ri—river sample; F2—fault 2 sample; GG—Gog Group sample.

(−6‰ to 0‰, Veizer and Prokoph, 2015; Henkes et al., 2018). Calculated Δ_{47} temperatures ($T\Delta_{47}$) of limestone range from 182 °C to 205 °C, which corresponds to a mean $\delta^{18}\text{O}_{\text{water}}$ (‰VSMOW) of +8.1‰. As carbonate Δ_{47} values are susceptible to resetting through prolonged burial heating (Lloyd et al., 2018), the measured temperatures of limestone reflect the minimum temperature of dynamic recrystallization (Ryb et al., 2017) rather than the true crystallization temperature. It is assumed that the Δ_{47} values of dolomite are reliable as dolomite is resistant to reordering up to temperatures of 250–300 °C (Lloyd et al., 2018). This is supported by the variability of the calculated temperatures of stable and clumped isotopes for replaced limestone clasts, RD, and SDC, which are interpreted to record replacement dolomitization and precipitation temperatures and not dynamic recrystallization.

Mean $T\Delta_{47}$ values of replacement dolomite increase from the fault (184 °C) to the dolomite body margins (193 °C). Compared to replacement dolomite, saddle dolomite cement exhibits an inverse temperature relationship, as fault-proximal phases precipitated at greater mean temperatures ($T\Delta_{47}$ 212 °C) than did the fault-distal equivalent (198 °C). The most likely explanation for the variable temperatures of each phase is that there were localized differences in temperature due to the convection of fluids along the fault plane (as shown by Benjakul et al., 2020) and during replacement dolomitization. The permeability of the Cathedral Formation may have also been a factor, with fluids potentially able to migrate farther from the fault during replacement dolomitization (up to ~6.5 km) than at the time of saddle dolomite cementation (up to ~18 m).

The maximum $T\Delta_{47}$ values of replacement dolomite and saddle dolomite cement are 66 °C and 60 °C, respectively, hotter than fluid inclusion homogenization temperatures (T_h) of the same phases (data from Jeary, 2002; Fig. 12). As the Δ_{47} values are assumed to reflect the true crystallization temperature, this difference is likely due to fluid inclusions only recording the minimum entrapment temperature (non-pressure corrected) (Goldstein, 2001). Despite the differences in temperature, both data sets demonstrate that the dolomitizing fluids at Whirlpool Point are truly hydrothermal (sensu Machel and Lonnee, 2002). This is corroborated by the significant positive Eu anomalies of all phases, which has previously been attributed to hydrothermal fluids (Bau, 1991; Bau and Dulski, 1996; Fig. 8D).

The existence of regional hydrothermal dolomitizing fluids is potentially evidence for high latent, post-rift heat flow during the Middle Cambrian. The latest rifting event along the

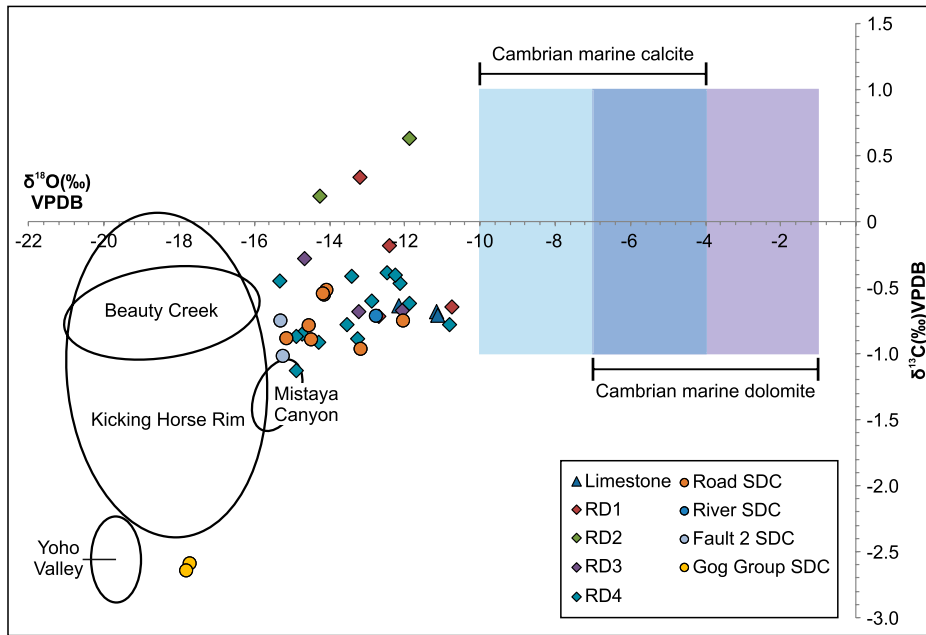


Figure 9. Plot shows stable isotope ($\delta^{18}\text{O}_{\text{VPDB}}$ versus $\delta^{13}\text{C}_{\text{VPDB}}$) data collected by this study compared with the data collected by Vandeginste et al. (2005) from the Mistaya Canyon, Beauty Creek, Kicking Horse Rim, and Yoho Valley areas. RD—replacement dolomite; SDC—saddle dolomite cement. Cambrian marine calcite and dolomite values (Veizer and Prokoph, 2015; Henkes et al., 2018; Ryb and Eiler, 2018) are included for comparison. VDPB—Vienna Pee Dee Belemnite.

western margin of Laurentia is known to have occurred during the Early Cambrian (Bond and Kominz, 1984), when the Gog Group was de-

posited (Desjardins et al., 2012), but heat flow and tectonic activity potentially remained high throughout the Middle Cambrian (Powell et al.,

2006). Assuming a normal post-rift geothermal gradient of 25 °C/km (Bertotti et al., 1999), and the maximum temperature calculated from clumped isotopes (238 °C), the depth at which the dolomitizing fluids could have originated is ~9.5 km. However, Koeshidayatullah et al. (2020) suggested that the geothermal gradient in the Western Canadian Sedimentary Basin during the Middle Cambrian was up to 40 °C/km (likely related to crustal thinning caused by rifting during the Early Cambrian). Based on this, dolomitizing fluids potentially originated at a depth of ~6 km before ascending faults to dolomitize the Cathedral Formation.

Fluid inclusion data from Jeary (2002) were compared with data from replacement dolomite (RD) and saddle dolomite cement (SDC) phases from the Kicking Horse Rim, Yoho Valley, Mistaya Canyon, and Beauty Creek areas (Vandeginste et al., 2005) (Fig. 12A). Linear regressions were conducted between the modal values of these phases and their distance from the Cathedral platform margin, which also produced calculated coefficients of determination (R^2). RD, pore lining SDC, and pore filling SDC exhibit R^2 values of 0.33, 0.82, and 0.91, respectively (Figs. 12C–12E). The linear regressions show that T_h increases from the platform interior (Whirlpool Point) to the platform margin (Kicking Horse Rim) (Figs. 12C–12E), although as the ranges of these phases overlap, it is possible that this temperature trend is not real. Despite this uncertainty, the $\delta^{18}\text{O}$ values of dolomite become progressively more depleted from Whirlpool Point to the Kicking Horse Rim, which suggests higher fluid temperatures at the platform margin than at the platform interior. One possible explanation for this is that hydrothermal fluids were derived from faults, and these fluids originated at greater depths below the platform margin than the platform interior. Alternatively, there might have been downdip migration of fault-derived fluids that were progressively heated toward the platform margin. It is possible that a combination of both processes was responsible for the emplacement of hydrothermal dolomitizing fluids in the Cathedral Formation during the Middle Cambrian, which suggests that the hydrology of this hydrothermal system was complex.

Sources of Dolomitizing Fluids

The strongest negative cerium anomalies and highest Y/Ho ratios of the samples analyzed in this study are from limestone (mean 1.39 and 37.35, respectively). Compared to this, RD phases have lower cerium anomalies and Y/Ho ratios. SDC phases also exhibit negative cerium anomalies and Y/Ho ratios comparable to those of replacement dolomite but do not plot in the

TABLE 4. STABLE AND CLUMPED ISOTOPE DATA

Sample	$\delta^{13}\text{C}_{\text{VPDB}}$ (‰)	$\delta^{18}\text{O}_{\text{VPDB}}$ (‰)	$\Delta_{47}\text{-RF}$	$T_{\Delta 47}$ (°C)	$\delta^{18}\text{O}_{\text{water}}$ (SMOW)
Limestone (n = 2)					
Min	-0.57	-10.74	0.329	182	7.39
Mean	-0.55	-10.70	0.338	193	8.10
Max	-0.53	-10.66	0.347	205	8.82
S.D.	0.017	0.043	0.008	11.46	0.71
Replaced Limestone Clast (n = 2)					
Min	-0.52	-10.26	0.365	130	4.35
Mean	-0.49	-10.10	0.382	146	5.54
Max	-0.45	-9.93	0.398	162	6.73
S.D.	0.033	0.163	0.016	15.83	1.19
Fault Proximal Replacement Dolomite (n = 2)					
Min	-0.514	-9.91	0.323	155	6.60
Mean	-0.511	-9.88	0.347	184	8.50
Max	-0.509	-9.85	0.371	213	10.41
S.D.	0.002	0.031	0.024	29.03	1.90
Fault Distal Replacement Dolomite (n = 2)					
Min	-0.434	-11.50	0.325	175	6.44
Mean	-0.436	-11.46	0.339	193	7.58
Max	-0.438	-11.42	0.353	210	8.72
S.D.	0.002	0.040	0.013	17.57	1.14
Fault Proximal Saddle Dolomite Cement (n = 2)					
Min	-0.65	-10.16	0.307	185	8.54
Mean	-0.61	-10.12	0.326	212	9.99
Max	-0.58	-10.08	0.344	238	11.45
S.D.	0.032	0.037	0.018	26.67	1.45
Fault Distal Saddle Dolomite Cement (n = 2)					
Min	-0.55	-12.90	0.332	195	6.31
Mean	-0.54	-12.82	0.334	198	6.57
Max	-0.52	-12.73	0.336	201	6.83
S.D.	0.014	0.085	0.002	2.88	0.26

Note: VPDB—Vienna Pee Dee Belemnite; SMOW—standard mean ocean water; S.D.—standard deviation.

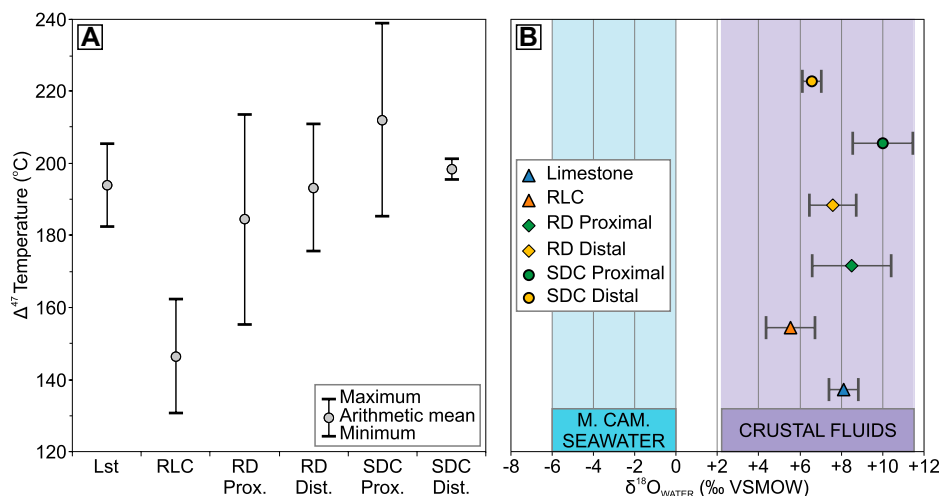


Figure 10. (A) Clumped isotope (Δ_{47}) temperature data of limestone and dolomite samples collected by this study are shown. RLC—replaced limestone clast; RD—replacement dolomite (proximal to fault and distal to fault); SDC—saddle dolomite cement (proximal to fault and distal to fault). (B) Plot of $\delta^{18}\text{O}_{\text{water}}$ values of the samples shown in (A). These values are compared to Middle Cambrian seawater (Veizer and Prokoph, 2015; Henkes et al., 2018) and crustal fluids (Schulze et al., 2003).

field of true cerium anomalies that are typical of modern seawater (Fig. 8C). As $\delta^{13}\text{C}$ values of replacement dolomite and saddle dolomite cement phases fit within the ranges of Cambrian marine dolomite (-1.0‰ to -1.0‰ , Veizer and Prokoph, 2015; Henkes et al., 2018; Ryb and Eiler, 2018), this suggests that fluid-rock ratios were sufficient to rock-buffer carbon isotope values (Banner et al., 1988). However, the variance in REE data indicates that fluid-rock ratios were high enough to preserve the trace element composition of the dolomitizing fluids.

The negative cerium anomalies of limestone and RD are consistent with replacement dolomitization by seawater (Tostevin et al., 2016). Wallace et al. (2017) suggested that weak negative cerium anomalies persisted during the early Paleozoic, as oceans during this time had a tendency toward anoxia. However, ocean stratification persisted throughout the Middle Cambrian with oxygenated surface waters overlying anoxic bottom waters (Gill et al., 2011). The Cathedral

Formation was deposited in shallow, oxygenated water, and this is reflected by the negative cerium anomalies reported by this study. Despite this, the Y/Ho values of limestone and dolomite samples are less (19–38) than expected for open marine (40–80) and near shore/restricted (33–40) settings (Tostevin et al., 2016, and references therein). Y/Ho can be affected by a number of different processes including salinity, biological processes, and redox cycling (Hill et al., 2000; Liu and Byrne, 1997). The Y/Ho values of the Cathedral Formation may have been affected by any one or a combination of these processes. In summary, this evidence supports the interpretation that the Cathedral Formation was dolomitized by seawater, and as negative cerium anomalies and Y/Ho ratios become weaker with each successive RD phase (Fig. 8C), this suggests that dolomitizing fluids became less seawater-dominated as replacement dolomitization progressed.

The REE profiles of SDC phases are significantly different from those of limestone and

RD (Figs. 8A–8B) and are extremely light rare earth element (LREE) depleted and heavy rare earth element (HREE) enriched (Table 3). These characteristics have been documented for hydrothermal fluids (Klinkhammer et al., 1983) and hydrothermal dolomites in the Viburnum Trend, USA (Graf, 1984), and the San Vicente District, Peru (Spangenberg et al., 1999), and are consistent with the presence of MVT mineralization on the Cathedral platform margin at the Kicking Horse Rim (Nesbitt and Muehlenbachs, 1994; Nesbitt and Prochaska, 1998; Symons et al., 1998; Swennen et al., 2003; Vandeginste et al., 2007). The presence of MVT deposits on the platform margin has been attributed to the localized emplacement of metalliferous brines (Vandeginste et al., 2007), which were not emplaced at Whirlpool Point. Despite this, the unusual REE characteristics of SDC may potentially indicate that the dolomitizing fluids at the platform margin and interior had a common origin, especially as RD and SDC have slightly elevated Zn concentrations compared to those of limestone.

$^3\text{He}/^4\text{He}$ values (Ra 0.065–0.077) are well below atmospheric values (1; Farley and Neroda, 1998) and are slightly elevated compared to those of radiogenic crustal fluids (0.01–0.05 Ra; Tolstikhin, 1978). Using the maximum recorded $^3\text{He}/^4\text{He}$ value of 0.077, the contribution of mantle He was calculated following the methodology of Kendrick et al. (2002) and was found to be negligible (0.4%), which indicates that the dolomitizing fluids at Whirlpool Point were predominantly crustal in origin. $^{40}\text{Ar}/^{36}\text{Ar}$ values of both RD and SDC are significantly elevated compared to air and are suggestive of fluids that originated in the deeper crust. The $^{40}\text{Ar}^*/^4\text{He}$ ratios ($^{40}\text{Ar}^*$ = radiogenic ^{40}Ar) of Road RD (0.54), Fault 2 RD (0.37), Road SDC (7.76), and Fault 2 SDC (4.51) are all significantly higher than the expected average crustal $^{40}\text{Ar}^*/^4\text{He}$ production of ~ 0.2 (Ballentine and Burnard, 2002), which indicates diffusive loss of He. Nonetheless, it is reasonable to suggest that a component of the dolomitizing fluids acquired both radiogenic ^4He and ^{40}Ar from a deeper crustal source. One possible explanation for the origin of this

TABLE 5. NOBLE GAS DATA

Sample*	$^3\text{He}/^4\text{He}$	Error	$^3\text{He}/^4\text{He}$ (R/R _A)	Error	$^{40}\text{Ar}/^{36}\text{Ar}$	Error	$^{84}\text{Kr}/^{36}\text{Ar}$	Error	$^{132}\text{Xe}/^{36}\text{Ar}$	Error
Air	-	-	1†	-	298.56§	-	0.041#	-	0.000745**	-
Serpentinite	-	-	-	-	-	-	0.028–0.047**	-	0.00075–0.0069**	-
R RD	N.D.††	-	N.D.	-	650.80	5.34	0.038	0.001	0.0029	3.27E-05
F2 RD	N.D.	-	N.D.	-	477.58	8.75	0.029	0.001	0.0014	1.27E-05
R SDC	1.08E-07	2.69E-08	0.077	0.019	556.18	3.38	0.046	0.003	0.0024	0.0002
F2 SDC	9.19E-08	3.02E-09	0.065	0.018	391.09	1.72	0.040	0.001	0.0019	0.0001

*Sample: R RD—road replacement dolomite; F2 RD—fault 2 replacement dolomite; R SDC—road saddle dolomite cement; F2 SDC—fault 2 saddle dolomite cement.

†Taken from Farley and Neroda (1998).

§Taken from Lee et al. (2006).

#Taken from Holland and Ballentine (2006).

**Taken from Kobayashi et al. (2017).

††N.D.—not determined.

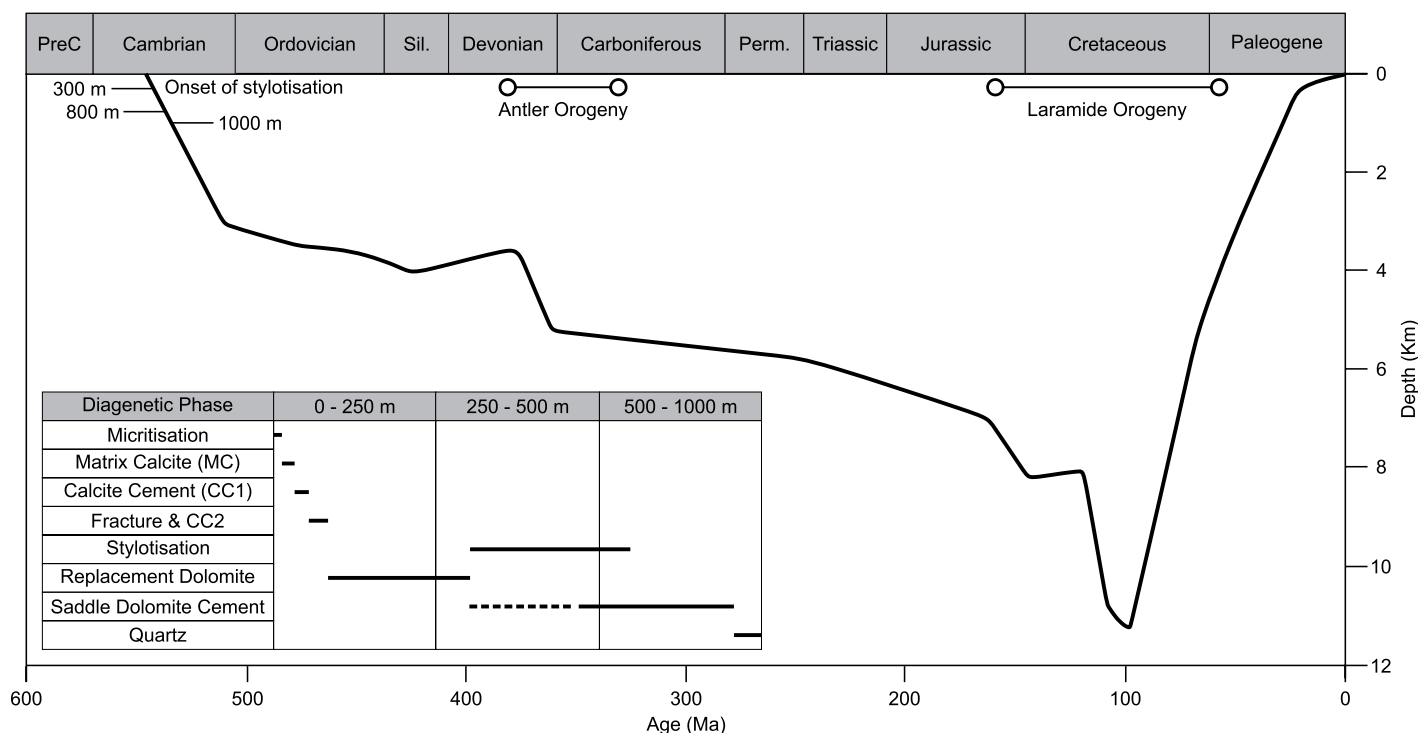


Figure 11. Burial history plot shows the Cambrian strata present in the Sukunka Front Ranges (modified after Vandeginste et al., 2007) with the interpreted paragenetic sequence of the Cathedral Formation at Whirlpool Point.

fluid is serpentinization of ultramafic rocks as invoked by Koeshidayatullah et al. (2020) for the underlying Mount Whyte Formation. They reported very hot fluids (max. 239 °C) with very high salinities (fluid inclusions did not freeze at -180 °C) and proposed that dolomitization occurred from a mixture of convected seawater and serpentinite-derived fluids along faults. Comparable temperatures were measured in this study (max. 238 °C), and high salinities have been reported across the Cathedral Platform from SDC (13–30 equivalent wt% NaCl) (Nesbitt and Muehlenbachs, 1994; Yao and Demicco, 1995; Nesbitt and Prochaska, 1998; Vandeginste et al., 2007). A serpentinite-derived component of the fluids that dolomitized the Cathedral Formation is supported by $^{84}\text{Kr}/^{36}\text{Ar}$ and $^{132}\text{Xe}/^{36}\text{Ar}$ data of RD (mean 0.033 and 0.002, respectively) and SDC (mean 0.043 and 0.002, respectively), which are consistent with ranges expected for serpentinites (0.028–0.047 and 0.00075–0.0069, respectively; Kobayashi et al., 2017). This is also corroborated by the occurrence of magnesite and talc hosted in the Cathedral Formation (Powell et al., 2006), both of which are thought to be formed as a by-product of serpentinization (Koeshidayatullah et al., 2020, and references therein). Additional evidence for serpentinite-derived fluids includes the occurrence of CO_2 in Cathedral Formation magnesite fluid inclusions (Nesbitt and Muehlenbachs, 1994), as CO_2 is

required for carbonation and serpentinization of ultramafic rocks (Lafay et al., 2017; Robertson, et al., 2019).

In summary, REE + Y and noble gas data suggest that the Cathedral Formation was dolomitized by seawater mixed with a deeper-sourced, serpentinite-derived brine. This is consistent with the $\delta^{18}\text{O}_{\text{water}}$ values of RD (+6.60‰ to +10.41‰) and SDC (+6.31‰ to +11.45‰), which exceed Middle Cambrian seawater (0‰ to -6‰; Veizer and Prokoph, 2015; Henkes et al., 2018) but are similar to those reported for crustal fluids (+2.20‰ to +11.50‰ Schulze et al., 2003, and references therein). The high $\delta^{18}\text{O}_{\text{water}}$ of limestone (+7.39‰ to +8.82‰) relative to Middle Cambrian seawater is likely due to recrystallization during burial.

Mechanisms of Dolomitization

Whirlpool Point

The evidence presented by this study indicates that the Cathedral Formation was dolomitized by a mixture of seawater and hot, serpentinite-derived brines that originated at ~6 km depth. This is far deeper than the interpreted depth of the Cathedral Formation when dolomitization took place (<1 km), which suggests that serpentinite-derived brines migrated upward along permeable faults. As the Cathedral Platform experienced frequent earthquakes during the Middle Cam-

brian (Pratt, 2002), it is possible that faults were permeable as a result of co-seismic dilatancy. Based on the high negative Ce anomalies of RD1 and RD2, seawater was likely the dominant fluid during the early stages of replacement dolomitization. This suggests that the fault at Whirlpool Point breached the Middle Cambrian seafloor, allowing seawater to descend and convect along the fault plane (Fig. 13A, T_1). As the negative Ce anomalies of RD3 and RD4 are lower than those of RD1 and RD2, this suggests that serpentinite-derived brines became more dominant as replacement dolomitization progressed. This is consistent with a reduction in the supply of seawater, possibly due to the deposition of the overlying Stephen Formation shale, through which the fault was unable to propagate (Fig. 13A, T_2).

The interpretation that faults controlled the dolomitization of the Cathedral Formation is supported by 3-D reactive transport modeling (Benjakul et al., 2020), which shows that fluid convection can be driven by the mixing of cool seawater descending through faults and hot, ascending, basement-derived brines. The model results show that the resulting dolomite bodies can extend away from the fault for hundreds of meters, which is equivalent in scale to the observed lateral and vertical extent of the dolomitized zone at Whirlpool Point. As well as fault-controlled fluid flow, it is likely that dolomitizing fluids exploited the underlying Gog

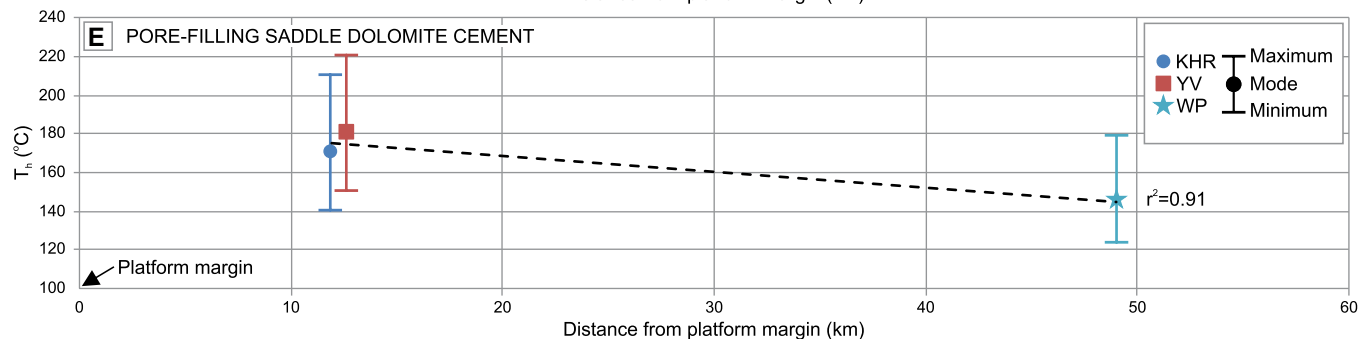
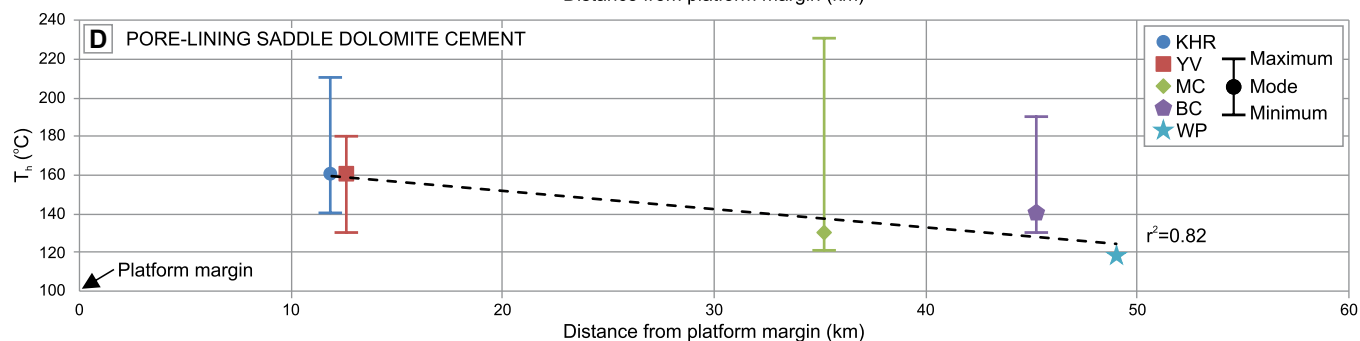
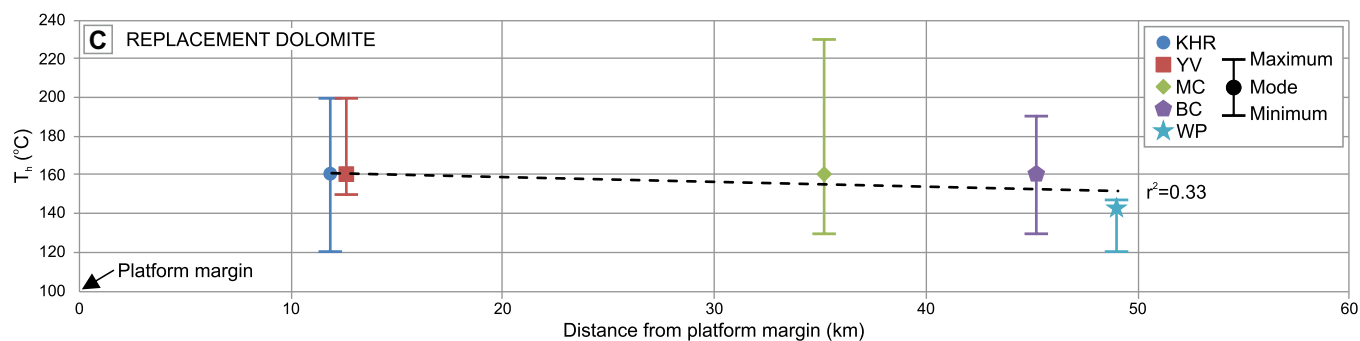
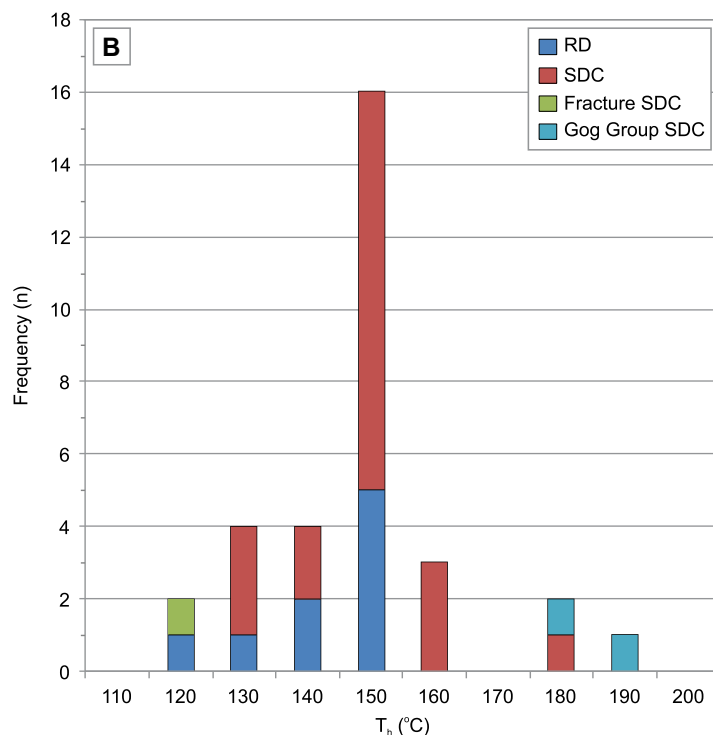
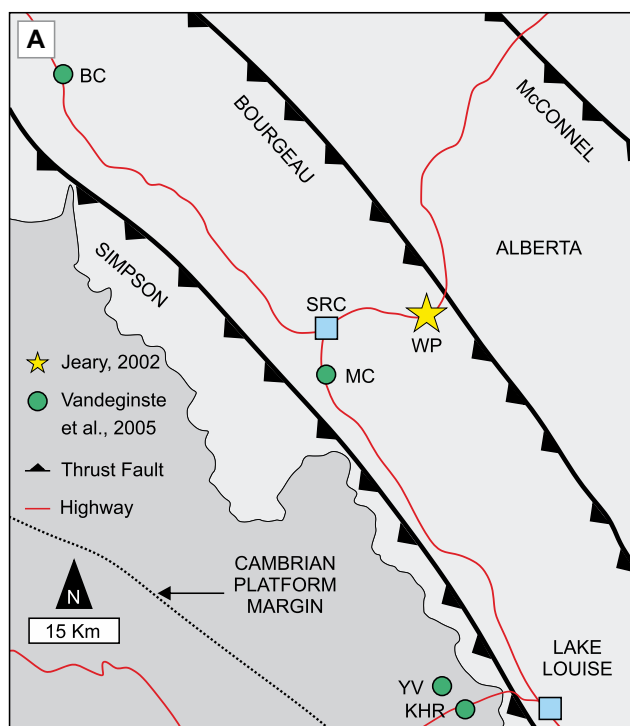


Figure 12. (A) Sample locations of fluid inclusion data are shown: Whirlpool Point (WP) (Jeary, 2002), Beauty Creek (BC), Mistaya Canyon (MC), Yoho Valley (YV), and Kicking Horse Rim (KHR) (Vandeginste et al., 2005). SRC—Saskatchewan River Crossing. (B) Fluid inclusion homogenization temperatures (T_h) of dolomite phases at Whirlpool Point (Jeary, 2002). RD—replacement dolomite; SDC—saddle dolomite cement. (C, D, and E) Fluid inclusion homogenization temperatures (T_h) (plotted against distance from the Cathedral platform margin) of dolomite phases from the Kicking Horse Rim (KHR), Yoho Valley (YV), Mistaya Canyon (MC), Beauty Creek (BC) (Vandeginste et al., 2005), and Whirlpool Point (WP) (Jeary, 2002).

Group. Previous work has implied that dolomitizing fluids fluxed through the Gog Group (Jeary, 2002; Powell et al., 2006; Vandeginste et al., 2007), but this study is the first to present direct evidence of this by observation of dolomite cement between quartz grains. Furthermore, the occurrence of albitized K-feldspar in Gog Group sandstones is evidence of fluid-rock interaction that perhaps resulted in the precipitation of the observed authigenic quartz and albite in the Cathedral Formation. Further support for this model comes from radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ in dolomite from Whirlpool Point (up to 0.7160; Jeary, 2002) that significantly exceeds MASIR-BAS (Maximum Strontium Isotope Ratio of Basinal Shale = 0.7120; Machel and Cavell, 1999), which is indicative of fluid interaction with K-rich clastic units. This finding is important, as it demonstrates that the Gog Group provided a permeable pathway between otherwise isolated faults that allowed fluids to convect and dolomitize larger areas of the Cathedral Platform than would otherwise have been possible.

Formation of Saddle Dolomite-Cemented Breccias

The brecciation of the Cathedral Formation appears to have been a complex process, as there is evidence for both brittle failure (angular clasts) and corrosion (rounded clasts with reaction rims) (*sensu* Jébrak, 1997). Brittle failure was likely driven by high fluid pressure that exceeded lithostatic pressure, possibly as a result of changes in fluid column height created by hydraulic or pneumatic connectivity between rocks at different depths (Peacock et al., 2019). Connectivity could have been facilitated by episodic pulses of deep-sourced, high-pressure fluids along the fault at Whirlpool Point (*sensu* Sibson, 1990). This is supported by the

concentrically zoned cathodoluminescence of SDC, which could be attributed to multiphase cementation driven by episodic fluid expulsion (e.g., Eichhubl and Boles, 2000). Fluids were likely expelled upwards along faults from the underlying Gog Group, which was probably overpressured during early burial as there is little evidence of compaction prior to the precipitation of dolomite cement in this unit. Once high-pressure fluids entered the Cathedral Formation, the Stephen Formation would have behaved as a low permeability top seal, leading to pressure build-up, rupturing, and brecciation. Subsequent pulses of these fluids might have corroded the dolomite clasts, particularly if fluids were deeply sourced and acidic due to high CO_2 saturation. Following this, a sudden drop in fluid pressure caused the rapid precipitation of SDC (*sensu* Davies and Smith, 2006), preserving breccia clasts in their present-day positions, apparently “floating” in saddle dolomite. This sudden drop in fluid pressure may have also caused the contemporaneous rapid precipitation of dolomite cement in the Gog Group, which effectively ended the dolomitization of the Cathedral Formation as dolomitizing fluids could no longer migrate through the Gog Group.

Geochemical evidence indicates that the dolomitizing fluids were similar to those that formed RD4 (Fig. 13A, T_3), which suggests that SDC precipitated relatively soon after. As SDC is observed cementing and crosscutting stylolites, this indicates that it likely precipitated during shallow burial (~300 m) in the Middle Cambrian. This timing contradicts the accepted view that hydrothermal dolomite breccias form during deep burial as a result of basin inversion and the formation of negative flower structures (Davies and Smith, 2006). Additionally, there appears to be a close temporal relationship between replacement dolomitization and saddle dolomite-cemented breccia formation, which suggests that these processes are inextricably linked. Again, this is contrary to the accepted view that saddle dolomite cementation can occur up to hundreds of millions of years after replacement dolomitization in hydrothermal systems (Davies and Smith, 2006).

Regional and Global Implications

The Gog Group is up to 4 km thick and is widespread across the Canadian Rocky Mountains, beneath the Cathedral Formation (Hein and McMechan, 1994), and cut by faults that also crosscut the Cathedral Formation (e.g., Jeary, 2002; Collom et al., 2009). This suggests that seawater was able to convect along these faults and mix with hot, highly saline, serpentine-derived brines across the platform. Downdip

migration and convection of these mixed brines could have been maintained through the Gog Group toward the Cathedral platform margin. As the fluids were driven deeper, under gravity, they were heated slightly in temperature, as demonstrated by the increasing T_h and the decreasing $\delta^{18}\text{O}$ of replacement dolomite from the northeast (Whirlpool Point) to the southwest (Kicking Horse Rim) (Fig. 11). Compared to replacement dolomite, the T_h and $\delta^{18}\text{O}$ of saddle dolomite cement increases significantly from Whirlpool Point to the Kicking Horse Rim. As saddle dolomite is interpreted as forming through seismic pumping along faults, it is possible that the fluids that precipitated saddle dolomite in the Kicking Horse Rim area originated at greater depths than at Whirlpool Point. Throughout replacement dolomitization and saddle dolomite precipitation in the Kicking Horse Rim area, it is likely that dolomitizing fluids discharged along the Cathedral Escarpment (Fig. 13B), where Johnston et al. (2009) found evidence of Mg-rich brine pools that supported Middle Cambrian fauna.

The mechanisms of the regional dolomitizing fluid flow proposed by this study are supported by the findings of Manning and Emsbo (2018). In this study, reactive transport modeling showed that dolomitizing fluids migrated through a basal clastic aquifer before ascending faults to dolomitize an overlying carbonate platform. Fluids increased in temperature as they migrated down dip and ultimately discharged at the platform margin. The results of Manning and Emsbo (2018) demonstrate that the regional dolomitization model proposed by this study is hydrologically possible and also explains the co-occurrence of dolomite and MVT along the Cathedral platform margin (e.g., Vandeginste et al., 2007).

Beyond the regional importance of understanding paleo-hydrological flow patterns in the Western Canadian Sedimentary Basin, the results of this work have wider implications. Since hydrothermal dolomite bodies often host economic volumes of Mississippi-Valley type mineralization, it is critical to mineral prospecting that the timing of dolomitization can be predicted. Furthermore, the contrast in rock-physical properties of dolomite, compared to those of limestone, means that any geological process that is dependent upon understanding the flow properties of a succession (e.g., oil and gas production, carbon sequestration and storage, and hydrogeological mapping of water resources including geothermal energy) requires that the distribution and extent of dolomitization can be predicted. The results of this study clearly demonstrate the relationships between seismicity, heat flow, fluid flux, and dolomitization prior to deep burial. This is contrary to many interpretations of fault-controlled hydrothermal

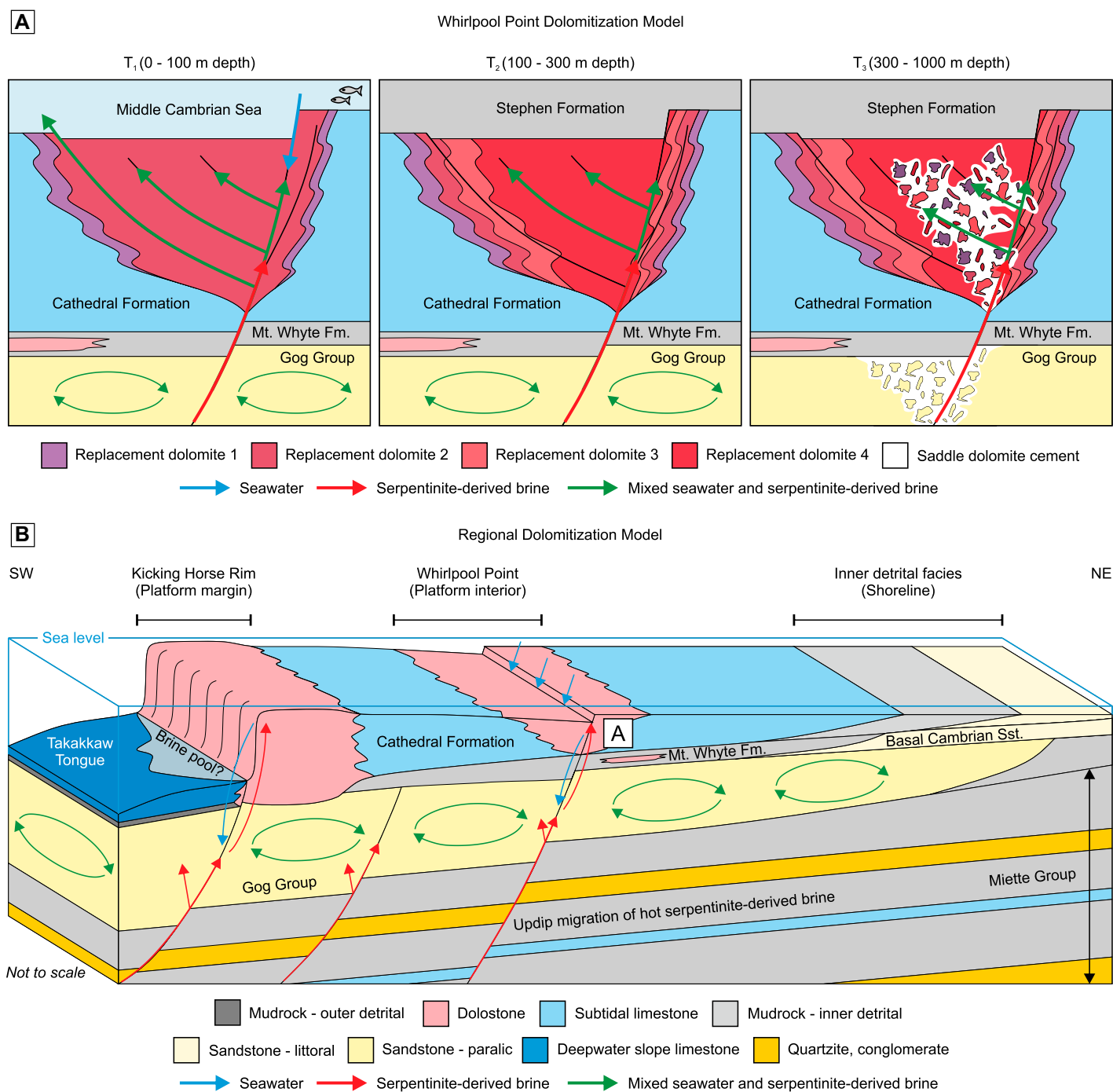


Figure 13. (A) Conceptual dolomitization model for the Cathedral Formation at Whirlpool Point is shown. Time 1 (T_1) is contemporaneous with (B); seawater and serpentinite-derived brine form Replacement Dolomites 1 and 2. Time 2 (T_2) after deposition of the Stephen Formation; mixed brines form Replacement Dolomites 3 and 4, and this reduces the porosity of the fault damage zone. Time 3 (T_3) saddle dolomite-cemented breccias develop due to overpressures caused by shallow burial and low porosity and permeability replacement dolomite. **(B)** Conceptual regional dolomitization model for the Cathedral Formation. Mixing of seawater and serpentinite-derived brine occurred in the Gog Group before migrating upwards along faults and dolomitizing the Cathedral Formation. Mixed brines ultimately discharged at the platform margin where brine pools formed throughout the Middle Cambrian.

dolomitization, which assume fault-controlled dolomitization during deep burial and/or basin inversion. This is important, as it shows that even platforms that do not have a complex his-

tory of burial and unroofing can undergo complex metasomatic alteration and that complex fabric-destructive textures—such as brecciation—can form early in the burial history. The

association of fluid flux and a basal sandstone aquifer also adds to growing evidence that large scale (over tens to hundreds of kilometers) dolomitization is facilitated by a basal sandstone

aquifer (e.g., Martín-Martín et al., 2015; Hollis et al., 2017; Lukoczki et al., 2019; Newport et al., 2020; Stacey et al., 2020). In totality, the results demonstrate the importance of a holistic, multi-scale evaluation of the post-depositional alteration of carbonate sedimentary rocks.

CONCLUSIONS

The Cathedral Formation is interpreted to have been dolomitized at a very shallow depth (<1 km) throughout the Middle and possibly Late Cambrian. This is constrained by RD phases that are crosscut by low-amplitude stylolites and that stylolites are cemented by SDC. Δ_{47} analyses of RD and SDC indicate that dolomitizing fluids had high temperatures of up to 238 °C. As dolomitization occurred at very shallow depths, these fluids are interpreted to be hydrothermal. Based on this, it is possible that geothermal gradients during the Middle Cambrian were high (40 °C/km) and were likely related to crustal thinning caused by rifting during the Early Cambrian. Convection along faults to depths of ~6 km heated dolomitizing fluids before they were emplaced in the Cathedral Formation.

The negative cerium anomalies of dolomite phases indicate that seawater was the dominant fluid during the early stages of replacement dolomitization. $^3\text{He}/^4\text{He}$ and $^{40}\text{Ar}/^{36}\text{Ar}$ values indicate that crustal fluids were also involved in dolomitization, becoming more dominant during the later stages of replacement dolomitization and saddle dolomite precipitation. Furthermore, $^{84}\text{Kr}/^{36}\text{Ar}$ and $^{132}\text{Xe}/^{36}\text{Ar}$ data are consistent with serpentinite-derived brines.

Dolomitizing fluids likely flowed through the underlying sandstones of the Gog Group before ascending faults to regionally dolomitize the Cathedral Formation. Evidence for this includes the co-occurrence of authigenic quartz and albite with dolomite and the elevated $^{87}\text{Sr}/^{86}\text{Sr}$ values of dolomite phases, all of which are indicative of fluid interaction with K-rich clastic units.

The findings of this study demonstrate that basal clastic aquifers can control the regional distribution of dolomitizing fluids on a far larger scale than has otherwise been realized. The widespread occurrence of hydrothermal fluids during the Middle Cambrian is evidence for high tectonic activity and heat flow, which is contrary to the accepted view that a tectonically quiescent and low heat flow passive margin existed at this time. The formation of saddle dolomite-cemented breccias at a shallow depth during the Middle Cambrian contradicts the accepted view that hydrothermal dolomite breccias form during deep burial as a result of basin inversion and the formation of negative flower structures. Further-

more, there appears to be a close temporal relationship between replacement dolomitization and saddle dolomite-cemented breccia formation, which contradicts interpretations suggesting that saddle dolomite cementation can occur up to hundreds of millions of years after replacement dolomitization in hydrothermal systems.

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