Burial dolomitization driven by modified seawater and basal aquifer-sourced brines: Insights from the Middle and Upper Devonian of the Western Canadian Sedimentary Basin

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Abstract
Dolomitization in the Western Canadian Sedimentary Basin has been extensively researched, producing vast geochemical datasets. This provides a unique opportunity to assess the regional sources and flux of dolomitizing fluids on a larger scale than previous studies. A meta-analysis was conducted on stable isotope, strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$), fluid inclusion and lithium-rich formation water data published over 30 years, with new petrographic, X-ray diffraction, stable isotope and rare-earth element (REE+Y) data. The Middle to Upper Devonian Swan Hills Formation, Leduc Formation and Wabamun Group contain replacement dolomite (RD) cross-cut by stylolites, suggesting replacement dolomitization occurred during shallow burial. Stable isotope, REE+Y and $^{87}\text{Sr}/^{86}\text{Sr}$ data indicate RD formed from Devonian seawater, then recrystallized during burial. Apart from the Wabamun Group of the Peace River Arch (PRA), saddle dolomite cement (SDC) is more $\delta^{18}\text{O}_{\text{PDB}}$ depleted than RD, and cross-cuts stylolites, suggesting precipitation during deep burial. SDC $^{87}\text{Sr}/^{86}\text{Sr}$ data indicate contributions from $^{87}\text{Sr}$-rich basinal brines in the West Shale Basin (WSB) and PRA, and authigenic quartz/albite suggests basinal brines interacted with underlying clastic aquifers before ascending faults into carbonate strata. The absence of quartz/albite within dolomites of the East Shale Basin (ESB) suggests dolomitizing fluids only interacted with carbonate strata. We conclude that replacement dolomitization resulted from connate Devonian seawater circulating through aquifers and faults during shallow burial. SDC precipitated during deep burial from basinal brines sourced from basal carbonates (ESB) and clastic aquifers (WSB, PRA). Lithium-rich formation waters suggest basinal brines originated as residual evapo-concentrated Middle Devonian seawater that interacted with basal aquifers and ascended faults during the Antler and Laramide Orogenies. These results corroborate those of previous studies but are verified by new integrated analysis of multiple datasets. New insights emphasize the importance of basal aquifers and residual evapo-concentrated seawater in dolomitization, which is potentially applicable to other regionally dolomitized basins.

Keywords
aquifers, basin fluids, carbonates, dolomitization, faults, seawater
INTRODUCTION

Previous research (Machel, 2004; Warren, 2000) has endeavoured to determine conceptual models of dolomitization that explain the diverse range of conditions under which dolomite can form. Although these are robust, it is clear that one single model cannot explain the occurrence of dolomitized carbonates across an entire basin. This is certainly true of the Western Canada Sedimentary Basin (WCSB), which has been the focus of substantial research as to the type and mechanism of dolomitization (e.g. Davies & Smith, 2006; Green & Mountjoy, 2005; Machel, 2004; Potma, Weissenberger, Wong, & Gilhooly, 2001; Sun, 1994). It has been proposed that the Middle to Upper Devonian strata of the WCSB were dolomitized by a combination of regional and local processes with successive phases of fluid migration and rock alteration. Models that have been proposed by prior studies include the fault and aquifer-controlled burial dolomitization model (Green & Mountjoy, 2005; Mountjoy, Machel, Green, Duggan, & Williams-Jones, and references therein). The freshwater–seawater mixing model and the reflux model have all been proven incapable (due to mass balance constraints) of forming the vast majority of replacement dolomite in the WCSB (Machel & Lonnee, 2002 and references therein). In particular, the seepage reflux model proposed by Potma et al. (2001) has been criticized for not acknowledging that geochemical data are consistent with burial dolomitization (Machel, Mountjoy, Jones, & Rostron, 2002).

The most recent dolomitization model to be applied to the WCSB is that of fault-controlled hydrothermal dolomitization (HTD) which has been proposed to explain dolomitization along major faults within the WCSB (e.g. Davies & Smith, 2006; Green & Mountjoy, 2005). Hydrothermal conditions are defined (Stearns, Stearns, & Waring, 1935; White, 1957) as occurring where fluids are >5 to 10°C hotter than the ambient temperature of the host formation. The HTD model has also been criticized for overstating the influence of hydrothermal fluids on the replacement of limestone by dolomite and the extent of precipitation of saddle dolomite cement across the WCSB (Machel & Lonnee, 2002).

This lack of consensus between previous studies is likely because they were conducted at a local (e.g. hydrocarbon reservoir) scale. Those studies that did interpret data on a regional and subregional scale (e.g. Mountjoy et al., 1999) advanced our knowledge of basin-scale dolomitization as they considered multiple stratigraphic units across large areas, and provided a springboard for this study. As such, this regional-scale study focuses on the differentially dolomitized carbonates of the Middle to Upper Devonian Swan Hills Formation, Leduc Formation and Wabamun Group across the WCSB. As such, this study is a meta-analysis of existing and new datasets collected in the WCSB, which are evaluated in the context of recent advances in our understanding of carbonate diagenesis, and specifically dolomitization of carbonate platforms based on field-based and reactive transport modelling studies (e.g. Gabellone & Whitaker, 2016; Hollis et al., 2017; Whitaker & Xiao, 2010).

The role of aquifers in dolomitization has previously been discussed in the WCSB (Davies & Smith, 2006; Duggan, Mountjoy, & Stasiuk, 2001; Green & Mountjoy, 2005; Kuflevskiy, 2015; Mountjoy et al., 1999). Strontium isotopes were first used to trace dolomitizing fluids in the WCSB by Machel and Anderson (1989). Mountjoy, Qing, and McNutt (1992) used strontium isotopes to determine potential interactions of dolomitizing fluids with basal aquifers, but the conclusions drawn from this work were limited by the fact that radiogenic Sr can be sourced from both clastic and metamorphic rocks. To address this, integration of multiple datasets is required, which includes utilizing authigenic albite as a tracer for brine migration (as employed in the European Alps and Carpathians by Spötl, Longstaffe, Ramseyer, & Rüdinger, 1999) and lithium-rich Devonian formation waters in the WCSB to determine brine origins (modern samples compiled by Eccles & Berhane, 2011). With this approach, in addition to the incorporation of new data, this study aims to differentiate the structural and sedimentological controls on regional-scale dolomite formation in the WCSB through the following objectives:

1. Determine the timing of dolomitization through petrographical and geochemical evidence.
2. Assess the spatial geochemical variability of dolomite phases across the WCSB to better understand how dolomitizing fluid populations differ on a regional scale.
3. Determine the importance of aquifers on the occurrence and spatial distribution of dolomitization within sedimentary basins.
The results of this study have implications for our understanding of basin-scale aquifer connectivity and migration of fluids, and the controls on upward fluid movement along fault networks. These findings are relevant to determining the location of dolomite bodies, which has implications for hydrocarbon exploration in frontier areas with limited well-control, evaluation of mineral resources, wastewater storage, geothermal heat production and carbon capture and storage.

2 | GEOLOGICAL SETTING & PREVIOUS STUDIES

The WCSB is a large sedimentary basin in Western Canada that ranges from northeast British Columbia and the southern edge of the Northwest Territories, underlies the majority of Alberta and extends into southwest Saskatchewan. The basin contains two major sub-basins: the Alberta and the Williston Basins, with this study focussing on the former (Figure 1). The WCSB is a mature hydrocarbon province, containing both conventional and unconventional resources, including productive dolomitized Devonian hydrocarbon reservoirs. Basement structure had a significant impact on the nucleation and development of carbonate platforms and reefs throughout the Palaeozoic (Hoffman, 1987; Ross & Stephenson, 1989) with reactivation interpreted to have occurred during the Antler and Laramide Orogenies (Lemieux, 1999; Ross & Eaton, 1999). Recent studies (Corlett et al., 2018; Schultz et al., 2016; Zhang, Eaton, Li, Liu, & Harrington, 2016) have proposed that induced seismic events in the Duvernay Formation shale play of the WCSB are closely associated with Devonian platform edges, furthering the hypothesis that reef nucleation and subsequent diagenesis was controlled by faults.

2.1 | Tectonic history

Sedimentation in the WCSB occurred in two phases (Ross, Broome, & Miles, 1994; Wright, McMechan, Potter, Mossop, & Shetsen, 1994). The Palaeozoic to Jurassic was dominated by carbonate deposition within a relatively stable cratonic passive margin (Price, 1990), but deposition on ep- eric carbonate platforms ended in the Permian (Henderson & Barclay, 1994). During the Devonian to Mississippian, regional extension related to slab rollback caused back- arc and intra-arc spreading (Nelson, Paradis, Christensen, & Gabites, 2002). This is in agreement with Hauck, Paná, and DuFrane (2017) who, based on detrital zircon data, concluded that the terrigenous sediments of the Upper Devonian Sassenach Formation were sourced from Northern Laurentia rather than to the west of the WCSB as previously suggested by Root (1987) (see Hauck et al., 2017, for a detailed discussion on the ‘Antler Orogeny’). In the Middle Jurassic, the WCSB developed into a foreland basin due to the depression of the North American continental lithosphere by the Cordilleran deformation front. This occurred during two events; the Columbian Orogeny (Middle Jurassic to Early Cretaceous) and the Laramide Orogeny (Late Cretaceous to Palaeocene) (Pana, Waters, & Grobe, 2001).

2.2 | Depositional setting and reservoir-scale diagenesis

The Middle to Upper Devonian Swan Hills Formation occurs throughout the west-central Alberta Basin (Figure 1). A marine transgression initially formed a wide platform bank, upon which subsequent isolated platforms and reefs developed (Green & Mountjoy, 2005). The Swan Hills Formation is subdivided into three sedimentary packages; basal platform, platform reef and capping platform (Kauffman & Meyers, 1988). In the platform reef stage, stromatoporoids (Amphipora) indicate lagoonal facies; stromatoporoid rubble comprises the reef flat and encrusting stromatoporoids form the reef margin (Wendte & Uyeno, 2005). Corlett et al. (2018 and references therein) identified several basement-rooted and basement-bounded transtensional faults that propagated along the margin of the upper Swan Hills Platform and isolated reef complexes. This study suggested that these faults localized reef growth and caused the development of platform channel and embayment morphologies, with the faults subsequently acting as conduits for fluids that originated in sub-Devonian strata. This is corroborated by Kaufman, Hanson & Meyers (1991), who suggested that the consistent NW-SE orientation of dolomite bodies in the Swan Hills Formation was due to fault-derived dolomitizing fluids.

The Upper Devonian Leduc Formation reefs are located in the East and West Shale Basins. This study examined the Leduc Formation in the East Shale Basin, comprising large isolated reef complexes that developed on the Cooking Lake Platform (Wendte, 1994). Build-ups in the Leduc Formation are composed of stromatoporoid-dominated reef flank and fore reef facies. The platform interior is comprised of small patch reefs, subtidal skeletal sands and peritidal algal laminites (Drivet & Mountjoy, 1997). Most of these reefs form the Rimby-Meadowbrook reef trend, a feature that extends for ca. 560 km from south-central Alberta to Athabasca in the NE, dipping <1° SW towards the Canadian Rockies (Drivet, 1993; Switzer et al., 1994 in: Mountjoy et al., 1999). The top of the Cooking Lake Platform is partially dolomitized, whereas the majority of the overlying Leduc Formation reefs are pervasively dolomitized. The exceptions to this are the Golden Spike and Redwater reefs (Wendte, 1994), which are off-trend, towards the edge of the Cooking Lake platform.
Golden Spike is not in hydrological communication with the Cooking Lake Platform (Amthor, Mountjoy, & Machel, 1993) and the Redwater reef, which sits directly east of the main Rimbey-Meadowbrook trend, was only partially dolomitized.

The Upper Devonian Wabamun Group consists of stacked cyclical carbonates with associated evaporites (Halbertsma, Mossop, & Shetsen, 1994) that extend over the majority of present-day Alberta (Figure 1). Facies are dominated by nodular limestones, mudstones, skeletal or peloidal wackestones and minor packstones (Halim-Dihardja & Mountjoy, 1988). Dolomite content in the Wabamun Group increases from the northwest to the southeast, where the overlying evaporites of the Stettler Formation are present (Al-Aasm & Raymus, 2007).
2.3 Study areas

The Swan Hills field is located on the Swan Hills Platform in the West Shale Basin (Figure 1b1), and is currently at a burial depth of 2,310–2,590 m, striking NW-SE. The reservoir dips 0.5° SW, with oil hosted primarily in reef margin facies, stratigraphically trapped updip by the shales of the Waterways Formation (Viau, 1987). Packard and Hills (2001) suggested that extensive meteoric dissolution of the Swan Hills Formation occurred during periods of subaerial exposure, with considerable porosity generation prior to significant burial. The vertical distribution of dolomite cements in the Swan Hills field is thought to be related to hydrothermal circulation of Devonian seawater through extensional normal faults (Viau, 1987). The Caroline gas field is located on the southern Swan Hills Platform on the border of the West and East Shale Basins (as it is directly overlain by the Leduc Formation of the ESB, it is considered for the purposes of this study to be in the ESB) (Figure 1b2) at a present day burial depth of ca. 3,500 m, striking NW-SE. The reservoir dips 25 m/km to the SW, with gas hosted in highly dolomitized reefal facies becoming stratigraphically trapped updip by the shales and argillaceous limestones of the Waterways Formation, and downdip by the limestones, siltstones and shales of the Calumet and Elk Point formations.

The Leduc Acheson oil field (Figure 1b3) is at a present day burial depth of ca. 1,500 m, striking N-S. The reservoir follows the dip of the Rimby-Meadowbrook reef trend, with oil hosted in pervasively dolomitized reefal facies stratigraphically trapped updip by the shales of the Ireton Formation. Edwards and Brown (1999) identified basement surface velocity pull-ups beneath the Rimby-Meadowbrook reef trend and suggested that reef nucleation possibly occurred on upthrown fault blocks. The same study also recognized a Bouguer gravity anomaly, interpreted to represent an extension of the Snowbird Tectonic Zone, which is coincident with the Rimby-Meadowbrook reef trend. However, Edwards and Brown (1999) concluded that the influence of this feature on the initiation and development of Leduc Formation reefs and the Cooking Lake Platform is unknown.

The Wabamun Eaglesham North oil field (Figure 1b4) is at a present day burial depth of ca. 2,100 m, striking W-E. Oil is hosted in dolomitized mudstones and peloidal wackestones and packstones stratigraphically trapped updip by the shales of the Exshaw Formation and the dolomitic marls of the Banff Formation (Saller & Yaremko, 1994). The field is bisected by the NW-SE trending Dunvegan Fault (Mountjoy & Halim-Dihardja, 1991). Dolomitization has been interpreted to have occurred by reflux of seawater, possibly focussed on palaeotopographic highs generated by syn-depositional faulting. This created high-porosity dolomite that was potentially more important than faults in terms of localizing later hydrothermal fluids (Saller & Yaremko, 1994). A second phase of hydrothermal dolomitization occurred during burial, with faults critical to controlling fluid flow (Ma, Al-Aasm, & Yang, 2006).

The Wabamun Pine Creek field (Figure 1b5) is at a present burial depth of ca. 3,000 m, striking NE-SW. Gas is hosted in dolomitized subtidal to intertidal peloidal wackestones to grainstones sealed by shales of the Exshaw Formation. Dolomite bodies at Pine Creek Field occur in intervals <20 m thick and are restricted to peloidal and pellet wackestones and packstones in a 2-km-wide zone oriented NW-SE, along the dolomitized reef margins of the underlying Leduc Formation (but physically separated by the Ireton and Nisku formations). An anomalous stratigraphic offset of 40 m occurs at the top of the Wabamun Group in this area, suggesting that a vertical fault system potentially acted as a conduit between the Wabamun Group and the underlying Leduc and Swan Hills formations (Green & Mountjoy, 2005).

3 METHODOLOGY

Cored intervals of 6 wells (Table 1) from the Swan Hills Formation, Leduc Formation and Wabamun Group were selected based on their proximity to mapped platform margin faults and/or regional Precambrian shear zones (Figure 1). This sampling strategy was chosen in order to determine whether faults in each area of the WCSB contributed fluids for dolomitization, and if so, where these fluids originated. Although the number of cores sampled by this study

| Well ID        | Interval (m)          | Thickness (m) | Field        | Formation  | Samples |
|---------------|-----------------------|---------------|--------------|------------|---------|
| 04-13-069-09W5 | 2128.11–2158.59       | 30.48         | Swan Hills   | Swan Hills | 11      |
| 03-10-035-05W5 | 3710.00–3766.00       | 56            | Caroline     | Swan Hills | 4       |
| 02-27-052-26W4 | 1551.43–1559.90       | 8.47          | Acheson      | Leduc      | 4       |
| 02-14-053-26W4 | 1513.03–1549.60       | 36.57         | Acheson      | Leduc      | 6       |
| 04-26-057-19W5 | 3048.00–3079.09       | 31.09         | Pine Creek   | Wabamun    | 4       |
| 13-13-078-26W5 | 2059.60–2126.60       | 67            | Eaglesham North | Wabamun  | 6       |
represents a small fraction of the wells drilled in the WCSB, this meta-analysis of the numerous previous core studies reduces any potential sampling bias, as these prior studies sampled cores that were both proximal and distal to faults. Cores selected for this study were described and sampled for petrographic and geochemical analyses. Eleven thin sections and 15 polished sections were stained with alizarin Red-S and potassium ferricyanide (Dickson, 1966) and impregnated with blue-dye resin to identify porosity. All thin and polished sections were examined under plane-polarized light (PPL) and cross-polarized light (XPL) using a Nikon Eclipse LV100N POL microscope. Calcite and dolomite crystal textures and porosity types were described based on the respective classifications of Flügel (2013), Sibley and Gregg (1987) and Choquette and Pray (1970). Polished sections were examined using a CITL Mk5 cold cathodoluminescence system (operating conditions 10–15 kV and 350–400 μA), mounted on a Nikon Eclipse LV100N POL microscope. Cathodoluminescence crystal zonation types were described using the classification of Machel and Burton (1991).

Twenty-nine bulk rock samples were analysed for mineralogical composition through standard powder X-ray diffractometry (XRD) using a Bruker D8 Advance diffractometer (operating conditions 40 kV and 30 mA, sample scans in the 2θ range from 5° to 70° – increments of 0.02°). Mineral identifications were made using standard peak-fitting software, with peak displacement corrections made using a quartz internal standard. Dolomite stoichiometry was calculated based on the method of Lumsden (1979), and quantitative Rietveld analyses were conducted using TOPAS XRD software.

A total of 38 representative calcite and dolomite powder samples were micro-drilled from thin section counterparts and the resulting powder underwent conventional acid digestion (McCrae, 1950). Gases were measured by dual-inlet, stable isotope ratio (δ13CVPDB, δ18OVPDB) 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 and are corrected for phosphoric acid fractionation. Average analytical precision from repeat analyses of three samples was better than ±0.1‰ for carbon and oxygen isotope ratios. Rare-earth element (REE) analysis was conducted on the same 38 samples using an Agilent 7700x inductively coupled plasma mass spectrometer (ICP-MS). REE concentrations were normalized to the post-Archean Australian Shales (PAAS) (Taylor & McLennan, 1985).

Precursor limestone fabrics are well preserved in the Swan Hills Formation of the West Shale Basin (WSB) (core UWI: 04-13-069-09W5), and contain abundant Amphipora, Stachyodes and abundant bulbous and tabular stromatoporoids that represent lagoonal, fore-reef, reef, back reef and shoal facies (sensu Wendte & Uyeno, 2005). Bulbous stromatoporoid rudstone contains stromatoporoids with mouldic porosity and fractures that are cemented with saddle dolomite. Saddle dolomite cement is most common in intervals with abundant bulbous stromatoporoids and a high degree of fracturing (Figure 2a).

The Swan Hills reef Caroline (core UWI: 03-10-035-05W5) in the East Shale Basin underwent variably fabric preserving to destructive dolomitization, with Amphipora and Stachyodes preserved but tabular stromatoporoids destroyed. Overall, the depositional textures are similar to the other Swan Hills Formation occurrences in the WSB with shoal, lagoon and back reef facies recognized. Bitumen occurs along the intercrystal boundaries of finely to medium-crystalline planar-e to planar-s dolomite (SH-RD1) and also commonly lines allochem moulds/vugs and stylolites.
Medium-crystalline dolomite is the most volumetrically significant phase, forming the matrix. Blocky calcite and double-terminated euhedral quartz (ca. 8 mm in length) occlude larger (ca. 3 cm) vugs (Figure 2b,c).

Replacement dolomitization of the Leduc Formation in the ESB (core UWI: 02-27-052-26W4, 02-14-053-26W4) is strongly fabric destructive, with moulds of Amphipora, Stachyodes and tabular stromatoporoids variably preserved. The presence of these may indicate lagoonal and shoal limestone precursor facies. Darker, finely crystalline planar-e to planar-s replacement dolomite (L-RD1) occurs along stylolites and wispy laminations (Figure 2d). Cream-
STACEY ET AL.

3 cm. (a) Bulbous stromatoporoid (SH-MC2) rudstone with darker areas of crinoidal packstone (SH-MC1) and coarsely-crystalline fracture-filling saddle dolomite cement (SH-SDC). Swan Hills Field, Swan Hills Fm. (04-13-069-09W5, 2132.21 m). (b) Tabular stromatoporoid floatstone pervasively replaced by medium-crystalline dolomite (SH-DRD2). Stromatoporoids are dissolved and replaced by finely crystalline replacement dolomite (SH-DRD1) and infilled with calcite cement (SH-CC2). Caroline Field, Swan Hills Fm. (03-10-035-05W5, 3719.93 m). (c) Stachyodes and Amphipora floatstone pervasively replaced by medium-crystalline dolomite (SH-DRD2) with molds infilled by finely-crystalline replacement dolomite (SH-DRD1). Same core interval as in (b) at 3740.72 m. (d) Pervasively dolomitised Stachyodes and Amphipora rudstone with darker finely-crystalline replacement dolomite (L-DRD1) along stylolites, cream to gold coloured medium-crystalline replacement dolomite (L-DRD2/3) and medium to coarsely crystalline dolomite cement (L-DC) that lines vugs. Acheson Field, Leduc Fm. (02-27-052-26W4, 1558.49 m). (e) Stachyodes floatstone with pervasively dolomitised matrix (L-DRD1), Stachyodes are replaced by medium-crystalline dolomite (L-DRD2/3) and molds infilled by dolomite cement (L-DC). Same core interval as in (d) at 1558.49 m. (f) Tabular stromatoporoid and Stachyodes floatstone pervasively dolomitised (L-DRD2/3) with minor dolomite cement (L-DC) lining Stachyodes molds. Same core interval as in (d) and (e), at 1559.35 m. (g) Partially dolomitised bioturbated wackestone primarily comprised of micrite (W-MC1) with minor finely-crystalline replacement dolomite rhombs (W-DRD1) disseminated throughout the matrix and coarsely crystalline anhydrite cement (W-A) that infills fenestrae. Pine Creek Field, Wabamun Gp. (04-26-057-19W5, 3058.14 m). (h) Pervasively dolomitised bioturbated wackestone with dark grey finely-crystalline dolomite infilling burrows (W-RD2) and lighter grey finely-crystalline dolomite replacing the matrix (W-RD1). Minor anhydrite cement (W-A) infills burrows. Same core interval as in (g) at 3,063 m. (i) Pervasively dolomitised and brecciated bioturbated crinoidal wackestone with darker coloured finely crystalline dolomite (W-RD3) that occurs along stylolites and coarser dolomite (W-RD4) that comprises the bulk of the matrix. Medium to coarsely crystalline saddle dolomite cement (W-SDC) lines breccia margins and coarsely crystalline calcite cement (W-CC2/3) fills the breccia. Eaglesham North Field, Wabamun Gp. (13-13-078-26W5, 2121.60 m).

4.1.2 Diagenetic phases

Diagenetic phases in the Swan Hills Formation (SH), Leduc Formation (L) and Wabamun Group (W) were identified from thin section (Figures 3 and 4). Petrographic (plane-polarized light and cathodoluminescence) observations are summarized in Table 2 and the paragenetic history of each formation is shown in Figure 10.

Swan Hills Formation

In the WSB (core 04-13), the undolomitized matrix (SH-MC1) comprises micrite (10–30 μm) with no zonation and a dull orange to purple luminescence (Figure 3a,b). Stromatoporoids are comprised of blocky calcite (SH-MC2) that also has dull orange to purple, unzoned luminescence but is more coarsely crystalline (50–150 μm). Bladed calcite cement (SH-CC1) crystals range from 10 to 150 μm in length and either fully occlude or fringe mouldic pores in SH-MC2 and in fractures that crosscut SH-MC1 and SH-MC2. SH-CC1 has a bright orange to dull purple luminescence with simple concentric and occasionally oscillatory zonation (Figure 3a,b). Coarsely crystalline (250 μm to 5 mm) nonplanar saddle dolomite cement (SH-SDC) occludes mouldic pores in SH-MC1 and SH-MC2 and has a dark purple luminescence with rare light purple simple concentric zonation. This phase also commonly fills fractures and contains hydrocarbons (Figure 3c,d).

In the Caroline reef (core 03-10), planar-e to planar-s replacement dolomite (SH-DRD1) ranges in size from 30 to 650 μm, with finer crystals lining vugs, and coarser crystals forming the matrix (Figure 3e). This phase has a blotchy luminescence and appears dull purple with rare dark orange cores. Nonplanar dolomite cement (SH-DC) occurs as overgrowths (75–250 μm) on coarser SH-DRD1 crystals and has...
intrasectoral zonation that alternates between dull orange and purple luminescence (Figure 3f). Intercrystal porosity associated with SH-RD1 is high, commonly contains bitumen and is partially occluded by fine to coarsely crystalline (50–500 μm) calcite cement (SH-CC2) that has a dark blue luminescence with no zonation (Figure 3e,f).

**Leduc Formation**

In the WSB (cores 02-27, 02-14), finely crystalline (ca. 20 μm) planar-e to planar-s replacement dolomite (L-RD1) occurs along stylolites and is associated with stylocumulate (sensu Flügel, 2013). This phase has a homogenous dark red luminescence with no zonation. Medium-crystalline
(30–100 μm) planar-s to nonplanar replacement dolomite (L-RD2) is only found adjacent to L-RD1 and has a dull red luminescence with no zonation. Coarsely crystalline (50–400 μm) nonplanar to planar-s replacement dolomite (L-RD3) is the most volumetrically significant phase (ca. 80%) and contains vugs. This phase has a blotchy luminescence and simple concentric zonation with purple/red cores and light/dark red rims. Nonplanar dolomite cement (L-DC) occurs as overgrowths (75–600 μm) on L-RD3 crystals and has intrasectoral zonation that alternates among green/yellow, bright orange and dark purple luminescence (Figure 3g,H). Rare, coarsely crystalline (200 μm to 3 mm) nonplanar fluorite (L-F) cements vertical fractures and stylolites within L-RD2 and L-RD3 and has a homogenous bright blue luminescence (Figure 4a,b).

**Wabamun Group**

In the WSB (core 04–26), undolomitized intervals are comprised of micritic (10–30 μm) calcite (W-MC1), which has a dull orange to dull purple luminescence with no zonation. In dolomitized sections, finely crystalline (ca. 20 μm) planar-e to planar-s replacement dolomite (W-RD1) has a dense-crystal mosaic with clay laminations lining crystal boundaries, and is the most volumetrically significant (ca. 70%) diagenetic phase. This phase has a simple concentric zonation, which alternates between dull pink and dull orange luminescence. Planar-e to planar-s (50–100 μm) replacement dolomite (W-RD2) has a sucrosic texture with intercrystal porosity that has simple concentric zoning with dull purple cores and dull pink rims. Intercrystal porosity is uncommonly occluded by blocky (25–100 μm) calcite cement (W-CC1), and has a dark purple luminescence with no zonation (Figure 4c,d).

In the PRA area (core 13–13), planar-e to planar-s (ca. 50 μm) replacement dolomite (W-RD3) is restricted to burrow traces, with intercrystal porosity occluded by organic material. This phase has a dark to light orange luminescence with simple concentric zonation. Coarser (75–250 μm) planar-s replacement dolomite (W-RD4) forms the majority (ca. 75%) of the matrix and has a simple concentric zonation, alternating between light and dark orange luminescence. Nonplanar to planar-s replacement dolomite (W-RD5) occurs as clear overgrowths (100–500 μm) on W-RD4 and has bright orange and yellow luminescence with simple concentric and oscillatory zonation (Figure 4e,f). Coarsely crystalline (200 μm to 2 mm) nonplanar saddle dolomite cement (W-SDC) occurs as overgrowths on W-RD4/5 at breccia margins and has well-developed simple concentric and oscillatory zonation that alternates between bright orange and dark brown luminescence. Coarsely crystalline (500 μm to 2 mm) irregular blocky calcite crystals (W-CC2) float within breccia cemented by blocky (300 μm to 7 mm) calcite (W-CC3). The luminescence of these phases, respectively, appears dark brown with dark orange inclusions (no zonation) and yellow with bright yellow inclusions (minor oscillatory zonation) (Figure 4g,h).

### 4.2 Geochemistry of diagenetic phases

#### 4.2.1 X-ray diffraction

Dolomite phases in the Swan Hills Formation are stoichiometric (49–51 mol% CaCO₃) in both the West and East Shale Basins (av. 49.83 mol% and 51.07 mol%, respectively), as is the Leduc Formation in the East Shale Basin (av. 49.46 mol%). Dolomite in the Wabamun Group is stoichiometric in the West Shale Basin (av. 50.12 mol%), but is nonstoichiometric in the Peace River Arch area (av. 51.35 mol%). Trace amounts of quartz are found in the Swan Hills Formation, but is more abundant in the West Shale Basin than in the East Shale Basin (av. 1.48% and 0.13% respectively). Despite this, double-terminated quartz is present within vugs in the Caroline Field in the East Shale Basin. In comparison, quartz
is completely absent in the Leduc Formation in the East Shale Basin but fluorite is present. Trace amounts of quartz and albite are found in the Wabamun Group, and are more abundant in the Peace River Arch area (av. 8.78% and 1.22% respectively) than in the West Shale Basin (av. 1.41% and 0.78% respectively).

### 4.2.2 | Stable isotopes

**Swan Hills Formation**

In the WSB, isotopic data generated in this study of micrite (SH-MC1) and stromatoporoid (SH-MC2) samples have a narrow range of δ¹⁸O (−5.6‰ to −6.2‰ (av. −5.9‰)
and −8.2‰ to −8.8‰ (av. −8.5‰), respectively, with calcite cement (SH-CC1) also fitting within this range ($\delta^{18}O = -7.4‰$). $\delta^{13}C$ values for these phases range from −0.5‰ to 1.5‰ (av. 1.0‰). Data for replacement dolomite (Duggan et al., 2001; Green & Mountjoy, 2005; Kaufman et al., 1991) show varying degrees of $\delta^{18}O$ depletion (−6.2‰ to −12.6‰ (av. −7.6‰)) and $\delta^{13}C$ enrichment (0.01‰–3.9‰ (av. 2.1‰)) compared to the calcite phases measured in this study. Similarly, data from this study for saddle dolomite cement (SH-SDC) exhibit $\delta^{18}O$ depletion (−9.4‰ to −11.4‰, av. −10.5‰) and similar $\delta^{13}C$ values (1.9‰ to 2.1‰, av. 2.0‰) to published replacement dolomite. Published data of saddle dolomite cement (Duggan et al., 2001; Kaufman et al., 1990) are similar to data generated in this study: $\delta^{18}O = -6.2‰$ to −13.6‰ (av. 9.8‰), $\delta^{13}C = -1.9‰$ to −3.7‰ (av. 2.4‰).

Replacement dolomite (SH-RD1) in the ESB has a narrow range of $\delta^{18}O$ (−5.9‰ to −6.6‰ (av. −6.2‰)) and $\delta^{13}C$ (1.6‰ to 2.9‰ (av. 2.1‰)) values. Dolomite cement (SH-DC) is isotopically similar to SH-RD1 ($\delta^{18}O = -6.6‰$, $\delta^{13}C = 2.8‰$). Published data of replacement dolomite (Laflamme, 1990) are similar to our data: $\delta^{18}O = -2.9‰$ to −7.4‰ (av. −5.6‰), $\delta^{13}C = 1.8‰$ to 3.8‰ (av. 2.4‰). Saddle dolomite cement (Laflamme, 1990) is $\delta^{18}O$ depleted (−4.6‰ to −8.5‰ (av. −6.5‰)) but has similar $\delta^{13}C$ values (−2.8‰ to 1.9‰ (av. −2.7‰)) when compared to replacement dolomite. Overall, diagenetic phases in the ESB are less $\delta^{18}O$ depleted than those in the WSB, but have similar $\delta^{13}C$ values (Table 3, Figure 5a).

**Leduc Formation**

In the ESB, isotopic analysis of replacement dolomite L-RD2 and L-RD3 in this study gives data that are similar to each other with respect to $\delta^{18}O$ (−5.6‰ to −6.1‰ (av. −5.8‰)) and $\delta^{13}C$ (1.8‰ to 2.7‰ (av. 2.2‰)). Dolomite cement (L-DC) is slightly more depleted in $\delta^{18}O$ than L-RD2/RD3 (−5.9‰ to −6.0‰, av. −6.0‰)) but has similar $\delta^{13}C$ values (1.9‰ to 2.3‰ (av. 2.1‰)). It was not possible to sample L-RD1 due to its fine crystal size. There was no significant variation in isotopic values in any phase between the two wells sampled. Published data of replacement dolomite (Drivet & Mountjoy, 1997; Kuflevskiy, 2015; Laflamme, 1990) have a greater range of $\delta^{18}O$ and $\delta^{13}C$ values (−2.8‰ to −9.1‰ and −5.4‰ to 5.7‰, respectively), but the averages are similar to data from this study (−5.5‰ and 2.3‰ respectively). Saddle dolomite cements (see replacement dolomite references) are typically slightly depleted with respect to $\delta^{18}O$ (−4.0‰ to −8.1‰; av. −6.4‰) and $\delta^{13}C$ (−4.8‰ to 3.8‰; av. −1.5‰) when compared to replacement dolomite.

Published data of replacement dolomite in the WSB (Green & Mountjoy, 2005) exhibit a narrow range of $\delta^{18}O$ and $\delta^{13}C$ values (−4.0‰ to −5.7‰ (av. −4.9‰) and 2.3‰ to 2.7‰ (av. 2.4‰) respectively). When compared to replacement dolomite, saddle dolomite cement (Green, 1999) is depleted with respect to $\delta^{18}O$ (−4.5‰ to −10.0‰ (av. −7.1‰)) and $\delta^{13}C$ (0.8‰ to 1.9‰ (av. 1.5‰)). Replacement dolomite in the ESB is marginally more $\delta^{18}O$ depleted than the WSB, but has similar $\delta^{13}C$ values. Conversely, saddle dolomite cement in the WSB is more $\delta^{18}O$ depleted and $\delta^{13}C$ enriched than the ESB (Table 3, Figure 5b).

**Wabamun Group**

In the WSB, data derived by this study indicate that replacement dolomite phase W-RD1 has a narrow range of $\delta^{18}O$ (−4.2‰ to −4.3‰ (av. −4.3‰)) and $\delta^{13}C$ values (1.4‰–1.7‰ (av. 1.5‰)). W-RD2 has a similar range of $\delta^{13}C$ values (1.7‰–1.8‰ (av. 1.8‰)) to W-RD1, but exhibits greater $\delta^{18}O$ depletion (−8.9‰ to −9.0‰; av. −9.0‰). Published data of replacement dolomite (Green & Mountjoy, 2005) are similar to our data: $\delta^{18}O = -4.2‰$ to −9.0‰ (av. −5.4‰) and $\delta^{13}C = -1.4‰$ to 1.8‰ (av. 0.9‰). Saddle dolomite cement (Green, 1999) has similar $\delta^{18}O$ values (−5.1‰ to
| Phase                        | Size         | Morphology | Extinction | Inclusions            | CL                      | Well  |
|------------------------------|--------------|------------|------------|-----------------------|-------------------------|-------|
| **Swan Hills Formation**     |              |            |            |                       |                         |       |
| Matrix Calcite 1 (SH-MC1)    | 10–30 µm     | Blocky     | N/A        | Turbid                | Dull orange to dull purple – no zonation | 04-13 |
| Anhydrite (SH-A)             | 500 µm - 3 mm| Blocky     | Straight   | Limpid                | Dark blue               | 04-13 |
| Matrix Calcite 2 (SH-MC2)    | 50–150 µm    | Blocky     | Undulose   | Limpid                | Dark purple to dull orange – no zonation | 04-13 |
| Calcite Cement 1 (SH-CC1)    | 10–150 µm    | Bladed     | Straight   | Limpid                | Simple concentric and uncommon oscillatory zoning bright orange to dull purple | 04-13 |
| Replacement Dolomite 1 (SH-RD1) | 30–650 µm | P-e/P-s     | Straight   | Turbid                | Blotchy – dull purple with rare dark orange cores | 03-10 |
| Dolomite Cement (SH-DC)      | 75–250 µm    | Np         | Straight   | Limpid                | Intrasectoral zoning (see text for details) | 03-10 |
| Calcite Cement 2 (SH-CC2)    | 50–500 µm    | Blocky     | Straight   | Limpid                | Dark blue – no zonation | 03-10 |
| Saddle Dolomite Cement (SH-SDC) | 250 µm - 5 mm | Np         | Sweeping   | Limpid to turbid      | Dark purple, rare light purple simple concentric zonation | 04-13 |
| Authigenic Quartz (SH-Q)     | 8 mm         | E          | Straight   | Limpid                | Unknown (no thin sections) | 03-10 |
| **Leduc Formation**          |              |            |            |                       |                         |       |
| Replacement Dolomite 1 (L-RD1) | ~20 µm     | P-e/P-s     | Straight   | Turbid                | Homogenous dark red – no zonation | 02-27, 02-14 |
| Replacement Dolomite 2 (L-RD2) | 30–100 µm   | P-s/Np     | Straight   | Turbid                | Dull red – no zonation | 02-27, 02-14 |
| Replacement Dolomite 3 (L-RD3) | 50–400 µm   | Np/P-s     | Straight   | Turbid                | Simple concentric zoning and blotchy – purple/red cores and light/dark red rims | 02-27, 02-14 |
| Dolomite Cement (L-DC)       | 75–600 µm    | Np         | Straight   | Limpid                | Intrasectoral zoning (see text for details) | 02-27, 02-14 |
| Fluorite (L-F)               | 200 µm - 3 mm| Np         | Straight   | Limpid                | Bright blue – no zonation | 02-14 |
| **Wabamun Group**            |              |            |            |                       |                         |       |
| Matrix Calcite 1 (W-MC1)     | 10–30 µm     | Blocky     | N/A        | Turbid                | Dull orange to dull purple – no zonation | 04-26 |
| Anhydrite (W-A)              | 100 µm - 3 mm| Blocky     | Straight   | Limpid                | Dark blue, lighter blue rims | 04-26, 13-13 |
| Replacement Dolomite 1 (W-RD1) | ~20 µm    | P-e/P-s     | Straight   | Turbid                | Simple concentric zoning – dull pink/dull orange – simple | 04-26 |
| Replacement Dolomite 2 (W-RD2) | 50–100 µm  | P-e/P-s     | Straight   | Turbid                | Simple concentric zoning – dull purple cores, dull pink rims | 04-26 |
| Calcite Cement 1 (W-CC1)     | 25–100 µm    | Blocky     | Undulose   | Limpid                | Dark purple – no zonation | 04-26 |
| Replacement Dolomite 3 (W-RD3) | ~50 µm     | P-e/P-s     | Straight   | Limpid to turbid      | Simple concentric zoning – dark orange/light orange | 13-13 |
| Replacement Dolomite 4 (WRD4) | 75–250 µm    | P-s         | Straight   | Turbid to limpid      | Simple concentric zoning – dark orange/light orange | 13-13 |
−6.0‰; (av. −5.7‰)) and has slightly enriched δ13C values (1.5‰−1.9‰; (av. 1.7‰)) when compared to replacement dolomite.

In the PRA area (northwest Alberta Basin), replacement dolomite (W-RD4) and saddle dolomite cement (W-SDC) are isotopically similar (δ18O = −8.5‰ to −8.7‰ (av. −8.6‰) and −8.6‰ to −8.6‰ (av. −8.6‰), respectively; δ13C = 0.2‰−0.3‰ (av. 0.2‰) and 0.1‰−0.2‰ (av. 0.2‰) respectively). Published data of replacement dolomite (Mountjoy & Halim-Dihardja, 1991; Saller & Yaremko, 1994) are less δ18O depleted (−2.8‰ to −11.4‰; (av. −5.3‰)) than replacement dolomite (−5.8‰ to −10.8‰; (av. −8.0‰), respectively) but has similar δ13C values (−1.5‰ to 1.0‰; (av. −0.2‰ and), −0.1‰ to 1.5‰; (av. 0.3‰) respectively). Analysis of calcite cements (W-CC2, W-CC3) in his study indicates extremely depleted δ18O values (−11.9‰ and −12.5‰ respectively) and slightly depleted δ13C (−0.6‰ and −0.8‰ respectively), similar to values reported by Saller and Yaremko (1994): δ18O = −8.9‰ to −13.4‰ and δ13C = −0.2‰ to −1.1‰. δ18O and δ13C values of replacement dolomite in the PRA are similar to the WSB, whereas saddle dolomite cement is significantly δ18O depleted (Table 3, Figure 5c).

**Interpretation**

In the Swan Hills Formation, micrite, stromatoporoid and calcite cement phases in the WSB are all slightly more depleted in δ18O than the estimated composition of Late Devonian marine calcite (δ18O = −4‰ to −6‰; δ13C = 3.5‰ to 1.5‰; Hurley & Lohmann, 1989; Carpenter & Lohmann, 1995), which may be explained through alteration by isotopically light meteoric fluids. This likely occurred shortly after deposition, as evidence for subaerial exposure has been identified in a number of Devonian carbonate buildups (Walls & Burrowes, 1985 and references therein). These phases are rock

| Phase                        | Size               | Morphology | Extinction | Inclusions                              | CL                                  | Well |
|------------------------------|--------------------|------------|------------|-----------------------------------------|-------------------------------------|------|
| Replacement Dolomite 5 (W-RD5) | 100–500 µm         | P-s/Np     | Straight   | Turbid to limpid                        | Simple concentric and oscillatory zoning – bright orange and yellow | 13-13 |
| Saddle Dolomite Cement (W-SDC) | 200 µm - 2 mm      | Np         | Sweeping   | Turbid to limpid                        | Simple concentric and oscillatory zoning – bright orange, dark brown | 13-13 |
| Calcite Cement 2 (W-CC2)      | 500 µm - 2 mm      | Blocky     | Straight   | Turbid to limpid                        | Dark brown–dark orange inclusions, no zoning | 13-13 |
| Calcite Cement 3 (W-CC3)      | 300 µm - 7 mm      | Blocky     | Straight   | Turbid to limpid                        | Minor oscillatory zoning. Yellow–bright yellow inclusions | 13-13 |

**Table 3** Summary of the isotope data of the Swan Hills Formation, Leduc Formation and Wabamun Group in the West Shale Basin (WSB), East Shale Basin (ESB) and Peace River Arch (PRA) areas.
buffered, as their $\delta^{13}C$ values are similar to Late Devonian calcite (Banner, Hanson, & Meyers, 1988). Conversely, the enriched $\delta^{13}C$ (possibly due to input of organic carbon) values of RD in the WSB and ESB suggest high fluid–rock ratios. The $\delta^{18}O$ depletion of RD compared to hypothetical Upper Devonian marine dolomite ($\delta^{18}O = -2.4\%$ to $0\%$; $\delta^{13}C = 3.5\%e-1.5\%e$; Amthor et al., 1993 and references therein) in both areas suggests replacement from fluids of an elevated temperature and/or recrystallization, and this is more pronounced in the WSB than the ESB. Similarly, SDC in the WSB exhibits greater $\delta^{18}O$ depletion than in the ESB, although both are more depleted than RD, suggesting even
higher precipitation temperatures. In both areas δ13C values of SDC are either enriched or depleted relative to RD, indicating that this phase was likely fluid buffered.

In the Leduc Formation, δ18O values of RD in the WSB and ESB are all depleted compared to hypothetical Upper Devonian marine dolomite (Amthor et al., 1993 and references therein), suggesting replacement from fluids of an elevated temperature and/or recrystallization. Average δ13C values of RD are enriched and depleted relative to hypothetical Upper Devonian marine dolomite, suggesting that fluid–rock ratios were high (Banner et al., 1988). SDC in the WSB is slightly more δ18O depleted than the ESB, and in both areas is more depleted than RD, suggesting higher precipitation temperatures. Average δ13C values of SDC are enriched in the WSB and depleted in the ESB relative to hypothetical Upper Devonian marine dolomite, indicating that fluid–rock ratios were high.

In the Wabamun Group of the WSB, burrow-filling RD and matrix RD are significantly δ18O depleted compared to hypothetical Upper Devonian marine dolomite (Amthor et al., 1993 and references therein) suggesting replacement at elevated temperatures and/or recrystallization. Both phases have similar δ13C values that are depleted relative to hypothetical Upper Devonian marine dolomite, suggesting that fluid–rock ratios were high. RD in the PRA area has comparable δ18O and δ13C values to the WSB, suggesting that replacement dolomitization occurred under similar conditions. SDC in the PRA is significantly more δ18O depleted than the WSB, and in both areas is more depleted than RD, suggesting higher precipitation temperatures. δ13C of SDC in both areas ranges from similar to hypothetical Upper Devonian marine dolomite to depleted, indicating that fluid–rock ratios were high. Calcite cements in the PRA area are extremely δ18O and δ13C depleted suggesting precipitation from hot fluids with no input of organic carbon.

Dolomitizing fluid temperatures were calculated from the measured oxygen isotopes of RD and SDC (Figure 6). The fractionation equation of Land (1983) was used as RD is interpreted as forming during early burial at low temperatures. Conversely, as SDC likely formed at higher temperatures, the fractionation equation of Horita (2014) was used. Assuming a δ18O SMOW for Late Devonian seawater of 0 to −3‰ (Carpenter & Lohmann, 1995; Popp, Anderson, & Sandberg, 1986), replacement dolomitization of the Swan Hills Formation occurred at higher temperatures in WSB (52–83°C) than in the ESB (42–67°C) (Figure 6a). Conversely, replacement dolomitization of the Leduc Formation took place at higher temperatures in the ESB (32–65°C) than in the WSB (42–59°C) (Figure 6b). In comparison, replacement dolomitization of the Wabamun Group occurred at similar temperatures in the WSB (39–86°C) and PRA area (39–83°C) (Figure 6c). SDC in the Swan Hills Formation precipitated at higher temperatures in the WSB (56–96°C) than in the ESB (47–67°C). Similarly, SDC in the Leduc Formation also precipitated at higher temperatures in the WSB (51–71°C) than in the ESB (48–68°C). Conversely, SDC precipitated at lower temperatures in the WSB (44–61°C) than the PRA area (49–81°C).

4.2.3 Rare-earth elements

Swan Hills Formation

In the WSB, SH-MC1, SH-MC2, SH-CC1 and SH-SDC all exhibit similar REE+Y patterns to stromatoporoid values (Nothdurft, Webb, & Kamber, 2004) and carbonates affected by meteoric diagenesis that retain seawater-like patterns (Webb, Nothdurft, Kamber, Kloprogge, & Zhao, J. X., 2009) (Figure 7a). Most samples cluster within the marine quadrant of a Ce/Ce* versus Pr/Pr* plot (Figure 7d). Yttrium–Holmium ratios (Y/Ho) of SH-MC1, SH-MC2 and SH-CC1 range from 28.86 to 50.77 (av. 39), and SH-SDC Y/Ho range from 31.93 to 37.19 (av. 34.60) (Bau & Dulski, 1996). ESB phases SH-RD1 and SH-DC display negative Ce and positive Y anomalies (Tostevin et al., 2016). The Eu anomalies of one SH-RD1 and one SH-DC sample are the result of Ba contamination (606 and 6,448 ppm, respectively) during analysis (Jarvis, Gray, & McCurdy, 1989).

Leduc Formation

L-RD2, L-RD3 and L-DC display negative Ce and positive Y anomalies (Figure 7b) and cluster within the marine quadrant of a Ce/Ce* versus Pr/Pr* plot (Figure 7d). L-RD2
FIGURE 6  Equilibrium oxygen isotope fractionation plots of replacement dolomite (RD) and saddle dolomite cement (SDC) with Late Devonian seawater (Carpenter & Lohmann, 1995; Popp et al., 1986). Average $\delta^{18}O_{\text{VPDB}}$ values were used to calculate the $\delta^{18}O_{\text{VSMOW}}$ and temperature of parent fluids. The fractionation equations of Land (1983) and Horita (2014) were used for RD and SDC respectively. The temperature ranges of SDC are from fluid inclusion data cited in the text, SDC fluid compositions were estimated based on these temperature ranges.
FIGURE 7  Post Archaean Australian Shale (PAAS) normalised rare earth element (REE) concentrations for limestone and dolostone samples. (a) REE profiles of Swan Hills Formation samples. (B) REE profiles of Leduc Formation samples. (c) REE profiles of Wabamun Group samples. (d) (Pr/Pr*)SN versus. (Ce/Ce*)SN cerium anomaly plot (Webb & Kamber, 2000), symbols are the same as those used in (a, b and c). (e) Y versus Y/Ho plot (Tostevin et al., 2016), symbols are the same as those used in (a, b, c and d).
L-RD3 have Y/Ho ratios of 56.69 to 65.22 (av. 62.04) and 50.96 to 66.90 (av. 61.55) respectively. L-DC has slightly lower Y/Ho ratios than L-RD2 and L-RD3 (49.35 to 50.29, av. 49.82) (Figure 7e).

**Wabamun Group**

In the WSB, W-RD1 and W-RD2 have similar REE patterns and Y/Ho ratios (26.06–31.91 (av.28.99) and 24.78–28.54 (av. 26.66) respectively) that display a slight middle REE bulge (Figure 7c,e). PRA phases W-RD4 and W-SDC exhibit similar REE patterns with negative Ce and positive Y anomalies. Calcite cement phases W-CC2 and W-CC3 display enrichment of light and medium REE + Y. All diagenetic phases have similar Y/Ho ratios (36.20–39.32, av. 37.87).

**Interpretation**

All diagenetic phases in the Swan Hills Formation have negative cerium anomalies consistent with precipitation from seawater (Tostevin et al., 2016), with matrix calcite in the WSB also suggesting alteration by meteoric fluids (Webb et al., 2009). The range of Y/Ho values for matrix calcite, calcite cement and saddle dolomite cement in the WSB suggests restricted marine conditions (limited circulation), whereas replacement dolomite and dolomite cement in the ESB suggest open marine seawater (Bau & Dulski, 1996). SDC in the WSB exhibits MREE enrichment possibly indicative of illite–smectite transition (Phan, Hakala, Lopano, & Sharma, 2019) at elevated burial temperatures. In the Leduc Formation of the ESB, replacement dolomite and dolomite cement have the strongest cerium anomalies of any phase sampled in this study, suggesting precipitation from seawater (Tostevin et al., 2016). Y/Ho ratios are consistent with this, indicating open marine conditions (Bau & Dulski, 1996). Diagenetic phases in the Wabamun Group of the WSB exhibit negative cerium anomalies consistent with precipitation from seawater (Tostevin et al., 2016) a slight middle REE bulge indicative of anoxic pore water (Haley, Klinkhammer, & McManus, 2004), although one sample has a silicilastic signal (Tostevin et al., 2016). Based on similar REE+Y, cerium anomalies and Y/Ho values, PRD replacement dolomite and saddle dolomite also precipitated from restricted seawater. Calcite cement phases in this region exhibit light and medium REE+Y enrichment indicative of crustal fluids (Lüders, Möller, & Dulski, 1993).

### 4.2.4 Strontium isotopes

Previous studies sought to determine the sources of dolomitizing fluids in the WCSB using Sr isotope ratios ($^{87}$Sr/$^{86}$Sr). Studies on the Swan Hills Formation (Duggan et al., 2001; Green & Mountjoy, 2005; Kaufman et al., 1990, 1991; Laflamme, 1990), Leduc Formation (Drivet & Mountjoy, 1997; Green, 1999; Green & Mountjoy, 2005; Kuflevskiy, 2015; Laflamme, 1990) and Wabamun Group (Al-Aasm, 2003; Green, 1999; Green & Mountjoy, 2005; Mountjoy & Halim-Dihadj, 1991; Saller & Yaremko, 1994) measured $^{87}$Sr/$^{86}$Sr ranging from 0.7078 to 0.7090; to >0.7120. For the first time, our study has compiled, compared and statistically analysed this data (Table 3, Figure 8) in order to determine spatial $^{87}$Sr/$^{86}$Sr variation across the WCSB.

**Swan Hills Formation**

$^{87}$Sr/$^{86}$Sr values for replacement dolomite (RD) and saddle dolomite cement (SDC) in the WSB are generally more radiogenic (RD = 0.7081–0.7336 (av. 0.7139) and SDC = 0.7100–0.7370 (av. 0.7198)) than in the ESB (RD = 0.7083–0.7089 (av. 0.7086) and SDC = 0.7088) (Table 3) (Figure 8a,d).

**Leduc Formation**

$^{87}$Sr/$^{86}$Sr values for RD and SDC in the WSB are generally more radiogenic (RD = 0.7082–0.7105 (av. 0.7092) and SDC = 0.7087–0.7138 (av. 0.7118)) than in the ESB (RD = 0.7080–0.7117 (av. 0.7085) and SDC = 0.7082–0.7112 (av. 0.7092)) (Table 3, Figure 8b,d).

**Wabamun Group**

$^{87}$Sr/$^{86}$Sr values for RD in the Wabamun Group of the WSB are typically more radiogenic than the PRA area (0.7083–0.7099 (av. 0.7092) and 0.7085 respectively) (Table 3). Conversely, SDC in the WSB is less radiogenic than the PRA area (0.7092–0.7131 (av. 0.7106) and 0.7082–0.7230 (av. 0.7124) respectively) (Table 3, Figure 8c,d).

**Interpretation**

The $^{87}$Sr/$^{86}$Sr values of all replacement dolomite and saddle dolomite phases in each formation across the WCSB overlap and exceed the estimated $^{87}$Sr/$^{86}$Sr composition of Middle to Upper Devonian seawater (0.7078–0.7090; Prokopf, Shields, & Veizer, 2008). RD phases in each formation in any area do not exceed MASIRBAS (Maximum Strontium Isotope Ratio of Basinal Shale, defined as 0.7120 by Machel & Cavell, 1999), with the exception of those sampled by Duggan et al. (2001) in the Swan Hills Formation of the WSB. The $^{87}$Sr/$^{86}$Sr values of these RD phases were likely increased by uptake of additional $^{87}$Sr during burial recrystallization from fault-derived fluids responsible for precipitating saddle dolomite cement (Duggan et al., 2001) and are therefore considered anomalous. The remaining non-anomalous RD values in each formation and area that exceed Middle to Upper Devonian seawater are likely the result of seawater interacting with clay minerals, which contributed additional $^{87}$Sr (Machel & Cavell, 1999). Additionally, elevated $^{87}$Sr/$^{86}$Sr values can be explained by the recrystallization of RD by connate waters, as discussed in great detail by Kuflevskiy (2015) for the Leduc Formation of the ESB. The
average $^{87}$Sr/$^{86}$Sr values of RD in the Swan Hills Formation (excluding the data of Duggan et al., 2001), Leduc Formation and Wabamun Group are higher than their equivalents in the ESB and PRA areas, suggesting that recrystallization and/or fluid interaction with clays is more significant in the WSB. With the exception of the Wabamun Group in the PRA area, average $^{87}$Sr/$^{86}$Sr values of SDC in the Swan Hills Formation and Leduc Formation are also more radiogenic in the WSB than the ESB. As the $^{87}$Sr/$^{86}$Sr values of SDC in the WSB and PRA areas exceed MASIRBAS, this indicates that the fluids SDC precipitated from were $^{87}$Sr rich, suggesting that they interacted with the underlying Precambrian basement or Cambrian clastic sediments (Machel & Cavell, 1999). Conversely, as SDC in the ESB does not exceed MASIRBAS, this suggests that fluids did not interact with either the Precambrian basement or Cambrian clastics prior to precipitating SDC.

### 4.3 Lithium-rich formation waters

Previous research (Eccles & Jean, 2010 and references therein) compiled 1511 geochemical analyses of lithium-rich (Li) formation waters from hydrocarbon wells drilled in the WCSB. Subsequently, Eccles and Berhane (2011) identified a significant anomaly (75–140 mg/L Li) in the Fox Creek area of the WSB based on a lower background estimate (av. 10 mg/L Li, median 0.2 mg/L Li) of formation
waters across the WCSB. These anomalous Li concentrations occur at depths that place the waters within the strata of the Beaverhill Lake (Swan Hills Formation), Woodbend (Leduc Formation) and Winterburn (Nisku Formation) groups.

Following the methodology of Eccles and Berhane (2011), the regional concentration of Li was replotted in this study by ordinary kriging of the 1511 geochemical analyses of formation water from oil and gas wells (Eccles & Jean, 2010). The extent of the Swan Hills Formation (Oldale et al., 1994) Cooking Lake and Leduc Formations (Switzer et al., 1994), Wabamun Group (Halbertsma, 1994) and inferred Precambrian faults (Burwash et al., 1994) are shown in relation to formation water lithium concentration (modified from Eccles & Berhane, 2011). (b) Arithmetic mean and range of values for formation water lithium concentration of the Middle to Upper Devonian strata in the Peace River Arch (PRA), West Shale Basin (WSB) and East Shale Basin (ESB) areas of the Alberta Basin (n = number of samples) (Eccles & Jean, 2010).

The occurrence of Li-rich fluids in the WSB and PRA area is also consistent with the radiogenic $^{87}\text{Sr}^{86}\text{Sr}$ values of dolomite formations.
phases in these areas when compared to the Li-poor fluids and nonradiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ of the ESB. Furthermore, Eccles and Berhane (2011) concluded that the variability of lithium concentration may be due to a greater contribution of silicate-bearing fluids sourced from basal clastic aquifers in the WSB and PRA areas than the ESB.

4.4 | Fluid inclusions

Published fluid inclusion (homogenization temperature, $T_h$) data (Al-Aasm, 2003; Drivet & Mountjoy, 1997; Duggan et al., 2001; Green, 1999; Kaufman et al., 1991; Mountjoy et al., 1999) provide the minimum entrapment temperatures (without pressure or phase corrections) of saddle dolomite cement. In the West Shale Basin, the $T_h$ of saddle dolomite ranges from 125 to 190°C (Swan Hills Formation), 127 to 195°C (Leduc Formation) and 133 to 174°C (Wabamun Group). Compared to the West Shale Basin, saddle dolomite cement in the East Shale Basin Leduc Formation has a lower range of $T_h$, ranging from 98 to 168°C (no fluid inclusion data are available for the Swan Hills Formation, so it is assumed saddle dolomite formed at similar temperatures to the Leduc). In the Peace River Arch area, saddle dolomite cement in the Wabamun Group exhibits $T_h$ ranging from 90 to 190°C.

**Interpretation**

The high homogenization temperatures recorded by fluid inclusions correlate with the significant $^{18}\text{O}$ depletion of SDC samples relative to RD and hypothetical Late Devonian marine dolomite (Amthor et al., 1993 and references therein) and are greater than the estimated fluid temperatures calculated from stable isotope data. This suggests that the fluids that precipitated saddle dolomite cement were isotopically heavier than Late Devonian seawater. Fluid inclusion homogenization temperatures were used to estimate the $^{18}\text{O}_{\text{SMOW}}$ of SDC precipitating fluids (Figure 6). SDC in the
Swan Hills Formation precipitated from fluids of a similar $^{18}$O SMOW in the WSB (3.3‰–11.3‰) and ESB (4.4–11.1‰). Conversely, SDC in the Leduc Formation precipitated from fluids of differing $^{18}$O SMOW in the WSB (7.1‰–12.3‰) when compared to the ESB (4.7‰–11.2‰). Similarly, SDC in the Wabamun Group of the WSB precipitated from fluids of a heavier $^{18}$O SMOW (9‰–12.4‰) compared to the PRA area (1.3‰–12.4‰).

5 | DISCUSSION

5.1 | Timing & temperature of dolomitization

In all formations in the WSB, ESB and PRA area, replacement dolomite overlaps and post-dates low-amplitude stylolite formation, implying that dolomitization of precursor limestone occurred after some pressure solution during burial. As stylolites begin to form at approximately 600–1500 m (Mountjoy et al., 1999), this would suggest that replacement dolomitization occurred during shallow burial (Figure 10), with the vast majority of previous researchers working in the WCSB also concluding this (e.g. Amthor et al., 1993; Green & Mountjoy, 2005; Machel & Anderson, 1989 and references therein).

Planar-e and planar-s crystal textures are common in early formed (prior to stylolites) replacement dolomite, whereas nonplanar textures are only observed cross-cutting stylolites. As nonplanar textures indicate formation at temperatures $>$50°C (sensu Sibley & Gregg, 1987), this suggests that the progression of replacement dolomite textures from planar-e to nonplanar records increasing temperatures with gradual burial. This is also supported by the CL characteristics of planar-e to planar-s replacement dolomite, which is typically homogenous when compared to the more complex luminescence and zoning of later nonplanar phases.

The paragenetic sequences proposed by this study for the Devonian succession are broadly similar (Figure 10), with replacement dolomitization occurring from the Middle Devonian to the Mississippian. This is constrained by the relationship of replacement dolomite to stylolites, and as the rates of burial during this period are similar across the WCSB (Figure 10) replacement dolomitization likely occurred at similar depths. With the exception of the Wabamun Group in the PRA area, saddle dolomite cement post-dates stylolite formation, suggesting precipitation during deeper burial. This is corroborated by the occurrence of hydrocarbon inclusions within saddle dolomite from the Swan Hills Formation in the WSB. As peak oil generation from the Duvernay Formation occurred around ca. 80 Ma during the Laramide Orogeny (Creaney et al., 1994), this suggests that saddle dolomite cement in the WSB was precipitated from fluids migrating with oil during deep burial (Figure 10). Previous research (e.g. Amthor et al., 1993; Kaufman et al., 1990; Mountjoy & Halim-Dihardja, 1991) inferred a similar timing for saddle dolomite precipitation in all formations across the WCSB, suggesting a common formation mechanism related to the Laramide Orogeny.

Oxygen isotope thermometry of samples analysed in this study indicates that replacement and saddle dolomite formed at similar temperatures to those calculated by previous studies (Figure 6). Geothermal gradients of 25°C/km (Devonian to Middle Cretaceous), 22°C/km (Middle to Late Cretaceous) and 23°C/km (Late Cretaceous to Present) were used to estimate rock temperatures during burial (Duggan et al., 2001 and references therein) (Figure 10). Replacement dolomitization of the Swan Hills Formation took place at higher temperatures in the WSB (52–83°C) than in the ESB (42–67°C). Conversely, replacement dolomitization of the Leduc Formation occurred at higher temperatures in the ESB (32–65°C) than in the WSB (42–59°C). Replacement dolomitization of the Wabamun Group took place at similar temperatures in the WSB (39–86°C) and PRA area (39–83°C). In all areas, these temperatures were achieved in the Late Devonian to the Late Cretaceous. However, these estimated dolomitization temperatures must be treated with caution, as they may reflect recrystallization by elevated temperatures during burial or the influence of hotter, deeper sourced fluids, either of which may have depleted the $^{18}$O PDB and enriched the $^{87}$Sr/$^{86}$Sr signatures of replacement dolomite.

If we assume that the replacement dolomite samples that have similar $^{87}$Sr/$^{86}$Sr values to Middle to Upper Devonian seawater have undergone minor alteration of their $^{87}$Sr/$^{86}$Sr and $^{18}$O values (sensu Green & Mountjoy, 2005), these dolomites likely formed from seawater at the elevated geothermal burial temperatures discussed above. Our geochemical data show that the majority of Leduc Formation replacement dolomites in the East Shale Basin are most similar to Devonian seawater. However, some samples exhibit slightly elevated $^{87}$Sr/$^{86}$Sr values, which led Kuflevskiy (2015) to conclude that significant recrystallization (sensu Machel, 1997) took place during burial. Based on the presence of nonplanar textures indicative of either replacement at an elevated temperature ($>$50°C) and/or recrystallization of a precursor phase (sensu Sibley & Gregg, 1987), our petrographic data suggest that recrystallization occurred in the Leduc Formation in the ESB and in the Wabamun Group in the PRA area. However, the elevated $^{87}$Sr/$^{86}$Sr values of replacement dolomite compared to the estimated composition of Middle and Upper Devonian seawater suggest recrystallization across the WCSB. This is corroborated by previous studies that suggested recrystallization potentially occurred in the Swan Hills Formation in the WSB (Duggan et al., 2001) and ESB (Laflamme, 1990), in the Leduc Formation in the WSB and ESB (Kuflevskiy, 2015; Mountjoy et al., 1999) and in the
Due to the proximity of the West Shale Basin to the Cordilleran deformation front, maximum burial temperatures are higher than in the East Shale Basin and Peace River Arch areas. Based on the burial history curves of Green and Mountjoy (2005), the Swan Hills Formation, Leduc Formation and Wabamun Group in the West Shale Basin have maximum burial depths of 5,525 m (ca. 180°C), 5,450 m (175°C) and 5,525 m (170°C) respectively. In comparison, the Swan Hills and Leduc Formations in the East Shale Basin have maximum burial depths of 5,000 m (ca. 122°C) and 2,600–4,800 m (75–122°C) respectively (Anthor et al., 1993; Drivet & Mountjoy, 1997; Laflamme, 1990). The Wabamun Group in the Peace River Arch area was also buried to a shallower maximum burial depth than in the West Shale Basin: 3,050 m (ca. 85°C) (Mountjoy & Halim-Dihardja, 1991).

In the West Shale Basin, the maximum homogenization temperatures recorded by fluid inclusions in all the Swan Hills and Leduc formations are greater than the maximum burial temperature (SDC in the Wabamun Group is geothermal). As fluid inclusions only record the minimum entrapment temperature (Goldstein, 2001), the temperatures of the fluids that precipitated saddle dolomite cement were potentially higher. This implies that saddle dolomite cement in the West Shale Basin precipitated from fluids that were >5–10°C warmer than the ambient formation temperature, and is therefore hydrothermal (Stearns et al., 1935; White, 1957). Based on this reasoning, saddle dolomite is also hydrothermal in the Swan Hills and Leduc formations of the East Shale Basin and Wabamun Group of the Peace River Arch area. The large range of homogenization temperatures in saddle dolomite suggests that even in areas where hydrothermal fluids were present, some mixing and cooling of these fluids occurred. This is most evident in the Swan Hills Formation in the West Shale Basin and in the Wabamun Group of the Peace River Arch. The ranges of $^{87}$Sr/$^{86}$Sr values are also consistent with this, with saddle dolomite in all formations except the Swan Hills in the West Shale Basin overlapping with the estimated composition of Middle to Upper Devonian seawater. The only area where saddle dolomite $^{87}$Sr/$^{86}$Sr values do not exceed MASIRBAS is the East Shale Basin. This suggests that these fluids, although hydrothermal, likely did not interact with the Precambrian basement.

### 5.2 Sources of dolomitizing fluids

The negative cerium anomalies of the replacement dolomite phases sampled by this study are consistent with replacement dolomitization by seawater (Tostevin et al., 2016), and this is corroborated by Y/Ho values that are indicative of restricted or open marine fluids (Bau & Dulski, 1996). Furthermore, the REE+Y data collected by this study record the composition of dolomitizing fluids rather than the inherited REE+Y characteristics of host limestones, as their δ$^{13}$C values are either enriched or depleted relative to hypothetical Upper Devonian marine dolomite (Amthor et al., 1993 and references therein), which indicates that fluid–rock ratios were high during dolomitization (Banner et al., 1988). As seawater is the most volumetrically viable source of water and magnesium, this would account for the large volumes of replacement dolomite present in the WCSB. This is supported by the presence of anhydrite in the Swan Hills Formation (WSB) and the Wabamun Group (WSB and PRA), as it is known to be a common by-product of dolomitization by seawater (Machel & Anderson, 1989). As $^{87}$Sr/$^{86}$Sr data range from the estimated composition of Middle to Upper Devonian seawater (Prokoph et al., 2008) to more radiogenic values, this suggests that recrystallization of RD and/or fluid interaction with $^{87}$Sr-rich clays occurred across the WCSB.

$^{87}$Sr/$^{86}$Sr data of saddle dolomite cement phases show evidence for a seawater component in the Swan Hills Formation of the WSB and the Wabamun Group of the PRA area, and radiogenic $^{87}$Sr/$^{86}$Sr values across the WCSB in all formations are consistent with precipitation from basinal fluids. The variability of $^{87}$Sr/$^{86}$Sr data for saddle dolomite cement phases in the WSB, ESB and PRA is indicative of distinct basinal fluid sources for each of these areas. This is most prevalent in the WSB and PRA areas where $^{87}$Sr/$^{86}$Sr values range from the estimated composition of Middle to Upper Devonian seawater (Prokoph et al., 2008) to values that significantly exceed MASIRBAS. As such, this section will evaluate potential basinal fluid sources based on the geochemical data presented by this study for the WSB, ESB and PRA areas.

### 5.2.1 West Shale Basin

$^{87}$Sr/$^{86}$Sr values of RD in the Swan Hills Formation, Leduc Formation and Wabamun Group overlap and exceed Middle to Upper Devonian seawater, indicating that replacement dolomitization took place from seawater, which possibly reacted with clay minerals during fluid migration or underwent subsequent recrystallization during burial. $^{87}$Sr/$^{86}$Sr values of SDC from the Swan Hills Formation and Wabamun Group exceed Devonian seawater and MASIRBAS. SDC in the Leduc Formation also exceeds MASIRBAS and overlaps with Devonian seawater. The radiogenic Sr values of SDC suggest that basinal fluids interacted with $^{87}$Sr-rich minerals (such as potassium feldspar or clay minerals) present in immature siliciclastic units (e.g. Basal Cambrian Sandstone) prior to their emplacement in the Devonian succession in this area. Additionally, our XRD data indicate the co-occurrence of dolomite with authigenic quartz, which further supports that basinal fluids interacted with a clastic aquifer. Although clastic aquifers beneath the Devonian
succession such as the Basal Cambrian Sandstone and Gilwood Member likely contributed the majority of SDC precipitating basinal fluids, contributions from fluids that interacted with the Precambrian basement cannot be ruled out (as discussed by Duggan et al., 2001). Additionally, our REE+Y data of SDC from the Swan Hills Formation exhibit MREE enrichment possibly indicative of illite–smectite transition (Phan et al., 2019) at elevated burial temperatures, suggesting a minor fluid contribution from clay-rich sediments.

5.2.2 | East Shale Basin

The \(^{87}\text{Sr}/^{86}\text{Sr}\) values of RD and SDC in the Swan Hills Formation and Leduc Formation overlap and exceed the estimated composition of Middle to Upper Devonian seawater but never exceed MASIRBAS, indicating that replacement dolomitization and SDC precipitation occurred from seawater, with subsequent recrystallization. This is in agreement with Kuflevskiy (2015), who concluded that warm connate waters and possibly fault-derived fluids were responsible for the recrystallization of RD in the Leduc Formation of the WSB. Evidence for seawater dolomitization is also corroborated by REE+Y data, as RD and DC in both the Swan Hills and Leduc formations have high negative cerium anomalies and Y/Ho values indicative of formation from open marine fluids. However, as shown by petrography and XRD data, authigenic quartz is present in the Swan Hills Formation, suggesting that basinal fluids may have interacted with a clastic aquifer prior to precipitating SDC. As \(^{87}\text{Sr}/^{86}\text{Sr}\) values of SDC are nonradiogenic, this indicates that fluids could have interacted with a potassium feldspar-poor unit such as the Gilwood Member (Shawa, 1969). Conversely, authigenic quartz is absent in the Leduc Formation, which suggests no interaction of fluids with clastic aquifers. As noted by Kuflevskiy (2015), fault-derived fluids were potentially emplaced in the Leduc Formation, and the present day occurrence of lithium-rich formation waters suggests that fluids sourced from the Prairie Evaporite Formation could have migrated through the underlying Winnipegosis Formation before entering the Leduc Formation via faults. This is also supported by the presence of fluorite, which cements fractures/stylolites in the Leduc Formation and is known to occur in the Prairie Evaporite Formation of north-east Alberta (Hauck et al., 2018).

5.2.3 | Peace River Arch

\(^{87}\text{Sr}/^{86}\text{Sr}\) values of RD in the Wabamun Group do not exceed the estimated composition of Upper Devonian seawater, whereas SDC overlaps and exceeds MASIRBAS. This indicates that RD formed only from seawater and SDC precipitated from seawater mixed with basinal fluids. A seawater component for both is supported by our REE+Y data which display minor negative cerium anomalies and Y/Ho values consistent with restricted marine fluids. The radiogenic \(^{87}\text{Sr}/^{86}\text{Sr}\) values of SDC suggest that basinal fluids interacted with immature clastic units that contain abundant potassium feldspar (e.g. the Granite Wash) prior to dolomitizing the Wabamun Group. This is corroborated by our XRD data, which indicate that authigenic quartz and albite are present. Despite this, contributions of basinal fluids that interacted with the Precambrian basement cannot be ruled out as our REE+Y data of breccia cementing calcite cements exhibit enrichment of LREEs and MREEs consistent with precipitation from crustal-derived fluids (Lüders et al., 1993).

5.2.4 | Present-day pore fluid composition

Michael, Machel, and Bachu (2003) found that the Devonian aquifers of the WCSB contain a heavy brine (TDS > 200 g/L) with evidence of albition that originated as residual Middle Devonian evaporitic brine either from the Elk Point Basin or from the dissolution of Middle Devonian evaporites. The same study found that a second lighter brine (TDS < 200 g/L) is also present in the Devonian aquifers, and likely originated from the dilution of heavy brine by influx of meteoric and metamorphic waters after the Laramide Orogeny. Michael et al. (2003) concluded that the current composition of these brines was determined by original seawater, evaporation beyond gypsum but below halite saturation, dolomitization, clay dehydration, thermochemical sulphate reduction and halite dissolution. Subsequently, Eccles and Berhane (2011) found that Li-rich formation water in the West Shale Basin is characterized by highly radiogenic \(^{87}\text{Sr}/^{86}\text{Sr}\) values (0.7204–0.7258), whereas Li-poor formation water is less radiogenic (0.7098–0.7194) and is more similar to Devonian seawater. Eccles and Berhane (2011) also found that Li-rich brine is enriched in K, suggestive of water–rock interactions that involved silicate alteration. Mg and Ca values are also far removed from the SET (modern day Seawater Evaporation Trajectory), which is consistent with these brines being involved in dolomitization and consequently being depleted in Mg as a result. Huff (20162019) recognized that Li-bearing brines in the West Shale Basin are typically more radiogenic than their East Shale Basin counterparts, and concluded that the reason for Sr and Li enrichment of brines in the Swan Hills Formation in the West Shale Basin was due to dissolution of halite and mixing with Li-enriched fluids expelled from the Precambrian basement. The same study found that Li-enriched brines in the Leduc Formation of the East Shale Basin formed by preferential dissolution of Li-enriched evaporite minerals (including Mg-rich carnallite) in the Middle Devonian Prairie Evaporite Formation by evapo-concentrated Middle Devonian seawater. This dense Li-enriched
Conceptual model of burial dolomitization controlled by faults and regional conduits. At the initiation of basin tilting in the Late Devonian to Mississippian, basinal fluids migrated updip through porous and permeable regional conduits, forming laterally extensive dolostone bodies. Faults also acted as conduits for basinal fluids, which flowed upward and produced isolated dolostone bodies. Where basal clastic units are connected to carbonate units by faults, radiogenic Sr and quartz/albite occur with dolomite (a and b). Conversely, where faults are only connected to basal carbonate units, these characteristics are absent (b). Reactivation of the same faults during the Laramide Orogeny likely acted as fluid pathways, resulting in the precipitation of deep-burial cement phases. Panel (a) is modified after Green and Mountjoy (2005). All stratigraphy is based on the Table of Formations produced by the Alberta Geological Survey.
brine then migrated downward into the underlying Early Devonian Winnipegosis Formation and moved west under gravity-driven flow due to basin tilting. This interpretation is also consistent with our invoked source of dolomitizing fluids for the Leduc Formation in the ESB. The findings of Huff (2019) are also in agreement with Bottomley, Clark, Battye, and Kotzer (2005) and Spencer (1987) who concluded that Ca-Cl basement hosted brines in the WCSB likely originated as residual evapo-concentrated Devonian seawater related to the Prairie Evaporite Formation. Bottomley et al. (2005) also noted that only 30% of the current Ca budget of these brines can be explained through dolomitization. Additional Ca was likely sourced by albitionization of feldspars within immature clastic units such as the Basal Cambrian Sandstone, which also explains the radiogenic Sr signatures of both the brines and saddle dolomite cements. This is in agreement with the $^{87}$Sr/$^{86}$Sr data compiled by our study, and also explains the occurrence of authigenic quartz and albite related to the dolomites in the West Shale Basin and Peace River Arch areas, as residual evapo-concentrated Middle Devonian seawater potentially interacted with immature clastic units prior to dolomitization.

5.3 | Mechanisms of dolomitization

Potma et al., (2001) concluded that the majority of replacement dolomite in the Frasnian of the WCSB precipitated through seepage reflux of brines that formed coevaly with the top of the Winterburn 1 and 2 sequences. However, this interpretation is not supported by the vast majority of data presented in this study and previous work. In particular, the estimated temperatures of replacement dolomitization and the evidence that dolomite post-dates the formation of low-amplitude stylolites suggest formation during early burial. The geochemical data presented by our study are more consistent with replacement dolomitization from modified Devonian seawater, and precipitation of saddle dolomite cement from basinal brines. Although the current composition of formation waters does indeed suggest a component of evapo-concentrated seawater, the likely origin of this is the Middle Devonian Prairie Evaporite Formation (Huff, 2019), which rules out the Frasnian origin suggested by Potma et al., (2001). Based on a similar line of reasoning, Machel et al. (2002) also concluded that this reflux model is untenable and that all the available evidence is more consistent with burial dolomitization.

As reported by Machel and Lonnee (2002) (and references therein), the compactional dewatering and freshwater–seawater mixing dolomitization models have been shown to be incapable (because of mass balance constraints) of producing the vast majority (85–90 vol.%) of replacement dolomite found in the WCSB south of the Peace River Arch. This is consistent with the findings of Warren (2000), who concluded that compactional dewatering and mixing zone dolomitization models are invalidated for most sedimentary basins.

Machel and Lonnee (2002) concluded that the hydrothermal dolomitization model proposed by Davies and Smith (2006) is hydrologically unfeasible and that the southern section of the WCSB has no history of regionally elevated heat flow. Data from this study support this and suggest that replacement dolomite across the WCSB formed under geothermal conditions. However, fluid inclusion data, alongside the association between saddle dolomite distribution and faults, suggests that there was a period of fault-related hydrothermal dolomitization which led to precipitation of saddle dolomite cements.

Bachu (1995 and references therein) identified two mega-hydrostratigraphic successions in the WCSB: pre-Cretaceous and post-Jurassic. The pre-Cretaceous succession consists of carbonate (and subordinate clastic) aquifer systems that are separated by shale aquitards and evaporite aquicludes. The same study found that formation waters in the Basal Cambrian Sandstone, Winnipegosis Formation, Beaverhill Lake, Woodbend, Winterburn and Wabamun groups are currently migrating updip to the east–northeast. Subsequent research by Mountjoy et al., 1999 and Green and Mountjoy (2005 and references therein) invoked the regional flow of dolomitizing fluids through the Devonian aquifers described by Bachu (1995 and references therein), with cross-formational flow facilitated by vertical faults to facilitate the flux of dolomitizing fluids. One potential mechanism for driving this regional-scale fluid flow is tectonic loading, although fluid volumes are low and flow slowly, driving fluids only 100–150 km into the WCSB (Machel & Cavell, 1999). An alternative is density-driven flow, which has been documented to occur within the Devonian succession in the present day. Low-density brines (TDS < 200 g/L) attempting to flow updip push high-density brines (TDS > 200 g/L) ahead of them, resulting in localized flow. High-density brines may be residual Middle Devonian evaporitic brine or originated from partial dissolution of the Prairie Evaporite Formation (Michael et al., 2003). This is corroborated by formation water database analysis by Huff (2019), who suggested that brines infiltrated the Keg River/Winnipegosis Formation and migrated westward by gravitationally driven flow related to basin tilting. Consequently, it is feasible that fluid flux along faults and via aquifers controlled dolomitization in the WCSB during burial based on the following evidence: firstly, this model explains the observed distribution of dolomite throughout the Devonian succession, and secondly, our stable isotope, rare-earth element, strontium isotope and formation water data indicate that each region of the WCSB is geochemically distinct, which can be explained by invoking multiple dolomitizing fluid sources from a number of fault connected regional aquifers.
5.4 | Role of basal aquifers in regional dolomitization

5.4.1 | West Shale Basin

Amthor et al. (1993) proposed that Devonian connate waters dolomitized the Leduc Formation and were sourced downdip to the west, with migration through the Lower Leduc Platform. Amthor et al., (1993) also invoked a similar dolomitization mechanism for the Swan Hills Formation, noting that the basal Swan Hills Platform is dolomitized where it is in contact with the underlying Gilwood Member. Duggan et al., (2001) also suggested that dolomitizing fluids migrated from the Basal Cambrian Sandstone. Both studies concluded that fault-derived fluids were responsible for the dolomitization of the Swan Hills Platform margin, with Kaufman et al., (1991) also suggesting that the consistent NE-SW orientation of dolomite bodies was due to faulting. Due to the presence of anomalous stratigraphic offsets, the Wabamun Group is interpreted to have been dolomitized by fault-derived fluids similar to those emplaced in the Swan Hills and Leduc formations (Green & Mountjoy, 2005).

We agree with the fluid pathways interpreted by these authors and propose that replacement dolomitization involved Middle to Upper Devonian seawater and saddle dolomite cement precipitated from residual Middle Devonian evaporitic brines which migrated through faults from the Precambrian basement, Basal Cambrian Sandstone and Elk Point Group (Gilwood Member sandstone) (Figure 11a). This accounts for the radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ values of saddle dolomite cement as well as the co-occurrence of authigenic quartz and albite with dolomite in the Swan Hills Formation, Leduc Formation and Wabamun Group. These fluids mixed with connate seawater, ensuring that the Mg/Ca ratio of the fluid was sufficiently high for dolomitization. Based on the presence of replacement dolomite and late saddle dolomite cements (associated with hydrocarbons), it is reasonable to suggest that the emplacement of Mg-rich fluids occurred at least twice; in the Late Devonian to Early Mississippian and during the Cretaceous. These timings coincide with fault reactivation during Antler-aged tectonism and the Laramide Orogeny.

5.4.2 | East Shale Basin

Kaufman et al., (1991) suggested that circulation of seawater along faults during early burial may explain the restriction of dolomite bodies to the Swan Hills Platform margin. We agree that faults provided flow pathways for seawater but we also conclude that basinal brines (residual Middle Devonian evaporitic brine) utilized the same pathways to dolomitize the Swan Hills Formation. These brines migrated through faults from the Basal Red Beds, the dolomitized Keg River Formation and the Gilwood Member, which accounts for the presence of authigenic quartz within vugs.

Conduit-controlled dolomitization has been invoked for the Leduc Formation, with fluid migration of seawater along the margin of the underlying Cooking Lake Platform (Amthor et al., 1993; Drivet & Mountjoy, 1997; Green, 1999; Mountjoy et al., 1997). Although we agree with this fluid pathway interpretation and that seawater was the principal dolomitizing fluid, we also propose a secondary fault-derived source of dolomitizing fluids that migrated from the Keg River Formation, which accounts for the presence of Li-rich formation fluids. These basinal fluids supplied additional Mg and migrated along the margin of the Cooking Lake Platform. The nonradiogenic character of dolomites in the ESB indicates that basinal fluids had no interaction with Sr-rich units such as the Basal Cambrian Sandstone or the Precambrian basement (Figure 11b).

5.4.3 | Peace River Arch

Mountjoy and Halim-Dihardja (1991) concluded that dolomitization of the Wabamun Group was controlled by faults, and that dolomitizing fluids were Devonian connate waters and basinal brines sourced from deeper strata or interacted with the Precambrian basement. Saller and Yaremko (1994) suggested the replacement dolomite formed from Upper Devonian seawater, whereas hydrothermal fluids migrated updip through the underlying Winterburn and/or Leduc formations and along faults.

We agree that faults and the underlying Devonian succession acted as dolomitizing fluid conduits and propose that basinal brines migrated updip from the Precambrian basement and through the Basal Cambrian Sandstone (Granite Wash) along the flanks of the Peace River Arch where they entered the Swan Hills, Leduc and Nisku formations. Basinal brines also migrated along normal faults and entered the Wabamun Group, resulting in the formation of dolomite bodies (Figure 11c). The presence of authigenic quartz and albite in our samples is similar to Packard, Al-Aasm, Samson, Berger, and Davies (2001) who attributed authigenic quartz to fluids sourced from the Granite Wash or fluids that interacted with the Precambrian basement. As our samples of replacement dolomite and saddle dolomite cement have seawater REE+Y characteristics and calcite cement has a crustal fluid signature, it is reasonable to suggest that fluid migration occurred at least twice, associated with Antler tectonism and the Laramide Orogeny.
6 | CONCLUSIONS

Replacement dolomitization in the WCSB occurred through the circulation of modified Middle to Upper Devonian seawater, whereas saddle dolomite precipitated from basinal brines. Previously ambiguous basinal brines are now recognized as residual evapo-concentrated Middle Devonian seawater that interacted with the Prairie Evaporite Formation in the East Shale Basin and the Precambrian basement in the West Shale Basin and Peace River Arch areas to produce Li- and Mg-enriched fluids capable of dolomitization. As a result of these interactions, the composition of these fluids varies across the basin and explains the observed spatial geochemical variability of dolomite.

Circulation and migration of seawater and basinal brines in porous carbonate reefs and platforms was facilitated by faults and regional-scale conduits, resulting in the present observed distribution of dolomite. Dolomitization began during early burial and in most cases precedes the formation of stylolites. This implies that replacement dolomite formed from the Upper Devonian through to the Mississippian during Antler tectonism. The majority of saddle dolomite and calcite cements post-date stylitization and therefore formed during late burial. Reactivation of faults during the Laramide Orogeny likely facilitated fluid flow along pathways previously utilized during early burial, resulting in the formation of late-stage saddle dolomite and calcite cements. Unlike replacement dolomite, these cement phases precipitated from hydrothermal fluids.

In the West Shale Basin basinal fluids responsible for precipitating saddle dolomite cement in the Swan Hills Formation, Leduc Formation and Wabamun Group were controlled by faults originating in the Precambrian Basement, Basal Cambrian Sandstone and Elk Point Group. The Wabamun Group in the Peace River Arch area was also dolomitized along faults, with fluids sourced from the Granite Wash and fluids that interacted with the Precambrian basement. The presence of co-occurring authigenic quartz and albite in the West Shale Basin and Peace River Arch areas is consistent with these interpretations, suggesting that fluids migrated through clastic aquifers prior to dolomitization.

Conversely, the absence of these phases in the Leduc Formation of the East Shale Basin suggests that dolomitizing fluids only interacted with carbonate strata. Regional-scale fluid flow along the Cooking Lake Platform resulted in dolomitization, with these fluids supplemented by brines that used faults as fluid conduits, likely originating in the underlying Keg River Formation. This is corroborated by the presence of modern Li-enriched formation fluids in the Leduc Formation.

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DATA AVAILABILITY STATEMENT

The authors declare no conflict of interest and the data that support the findings of this study are provided in the supplementary material.

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REFERENCES

Al-Aasm, I. (2003). Origin and characterization of hydrothermal dolomite in the Western Canada Sedimentary Basin. Journal of Geochemical Exploration, 78, 9–15. https://doi.org/10.1016/S0375-6742(03)00089-X
Al-Aasm, I., & Raymus, S. (2007). Petrologic and geochemical evidence for refluxing brines in the Devonian Wabamun Group, West-Central Alberta. In Proceedings of American Association of Petroleum Geologists Annual Meeting, p. 4.
Amthor, J. E., Mountjoy, E. W., & Machel, H. G. (1993). Subsurface dolomites in Upper Devonian Leduc Formation buildups, central part of Rimbey-Meadowbrook reef trend, Alberta, Canada. Bulletin of Canadian Petroleum Geology, 41(2), 164–185.
Bachu, S. (1995). Synthesis and model of formation-water flow, Alberta Basin, Canada. AAPG Bulletin, 79(8), 1159–1178. https://doi.org/10.1306/8d2b2209-171e-11d7-8645000102c1865d
Banner, J. L., Hanson, G. N., & Meyers, W. J. (1988). Rare earth element and Nd isotopic variations in regionally extensive dolomites from the Burlington-Kokuk Formation (Mississippian); implications for REE mobility during carbonate diagenesis. Journal of Sedimentary
Edwards, D. J., & Brown, R. J. (1999). Understanding the influence of Precambrian crystalline basement on Upper Devonian carbonates in central Alberta from a geophysical perspective. *Bulletin of Canadian Petroleum Geology, 47*(4), 412–438.

Flügel, E. (2013). *Microfacies of carbonate rocks: Analysis, interpretation and application*, New York, NY: Springer Science & Business Media.

Gabellone, T., & Whitaker, F. (2016). Secular variations in seawater chemistry controlling dolomitization in shallow reflux systems: Insights from reactive transport modelling. *Sedimentology, 63*(5), 1233–1259. https://doi.org/10.1111/sed.12259

Goldstein, R. H. (2001). Fluid inclusions in sedimentary and diagenetic systems. *Lithos, 55*(1–4), 159–193. https://doi.org/10.1016/S0040-4103(00)00044-X

Green, D. (1999). *Dolomitization and burial diagenesis of the Devonian of west-central Alberta deep basin*, (Doctoral dissertation), McGill University, Montreal, Canada.

Green, D. G., & Mountjoy, E. W. (2005). Fault and conduit controlled burial dolomitization of the Devonian west-central Alberta Deep Basin. *Bulletin of Canadian Petroleum Geology, 53*(2), 101–129. https://doi.org/10.2113/53.2.101

Halbertsma, H. L., Mossop, G. D., & Shetsen, I. (1994). Devonian Wabamun Group of the western Canada Sedimentary Basin. *Geological Atlas of the Western Canada Sedimentary Basin, 4*, 203–220.

Haley, B. A., Klinkhammer, G. P., & McManus, J. (2004). Rare earth elements in pore waters of marine sediments. *Geochimica Et Cosmochimica Acta, 68*(6), 1265–1279. https://doi.org/10.1016/j.gca.2003.09.012

Halim-Dihardja, M. K., & Mountjoy, E. W. (1988). A stromatoporoid patch reef in the Upper Devonian Wabamun Group, Normandville Field, north-central Alberta. *CSPG Special Publications, Reef: Canada and Adjacent Areas – Memoir 13, 1988, 448–453.

Hauck, T. E., Corlett, H. J., Grobe, M., Walton, E. L., & Sansjofre, P. (2018). Meteoric diagenesis and dedolomite fabrics in precursor primary dolomictite in a mixed carbonate–evaporite system. *Sedimentology, 65*(6), 1827–1858. https://doi.org/10.1111/sed.12448

Hauck, T. E., Panâ, D., & DuFrane, S. A. (2017). Northern Laurentian provenance for Famennian clastics of the Jasper basin (Alberta, Canada): A Sm-Nd and U-Pb detrital zircon study. *Geosphere, 13*(3), 1149–1172. https://doi.org/10.1130/GEOS1453.1

Henderson, C. M., & Barclay, J. E. (1994). Permian strata of the Western Canada Sedimentary Basin. *Geological Atlas of the Western Canada Sedimentary Basin, 15*, 251–258.

Hoffman, P. F. (1987). Continental transform tectonics: Great Slave Lake shear zone (ca. 1.9 Ga), northwest Canada. *Geology, 15*(9), 785–788. https://doi.org/10.1130/0091-7613(1987)15<785:cttgf>2.0.co;2

Hollis, C., Bastesk, E., Boyce, A., Corlett, H., Gawthorpe, R., Hirani, J., … Whitaker, F. (2017). Fault-controlled dolomitization in a rift basin. *Geology, 45*(3), 219–222. https://doi.org/10.1130/G38394.1

Horita, J. (2014). Oxygen and carbon isotope fractionation in the system dolomite–water–CO₂ to elevated temperatures. *Geochimica Et Cosmochimica Acta, 129*, 111–124. https://doi.org/10.1016/j.gca.2013.12.027

Huff, G. F. (2019). Origin and Li-enrichment of selected oilfield brines in the Alberta Basin, Canada; Alberta Geological Survey/Alberta Energy Regulator, AER/AGS Open File Report 2019-01, 29 p.
Basin, Western Australia: Confirmation of a seawater REE proxy in ancient limestones. *Geochimica Et Cosmochimica Acta*, 68(2), 263–283. https://doi.org/10.1016/S0016-7037(03)00422-8

Oldale, H. S., Munday, R. J., & Ma, K. (1994). Devonian Beaverhill Lake Group of the western Canada Sedimentary Basin. In G. M. Ross & R. A. Stephenson (Eds.), *Geological Atlas of the Western Canada Sedimentary Basin* (Vol. 4). Calgary, AB: Canadian Society of Petroleum Geologists and Alberta Research Council.

Packard, J. J., Al-Aasm, I., Samson, I., Berger, Z., & Davies, J. (2001). A Devonian hydrothermal chert reservoir: The 225 bcf Parkland field, British Columbia, Canada. *AAPG Bulletin*, 85(1), 51–84. https://doi.org/10.1306/8626C75D-173B-11D7-8645000102C165D

Packard, J. J., & Hills, D. (2001). The Importance of Early (Penecontemporaneous) Meteoroic Diagenesis in the Development of Limestone Porosity in the “Platform” of the Devonian Swan Hills Formation. Abstracts (extended) of Technical Talks, Posters and Core Displays: The CSPG Annual convention, 2001, 530–556.

Pana, D., Waters, J., & Grobe, M. (2001). GIS compilation of structural elements in northern Alberta. *Alberta Geological Survey. Earth Sciences Report*, 1, 53.

Phan, T. T., Hakala, J. A., Lopano, C. L., & Sharma, S. (2019). Rare earth elements and radiogenic strontium isotopes in carbonate minerals reveal diageneric influence in shales and limestones in the Appalachian Basin. *Chemical Geology*, 509, 194–212. https://doi.org/10.1016/j.chemgeo.2019.01.018

Popp, B. N., Anderson, T. F., & Sandberg, P. A. (1986). Brachiopods as indicators of original isotopic compositions in some Paleozoic limestones. *Geological Society of America Bulletin*, 97(10), 1262–1269. https://doi.org/10.1130/0016-7606(1986)97<1262:BAIOIC>2.0.CO;2

Potma, K., Weissenberger, J. A., Wong, P. K., & Gilhooly, M. G. (2001). Toward a sequence stratigraphic framework for the Frasnian of the Western Canada Basin. *Bulletin of Canadian Petroleum Geology*, 49(1), 37–85. https://doi.org/10.2113/49.1.37

Price, R. A. (1990). Cordilleran tectonics and the evolution of the Western Canada Sedimentary Basin. *Bulletin of Canadian Petroleum Geology*, 38(1), 176–177.

Prokopf, A., Shields, G. A., & Veizer, J. (2008). Compilation and time-series analysis of a marine carbonate δ18O, δ13C, 87Sr/86Sr and δ34S database through Earth history. *Earth-Science Reviews*, 87(3–4), 113–133. https://doi.org/10.1016/j.earscirev.2007.12.003

Root, K. G. (1987). *Geology of the Delphine Creek area, southeastern British Columbia: implications for the Proterozoic and Paleozoic development of the Cordilleran Divergent Margin*. (Unpublished doctoral thesis), Calgary, AB: University of Calgary. https://doi.org/10.11575/PRISM/19492

Ross, G. M., Broome, J., & Miles, W. (1994). Potential fields and basement structure—Western Canada Sedimentary Basin. In geological atlas of the Western Canada Sedimentary Basin. Canadian society of petroleum geologists and Alberta research council, special report, 4.

Ross, G. M., & Eaton, D. W. (1999). Basement reactivation in the Alberta Basin: Observational constraints and mechanical rationale. *Bulletin of Canadian Petroleum Geology*, 47(4), 391–411. https://doi.org/10.2113/49.3.429

Ross, G., & Stephenson, R. A. (1989). Crystalline basement: the foundations of Western Canada Sedimentary Basin. *Western Canada Sedimentary Basin: A Case History, 1989*. 33–45.

Saller, A. H., & Yaremko, K. (1994). Dolomitization and porosity development in the middle and upper Wabamun Group, southeast Peace River arch, Alberta. *Canada. AAPG Bulletin*, 78(9), 1406–1430. https://doi.org/10.1306/A25FECBB-171B-11D7-86450000102C1865D

Schultz, R., Corlett, H., Haug, K., Kocon, K., Maccormack, K., Stern, V., & Shipman, T. (2016). Linking fossil reefs with earthquakes: Geologic insight to where induced seismicity occurs in Alberta. *Geophysical Research Letters*, 43(6), 2534–2542. https://doi.org/10.1002/2015GL067514

Shawa, M. S. (1969). Sedimentary history of the Gilwood Sandstone (Devonian) Utikuma Lake Area, Alberta. *Canada. Bulletin of Canadian Petroleum Geology*, 17(4), 392–409.

Sibley, D. F., & Gregg, J. M. (1987). Classification of dolomite rock textures. *Journal of Sedimentary Research*, 57(6), 967–975. https://doi.org/10.2110/12FSCBA-2B24-11D7-8648000102C1865D

Spencer, R. J. (1987). Origin of CaCl brines in Devonian formations, Western Canada Sedimentary Basin. *Applied Geochemistry*, 2(4), 373–384. https://doi.org/10.1016/0883-2927(87)90022-9

Spötl, C., Longstaffe, F. J., Ramseyer, K., & Rüdinger, B. (1999). Authigenic albite in carbonate rocks—a tracer for deep-burial brine migration? *Sedimentology*, 46(4), 649–666. https://doi.org/10.1046/j.1365-3091.1999.00237.x

Stearns, N. D., Stearns, H. T., & Waring, G. A. (1935). Thermal springs in the United States. United States Geological Survey, *Water Supply Paper*, 679-B, 59–191. https://doi.org/10.3133/wsp679B

Sun, S. Q. (1994). A reappraisal of dolomite abundance and occurrence in the Phanerozoic. *Journal of Sedimentary Research*, 64(2a), 396–404. https://doi.org/10.1306/D4267DB1-2B26-11D7-8648000102C1865D

Switzer, S. B., Holland, W. G., Christie, D. S., Graf, G. C., Hedinger, A. S., McAuley, R. J. …Shetsen, I. (1994). Devonian Woodbend-Winterburn strata of the Western Canada sedimentary basin. *Geological Atlas of the Western Canada Sedimentary Basin: Canadian Society of Petroleum Geologists and Alberta Research Council*, 165-202.

Taylor, S. R., & McLennan, S. M. (1985). The continental crust: its composition and evolution (book). United States.

Tostevin, R., Shields, G. A., Tarbuck, G. M., He, T., Clarkson, M. O., & Wood, R. A. (2016). Effective use of cerium anomalies as a redox proxy in carbonate-dominated marine settings. *Chemical Geology*, 438, 146–162. https://doi.org/10.1016/j.chemgeo.2016.06.027

Viau, C. (1987). The swan Hills formation and the Beaverhill Lake Group at swan Hills field and adjacent areas, central Alberta, Canada. Devonian Lithofacies and Reservoir Styles in Alberta: 13th CSPG Core Conference and Display, 1987. 201–239.

Walls, R., & Burrowes, G. (1985). The role of cementation in the diagenetic history of Devonian reefs, Western Canada. *SEPM Special Publication - Carbonate Cements*, 36, 185–220.

Warren, J. (2000). Dolomite: Occurrence, evolution and economically important associations. *Earth-Science Reviews*, 52(1–3), 1–81. https://doi.org/10.1016/S0012-8252(00)00022-2

Webb, G. E., & Kamber, B. S. (2000). Rare earth elements in Holocene reefal microbialites: A new shallow seawater proxy. *Geochimica Et Cosmochimica Acta*, 64(9), 1557–1565. https://doi.org/10.1016/S0012-8252(00)00040-7

Webb, G. E., Nothdurft, L. D., Kamber, B. S., Kloprogge, J. T., & Zhao, J. X. (2009). Rare earth element geochemistry of scleractinian coral skeleton during meteoric diagenesis: A sequence through neomorphism of aragonite to calcite. *Sedimentology*, 56(5), 1433–1463. https://doi.org/10.1111/j.1365-3091.2008.01041.x

Wendte, J. C. (1994). Cooking Lake platform evolution and its control on Late Devonian Leduc reef inception and localization, Redwater, Alberta. *Bulletin of Canadian Petroleum Geology*, 42(4), 499–528. https://doi.org/10.2110/scn.92.28.0041
Wendte, J., Stoakes, F. A., & Campbell, C. V. (1992). Cyclicity of Devonian strata in the Western Canada Sedimentary Basin. In J. Wendte (Ed.), Devonian-Early Mississippian Carbonates of the Western Canada Sedimentary Basin: A sequence stratigraphic framework (pp. 25–40). Broken Arrow, OK: Society of Economic Paleontologists and Mineralogists, Short Course no. 28.

Wendte, J., & Uyeno, T. (2005). Sequence stratigraphy and evolution of Middle to Upper Devonian Beaverhill Lake strata, south-central Alberta. *Bulletin of Canadian Petroleum Geology*, 53(3), 250–354. https://doi.org/10.2113/53.3.250

Whitaker, F. F., & Xiao, Y. (2010). Reactive transport modeling of early burial dolomitization of carbonate platforms by geothermal convection. *AAPG Bulletin*, 94(6), 889–917. https://doi.org/10.1306/12090909075

White, D. E. (1957). Thermal waters of volcanic origin. *Geological Society of America Bulletin*, 68(12), 1637–1658. https://doi.org/10.1130/0016-7606(1957)68[1637:TWVOV]2.0.CO;2

Wright, G. N., McMechan, M. E., Potter, D. E. G., Mossop, G. D., & Shetsen, I. (1994). Structure and architecture of the Western Canada sedimentary basin. *Geological Atlas of the Western Canada Sedimentary Basin*, 4, 25–40.

Zhang, H., Eaton, D. W., Li, G., Liu, Y., & Harrington, R. M. (2016). Discriminating induced seismicity from natural earthquakes using moment tensors and source spectra. *Journal of Geophysical Research: Solid Earth*, 121(2), 972–993. https://doi.org/10.1002/2015JB012603

**SUPPORTING INFORMATION**

Additional Supporting Information may be found online in the Supporting Information section.

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