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Title: Challenges of structural diagenesis in foreland fold-and-thrust belts: a case study on paleofluid flow in the Canadian Rocky Mountains West of Calgary

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Abstract: Foreland fold-and-thrust belts are challenging because their structural complexity highly impacts fluid flow and diagenetic processes. By applying a structural diagenetic approach paleofluid flow in the Rocky Mountain fold-and-thrust belt west of Calgary is investigated. Using vein morphology (completely filled, en echelon, slickenfibres, bed-parallel, open or micro-breccia veins), vein orientation and geochemistry (stable oxygen and carbon isotope and strontium isotopes) paleofluid flow or mass transfer mechanisms are inferred. Cement in (i) bed-parallel veins, that probably developed by flexural slip during Laramide folding, and in (ii) most completely filled and slickenfibre veins, that formed or were reactivated during Laramide compression, precipitated under low fluid flux conditions, dominated by diffusional processes as inferred from their host rock similar stable isotopic signature. The open veins with meteoric calcite cement, marked by cathodoluminescence zonations and strongly depleted oxygen isotopic signature, point to advective fluid flow processes in a post-Laramide extensional stress field. Some slickenfibre and completely filled veins that originally formed during Laramide compression were probably reactivated during open vein formation, based on the occurrence of the same open vein cements in the center of the slickenfibre and completely filled veins. In conclusion, there is no evidence for large-scale fluid flow during the Laramide Orogeny, but post-Laramide large-scale fluid advection was prevalent. Challenges in this structural diagenetic study consist of (i) the lack of abundant vein-vein and vein-stylolite cross-cutting relationships in the outcrops studied, (ii) the difference between structural versus diagenetic concepts, (iii) the uncertainty of chronology and attribution of fracture sets and diagenetic cements to either a single or discrete episodes, and (iv) reactivation of veins.

Highlights

We analyse different vein types using a structural diagenetic approach.

We reconstruct the fluid flow evolution in the Canadian Rocky Mountains study area.

The bed-parallel veins and most completely filled and slickenfibres veins are related to low fluid flux during the Laramide Orogeny.

Open veins are associated with post-Laramide large scale meteoric fluid advection.

Challenges of structural diagenesis in foreland fold-and-thrust
belts: a case study on paleofluid flow in the Canadian Rocky
Mountains West of Calgary

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ABSTRACT

Foreland fold-and-thrust belts are challenging because their structural complexity highly impacts fluid flow and diagenetic processes. Paleofluid flow in the Rocky Mountain fold-and-thrust belt west of Calgary was investigated following a structural diagenetic approach. Paleofluid flow or mass transfer mechanisms have been inferred based on vein morphology (completely filled, en echelon, slickenfibres, bed-parallel, open or micro-breccia veins), orientation and geochemistry (stable oxygen and carbon isotope and strontium isotopes). Bed-parallel veins probably developed by flexural slip during Laramide folding, and most completely filled and slickenfibre veins formed or were reactivated during the Laramide Orogeny. Both types of veins associated with the Laramide Orogeny precipitated under low fluid flux conditions, dominated by diffusional processes as inferred from stable isotopic signatures similar to the host rock. The open veins with meteoric calcite cement, marked by cathodoluminescence zonations and strongly depleted oxygen isotopic signature, point to advective fluid flow processes in a post-Laramide extensional stress field. Some slickenfibre and completely filled veins that originally formed during the compressional phase of the Laramide Orogeny were probably reactivated at time of the open vein formation. The latter inference is based on the occurrence of the same cement in the open veins as in the center of the slickenfibre and completely filled veins. In conclusion, there is no evidence for large-scale fluid flow during the Laramide Orogeny, but evidence points to post-Laramide large-scale fluid advection being prevalent. Challenges in this structural diagenetic study consist of (i) the lack of abundant vein-vein and vein-stylolite cross-cutting relationships in the outcrops studied, (ii) the difference between structural versus diagenetic concepts, (iii) the uncertainty of chronology and attribution of fracture sets and diagenetic cements to either a single or discrete episodes, and (iv) reactivation of veins.

Keywords:

Canada; diagenesis; fracture; stable isotopes; thrust; vein

1. Introduction

Foreland fold-and-thrust belts are challenging target areas in hydrocarbon and mineral exploration due to their structural complexity and heterogeneous distribution of reservoir properties. Reservoir properties are strongly influenced by diagenetic processes, such as cementation, fracturing and/or secondary porosity development. The complexly deformed fold-and-thrust belts are commonly compartmentalized as a result of structures and heterogeneous distribution of cement (e.g. Breesch et al., 2009; Vilasi et al., 2009). Reservoir heterogeneity and compartmentalization are key factors in predictions for hydrocarbon exploration and production. Therefore, studies are needed that provide insight in the fluid flow history of the area by reconstructing (i) changes in the volume and composition of fluid along fractures and through the matrix and (2) changes in reservoir porosity and permeability through the geological history of the reservoirs. In a second step, the resulting structural diagenetic framework can be tied to hydrocarbon migration. Regional scale fluid flow in orogenic belts is driven generally by two processes. First, gradients in hydraulic head drive fluid flow over large (up to basin-scale) distances and are caused by topography (Bethke and Marshak, 1990; Garven, 1995). Fluids in this system generally have a chemical signature related to meteoric water. Second, fluid overpressure during tectonic compression can lead to fluid expulsion in the 'squeegee' model of Oliver (1986). Besides the regional driving factors, fluid flow is also controlled on a smaller scale by anisotropic permeability in the rocks and by faults. The effect of faults on fluid flow is ambiguous, since fault zones act as either preferential fluid pathways or seals (Knipe, 1993; Travé et al., 2000). Most previous studies

focus on cross-fault flow. Still, fault-parallel flow or fault-controlled diagenesis is not uncommon and results in modifications of fault properties (e.g. Travé et al., 2000).

This paper presents the results of a structural diagenetic study aimed at reconstructing processes at different scales in the Rocky Mountains Foreland Belt west of Calgary, Canada. The paleostress evolution derived from striated fault slip data in the sites studied is reported in Vandeginste et al. (2012) and the current paper elaborates mainly on the diagenetic vein infillings. Structural diagenesis, which is a cross-disciplinary approach linking deformation and diagenesis in the low-temperature realm of sedimentary basins, is novel and has a high potential to unlock new scientific knowledge (e.g. Laubach et al., 2010). Structures reveal information on the evolving deformation of the fold-and-thrust belt. Petrography and geochemistry (stable carbon, oxygen isotopes and strontium isotopes) of the infilling cements provide information on the material transfer mechanisms (diffusion or advection) as well as the fluid type that formed the cements and, hence, paleofluid flow. Cross-cutting relationships are indications for relative chronology. Combining a structural analysis with petrography and geochemistry on diagenetic cements is thus powerful and helps to better understand the changes in reservoir petrophysical properties with development or destruction of matrix and fracture permeabilities through time. More insight in the structural diagenetic framework and interpreted fluid flow history leads to better predictions of hydrocarbon prospects. In this paper we take a structural diagenetic approach to reconstruct the paleofluid flow evolution in the study area and we point out which aspects in our approach can be challenging in fold-and-thrust belts.

2. Geological setting

The foreland fold-and-thrust belt (FFTB) investigated in this study is the easternmost part of the Canadian Cordilleran Orogen (Fig. 1) which developed at the western rim of North

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95 America as a result of convergent plate motions. The FFTB is a northeast-tapering
96 accretionary wedge consisting of deformed sedimentary strata that were scraped off from the
97 underriding North American craton and accreted to the overriding intermontane terrane during
98 Jurassic to Paleogene convergence (Monger and Price, 1979; Price, 1981; Price, 1994).

99 The FFTB in Southern Canada consists of four physiographic-tectonic zones: the
100 Western Ranges, Main Ranges, Front Ranges and Foothills, from west to east respectively
101 (Fig. 1, 2). The distinction between different zones is based on a combination of stratigraphic
102 composition, structural style, erosional level and physiography (Douglas, 1970; Dahlstrom,
103 1970; Osborn et al., 2006). The Lower Paleozoic transition from carbonate platform to basin
104 in the eastern Main Ranges coincides with a difference in deformation style. The Cambrian-
105 Ordovician deep-water shales and argillaceous limestones are characterized by cleavage
106 development and folding. In contrast, the coeval strata to the east are composed of massive,
107 less internally deformed thrust sheets of thick shallow-water layers. The Simpson Pass thrust
108 fault separates the Main Ranges from the Front Ranges. The Front Ranges comprise west-
109 dipping thrust sheets of competent Paleozoic carbonate rocks overlain by a thin Permo-
110 Triassic succession, in turn overlain by Jurassic and younger siliciclastic rocks. The
111 McConnell thrust fault represents the border with the Foothills, marked by many imbricate
112 thrust faults developed mainly in the Mesozoic and Tertiary siliciclastic succession (Fig. 2).

113 The structure of the accretionary wedge is dominated by northeasterly verging flat-
114 ramp thrust faults. The latter generally follow long bedding parallel detachments linked by
115 ramps and merge downward into a basal detachment that converges with the contact between
116 the sedimentary cover and the underlying crystalline basement (Bally et al., 1966). The
117 westward dipping basal detachment extends into the Cordilleran metamorphic core where it
118 becomes ductile at mid-crustal levels (Price and Fermor, 1985).

Vein (i.e. cemented fracture) and host rock samples were collected at 16 sites, most of them in the Front Ranges, a few in the Foothills and a few in the Main Ranges (Table 1). Since the FFTB is heavily deformed and contains many thrust faults, each site was selected only a few hundreds of meters up to a few kilometers away from a major thrust fault.

3. Methodology

The sites studied were selected mainly along the Trans-Canada Highway N°1, since this highway provides a transect through the FFTB with accessible outcrops. Each site is about 200 to 400 m long. Veins with macroscopically visible infilling (preferentially cross-cutting veins or vein-stylolite contacts) were sampled by hammer or rock drill where feasible. Vein length was not measured and sampling of veins was not restricted to only bed-confined veins or veins of similar length. The authors recognize that some sites may not be located in the most representative area of the thrust sheets in terms of structures. Sites 1 and 2 are located on the Moose Mountain dome which is a doubly-plunging antiformal stack of thrust sheets bounded by lateral (transverse to regional strike) ramps in the underlying thrust fault (McMechan, 1993; Feinstein et al., 1999). The Moose Mountain dome area was also studied by Feinstein et al. (1999) to derive the deformation history. Site 13 is close to reactivated Cambrian normal faults (Price, 1994). Most sites lie above basement gravity and magnetic anomalies that are related to basement-tectonic elements that controlled Paleozoic sediment accommodation and accumulation (Brandley et al., 1996), and some of the sites are close to transverse fractures that were intermittently reactivated, affecting Paleozoic (Spratt et al., 2004) and Lower Cretaceous deposition (McLean, 1977). Despite the complexity of some sites, the results in this study do show the variety of structures that are expected and formerly reported in the Canadian Rocky Mountains.

Alizarin Red S and potassium ferricyanide were used to stain finely polished and etched slabs and thin sections in order to distinguish calcite and dolomite and their ferroan equivalents. Thin sections were examined by microscopic techniques including cathodoluminescence (CL). For CL analysis, unstained sections were studied, using a cold cathode luminescope with a beam voltage of 17 kV and a current of 600 μ A.

Stable carbon and oxygen isotopic compositions were analysed in samples of carbonate-infilled veins (sample taken over the whole vein width) as well as host rocks. A few milligrams of sample were drilled with a microdrill and subsequently analysed at the University of Erlangen (Germany). Carbonate powders were reacted with 100% phosphoric acid (density >1.9 g/cm³, Wachter and Hayes, 1985) at 75°C in a carbonate preparation line (Carbo-Kiel - single sample acid bath) connected to a Finnigan Mat 252 mass spectrometer. All values are reported in per mil relative to VPDB by assigning a $\delta^{13}\text{C}$ value of +1.95‰ and a $\delta^{18}\text{O}$ value of -2.20‰ to NBS19. The oxygen isotopic composition of dolomite was corrected using the fractionation factors given by Rosenbaum and Sheppard (1986). Reproducibility was checked by replicate analysis of laboratory standards and was better than ± 0.03 ‰ for $\delta^{13}\text{C}$ (1σ) and ± 0.04 ‰ for $\delta^{18}\text{O}$ (1σ) during this study.

Sr isotope analyses were carried out at SUERC (Scottish Universities Environmental Research Centre, East Kilbride, Scotland). Carbonate samples were leached in 1N NH_4Ac prior to acid digestion with 2.5M HCl. Sr was separated in 2.5M HCl using Bio-Rad AG50W X8 200-400 mesh cation exchange resin. Total procedure blank for Sr samples prepared using this method was < 200 pg. In preparation for mass spectrometry, Sr samples were loaded onto single Ta filaments with 1N phosphoric acid. Sr samples were analysed with a VG Sector 54-30 multiple collector mass spectrometer. A ^{88}Sr intensity of 1V ($1 \times 10^{-11}\text{A}$) $\pm 10\%$ was maintained. $^{87}\text{Sr}/^{86}\text{Sr}$ ratio was corrected for mass fractionation using $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and an exponential law. The mass spectrometer was operated in the peak-jumping mode with

data collected as 15 blocks of 10 ratios. For this instrument NBS 981 was 0.710263 ± 0.000010 (1σ , $n = 16$) during the course of this study. The 2 standard error internal precision on individual analyses was between 0.000014 and 0.000020 for 2σ .

4. Vein classification

The 240 veins sampled were separated in groups based on macroscopic vein morphology and microscopic vein characteristics (and based on Passchier and Trouw, 2005), not the measured fracture orientation. Six vein types were distinguished: completely filled veins, en echelon veins, slickenfibres veins, bed-parallel (slickenfibre) veins, micro-breccia veins and open (or partially open) veins (see examples in section 6 and Figs.4-9). In addition, diagenetic cements that occur on transverse stylolite surfaces make up a seventh sample type. Veins are created by precipitation of material from solution in an aqueous fluid during or after local dilatation in the host rock (Passchier and Trouw, 2005). The group of completely filled veins are veins that do not show any of the characteristics of the other groups of veins (such as presence of slickenfibres or en echelon arrays of veins). The completely filled veins are generally formed by crack opening highly oblique to the vein wall. En echelon veins are en echelon sets of veins that develop in brittle fault zones and some ductile shear zones. Slickenfibre veins are recognized by fibres or elongate crystals that have grown at a small angle to the vein wall. Bed-parallel (slickenfibre) veins are slickenfibre veins that are parallel to layering in sedimentary rocks. This type of vein can form by fault motion or flexural (bedding-parallel) slip due to thrusting or folding. Micro-breccia veins defined in this study are veins that are marked by small (up to 3 mm) host rock fragments that are cemented together. The group of open (or partially open) veins consists of veins that are only partially filled with diagenetic cement, and are thus still open and display well-formed crystal outlines. Stylolites are pressure solution features marked by a highly indented surface. There are

generally two types of stylolites, namely (i) bedding parallel stylolites which develop due to burial compaction and vertical shortening, and (ii) transverse stylolites which are generated when the main shortening axis is different than vertical (usually horizontal) and thus relates to tectonic shortening. Stylolite surfaces concentrate non-soluble phases during their formation. These discontinuity surfaces can be re-opened and cemented during later (tectonic) stress especially if the main shortening axis is parallel to the stylolite plane.

5. Structural analysis

Structural data for veins collected at the sites studied as well as the orientation of bedding planes, bedding parallel stylolites and transverse stylolites are shown on stereoplots in Figure 3. The bedding has a similar strike (N145) at most sites, but N170 strike at sites 1 and 12. The dip of the bedding planes varies more among the different sites, but there is a rough trend of shallower dip to the SSW in the Foothills (sites 1 and 2) and steeper in the Front Ranges (sites 3 till 12). The layers dip to the NNE at sites 13 and 14 in the Main Ranges. A few transverse stylolites were measured at sites 1 and 8 and most of them have a N090 strike, which deviates from the tectonic stylolite orientation expected to develop during NE-SW compression associated with the Laramide Orogeny. Since sites 1 and 8 lie above structurally complex oblique thrust ramps in underlying fault surfaces, the transverse stylolites are likely caused by localized transpression related to pre-existing structures.

The stereoplots on Figure 3 show a wide range in vein orientations. However, some general trends are evident. Bed-parallel veins occur at all but one site in the Front and Main Ranges. Some completely filled and slickenfibred veins in the Foothills and Front Ranges strike N040 to N070 (roughly perpendicular to the bedding strike) and dip 65° or more. In site 12, the open veins strike N060 to N090. In sites 13 and 14 in the Main Ranges, veins of a

N040 to N090 strike are rare. Most veins (mainly completely filled veins) strike N020 or N160.

6. Vein morphology and microscopy

6.1. Completely filled veins

Completely filled veins are present in nearly all the studied sites. These veins are generally straight, some have a few branches and they have a mean vein width of 3 mm (range of 1 to 6 mm, with one outlier of 11 mm). Thin section analysis indicates that most completely filled veins are actually composite veins of several fracture and infilling generations (Fig. 4A-D) or are characterized by randomly distributed microspar between blocky calcite crystals with large cleavage twins (Fig. 4C-D). Some composite veins contain transparent cement (lacking cleavage twins) in the center of the vein (Fig. 4A-B). Some tension veins contain bands of calcite microspar, quartz microspar or host rock inclusions that are parallel to the vein wall (Fig. 4E-F). The veins consist generally of calcite, but some contain ferroan calcite, calcite and minor amounts of quartz, dolomite (Fig. 4A-B) or fluorite (Fig. 4G-H). Under CL, the calcite cements are non luminescent to dull dark reddish brown or dull yellowish brown (Fig. 4B, D, F), whereas fluorite has been recognized by its light blue color (Fig. 4H). Dolomite in the tension veins is dull dark red luminescent (Fig. 4B). There is no correlation between the vein width and mineral infill; the veins containing fluorite, dolomite or quartz as well as calcite are 2 to 5 mm wide.

6.2. En echelon veins

En echelon arranged veins were observed and sampled in sites 2, 8-11 and 13. Most of these veins have a lensoid shape with maximum vein width (variable among veins) of 10 to 30 mm and are composed of calcite. Only in site 13 (Field, where part of the host rock is

dolomitized) are the en echelon veins composed of both dolomite and calcite (Fig. 5). The dolomite crystals color is light brownish in thin section (Fig. 5C) and the crystals display sweeping extinction under crossed polarized light. The dolomite crystals are partially replaced by calcite, as evidenced by the corrosive contact where calcite penetrates along dolomite crystal rims. The calcite consists mainly of elongate blocky crystals of 100 to 500 μm long that are characterized by both thick straight and bent cleavage twin planes that cross-cut each others, and kink deformation bands. Bands of microcrystalline to microsparitic crystals were also observed. Calcite has a dull yellowish brown colour under CL, whereas dolomite in the veins is either not luminescent or dull dark brown luminescent (Fig. 5D).

6.3. *Slickenfibre veins*

Slickenfibre veins have been observed and sampled at all sites. The mineral precipitated as slickenfibres is intimately related to the host rock, i.e. dolomite slickenfibres in dolostone, calcite in limestone and calcite and quartz in chert-bearing limestone. In thin section, we observe that the slickenfibre veins are commonly composite veins with different cement generations. Dolomite in the slickenfibre veins is characterized by sweeping extinction under crossed polarized light. Calcite occurs as blocky, elongate blocky or lensoid crystals of up to 2 mm. The crystals have thick bent cleavage twin planes cross-cutting each others (Fig. 6A). In a few samples (mainly in site 3), more transparent zones with few thin twin cleavage planes are present between darker more intensely twinned calcites in (composite) slickenfibre veins. The more transparent calcite zones, in contrast to the intensely twinned dull dark reddish brown luminescent calcites (Fig. 6B), are darker reddish luminescent and part of them display minor zonations. Quartz in the slickenfibre veins is marked by undulose extinction under crossed polarized light and subgrain formation.

6.4. *Bed-parallel veins*

Bed-parallel veins are present in most of the studied localities (sites 3, 5, 8-14). The veins are straight or slightly wavy and generally slightly thicker than the veins described above, i.e. an average of about 20 mm and up to 60 mm. At site 14 (Kicking Horse Mine), the dolomitic bed-parallel veins have an irregular outline with pinch-and-swell-like variable width of 1 to 3 mm. Under the microscope, most bed-parallel veins consist of twinned blocky, or occasionally elongated, calcite crystals (some are rich in Fe based on the purple color after staining). Some veins also contain dolomite (Fig. 7A-D). A small amount of microspar grains occur randomly dispersed in the veins, and what appears to be crushed material is observed between larger crystals in a few samples. In two samples, fine crystalline quartz is present in bands parallel to the vein wall (both near the vein wall and closer to the vein center). Also some fluorite has been observed in thick (50 to 60 mm) veins (Fig. 7C-D). Two sets of thick cleavage twin planes, bent cleavage twins and deformation kink bands have been observed in the calcite crystals of a few bed-parallel veins. The bed-parallel veins are generally non-to-dull dark reddish brown luminescent.

6.5. *Micro-breccia veins*

This type of vein is rare; only two samples, both from site 3 (McConnell), belong to this group. The micro-breccia veins are about 20 mm thick and are composed of finely crushed and large fragments of host rock. These fragments are cemented together by large white and grey blocky cleavage-twinned calcite crystals; some crystals are zoned (Fig. 8A). Between large crystals, small (μm scale) calcite crystals are observed. All calcite crystals are dull dark or light yellowish brown luminescent (Fig. 8B).

6.6. *Open (or partially open) veins*

Open, partially cemented veins were collected at six sites (sites 2 and 10-14). They are subordinate, except in site 12 (Sunshine) where most of the sampled veins belong to this type. The veins are on average 2 mm thick (general range of 1 to 4 mm and two outliers of 15 and 20 mm) and have a straight outline. All open veins are partially cemented with calcite; mostly well-formed scalenohedral type crystal outlines face the open centre of the vein. Under the microscope, the vein filling consists of clear transparent blocky calcite crystals of 150 to 600 μm in diameter either with only a few thin twin cleavage planes or none (Fig. 9A). The crystals have a CL colour varying from dull red to non-luminescent to bright reddish luminescent with thin yellow luminescent zones (Fig. 9B).

6.7. Cemented transverse stylolites

Cements in opened transverse stylolites are only collected at site 2 (Moose Mountain North) in the Foothills. The cement layer on these stylolite surfaces is only 3 mm wide. Microscopic observation shows that it is a composite of several generations of cement and it has blocky and elongated crystals (elongated parallel to the main stylolite surface). The cement consists of dolomite bands between calcite crystals with cleavage twins and also some fluorite is present along the stylolite insoluble residue. The calcite is dull orange brown luminescent, dolomite crystals are dull reddish brown luminescent and fluorite has a typical bright blue luminescence.

7. Stable isotope geochemistry

The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ results of vein fill cements and host rock are presented in Figure 10. The plots represent either a single site or a small group of sites given that they are geographically close to each other and that the host rocks consist of the same stratigraphic

layers. Most of the samples are calcitic, but some are dolomitic (mainly in sites 13-14 in the Main Ranges).

For many sites, the stable oxygen and carbon isotopic values for host rocks and part of the veins fall in the wide range expected for the respective stratigraphic layers, i.e. Cambrian ($\delta^{13}\text{C}$: -2 to +1‰ and $\delta^{18}\text{O}$: -10 to -7‰ VPDB) for site 3 and 13-16 and Mississippian ($\delta^{13}\text{C}$: -2 to +7‰ and $\delta^{18}\text{O}$: -9 to 0‰ VPDB) for most other sites (Fig. 10). This is not the case for sites 13-14 in the Main Ranges, where dolomitized host rocks have a $\delta^{18}\text{O}$ signature that is more negative (-17 to -15‰ VPDB) than the Cambrian marine carbonate signature. In most sites in the Front Ranges (sites 3-12), the host rock $\delta^{18}\text{O}$ values lie generally at the high end of the total vein $\delta^{18}\text{O}$ range. However, in sites 8-9 the isotopic results of both host rock and veins fall in the same tight data cluster (mainly $\delta^{13}\text{C}$: 0 to +3‰ and $\delta^{18}\text{O}$: -7 to -3‰ VPDB). The veins in this case are completely filled veins, en echelon veins, slickenfibres veins and bed-parallel veins. Only one slickenfibre vein sample has a significantly more negative $\delta^{18}\text{O}$ value of -23‰ VPDB. In general, $\delta^{18}\text{O}$ values significantly more negative than the host rock signature are measured in cements in some slickenfibre veins, completely filled veins or bed-parallel veins and all open veins ($\delta^{18}\text{O}$ mostly below -22‰ VPDB). In the Main Ranges (sites 13-16), the dolomite host rocks and dolomite veins also have a relatively low $\delta^{18}\text{O}$ value (-20 to -15‰ VPDB). In these sites, we recognize three main groups: (i) the least negative $\delta^{18}\text{O}$ values (-12 to -8‰ VPDB) for the limestone host rock and en echelon veins (and a few completely filled veins), (ii) the more negative $\delta^{18}\text{O}$ signature of -20 to -15‰ VPDB in dolomite host rocks, bed-parallel veins and some completely filled veins, and (iii) the most negative $\delta^{18}\text{O}$ signature (down to -28‰ VPDB) for open veins as well as slickenfibre veins (and one bed-parallel vein). The isotopic signature in most veins is thus influenced by the mineralogy and isotopic signature of the host rock, but there is no correlation with vein width,

since both thin (1 mm) and thick (60 mm) veins reflect the host rock isotopic signature and the most depleted oxygen isotopic values belong to open veins of only 1 to 4 mm width.

A distinct trend of stable isotopic signatures from the Foothills, through the Front Ranges to the Main Ranges has not been observed. However, we note that the Foothills sites 1-2 lack bed-parallel veins and the isotopic signature of the collected veins and host rock at these sites form a cluster. In the Front Ranges, the isotopic data vary widely in sites 3-7 in contrast to the tight cluster of data in sites 8-11. The majority of the veins in site 12 has a strongly depleted $\delta^{18}\text{O}$ signature. Finally, we observe a wide range (see above) in isotopic values in the Main Ranges (sites 13-16), which is partially caused by depleted $\delta^{18}\text{O}$ values in dolomitic veins and open veins (similar to site 12).

8. Strontium isotope geochemistry

A limited number of samples was analysed for Sr isotopic composition (Fig. 11). The data are presented in two plots, one for the Cambrian sites (sites 3 and 13) and one for the other sites, with mainly Lower Carboniferous host rocks (site 2 and 5-12). Based on the host rock age and the seawater $^{87}\text{Sr}/^{86}\text{Sr}$ curve through geological time, it is concluded that the host rock $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is for almost all samples the same as the $^{87}\text{Sr}/^{86}\text{Sr}$ signature of marine water contemporaneous to host rocks deposition (Fig. 11). The veins generally have a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio that is higher than marine seawater or host rock signature, especially in the Cambrian formations in sites 3 and 13. Here, the $^{87}\text{Sr}/^{86}\text{Sr}$ of the vein samples lies either close to or much higher than 0.7120, which is defined by Machel and Cavell (1999) as the MASIRBAS-value (the regional value of Maximum Sr Isotope Ratio of Basinal Shale in the Western Canada Sedimentary Basin). There is no clear correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ in sites 3 and 13 (Fig. 11). However, in the other sites in the Front Ranges, the three vein samples with $^{87}\text{Sr}/^{86}\text{Sr}$ higher than 0.709 have $\delta^{18}\text{O}$ value below -22‰ VPDB; these veins are

either slickenfibres veins or open veins. Two other samples (one slickenfibre vein and one completely filled vein) have a similar depleted $\delta^{18}\text{O}$ signature but have a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio close to or slightly higher than the host rock and comparable to the ratio of the completely filled, slickenfibre and bed-parallel veins with less negative $\delta^{18}\text{O}$ values (Fig. 11).

9. Discussion

9.1. Tectonic context of vein formation

The structural data of most of the veins observed are consistent with vein formation during the regional Laramide tectonic compression. We suggest that the bed-parallel veins are slickenfibre veins resulting from bedding-parallel flexural slip during folding. Bed-parallel veins can also develop by seepage forces in absence of tectonic stresses (Cobbold and Rodrigues, 2007) or by hydraulic fracturing before the onset of tectonic or layer parallel shortening in foreland belts (e.g. Roure et al., 2005). Still, both seepage and hydraulic type of bed-parallel veins generally do not have slickenfibres. It is also possible that some of the bed-parallel veins in our study were created as fractures that opened highly oblique to the vein wall and were later reactivated and used as shear planes with slickenfibre growth.

The second abundant orientation observed in the Front and Main Ranges is the N040 to N070 strike for steep dipping completely filled and slickenfibre veins. These completely filled and slickenfibre veins form a second fracture set during the Laramide compression that is compatible with fracture development associated with folds (Stearns, 1969; Stearns and Friedman, 1972). The composite and cross-cutting veins suggest several vein formation episodes during Laramide compression. The variable dip of the N055 striking veins is likely the result of the complex folding and thrusting during and after fracture/vein formation and the proximity of most sites to transverse faults or changes in fold plunge. Local changes in the

stress field during Laramide compression are recorded in striated fault slip planes (Vandeginste et al., 2012).

In sites 5, 7 and 14, some completely filled veins have a strike similar to that of the bedding planes but have a dip that is about perpendicular to bedding. This vein orientation is consistent with fracture development in the convex part of the Laramide folds.

The most abundant orientation of open, partially calcite cemented fractures in site 12 is similar to the main orientation of the completely filled veins in the other sites in the Front Ranges. However, instead of having developed during Laramide compression, the open veins formed probably in an extensional stress field with the horizontal σ_3 axis perpendicular to the compressive Laramide direction (Vandeginste et al., 2012). The open veins most likely developed more recently during post-Laramide uplift because these veins are steep and still open, and based on vein infill (see below) and on the paleostress interpretations derived from striated fault slip planes (Vandeginste et al., 2012). An alternative explanation for the open veins could be opening of this fracture set by the current NE-SW compressive stress field (Bell et al., 1994).

In summary, we have evidence of both the Laramide compression and a post-Laramide tectonic deformation phase of vein formation based on the types of veins observed. Three sets of veins are related to Laramide compression including folding: (i) steep completely filled veins with strike similar to that of the bedding, (ii) steep N040 to N070 completely filled and slickenfibred veins and (iii) bed-parallel veins. Alternatively, the bed-parallel veins could also have developed as fractures that opened highly oblique to the vein wall and that were later reactivated as slickenfibred veins. The open veins are related to a post-Laramide tectonic deformation phase, probably an extensional stress field or, alternatively, the current compressive stress field.

9.2. Challenge in diagenetic studies and vein chronology

In diagenetic studies, veins are generally separated in groups based on their relative chronological order, which is principally derived from cross-cutting vein-vein and vein-stylolite relationships. Stylolites are generally divided in two groups in tectonically deformed areas: (i) burial stylolites, also called bedding parallel stylolites, which form due to vertical shortening during burial compaction and (ii) tectonic stylolites, also named layer parallel shortening stylolites, which develop generally at the onset of horizontal shortening during tectonic activity (Van Geet et al., 2002) or intraplate stresses (Zoback and Mooney, 2003). Unfortunately, abundant cross-cutting relationships may be lacking, which is the case for this study, at least at the small scale (of vein-vein and vein-stylolite cross-cutting relationships) within the sites. Hence, caution is needed when extrapolating the few observed relative chronologies to whole vein sets. In addition, interpretations from studies based on a structural geological approach are not always in line with those based on a diagenetic approach. For example, stylolites and perpendicular veins can have developed simultaneously under the same stress regime, even though they may crosscut each other. The resulting cross-cutting relationship could be wrongly used as an argument to derive a relative chronology in a diagenetic approach. It is not always evident to which extent fracture sets are the result of discrete episodes and to which extent diagenetic vein infills (cements) result from discrete diagenetic episodes. Hence, structural and diagenetic studies require careful and abundant, but especially consistent cross-cutting relationships in order to not over-interpret the data. An additional challenge relates to the fact that most veins in this study are composite, reactivated veins, which should induce careful data interpretation.

Besides the macroscopic and microscopic differences we used to separate the different vein groups, the presence of cleavage twins in carbonate veins provides information on timing. The cleavage twin texture is related to the degree of deformation (Burkhard, 1993). In

our study, cleavage twins allow a distinction between veins that formed before or during Laramide compression, and those that did not undergo tectonic or burial shortening during post-Laramide time. The majority of the veins sampled has calcite crystals with thick, bent or cross-cutting sets of cleavage twins, which testifies to a high degree of deformation at a temperature of more than 200°C (Burkhard, 1993). Moreover, scattered or clustered microspar in the veins with cleavage twinned crystals is interpreted as subgrain formation during Laramide deformation; subgrain formation is a process more commonly described in quartz veins that is caused by dynamic recrystallization (Passchier and Trouw, 2005). The open veins contain calcite crystals that show no or only thin and few cleavage twins. This fact is compelling evidence that the open veins formed after the Laramide Orogeny.

9.3. Material transfer in veins and its relation to fluid flow

The circulation of fluids in rocks plays an important role in the development of veins, both for transport of material and for fracture opening. When the pore fluid pressure in rocks reaches a critical value, cracks open and minerals are precipitated in them if conditions are favourable (Engelder and Lacazette, 1990). Veins are excellent examples of channelized flow or non-pervasive mass transfer. There are two main processes of material transport in veins, namely advection and diffusion. Advection is the process whereby material is transported towards the dilatation site in an open system along fracture networks, through the pore space, or along grain boundaries (Passchier and Trouw, 2005). Advection is driven by hydraulic gradients caused by pressure differences or convective instabilities within the fluid. This process has the potential of causing changes in the chemical and isotope composition of a vein and its wall rock. Diffusion is the process whereby material deposited in the veins is derived from the surrounding wall rock in a (semi-)closed system by a stationary fluid or through grain boundary or crystal lattices. This process is driven by a gradient in chemical

potential within a rock volume. The scale of diffusional mass transfer is maximum ~ 2 km per million year for diffusion in a free fluid phase, and a few meters or less per million year for grain-boundary or lattice diffusion (McCaig and Knipe, 1990).

The geochemistry of the vein material reflects the mass transfer process dominating vein cementation. Figure 12 shows the deviation of the stable oxygen and carbon isotopic value of the vein cement compared to that of the host rock. A large part of our vein data has an isotopic signature that is close to that of the host rock (Fig. 10). Most of the bed-parallel vein values plot close to host rock values, implying that the calcite slickenfibres making up these veins are derived from nearby host rock by diffusion processes. During tectonic folding, the Front Ranges were a (semi-)closed system with low fluid flux. This interpretation is consistent with the radiogenic Sr isotopic data that show bed-parallel vein values that are dominantly inherited from the host rock signature (Fig. 11).

There is a significant depletion in $\delta^{18}\text{O}$ (up to 22‰ more depleted) in open veins and some slickenfibre as well as completely filled veins. In the discussion above, we argue for a post-deformation origin of the open veins. This interpretation is supported by the depleted $\delta^{18}\text{O}$ signature and by the CL characteristics. The CL zonations (Fig. 9) reflect changes in Fe and/or Mn content, which can relate to changing redox conditions (Machel, 2000). The observed alternation of small non-luminescent and bright yellowish luminescent zones is typical for precipitation from meteoric fluids (e.g. Muchez et al., 1998). A low temperature meteoric water origin is supported by fluid inclusion data reported in Vandeginste (2006), i.e. single-phase nature of fluid inclusions suggesting formation temperature of less than 50°C and final melting temperature of $\approx 0.0^\circ\text{C}$. This result is consistent with the stable oxygen isotopic data of the open vein calcite cements, since a strongly depleted $\delta^{18}\text{O}$ value for meteoric water in the study area is common, e.g. -19.3‰ VSMOW for surface water of Bow River (Hitchon and Friedman, 1969), -20.5‰ VSMOW for hot springs along the Sulphur Mountain Thrust

(Grasby and Hutcheon, 2001). When calcite precipitates from meteoric water with a $\delta^{18}\text{O}$ value of -20‰ VSMOW at 25°C, it has a $\delta^{18}\text{O}$ value of -22‰ VPDB (based on the equation from Friedman and O'Neil, 1977), which is in the range of the values measured (-19 to -28‰ VPDB). The more negative values measured in the calcite cements in site 13 in the Main Ranges either result from precipitation at slightly higher temperature (up to 60°C) or to slightly different meteoric water stable oxygen isotopic composition. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio measured in the open veins are enriched in ^{87}Sr . Since Sr contents of marine carbonates are much higher than the Sr content normally seen in meteoric waters (Banner, 1995), $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in meteoric cements are generally rock-buffered. The fact that the measured values are higher than the marine $^{87}\text{Sr}/^{86}\text{Sr}$ ratio implies that large volumes of meteoric water must have interacted with strata that are enriched in ^{87}Sr (Moore et al., 1988). Enrichment in ^{87}Sr might have been derived from meteoric water interaction with Cretaceous sandstones, if there was a connection of fluids between these layers and the Mississippian layers in site 12. The cement in the open veins is an example of mass transfer by advection, with the vein isotopic signature different from the host rock signature and compatible with a fluid rather than host rock signature.

Some slickenfibres and completely filled veins are significantly more depleted in $\delta^{18}\text{O}$ than the host rock, but still less depleted compared to the signature of the open veins. The lithology impacts on the mineralogy of the veins, i.e. calcite veins in limestones and dolomite veins (but some were later partially calcitized) in dolostones, but there is no correlation between the vein width and the isotopic signature of the vein cement. We propose two explanations for the depleted $\delta^{18}\text{O}$ values in some slickenfibres and completely filled veins. First, the depletion in $\delta^{18}\text{O}$ results from precipitation of calcite cement in the veins at elevated temperatures. However, if this scenario was the case, one might expect a tighter cluster of data, consistent with precipitation from a specific fluid at a specific temperature, unless the

cements formed from multiple cementation phases from potentially different fluids at different temperatures. The second explanation, which is favoured, is that the range in depleted $\delta^{18}\text{O}$ values relates to reactivation of veins, and thus is influenced by cements in the vein that were either formed or recrystallized from the same meteoric fluids that precipitated cements in the open veins. The slickenfibres and completely filled veins in which the depleted $\delta^{18}\text{O}$ values are measured show a complex microscopic texture of (a) dark intensely twinned calcite and (b) transparent clear calcite that has no twin cleavage planes and that commonly displays fine CL zonations (Fig. 4A-B). Most transparent cements occupying the more central parts of the vein have similar characteristics as the open vein calcite cement. The completely filled and slickenfibre veins with a stable isotopic signature close to that of the host rock do not show microscopic evidence of reactivation and probably relate to small-scale diffusion dominated fluid flow and material transfer.

A strongly depleted $\delta^{18}\text{O}$ value measured in the veins accompanies a ^{87}Sr enrichment for most of the samples (Fig. 11). This result is expected considering advective transport of ^{87}Sr -enriched and ^{18}O -depleted fluids. However, there are two low $\delta^{18}\text{O}$ values in samples that do not have a high ^{87}Sr enrichment in the Mississippian group, and all veins in the Cambrian sites have ^{87}Sr enriched values independent of the $\delta^{18}\text{O}$ values (Fig. 11). The values in the Cambrian sites can be explained by the stratigraphic context, since fluids interacted with interbedded shales of the Middle Cambrian Mount Whyte, Stephen and Pika Formations or feldspathic sandstones of the Lower Cambrian. These strata were local potential sources for the ^{87}Sr enrichment.

9.4. Paleofluid flow in the Rocky Mountains foreland fold-and-thrust belt west of Calgary

A conceptual model of deformation and fluid flow evolution is presented in Figure 13. As argued above, our structural diagenetic study has revealed that: (i) the bed-parallel veins

developed during Laramide folding and slickenfibres precipitated by low fluid flux and
 diffusional processes, (ii) most completely filled and slickenfibre veins formed or were
 reactivated during Laramide compression in a low fluid flow system and they were probably
 also reactivated in a post-Laramide extensional regime with higher fluid flow of meteoric
 waters, (iii) the open veins relate to a post-Laramide extensional stress field and their cements
 precipitated from meteoric waters by advective processes. Hence, no large-scale fluid flow
 occurred during the Laramide Orogeny, but large-scale fluid advection was prevalent after the
 main deformation phase, thus during post-Laramide uplift. These interpretations and data
 agree well with kinematic and fluid flow modeling for the study area in Canada, presented in
 Faure et al. (2004), Roure et al. (2005) and Schneider (2003). Roure et al. (2005) show that
 fluids were close to chemical equilibrium with the host rocks before the onset of thrust
 loading and development of the foreland basin. Subsequent thrusting generated lateral low-
 flux, squeegee-type fluid expulsion with an average velocity of less than 2 km/Ma,
 accompanied by an increase in hydraulic head up to 10 MPa (Faure et al., 2004; Schneider,
 2003). Still, episodic fluid flow during the Laramide Orogeny probably existed, consistent
 with the composite and reactivated nature of the veins, and was linked to pressure buildup and
 release during thrust fault activity (Sibson, 1994). Fluid flow after the Laramide event was
 controlled by topography and geometry (Schneider, 2003), whereby the hydraulic head
 decreased during the main erosion phase and increased again during uplift of the last 20 Ma
 (Faure et al., 2004). Also Robion et al. (2004) suggest limited fluid flow to explain the
 recrystallization of dolomite in the Canadian study area.

Our interpretation of limited fluid flow during the Laramide Orogeny is also in
 agreement with Kirschner and Kennedy (2001) reporting a study on syntectonic veins in the
 Front Ranges. Machel and Cavell (1999) provide evidence of a tectonically-induced,
 squeegee-type fluid flow event during Laramide thrusting based on Sr isotope data (Devonian

carbonates, Western Alberta Basin) and agree that this flow is a low-flux fluid flow. Our conclusions are also in agreement with Nesbitt and Muehlenbachs (1995), who argue that there is no large-scale, thrust-associated fluid movement. The latter authors explain this interpretation by the absence of any high-volume fluid reservoir during thrusting and the fact that the units involved in the thrusting events were well lithified and lack significant porosity. Nesbitt and Muehlenbachs (1995) also argue that the input of external, surface fluids to the zones of active deformation was restricted due to the closure of fracture systems during compression. In contrast, the authors favor high fluid flow involving surface fluids in a tensional regime, which occurred as passive extension related to relaxation and uplift following compression in the Rocky Mountains. Indeed, this interpretation is similar to ours on the precipitation conditions of cements in the open veins. Moreover, Kirschner and Kennedy (2001) suggest that precipitation from evolved meteoric waters occurred probably during uplift and exhumation of the studied outcrops in the foreland fold-and-thrust belt. Cooley (2007) investigates fluid flow along many tear/transverse faults and larger thrust faults in the Livingstone Range anticlinorium and suggests that initial syn-thrusting fluid flow occurs by a small fluid volume in a rock-buffered system. The latter author interprets calcite veins marked by very negative $\delta^{18}\text{O}$ values as a result of regional syn-thrusting meteoric fluid infiltration. He suggests that calcite precipitated along faults that were active while the Livingstone Range anticlinorium was transported eastward and became elevated by underlying thrust faults. Subsequently, the anticlinorium rapidly cooled by infiltrating meteoric water.

In contrast, a few studies argue in favour of significant fluid flow along thrusts, e.g. Woodwell (1985) and Bradbury and Woodwell (1987) who carried out a stable isotopic study of veins close to the McConnell thrust fault. However, as Kirschner and Kennedy (2001) also suggested, some data in Woodwell (1985) and Bradbury and Woodwell (1987) are probably

caused by occurrence of younger cements within the syntectonic veins sampled. Our observations have identified the occurrence of composite veins, i.e. younger cement infillings in older veins, which complicates geochemical analysis and interpretation. As a consequence, the observed complexity emphasizes the importance of fieldwork and microscopic investigation of each sampled vein in the interpretation of the chemical analysis.

10. Conclusions

The following conclusions are drawn from the present structural diagenetic study in the Rocky Mountains, west of Calgary.

First, the veins are related to both the Laramide compression and a post-Laramide tectonic deformation phase: (i) three sets of veins developed during Laramide compression, i.e. bed-parallel veins, steep completely filled veins striking parallel to bedding and steep N040 to N070 completely filled and slickenfibred veins and (ii) open veins developed during a post-Laramide tectonic deformation phase.

Second, based on microscopy, at least two different types of cements occur in the veins: (i) cloudy or turbid vein cements (with dull brownish or reddish luminescence) that testify to a high degree of deformation based on thick cleavage twins and subgrain formation and (ii) transparent calcite cements with no or only thin and few cleavage twins but with CL zonations. However, attention needs to be paid to the complexity of the deformed veins as they are generally formed by several fracturing and/or cementation episodes. The open veins are cemented by the undeformed calcite cement type.

Third, based on isotopic data two main mass transfer mechanisms are distinguished: (i) diffusion for bed-parallel veins, where the stable carbon and oxygen and the radiogenic strontium isotope signature is similar to that of the host rock and (ii) advection for open veins, where the stable oxygen isotopic value is strongly depleted and the $^{87}\text{Sr}/^{86}\text{Sr}$ is high relative to

the host rock signature. The cements in the open veins formed from meteoric fluids at low temperature (less than 50°C). The completely filled and slickenfibres veins with an intermediate stable oxygen isotope value are composite veins with partial cementation or recrystallization by the younger meteoric fluids.

Finally, linking the two previous conclusions together, it is inferred that the Laramide compressional regime was governed by limited intra-stratal fluid flow, while fluid flow during post-Laramide uplift was characterized by a high meteoric fluid flow rate.

Although we have obtained and presented compelling evidence to support our main conclusions, it is clear that reactivation played a major role in obliterating original geochemical information, which complicates the reconstruction of the structural-diagenetic history. This complexity leaves the foreland fold-and-thrust belts challenging areas.

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Figure captions

Figure 1 Map of the Southern Canadian Cordillera with indication of morphogeological belts (modified from Gabrielse et al., 1991) and location of the study area west of Calgary.

Figure 2 (A) Google Earth image of the study area in the Foothills, Front Ranges and Main Ranges of the Canadian Rocky Mountains west of Calgary with rough indication of sites studied. The white boxes indicate the location of the more detailed geological maps in B, C and D. (B) Geological map of the study area in the Front Ranges (modified from Ollerenshaw, 1975) with detailed indication of the study sites 3 to 12. (C) Geological map of the study area in the Main Ranges (modified from Price et al., 1980) with detailed indication of the study sites 13 to 16. (D) Geological map of the study area in the Foothills (modified from McMechan, 1995) with detailed indication of study sites 1 and 2.

Figure 3 Google Earth image of the study area as presented in Figure 2. Numbers indicated on the map refer to the different sites studied as listed in Table 1. Equal area lower hemisphere stereographs are presented for sites with a minimum of 8 structural data. Each stereoplot shows the site number at the left top side and the amount of structural data at the right bottom. The data were plotted using the software OSXStereonet.

Figure 4 Transmitted light (A, C, E, G) and CL (B, D, F, H) microphotographs of completely filled veins. Scale bar is 1000 μm . (A, B) Part of a composite completely filled vein in Lower Carboniferous Rundle Group dolostone from site 2 with intensely cleavage twinned dull brown luminescent calcite (CTC), dull red luminescent dolomite crystals (D) and in the centre undeformed pure calcite with alternating non-luminescent and bright yellowish luminescent zones (ZC). The dark impure linings also display a bright light yellow luminescence. (C, D) Composite completely filled vein in Cambrian Eldon Formation dolomitic limestone from site 3 with large cleavage twinned calcite crystals (CTC) and some scattered calcite microspar

(CM). The strongly twinned and impure parts in the calcite crystals display a slightly lighter or more yellowish luminescence colour than the dull (red) brownish colour of the bulk part of the calcite cement. Also note the thin oblique dull dark brown luminescent veins (arrow) cross-cutting the main large vein. (E, F) Calcite completely filled vein in Lower Carboniferous Rundle Group dolomitic limestone from site 2 with sector zoned dull light brown luminescence. This vein contains patches of calcite microspar (CM) aligned parallel to the vein wall. (G, H) Part of a completely filled vein in Mississippian Livingstone Formation limestone from site 11 containing fluorite (F) with blue luminescence besides red luminescent calcite.

Figure 5 Macrophotographs and microphotographs of parts of en echelon veins in Cambrian dolomitic limestones from site 13. (A, B) Hand sample macrophotographs showing partially dolomitized limestone (L) with en echelon vein composed of both dolomite (D) and calcite (C). The hand samples are etched in 1 M HCl and stained with Alizarin Red S (causing the pink stain for calcite) and potassium ferricyanide (causing the blue stain for ferroan dolomite). Scale is in centimeters. (C, D) Microphotograph using transmitted light (C) and CL (D) showing dark brown luminescent dolomite (D) and dull yellowish brown luminescent calcite (C) in the vein. Also note the small dull reddish brown luminescent dolomite rhombohedrons (arrow) in the dull yellowish brown luminescent limestone host rock. Scale bar is 1000 μ m.

Figure 6 Transmitted light (A) and CL (B) microphotograph of a slickenfibre vein in Lower Carboniferous Rundle Group dolomitic limestone from site 2. The slickenfibre vein is a composite vein with thick cleavage twins in the calcite crystals (CTC) and random or clustered microspar (CM). Note also the thin oblique dark luminescent vein (arrow) cross-cutting the thick slickenfibre vein. Scale bar is 1000 μ m.

Figure 7 Transmitted light (A, C) and CL (B, D) microphotograph of details of bed-parallel veins. Scale bar is 1000 μ m. Bedding orientation is indicated by line with perpendicular arrow

849 towards younger beds; thin section is cut perpendicular to bedding. (A, B) Yellowish
850 luminescent calcite completely filled vein (CTC2) cross-cutting bed-parallel vein containing
851 dull reddish luminescent calcite (CTC1) and non luminescent dolomite (D) in Cambrian
852 Eldon Formation limestone from site 3. (C, D) Vein wall parallel lining of non luminescent
853 dolomite (D) in mainly red luminescent calcite (CTC) vein in Mississippian Livingstone
854 Formation dolomitic limestone from site 8. Note also the few blue luminescent fluorite
855 crystals (F).

856 Figure 8 Transmitted light (A) and CL (B) microphotograph of a micro-breccia vein in
857 Cambrian Eldon Formation dolomitic limestone from site 3. A part of a dark host rock clast
858 (HRC) is present at the bottom. Part of the cleavage twinned calcite crystals (CTC) display a
859 CL zonation. Some small red luminescent dolomite (arrow) occurs scattered within the
860 microspar. Scale bar is 1000 μm .

861 Figure 9 Transmitted light (A) and CL (B) microphotograph of an open vein in Mississippian
862 Livingstone Formation dolomitic limestone from site 11. The calcite crystals (CZ) have
863 almost no impurities, and are thus transparent, and they do not show any cleavage twins. The
864 calcite is characterized by a zoned CL pattern with a dominant dull red luminescence in the
865 center and then a main non luminescent zone and at the rim an alternation of non luminescent
866 with dominantly bright yellowish luminescent bands. Scale bar is 1000 μm .

867 Figure 10 Stable oxygen and carbon isotope plots for host rock and different vein types
868 sampled at the sites indicated. The grey shaded boxes represent the isotopic marine signature
869 for the respective time periods (Veizer et al., 1999). Most samples consist of calcite; the
870 dolomite samples are indicated by the same type of vein type symbols but with a dark grey
871 filling.

872 Figure 11 Cross-plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $\delta^{18}\text{O}$ for host rock and different vein types sampled at
873 the sites indicated. Sites 3 and 13 have host rocks of Cambrian age, whereas sites 2 and 5-12

have host rocks of mainly Lower Carboniferous age (see Table 1 for details). The grey shaded boxes represent the marine Sr isotope signature for Cambrian and Upper Devonian to Triassic respectively (based on Veizer et al., 1999 for stable oxygen isotopes and McArthur et al., 2001 for Sr isotopes).

Figure 12 Cross-plot of the difference in stable carbon and oxygen isotopic composition between the host rock and vein for samples collected in the same hand sample.

Figure 13 Conceptual model of the deformation and fluid flow evolution (from Jurassic till recent) in the Canadian Rocky Mountains foreland Belt at latitude of about 51°N. Structural cross-section is based on Price (1981).

Tables

Table 1 List of sites studied with information on geographic location, the studied stratigraphic layers and the main thrust fault to which they are associated (or normal fault for the Kicking Horse and Monarch Mine sites)

Figure 1

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Table 1

Table 1 List of sites studied with information on geographic location, the studied stratigraphic layers and the main thrust fault to which they are associated (or normal fault for the Kicking Horse and Monarch Mine sites)

Site number and name	Longitude	Latitude	Age and formation	Lithology	Thrust sheet
1 Moose Mountain South	114°50' W	50°48' N	Lower Carboniferous Rundle Group	skeletal, argillaceous and dolomitic limestone and dolostone	Dyson Mountain
2 Moose Mountain North	114°48' W	50°51' N	Lower Carboniferous Rundle Group	skeletal, argillaceous and dolomitic limestone and dolostone	Prairie Mountain
3 McConnell	115°07' W	51°04' N	Cambrian Eldon Fm	limestone, dolomitic limestone and dolostone	McConnell
4 Lafarge Quarry	115°10' W	51°03' N	Upper Devonian Palliser Fm	limestone, dolomitic limestone and dolostone	Exshaw
5 Lower Exshaw	115°11' W	51°04' N	Mississippian Exshaw and Banff Fms	argillaceous and cherty limestone	Exshaw
6 Upper Exshaw	115°14' W	51°03' N	Mississippian Exshaw and Banff Fms	argillaceous and cherty limestone	Lac des Arcs
7 Upper Spray Lake	115°25' W	51°03' N	Devonian Palliser and Mississippian Exshaw and Banff Fms	limestone and dolomitic limestone	Rundle
8 Banff	115°34' W	51°11' N	Mississippian Livingstone Fm	skeletal and cherty limestone, dolomitic limestone and dolostone	Rundle