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**Clinof orm identification and correlation in fine-grained sediments: A case study using the  
Triassic Montney Formation**

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## ABSTRACT

Stratigraphic correlation of fine-grained successions is not always straightforward. Complicating factors such as unconformities, structural complexity, subsidence, and especially minimal grain-size variation, make the application of traditional correlation methods to fine-grained successions problematic. Alternatively, the analysis of detailed geochemical data can allow for the determination of variations in sediment provenance, mineralogy, detrital flux and hydrothermal input. When compared with modelled clay input over time, these geochemical indicators can be used to determine changes in relative sea-level and palaeoclimate, allowing for the identification of clinoform surfaces. As an example, this study outlines detailed correlations of chemostratigraphic packages within the lower Triassic Montney Formation in western Canada to demonstrate the effectiveness of chemostratigraphy in defining and correlating fine-grained clinoforms across a sedimentary basin. The data set used includes five wells and one outcrop succession, from which geochemical profiles were generated and tied directly to mineralogical data and well logs. These analyses reveal 13 distinct chemostratigraphic packages that correlate across the basin. Observed elemental and inferred mineralogical changes highlight trends in relative sea-level and palaeoclimate, as well as episodes of inferred hydrothermal input to the Montney basin. Cross-plots of La/Sm and Yb/Sm further suggest hydrothermal input as well as the scavenging of middle rare earth elements by phosphatic fish debris. Additionally, plots of La/Sm versus Yb/Sm, which show volcanic arc input within the Doig Formation, suggest an additional sediment source from the west during the Anisian. Pairing detrital and clay proxies demonstrates changes in relative sea-level and, at the Smithian/Spathian boundary, the lowest relative sea-level in the Montney Formation is observed, corresponding to a change in climate.

**Keywords** *Chemostratigraphy, chronostratigraphy, clay proxies, correlation, detrital proxies, provenance proxies, relative sea-level, shale.*

## **INTRODUCTION**

Correlation of thick, fine-grained lithological successions often poses challenges that are commonly not resolvable through traditional stratigraphic techniques. These include: (i) minimal grain-size variation; (ii) lateral changes in unit thicknesses tied to structural features; (iii) differential subsidence and the occurrence of broad internal clinoform; and (iv) the occurrence of local and regional unconformities. Elemental chemostratigraphy provides a solution to these challenges by identifying lithological changes that are not apparent under direct observation, and in recent years it has been shown to be an invaluable tool for stratigraphic correlation in a number of successions (*e.g.* North *et al.*, 2005; Hildred *et al.*, 2010; Wright *et al.*, 2010; Ratcliffe *et al.*, 2015). Questions pertaining to regional anoxia (Retallack *et al.*, 1997; Algeo *et al.*, 2004; Ratcliffe *et al.*, 2012), productivity (*e.g.* Hays *et al.*, 2007), sediment provenance and source (Armstrong-Altrin *et al.*, 2004; Pearce *et al.*, 2005), as well as palaeoclimate (Armstrong-Altrin *et al.*, 2004; Ratcliffe *et al.*, 2010), have also been successfully investigated using chemostratigraphy.

Despite the wide applicability of chemostratigraphic analysis, it has largely been under-utilized in identifying and correlating chronostratigraphic surfaces (such as clinoforms). This paper outlines the application of chemostratigraphic analysis for determining chronostratigraphic surfaces in fine-grained sediments, using the Lower Triassic Montney Formation of Western Canada as an example. The Montney Formation is a fine-grained, locally organic-rich formation deposited over a wide range of sedimentary environments, from the proximal to distal clastic ramp.

Traditional methods of stratigraphic correlation often focus on lithology and fossil content; however, this method can be challenging in units of apparent lithological homogeneity (such as in thick shale or siltstone successions), especially when fossil evidence is sparse. Analyzing chemical trends allows for the identification of subtle mineralogy-based variations that cannot typically be identified by traditional correlation techniques. Geochemical proxies for clay input can be analyzed alongside proxies for sediment provenance, mineralogy and detrital influx. This provides a stratigraphic context that allows for genetically related deposits to be correlated.

The determination of provenance or redox specific information requires the use of specific elemental relationships or 'proxies', which can be selected on the basis of demonstrated correlation with specific factors, such as: the effects of oxidation state on the formation/alteration of some mineral components (*e.g.* Wedepohl, 1971; Arthur *et al.*, 1990; Calvert & Pedersen, 1993; Algeo *et al.*, 2004; Algeo & Lyons, 2006; Kendall *et al.*, 2011; Asael *et al.*, 2013; Chappaz *et al.*, 2014; Reinhard *et al.*, 2014; Planavsky *et al.*, 2014), known effects of trace element sequestration due to biological activity and organic matter (*e.g.* Berner & Westrich, 1985; Rabouille & Gaillard, 1991; Fein *et al.*, 1997; Tribovillard *et al.*, 2006; Lalonde *et al.*, 2008; Anbar & Rouxel, 2007; Gadd, 2010; Liermann *et al.* 2011, Liang *et al.*, 2013; Pokrovsky *et al.*, 2014), the influence of weathering, palaeogeography and palaeoclimate on mineralogy (*e.g.* Plank & Langmuir, 1998; Preston *et al.*, 1998; Pearce *et al.*, 1999, 2010; Hofmann *et al.*, 2001; Hofer *et al.*, 2013; Clift *et al.*, 2014; Ratcliffe *et al.*, 2015), the unique compositional signature of mafic/felsic/ultramafic source rocks (*e.g.* Reátegui *et al.*, 2005) and diagenetic reactions (*e.g.* Froelich *et al.*, 1979; Morton, 1985; Curtis *et al.*, 1986; Canfield *et al.*, 1993).

The overarching goal of this work is a consistent, regional correlative framework of the Triassic Montney Formation. Geochemical elements and ratios used in this study were chosen to reflect indicators that are not: (i) heavily influenced by processes such as oxidation state (which can vary with water depth as well as with diagenesis); and (ii) palaeoproductivity (which can vary geographically). As such, this study used various elemental ratios, including: (i) clay indicators (Cr/Sc, Zr/La, Zn/Sc, SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>, Ga/Rb, K<sub>2</sub>O/Al<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O/Rb, Na<sub>2</sub>O/Al<sub>2</sub>O<sub>3</sub>, Rb/Al; Plank & Langmuir, 1998; Preston *et al.*, 1998; Pearce *et al.*, 1999, 2010; Hofmann *et al.*, 2001; Hofer *et al.*, 2013; Clift *et al.*, 2014; Ratcliffe *et al.*, 2015); (ii) detrital input and sediment recycling indicators (TiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>/K<sub>2</sub>O, Lu/Hf, Sc/Zr; Dean *et al.*, 2002; Croudace *et al.*, 2006; Cuven *et al.*, 2010; Ratcliffe *et al.*, 2006); (iii) provenance indicators (Ni/Al, Cr/Al, Th/Sc, Ti/Zr, MgO/Al<sub>2</sub>O<sub>3</sub>, Ti/Nb; Amarosi *et al.*, 2007; Dinelli *et al.*, 2007); and (iv) mineralogical indicators (P<sub>2</sub>O<sub>5</sub>/Al<sub>2</sub>O<sub>3</sub>, Cr/Nb, Lu/Zr, Cr/Zr; Bhatia & Crook, 1986; Morton & Hallsworth, 1994; Cingolani *et al.*, 2003; Ratcliffe *et al.*, 2004, 2006; Wright *et al.*, 2010; Clift *et al.*, 2014). Some elements used, such as Fe, S, U and P, are redox-sensitive and palaeoproductivity indicators. However, in this study, these elements were analyzed in the context of mineralogical and hydrothermal indicators only.

By utilizing these geochemical proxies, this paper outlines correlative chemostratigraphic packages, herein referred to as chemofacies, within the Montney Formation and ties them to well logs. Additionally, conodont analyses published by Golding *et al.* (2014) and Orchard & Tozer (1997), on outcrop and one of the wells used in this study, anchor the geochemical data set of the current study to the existing regional biostratigraphic framework. The identification and correlation of these geochemically distinct packages reveals regional clinoform surfaces within the Montney Formation and

provides an initial template for developing regionally consistent stratigraphic and palaeogeographic models for other fine-grained successions. Elemental correlations, analyzed through Pearson product-moment correlation analysis (PPMC) and eigenvector analysis (EA), support mineralogical data obtained using X-ray diffraction (XRD). When combined with geochemical proxies for provenance, mineralogy, clay and detrital input, these observations highlight trends in sediment sourcing, relative sea-level, climatic effects and identify intervals of inferred hydrothermal input to the basin.

## **GEOLOGICAL SETTING**

Within the Western Canada Sedimentary Basin (WCSB), the earliest Triassic deposits in the subsurface are assigned to the Montney Formation. The Montney Formation was deposited on the western margin of Pangaea (eastern Panthalassa margin) and is thickest in the area of the Peace River Embayment (the Peace River Basin) (Fig. 1; Davies *et al.*, 1997). The Peace River Embayment is a broad structural basin formed during the Carboniferous as a result of the collapse of the Peace River Arch, a structural Precambrian high that remained emergent until the end of the Devonian (Richards *et al.*, 1994; Davies *et al.*, 1997; Moslow & Davies, 1997). During the early Triassic, western Canada was rotated approximately 30° clockwise from its current orientation, with the regional shoreline trend approximately parallel to the axis of the modern Rocky Mountains (Golonka *et al.*, 1994; Davies, 1997; Golonka & Ford, 2000).

The Montney Formation is *ca* 300 m thick, and extends over 150,000 km<sup>2</sup> of northeastern British Columbia and west-central Alberta (Edwards *et al.*, 1994). It consists of siltstone, sandstone and coquina deposited in environments that range from shoreface to

distal offshore, including turbidites (Davies *et al.*, 1997; Moslow & Davies, 1997; Dixon, 2000; Moslow, 2000; Utting *et al.*, 2005; Hays *et al.*, 2007; Zonneveld *et al.*, 2010a). Within the study area, the Montney Formation is unconformably overlain by the Doig Formation and unconformably underlain by the Belloy Formation.

Previous stratigraphic analyses of the Montney Formation have focused on traditional core and well log correlations supported by limited biostratigraphic (conodont) data (Zonneveld *et al.*, 2007; Beatty *et al.*, 2008; Zonneveld *et al.*, 2010a,b; MacNaughton & Zonneveld, 2010; Golding *et al.*, 2014; Sanei *et al.*, 2015; Wood *et al.*, 2015). Temporal constraints on Montney deposition are limited to biostratigraphic analyses in outcrop and subsurface and demonstrate deposition occurred from the start of the Triassic (250 Mya) to the Anisian (247 Mya; *e.g.* Tozer, 1994; Paull *et al.*, 1997; Utting *et al.*, 2005; Orchard & Zonneveld, 2009; Zonneveld *et al.*, 2010a; Golding *et al.*, 2014). Although palynomorphs, bivalves and ammonoids have proven useful in some studies (*e.g.* Tozer, 1994; Utting *et al.*, 2005), conodont biostratigraphy is the most effective, provided sufficient material is available to produce diagnostic elements (Paull *et al.*, 1997; Orchard & Zonneveld, 2009; Golding *et al.*, 2014). To this end, the key well used for this study (UWI 16-17-083-25W6; full core) has been lithologically described and dated using conodont analysis (Golding *et al.*, 2014).

## **METHODS**

(A)

A total of 641 samples were analyzed and include core samples (wells c-74-G/94-b-09, d-48-A/94-b-09, 2-30-070-24W5, 16-17-083-25W6 and 11-20-082-02W6) and outcrop samples (Ursula Creek, British Columbia; Fig. 1). The wells and outcrop were chosen to create a

transect perpendicular to the Triassic palaeoshoreline. Samples from these locations were analyzed using Thermo Scientific XSERIES 2 ICP-MS and iCAP 7000 Series ICP-OES (Thermo Fisher Scientific, Waltham, MA, USA) at Chemostrat and a Perkin Elmer ICP-MS and Spectro ICP-OES (Perkin Elmer, Waltham, MA, USA) at Bureau Veritas Mineral Laboratories. Additionally, one data set, 2-30-070-24W5, was analyzed using a Bruker AXS D8 Advance Diffractometer (Bruker, Billerica, MA, USA) at SGS Mineral Services in Lakefield, Ontario.

A statistical evaluation of the correlation between mineralogical and elemental data was conducted using PPMC and EA on DataDesk® 6.3.1 (Data Description Inc., Ithaca, NY, USA). Additionally, chemostratigraphic packages were defined using principle component analysis and cluster analysis on the most complete core data set (16-17-083-25W6), which was used as the type section. In total, 84 variables were considered (Table 1). The variables used fall into eight categories: (1) oxides, (2) unaltered trace element data provided by the analytical laboratories, (3) oxide elements, with the calculated elemental portion of the oxides converted to ppm, and (4) to (8) indicators, comprised of ratios of elements or oxides.

Chemofacies were then analyzed and summarized using clay indicator ratios (Cr/Sc, Zr/La, Zn/Sc, SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>, Ga/Rb, K<sub>2</sub>O/Al<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O/Rb, Na<sub>2</sub>O/Al<sub>2</sub>O<sub>3</sub>, Rb/Al), provenance indicator ratios (Ni/Al, Cr/Al, Th/Sc, Ti/Zr, MgO/Al<sub>2</sub>O<sub>3</sub>, Ti/Nb), detrital input indicators (TiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>/K<sub>2</sub>O, Lu/Hf, Sc/Zr) and mineralogical indicators (P<sub>2</sub>O<sub>5</sub>/Al<sub>2</sub>O<sub>3</sub>, Cr/Nb, Lu/Zr, Cr/Zr). An average value of each ratio was determined from the type section. These overall average values were compared to the averaged values generated from within each chemofacies in order to make broad interpretations. Due to the low elemental immobility, and the relation to detrital input, subsequent data sets were correlated primarily using the

signatures of Sc/Zr, Lu/Hf, and Zr/La (see the *Elemental Indicators* section below for a more detailed explanation of the ratios used in this study). For a detailed methodology, refer to the supplementary information.

## **Elemental Indicators**

### *Clay indicators*

Some elemental ratios, for example Ga/Rb, are interpreted to reflect the proportion of kaolinite to illite (Ratcliffe *et al.*, 2010, 2015; Hofer *et al.*, 2013) because kaolinite is a major carrier of Ga (Wang *et al.*, 2011; Dai *et al.*, 2012a). Although K/Rb can reflect weathered versus volcanoclastic input (Plank & Langmuir, 1998), when compared to the ratio  $K_2O/Al_2O_3$ ; K/Rb can also indicate high illite content (i.e. low values of K/Rb paired with high  $K_2O/Al_2O_3$  indicate high illite content; Ratcliffe *et al.*, 2006, 2015; Hofmann *et al.*, 2001; Hofer *et al.*, 2013). Additionally, high Rb/ $Al_2O_3$  ratio values indicate high proportions of illite and mica with little kaolinite (Pearce *et al.*, 2005). The ratio of Na/Al can act as a proxy for smectite content (Hofmann *et al.*, 2001; Hofer *et al.*, 2013). Chromium is associated with chlorite while Sc is associated with kaolinite (Ratcliffe *et al.*, 2015). In general, Sc and Ga are observed to correlate with light rare earth elements (LREE) and Al in kaolinite, although Ga has been observed to adsorb onto illite and montmorillonite under certain pH conditions and can be associated with Cr-spinels (Esser *et al.*, 1991; Paktunc & Cabri, 1995; Takahashi *et al.*, 1999; Hofmann, 2003; Tyler, 2004; Dai *et al.*, 2006, 2008, 2012a,b; Pearce *et al.*, 2010; Wang, 2011; Benedicto *et al.*, 2014). The ratio of Zr/La can indicate clay and mica content as Zr is often associated with heavy minerals such as garnet and zircon, while La is often bound in the clay and mica fraction (Plank & Langmuir, 1998; Preston *et al.*, 1998; Pearce *et al.*, 1999, 2010). For example, ratios such as Zr/La can be used to assess for elemental dilution

(Preston *et al.*, 1998). Pearce *et al.* (1999) discussed the need to account for elemental dilutions due to elements of a more detrital nature (for example, Si and Al) being 'diluted' in zones that have been highly cemented by carbonate. By comparing the Zr/La ratio to geochemical proxies for carbonate input (such as Ca, Sr and Mg), the dilution effect can be investigated. Because illite fixes Zn much more readily into its structure than kaolinite (Reddy & Perkins, 1973) and Sc (along with Ga) is often sequestered with other REE and Al into kaolinite (Esser *et al.*, 1991; Paktunc & Cabri, 1995; Takahashi *et al.*, 1999; Hofmann, 2003; Tyler, 2004; Dai *et al.*, 2006, 2008, 2012a a,b; Pearce *et al.*, 2010; Wang, 2011; Benedicto *et al.*, 2014 ), the ratio of Zn/Sc, in the context of other clay proxies, can be used to determine illite/kaolinite proportions (Pearce *et al.*, 1999). Similarly, the TiO<sub>2</sub>/K<sub>2</sub>O ratio is representative of the amount of anatase relative to illite (Ratcliffe *et al.*, 2006).

#### *Detrital indicators*

Perhaps the most commonly used; the TiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio can indicate specific sediment flux, in this case aeolian input and also detrital flux associated with relative sea-level change (Chen *et al.*, 2013). Additionally, sediment recycling concentrates heavy minerals, especially zircon, in the sediment, allowing for ratios such as Sc/Zr to be used to indicate the relative intensity of sediment recycling (McLennan *et al.*, 1993; Mongelli *et al.*, 2006). Likewise, the ratio of Lu/Hf, because of the higher concentration of Hf in zircons, can indicate continental shelf versus pelagic clay deposits (Patchett *et al.*, 1984; Plank & Langmuir, 1998). Because the mineralogical products of weathering are often higher in K content, while Ti content largely remains unchanged during weathering, the ratio of TiO<sub>2</sub>/K<sub>2</sub>O can be used to determine the relative input of weathered material into the basin over time (Wei *et al.*, 2003).

### *Provenance indicators*

Ratios, such as Cr/Al and Ni/Al, are uninfluenced by grain-size changes (Dinelli *et al.*, 2007). Because Cr can be associated with both heavy minerals and clays (Meinhold *et al.*, 2007), the ratio Cr/Al can indicate Cr enrichment associated with heavy minerals sourced from igneous rocks (Preston *et al.*, 1998; Ratcliffe *et al.*, 2004; Wright *et al.*, 2010). Likewise, an excess of Ni relative to Al can indicate ultramafic provenance (Amarosi *et al.*, 2007).

Zirconium/Niobium has been demonstrated to indicate ultramafic igneous input, with Nb being associated with Nb-rich rutile (Ratcliffe *et al.*, 2006). High values of Th/Sc are interpreted as resulting from felsic sediment components, with Th/Sc having been used as a measure of the degree of igneous differentiation (McLennan *et al.*, 1990, 1993; Hofmann *et al.*, 2003; López de Luchi *et al.*, 2003; Bracciali *et al.*, 2007). The ratio Mg/Al (normalized to account for grain-size variation), can indicate ultramafic input or dolomite when associated with Ca (Amarosi *et al.*, 2007; Dinelli *et al.*, 2007). This ratio has also been demonstrated to indicate Mg-rich clay (*e.g.*, palygorskite) input in deposits related to the Negev loess (Israel *et al.*, 2015). Additionally, Ti/Nb has been demonstrated to indicate igneous input and has been linked to intraplate settings with basaltic volcanism (Bonjour and Dabard, 1991). The ratio of Ti/Zr has been demonstrated to distinguish turbidites from various tectonic sources and can (when plotted against La/Sc) reveal the tectonic setting of the sediment (Bhatia & Crook, 1986; Cingolani *et al.*, 2003).

### *Mineralogical indicators*

In terms of trace element abundance, Ti, Nb and Ta are related to the presence of heavy minerals (foremost rutile, but also anatase, ilmenite and leucoxene; Pearce *et al.*, 2010).

Niobium is associated with Ti in rutile (Preston *et al.*, 1998) and therefore the TiO<sub>2</sub>/Nb ratio

can be used to account for rutile-associated Nb. Iron has been linked to the presence of Fe-oxyhydroxides (for example, goethite), pyrite and/or ferroan dolomite (Pearce *et al.*, 2010). Calcium, Mg, Mn and Sr are generally associated with carbonate minerals (for example, calcite, dolomite and siderite; Pearce *et al.*, 2010). In addition to feldspar, Na can be present in the clay fraction as well as in halite (Pearce *et al.*, 2005, 2010). The concentration of K, Rb and Cs are primarily controlled by the amount of illite and mica present (Pearce *et al.*, 2010). The deposition of P in sediments is related to multiple factors including palaeoproductivity and hydrothermal flux (Feely *et al.* 1994; Wheat *et al.* 1996; Tribovillard *et al.*, 2006). Because of the co-occurrence with organic matter, phosphorous is often present in association with clays and can indicate the presence of biogenic phosphatic fish remains and calcareous microfossils (Pearce *et al.*, 2010). When present with Fe, Mn, and REE, the presence of P has been linked to siderite (Pearce *et al.*, 2010). Substitutions within apatite include Y and REE for Ca, with Sr balancing the remaining charge (Preston *et al.*, 1998). Chromium (III) occurs within spinel, often substituting for Al (III) or Fe (III) (Preston *et al.*, 1998). Chromium-spinel is found in primitive basic igneous rocks and ultrabasic igneous rocks (Preston *et al.*, 1998). The similar ionic radii of Nb and Ti allows the former to substitute into the crystal lattice of Ti-bearing minerals such as illmenite and rutile; however Nb-rich rutile is generally restricted to ultramafic, alkaline, igneous rocks (Preston *et al.*, 1998). Therefore, the ratio of Cr/Nb can be used to estimate the abundance of Ti-oxide heavy minerals, and is thought to reflect variation in the abundance of Ti-oxide heavy minerals with respect to spinel (Ratcliffe *et al.*, 2015). The ratio of Lu/Zr is closely related to the garnet-zircon index (GZi index) and reflects the proportion of garnet to zircon (Wright *et al.*, 2010). The GZi index has been used to fingerprint unique heavy mineral populations related to different sandstone types, which reflect overall lithological differences (Morton &

Yaxely, 2007). Likewise, Cr/Zr is a proxy for the chrome spinel-ziron index (CZI index), which is another provenance-sensitive ratio (Morton & Hallsworth, 1994; Ratcliffe *et al.*, 2006; Morton & Yaxely, 2007; Wright *et al.* 2010).

## **RESULTS AND INTERPRETATIONS BY CATEGORY**

### **Chemofacies Descriptions**

#### *Results*

Thirteen chemofacies were recognized based on differences in the abundances of major oxides, trace elements and elemental ratios. Twelve packages were first identified and defined in the most complete sample set (16-17-083-25W6; Figs 2 to 5) using cluster and principal component analyses; although only occurring in the basal data point (and thus statistically insignificant), a thirteenth division was added based on the published contact between the Permian Belloy Formation and the Montney Formation in this data set (Golding *et al.*, 2014). Chemofacies are herein defined as distinct bodies of rock characterized by a particular combination of stable isotopic signatures, oxide elemental patterns, trace element signatures, or element ratios dependent on underlying mineralogical controls and organic matter that distinguish it from surrounding strata. The chemofacies identified in this study are labelled in stratigraphic order, beginning at the base. Numerical values for each chemical ratio were averaged for the entire 16-17-083-25W6 data set; this average was compared to the calculated average value for each chemofacies in Tables 5 to 8.

### *Interpretation*

Average values displayed in Tables 5 to 8 were used to guide the interpretation of each chemofacies, which are listed in Table 9. These interpretations highlight perceived changes in clay content throughout the sample set. Namely, chemofacies 1 to 5 show high clay input, with low smectite and kaolinite content and greater amounts of illite (Fig. 4). Within chemofacies 5, there is a shift to high smectite content, and, by chemofacies 7, a switch from generally high to low clay content. Additionally, illite is replaced by kaolinite and smectite as the more abundant clay phases. Chlorite appears in higher than average proportions in chemofacies 1 (Belloy Formation) and chemofacies 13 (Doig Formation).

### **Chemostratigraphic correlation**

#### *Results*

Correlation between wells reveals the presence of various chemofacies within each well or outcrop sample set. Data sets were correlated with the type well using proxy ratios for detrital flux ( $Sc/Zr$  and  $Lu/Hf$ ) and clay input ( $Zr/La$ ), which should not be affected by fluctuations in redox conditions or diagenesis. Detailed correlation of each data set is visible in Figs S1 to S20; additional supplementary figures illustrate points of correlation between the type data set and each additional well (Figs S21 to S25), as well as lithologs for four data sets (Figs S26 to S29).

### *Interpretation*

Data from Ursula Creek were found to correspond with all 13 defined chemofacies (Fig. 6). Wells d-48-A/94-B-9 and c-74-G/94-B-9 were found to contain chemofacies 8, 9, 10 and a small portion of 11. This suggests that an unconformity is present, with erosion having

removed most of chemofacies 11, and all of chemofacies 12. Data from well 11-20-82-2W6 was found to correspond to chemofacies 2 and 3. Well 2-30-70-24W5 was interpreted to correspond to chemofacies 1, 2, 3, 7 and 8. Both Wells 11-20-82-2W6 and 2-30-70-24W5 are missing chemofacies 9 to 12, which suggests erosion, and have thicker lower chemofacies. Thicker lower chemofacies in the eastern data sets (wells 11-20-82-2W6 and 2-30-70-24W5) suggests clinoformal deposition from the east.

Correlatable conodont intervals, as previously described by Golding *et al.* (2014) and Orchard & Tozer (1997), occur in chemofacies 7 (well 16-17-083-25W6 and Ursula Creek; Fig. 6). The precise horizons from which the conodont samples were obtained are indicated on the sections identified herein. These samples provide a means of calibrating the chemofacies with the global integrated ammonoid-conodont biostratigraphic zonation, which is based in large part on the British Columbia Triassic succession (Tozer, 1994; Orchard & Tozer, 1997; Orchard & Zonneveld, 2009; Golding *et al.*, 2014). Additionally, P/Fe data from wells 16-17-083-25W6, d-48-A/94-B-9, c-74-G/94-B-9, and the outcrop Ursula Creek all indicate high P/Fe within chemofacies 7 and 8, which supports the interpreted correlations.

## **Elemental associations and mineralogy**

### *Results*

The PPMC for each oxide and element was calculated to determine mineralogical associations for each core and the Ursula Creek outcrop (Table 2 and S1 to S6). Values exceeding  $\pm 0.8$  were considered to represent strong positive or negative correlations, where a value of  $\pm 1$  implies perfect positive or negative correlation (Deutsch, 2002). Elements that have a high correlation with each other include;  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$  and  $\text{K}_2\text{O}$  (referred to as the

silicate oxides). CaO correlates negatively with the SiO<sub>2</sub> and positively with MnO and MgO. Of note, Th, Ta, Nb, Rb, Ga and Sc share a high PPMC with the SiO<sub>2</sub>, and negatively correlate with CaO. Nickel and Barium also correlate positively with K<sub>2</sub>O. Hf correlates well with Na<sub>2</sub>O and Zr. As would be expected, the REE correlate strongly with one another.

Bulk results of the XRD analysis (detection limit: 0.5 to 2.0%) reveals the presence of quartz (42 to 71%), dolomite (3 to 20%), microcline (4 to 15%), muscovite (2 to 16%), albite (2 to 9%), diopside (1 to 4%) and accessory minerals (Table 4). Accessory minerals include; pyrite, clinocllore, calcite, ankerite, kaolinite, chlorapatite, fluorapatite, brookite, siderite and magnesian calcite. Within the XRD sample set quartz is consistently the most abundant mineral, followed by dolomite.

Principal component analyses were conducted on all data sets and plots of eigenvector one versus two were produced (Fig. 7). Four major, consistent elemental clusters are observed within the plot series. A cluster of elements, termed the heavy element cluster, occurs in the centre and includes Mo, Zn, V, W, Ni and Cr. The REE and Y occur together in all plots and are referred to as the REE+Y cluster. K<sub>2</sub>O, Rb, Al<sub>2</sub>O<sub>3</sub>, Nb, TiO<sub>2</sub>, Ga, Ta, Cs, Be and Sc also occur in close association and comprise the Al<sub>2</sub>O<sub>3</sub> cluster. MnO, MgO, and CaO generally plot very closely together and are defined as the MgO group. Interestingly, in well c-74-G/94-B-9, CaO occurs in a cluster with Sr, P<sub>2</sub>O<sub>5</sub> and U, separate from MgO and MnO (Fig. 7F). Na<sub>2</sub>O occurs apart from major clusters, and is associated with various other elements (Cr, Cu, Sn, Be, Zn, Co, Ni and Pb). TiO<sub>2</sub> clusters with Nb in all plots. Chromium is observed to occur in association with varying elements (Ni, Sr, Ce and Co) but is often isolated from the major clusters (Fig. 7D). Zirconium occurs in close proximity to Hf in all plots. SiO<sub>2</sub> occurs in isolation in the plots for wells 11-20-082-02W6 and 2-30-070-24W5. In the remaining wells and outcrop, SiO<sub>2</sub> occurs in association with the Al<sub>2</sub>O<sub>3</sub> cluster.

Fe<sub>2</sub>O<sub>3</sub> plots with S in the plots for Ursula Creek and wells 16-17-083-25W6, d-48-A/94-B-9, and c-74-G/94-B-9. These two elements are closely associated in well 11-20-082-2W6, and plot near the Al<sub>2</sub>O<sub>3</sub> cluster. Strontium is often closely associated with CaO (Fig. 7A, C, D and F).

### *Interpretation*

Principal component analysis has been an integral tool for assessing the mineralogy in a number of chemostratigraphic studies (e.g. Pearce *et al.* 2005; Pearce *et al.*, 2010). Mineral affinities identified by this method (Pearce *et al.*, 2010) are presented in Table 3. The close proximity of Hf and Zr in the eigenvector plot suggests the presence of zircon despite the apparent lack of zircon in XRD analyses. Hafnium, Zr and Cr are also associated with Cr-spinel; however, this phase was also not identified in the XRD data. It is possible that both zircon and Cr-spinel phases are present but at levels below the detection limit for XRD. The co-occurrence of TiO<sub>2</sub>, Nb, Ta and Th is explained by the presence of rutile, detected during XRD analysis. The proximity of U and REE to P<sub>2</sub>O<sub>5</sub> suggests scavenging of these elements by phosphatic debris. This is consistent with the identification of both fluorapatite and calcium phosphate in XRD analysis.

Al<sub>2</sub>O<sub>3</sub> and Ga are associated with kaolinite, while the close proximity of K<sub>2</sub>O, Rb, and Cs is accounted for by the presence of illite/smectite. Given that K<sub>2</sub>O plots much closer to SiO<sub>2</sub> than to Rb and Cs, it is likely that K-feldspar is present in a higher concentration than these clays. This interpretation is supported by the XRD data, which shows high concentrations of microcline (Table 4).

The association of MnO and MgO is explained by the presence of dolomite, which is consistent with the XRD results. CaO plots slightly away from both MnO and MgO, suggesting the presence of minor calcite cement. Indeed, calcite, as a distinct phase, occurred only in minor amounts in samples analyzed by XRD.

## **Provenance**

### *Results*

Plotting La/Sm versus Yb/Sm (after Plank & Langmuir, 1998; Fig. 8) reveals a similar trend between the sample sets of 16-17-083-25W6 and Ursula Creek. A strong linear trend is visible, overprinted by a data cluster near the origin. Data points with the highest values of La/Sm and Yb/Sm occur in chemostratigraphic interval 8. Data from well 2-30-070-24W5 exhibit a clustering trend similar to that seen in 16-17-083-25w6, with a slight vertical spread. Data points from well 11-20-082-02W6 are consistently moderate in La/Sm and Yb/Sm values, and no linear trend is apparent. As observed in the data from 16-17-083-25W6 and Ursula Creek, data for wells d-48-A/94-B9 and c-74-G/94-B-9 display a central cluster and a positive, linear trend.

Plots of Th/Sc (felsic) versus Cr/Th (mafic) after Bracciali *et al.*, (2007) are shown in Figs 9 and 10 and reveal a near vertical trend in all data sets with low values of Cr/Th. Data points from the Belloy Formation (Chemofacies 1) exhibit high Cr/Th and low Th/Sc values. Samples from the Doig Formation (Chemofacies 13) occur as a spread of points between the main linear trend and the Belloy outliers. Samples from chemostratigraphic interval 8 plot in an arc between the main linear trend and Doig Formation data points. Generally, stratigraphically older Montney data points plot closer to the origin, with increasing Th/Sc content associated with stratigraphically younger points.

### *Interpretation*

Plotting La/Sm versus Yb/Sm can help differentiate continental, hydrothermal and volcanic arc sediment sources (Plank & Langmuir, 1998). Most data (from all sample sets) plot within the zone of continental detritus and clay scavenging. The exceptions to this are high La/Sm and Yb/Sm data points associated with the sample sets from 16-17-083-25W6 and Ursula Creek, which suggest hydrothermal input. These hydrothermally influenced samples occur within chemofacies 8, and, when compared to the work of Golding et al. (2014), are Spathian in age.

Upper crustal (felsic) and mantle (mafic and ultramafic) sources of sediments contain unique geochemical signatures expressed in the Th, Sc and Cr content. Felsic sources are indicated by high Th/Sc and low Cr/Th signatures, while mafic and ultramafic sources have characteristic high Cr/Th and low Th/Sc values (Bracciali *et al.*, 2007). The increase in felsic content in stratigraphically younger samples suggests a gradual change in sediment source over time. This could be attributed to a gradual change in riverine output/sourcing (possibly related to climate and weathering) or could represent the introduction of a completely new sediment source (such as an approaching terrane). The approach of a new terrane is entirely feasible as terrane accretion is thought to have begun by the Early-Middle Triassic (Beranek & Mortensen, 2011).

### **Biogenic versus abiotic carbonate**

#### *Results*

The data plots of Sr versus Mg (Fig. 11) reveal a low angle, positive linear trend with Sr levels generally remaining below 400 ppm. A high-Sr, low-Mg outlier (16-17-083-25W6), indicating Sr levels of over 700 ppm, corresponds to a depth of 2440.2 m. Scatter in the Sr values

appear related to the low-Mg samples (<30000 ppm Mg). Scatter in Mg values occurs in the samples of high-Mg content (30000 to 60000 ppm Mg). These values follow the abiotic trend of values published by Carpenter & Lohmann (1992).

### *Interpretation*

Non-skeletal, calcite cements have been shown to contain significantly less Sr than biotic marine calcite (Carpenter & Lohmann, 1992). When Sr–Mg trends are compared, biotic calcite values can be up to five orders of magnitude higher than abiotic calcite, offset by *ca* 1250 ppm (Carpenter & Lohmann, 1992). Biotic calcite trends between low values (Sr= 1400 and Mg = 2000) and high values (Sr = 2600 and Mg = 56000), while abiotic calcite trends between Sr/Mg of 300/10000 and 1300/50000; abiotic calcite exhibits significantly lower Sr values (Carpenter & Lohmann, 1992).

With the understanding that abiotic calcite is the predominant phase, zones of calcite cement were interpreted to be present where positive excursions in CaO and Sr occurred in association with low concentrations of MgO, MnO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> (Fig. 12). Strontium can be associated with minerals such as gypsum, anhydrite, strontianite and celestite, in addition to calcite and aragonite (Banner, 1995). Data from wells examined here demonstrate a close correlation between CaO and Sr in the principal component analysis. Furthermore, XRD analysis did not identify the presence of gypsum, anhydrite, strontianite, or celestite, thus supporting the interpretation that calcite is the principal Sr-bearing mineral. Within well 16-17-083-25W6, zones of calcite cement occur within chemofacies 5, 7 and 11; the highest frequency of calcite occurrence is within chemofacies 7.

Calcite is probably a cement phase as evidenced by the Sr–Mg plot (Fig. 11). The data in this study clearly trends along the abiotic vector, with Sr values well below 1000 ppm (*cf.*

Carpenter & Lohmann 1992). The outlier with the highest Sr content (over 700 ppm) is from an interval identified as having been sourced from high sediment recycling (Fig. 2).

Therefore, the high Sr values in this sample may reflect increased weathering input (Pett-Ridge *et al.*, 2009).

Dolomite-rich horizons were identified as having high CaO content and being enriched in MgO and MnO. The presence of MnO within dolomite has been confirmed in cathodoluminescence studies of dolomite (e.g. Pierson, 1981). Dolomite-rich horizons were observed within the majority of chemofacies for well 16-17-083-25W6, with the notable exceptions being chemofacies 4 and a large portion of chemofacies 10 and 11.

## **Hydrothermal Indicators and iron mineral phase changes**

### *Results*

Using the data set from well 16-17-083-25W6, a depth plot of P/Fe (Fig. 13) reveals low values overall, below 0.1. Positive excursions in this ratio occur mid-section and also near the top of the section. The two intervals with the highest P/Fe values occur at a depth of 2375 m (values approaching 1) corresponding to chemofacies 8, and within the Doig Formation above 2260 m depth, where values reach as high as 8. The Ursula Creek data set also exhibits values within the range of those observed in the key data set, 16-17-083-25W6; specifically high values are observed in chemofacies 7 and 8 (Fig. 14). Samples from wells d-48-A/94-b-9, c-74 g-94-B-9, and 2-30-070-24W5 also exhibit similar P/Fe value ranges for chemofacies 7, 8 and 13 (the Doig Formation). Well 11-20-82-2W6 shows consistently high P/Fe values evident in chemofacies 4, 5 and 6.

To further investigate possible hydrothermal effects, chondrite-normalized plots of REE were constructed for all depths within the most complete sample set (UWI 16-17-083-

25W6). This reveals severe middle rare earth element (MREE) depletion at depths of 2367.6 m and 2368 m (Figs 13 and 15). At these intervals, values of Nd, Sm, Eu, Gd, Tb, Dy, Ho and Er plot well below the values observed in surrounding intervals (Fig. 15). A depth plot of Fe/S (Fig. 13) from the type well 16-17-083-25w6 reveals relatively low ratio values (averaging 20) in samples below 2400 m depth. Negative excursions to values below 5 occur at 2401 and 2440 m depth. Above 2400 m, the ratio value increases to over 60, remaining high until 2260 m depth. Iron/sulphur values return to low levels (averaging 20) at 2260 m depth.

### *Interpretation*

The ratio of P/Fe has been evaluated in hydrothermal deposits, with hydrothermal plume deposits yielding a P/Fe value of 0.12 to 0.23 (Feely *et al.*, 1994; Wheat *et al.*, 1996). Data sets located proximally to one another, from 16-17-083-25W6, Ursula Creek, c-74-G/94-B-9, and d-48-A/94-B-9, show P/Fe values within chemofacies 7 and 8 that fall within the range identified for hydrothermal plumes (between 0.12 and 0.23) by Feely *et al.* (1994). High P/Fe values also occur in the Doig phosphate zone (chemofacies 13; Fig. 13), but REE plots within the Doig samples show no evidence for high temperature hydrothermal input. Therefore, this signature is interpreted here to represent the input of hydrothermal plume particles enriched in Fe. This would also explain the P/Fe values observed within data sets 11-20-82-2w6 and 2-30-70-24W5.

Additionally, the molar ratio of Fe/S has been used to determine relative abundance of pyrite; ratio values near 2 signify the dominance of pyrite as the Fe-incorporating phase (Zhao & Zheng, 2015). A change in this ratio can signify a change in Fe-bearing phase (such as Fe-hydroxide, which can be related to hydrothermal plumes). A depth profile for Fe/S

within the key data set (16-17-083-25W6) shows that, at approximately 2400 m, there is a switch in the relative abundance of pyrite as a major iron phase to Fe (III) oxyhydroxides and clays (Fig. 13). Increased Fe/S values of this phase occur near the phosphate excursion indicating the possibility of Fe (III) oxyhydroxide plume particles being deposited. Furthermore, the sample sets from 16-17-083-25W6, Ursula Creek, and d-48-A/94-B-9, show a strong signature of hydrothermal input as indicated by high La/Sm and Yb/Sm outliers (Plank & Langmuir, 1998; Fig. 8). These hydrothermal signatures are associated with dolomitization in chemofacies 8.

## **DISCUSSION**

### **Hydrothermal Input and Implications**

The evidence of hydrothermal input co-occurring with dolomitization suggests that hydrothermal input to deeper water regions, possibly associated with basin margin faults, may have been a source of dolomitizing fluids in the Montney Formation. This would necessitate that hydrothermal input occurred post-depositionally. Chondrite-normalized plots for these samples indicate severe depletion of MREE (Fig. 15). A similar depletion was documented by Lev *et al.* (1999) and attributed to MREE sequestration by phosphate, then subsequent dissolution and a concomitant loss of P and MREE. Dissolution of phosphatic phases (such as apatite) may be promoted when sediments are exposed to hydrothermal fluids. However, evidence for high levels of hydrothermal plume activity complicates the timing of hydrothermal input. An alternative removal pathway for phosphate involves the adsorption onto Fe–Mn oxyhydroxides within hydrothermal plumes, resulting in transport to more distal environments (Wheat *et al.*, 1996). This adsorption severely depletes the seawater phosphate concentrations surrounding the hydrothermal plume and high P/Fe

values, observed in this study's data set, can be considered to indicate hydrothermal Fe particle scavenging of P (Feely *et al.* 1994; Wheat *et al.* 1996). Hydrothermal plume inputs have also been suggested to explain high levels of trace elements, such as Cu, in Cretaceous black shales (Brumsack, 2006). Such a mechanism would be consistent with the high levels of Cu observed in the present data in association with high P/Fe and depleted MREE.

The timing of this hydrothermal flux is uncertain, although it does appear to coincide with the dolomitization identified in chemofacies 8 (Fig. 12). The involvement of hydrothermal fluids has two implications. First, there is the potential for trace element signatures to have been diagenetically altered proximal to this stratigraphic interval. However, hydrothermal alteration of underlying sediment appears to have been negligible owing to the presence of phosphatic lenses and nodules. The REE signature characteristic of the hydrothermally influenced interval indicates possible phosphate dissolution or scavenging by hydrothermal activity but it seems unlikely that the phosphate would be preserved at this lower stratigraphic interval if hydrothermal alteration had taken place. Second, hydrothermal fluids could also provide a mechanism for the observed dolomitization within the Montney Formation. This is significant as it has implications regarding the propagation of fractures, as dolomite and calcite contribute to the brittleness and hence the ability to generate fractures within a horizon compared to dominantly clay-rich layers (Jin *et al.*, 2015).

### **Climate Change in the Early Triassic**

This study demonstrates a marked shift in the nature of the clay component, as indicated by the geochemical proxies, as well as the average amount of clay over time (Fig. 4). There are marked changes in clay proportions, such as the change in abundance of illite to kaolinite and smectite, and the occurrence of chlorite. These transitions are of interest because they correspond to chronostratigraphic boundaries, namely the Permian/Triassic boundary, the Smithian/Spathian boundary, and the Early/Middle Triassic boundary (Fig. 16), all of which are important sequence stratigraphic boundaries in the Montney Formation (Zonneveld *et al.*, in press).

Li *et al.* (2000) and Chaudhri & Singh (2012) highlight the lithological and climatic drivers behind changes in clay content, although climate analysis using clay alone, should be interpreted with caution (Thiry, 2000). With regards to lithology, illite may be detrital, having been weathered from feldspars and micas, while chlorite is produced from the weathering of crystalline intermediate and basic, or low grade metamorphic rocks (Chaudhri & Singh, 2012). Detrital illite is attributed to physical erosion being the predominant process within the hinterlands (Ruffell & Batten, 1990; Ruffell *et al.*, 2002a). In contrast, kaolinite forms from the weathering of basic and granitic sources (Chaudhri & Singh, 2012). Additionally, as kaolinite is more prone to flocculation than other clays (*e.g.* Playter *et al.*, 2017), the relative abundance of detrital kaolinite can indicate the relative source proximity (Ruffell *et al.*, 2002a,b). The abundance of detrital kaolinite also increases with humid weathering (Chamley, 1989, Ruffell *et al.*, 2002a,b). Smectite forms in seasonally dry and wet climates, although smectite and kaolinite can also be a product of volcanic ash deposition (Chamley, 1989, Li *et al.*, 2000, Ruffell *et al.*, 2002a,b).

The high average values of illite, and higher overall clay component in the pre-Smithian/Spathian boundary samples here, suggest high rates of physical erosion. This is consistent with observations from Early Triassic (Griesbachian) deposits in China, where anomalously high sediment fluxes, with clay-rich compositions were observed (Algeo & Twitchett, 2010). These high sedimentation rates have been hypothesized to be related to higher surface temperatures, increased acid rain and the loss of terrestrial ecosystems owing to the end-Permian Siberian Trap eruptions (Algeo & Twitchett, 2010). The arid Pangean western coastline, where the Montney Formation was deposited, was probably characterized by rare perennial deltas and more numerous ephemeral fluvial sediment sources (Zonneveld & Moslow, 2014; Zonneveld *et al.*, in press). Seasonal or intense periodic rainfalls in an arid, sparsely-vegetated interior would have resulted in high rates of erosion and sediment delivery during periodic flash floods.

The shift to smectite and kaolinite content at the Smithian/Spathian boundary may correspond to an observed change in the Early Triassic climate regime. At this time within eastern Pangea, a shift in climate from humid, with higher rainfall to more arid is observed through ammonoid and plant fossil assemblages (Galfetti *et al.*, 2007a,b; Romano *et al.*, 2013). On the west coast of Pangaea, arid conditions already existed, although a shift to an even more arid climate would correlate with an increase in smectite content observed in samples from this study (Ruffell *et al.*, 2002a, b). Additionally, a decrease in rainfall across this boundary, and a concomitant decrease in the proportion of sediment delivered by perennial river systems versus that delivered by ephemeral fluvial systems, is consistent with the observed drop in clay content. Interestingly, the points of highest detrital input, and the lowest relative sea-level, correspond to the climatic shift at the Smithian/Spathian boundary and the Early Triassic/Middle Triassic transition. Generally speaking, climatic

changes may then correspond to longer-term shoreline shifts. Although it could be argued that the changes in detrital and clay indicators may reflect fluctuations in the fluvial system due to climate or hinterland changes, the correspondence of the shoreline (current study) shifts with those of Davies *et al.* (1997) suggest that these proxies accurately model relative sea-level changes. Additionally, if these changes indeed reflect shifts in fluvial input associated with climate, the observed modelled climate changes would be expected to correspond to each inferred shoreline shift. Based on these observations, the changes in clay and detrital input are interpreted to be reflective of relative sea-level change.

### **Identification of clinofolds and implication for sequence stratigraphy in fine-grained successions**

The chemostratigraphic correlation presented here implies that the sample sets from western Alberta (11-20-082-2W6 and 2-30-070-27W5) are lacking the uppermost chemostratigraphic intervals observable in British Columbia (Fig. 6). This signifies a significant loss of strata that could be the result of considerable erosion following clinofold deposition, as first suggested by Davies *et al.* (1997). The Montney/Doig contact has been recognized as being unconformable and chronostratigraphic, corresponding to the Lower/Middle Triassic boundary (Davies *et al.*, 1997). The model of Montney Formation deposition presented herein shows that the 'Upper Montney' of Alberta is, in fact, temporally equivalent to the lower horizons in British Columbia (Fig. 17).

The identification of clinofold surfaces within the current study's data set suggests that geochemical data, such as detrital and clay proxies, can be used to identify stratigraphic sequences. Because the detrital signatures used for correlation show consistent and correlatable patterns in all of the data sets (which span the palaeobasin), and these

signatures tie into relative sea-level and climatic changes observed elsewhere, with the chemostratigraphic units appearing to be chronostratigraphic in nature and not merely lithostratigraphic. The identification of stratigraphic sequences using chemostratigraphic analysis in the past has been done largely using isotopic analysis, such as  $\delta^{13}\text{C}$  or  $\delta^{15}\text{N}$  (e.g. Pelechaty, 1998; Nance & Rowe, 2015), while correlations have relied heavily on biostratigraphic frameworks (e.g. Bergström *et al.*, 2010). In contrast, results in this study suggest that inorganic chemical analysis, which can be generated both non-destructively and *in situ* using a portable X-ray fluorescence spectrometer (Rowe *et al.*, 2012), allow for the identification of depth-bound chemofacies corresponding to subsurface clinoforms in fine-grained successions on a basin-wide scale. Indeed, cyclic variations in sediment provenance have already been identified as allowing for the identification of transgressive surfaces in alluvial, littoral and shallow-marine deposits from Italy (Amorosi, *et al.*, 2007). In this case, transgressive surfaces were found to correspond to peaks in Ni/Al content, and maximum flooding surfaces were characterized by high Mg/Al values that correspond to a change in sediment sourcing during shoreline migration. While Amorosi *et al.* (2007) focused on two wells, the correlation of these peaks in Ni/Al and Mg/Al within a regional cross-section would, in theory, produce clinoform surfaces.

Perhaps some of the most well-documented and well-studied instances using geochemical data to demonstrate relative sea-level changes in the literature involve Cretaceous deposits. For example, a state of low relative sea-level has been identified in Late Cretaceous deposits that correlates with increased terrigenous input, low kaolinite/chlorite + mica ratios, high Sr/Ca ratios, and high TOC; conversely, high relative sea-level may generally be associated with the inverse of these indicators (Li *et al.*, 2000). This correlation of detrital input with relative sea-level has also been demonstrated in

Cretaceous deposits (Adatte *et al.*, 2002; Chenot *et al.*, 2016; Keller *et al.*, 2016; Petrash *et al.*, 2016). In fact, changes in clay content and detrital input have been recognized as providing reliable relative sea-level proxies, as well as climate, even in deep marine environments (Li *et al.*, 2000). During periods of transgression and rising sea-level, clay input predominates, while during regression and relative sea-level fall, detrital input increases (Fig. 16).

When compared with second and third order relative sea-level curves for the Early Triassic (Haq *et al.*, 1987; Embry & Gibson, 1995; Davies *et al.*, 1997), this data correlates well by showing instances of relative sea-level fall at the end of the Dienerian, the end of the Smithian, within the Spathian, and at the end of the Spathian (Fig. 16). While global correlations of sea-level can be problematic, the proxies used for detrital input (Sc/Zr and Lu/Hf) and clay input (Zr/La) provide reliable information about basin-scale relative sea-level change. Consistency in these signatures across the basin indicates that causative events were regional in nature, allowing for clinofolds to be delineated. In addition to surfaces inferred to be global in nature (Barclay *et al.*, 1990; Davies *et al.*, 1997), three additional periods of relative sea-level rise and marine transgressions are suggested by the data. Additional relative sea-level rises occur within the Griesbachian, Dienerian and Spathian. Whether these reflect localized tectonic influences, or larger-scale sea-level changes, remains unclear. It has been suggested that the basin margin was tectonically active during deposition of the Montney Formation, and therefore, tectonic activity may be the driving factor. Fault reactivation and subsidence within the graben complexes of the collapsed Peace River Arch is thought to have influenced Montney deposition (Barclay *et al.*, 1990; Davies *et al.*, 1997). The collapsed Peace River Arch forms the basis for the Peace River Embayment, wherein the Montney Formation was deposited. In addition, recent evidence

has indicated that accretion of pericratonic terranes to the northwestern autochthon was initiated during the Lower Triassic (Beranek *et al.*, 2010). These terrane accretions would have had broad regional influences and may have been a primary driving force in relative sea-level throughout the studied interval (Ferri & Zonneveld, 2008), specifically with regards to the additional sea-level changes noted within the current data set.

An active tectonic margin agrees well with observations in this study of felsic signatures and the pattern of change the data exhibits stratigraphically. Felsic signatures, as recorded by elevated Th/Sc and Cr/Th cross-plots (Condie & Wronkiewicz, 1989; Totten *et al.*, 2000; Bracciali *et al.*, 2007), have been identified in well 16-17-83-25W6 (Fig. 9). The increase of felsic input up-section (Fig. 9) may be associated with the approach of the Yukon-Tanana terrane from the west (Beranek & Mortensen, 2011), and partial contribution from a western sediment source to Montney sediments. Detrital zircon and monazite analyses (Beranek & Mortensen, 2011) indicate that the Yukon–Tanana terrane was situated just off the west coast of Pangaea by the Early–Middle Triassic and that by the late Triassic the terrane had been fully accreted onto the continental margin. The cross-plots of La/Sm and Yb/Sm in this study suggest volcanic arc signatures within the Doig samples (Fig. 8), indicating that terrain accretion was well underway by the Anisian. This approaching terrane may be linked to fault reactivation and hydrothermal activity, specifically related to the horst and graben complexes associated with the collapsed Peace River Arch within the basin during the Early Triassic (Ferri & Zonneveld, 2008). This, in addition to the migration of the back-bulge associated with the approaching terrane, could explain why the additional relative sea-level changes, identified in this study’s data, have not been recognized globally.

## CONCLUSIONS

The goal of this study was to demonstrate the applicability of chemostratigraphic analysis for determining chronostratigraphic surfaces in fine-grained successions, using the Triassic Montney Formation as a field example. Utilizing geochemical trends to highlight changes in provenance, mineralogy, clay and detrital input proved useful in pinpointing changes in relative sea-level, climate change and hydrothermal input. Analysis of geochemical profiles revealed 13 distinct chemofacies that can be identified across the basin. Correlation of these facies reveals broad clinoform surfaces that indicate the upper Montney Formation in Alberta is temporally equivalent to lower-mid-Montney deposits in British Columbia. Additionally, analysis of clay proxies indicates high sedimentation rates within the Griesbachian and Dienerian Montney deposits and a correspondent shift in climate and sediment sourcing that is observable at the Smithian/Spathian boundary. This climatic shift is indicated by the point of highest detrital input and lowest relative sea-level within the preserved Montney deposits.

Cross-plots of La/Sm and Yb/Sm probably reveal hydrothermal input during the time immediately following the Smithian/Spathian boundary, as well as the scavenging of middle rare earth elements (MREE) by phosphate. Depleted MREE patterns within these hydrothermally influenced samples are suggestive of either the dissolution of phosphatic debris by hydrothermal fluids and loss of MREE, or the primary scavenging of phosphate by hydrothermal plume particulates and subsequent loss of MREE. These observations coincide with dolomite-rich horizons suggesting that hydrothermal fluid interaction accounts for at least part of the dolomitization within the Montney Formation. The presence of phosphatic debris immediately below this interval suggests that the diagenetic influence from the hydrothermal fluids was localized.

Additionally, early accretion of the Yukon–Tanana terrane is surmised to have occurred by the Early Anisian. This is supported by cross-plots of Th/Sc versus Cr/Th, which indicate increasing felsic input up-section. Moreover, plots of La/Sm versus Yb/Sm show volcanic arc input within the Doig Formation. Collectively, these lines of evidence imply an additional, western source of sediment input by the Anisian. This is significant as it supports the early-terrane accretion model (*e.g.* Beranek *et al.*, 2010) which argues that accretion began during the Triassic along the western coast of Canada.

Overall, this study demonstrates that geochemical trends can be used to correlate fine-grained successions and highlight detailed, chronostratigraphic changes such as relative sea-level, hydrothermal input and climate when lithological homogeneity and poor palaeontological control exist.

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### **Figure Captions**

**Fig. 1.** Palaeogeographic map outlining the location of all sample sets. Map after Zonneveld *et al.* (2011) and Blakey (2011). Sample locations are denoted by circles, an outcrop location is shown by an x and the type well is also marked. Locations of sample sets are as follows: (A) Ursula Creek outcrop; (B) 16-17-083-25W6; (C) c-74-G/94-B-9; (D) d-48-A/94-B-9, (E) 11-20-082-02W6; and (F) 2-30-070-24W5.

**Fig. 2.** Detrital indicator profiles for well 16-17-083-25W6. Depths are in metres. Chemofacies are numbered from 1 to 13 (right). Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. 3.** Provenance indicator profiles for well 16-17-083-25W6. Depths are in metres. Chemofacies are numbered from 1 to 13 (right). Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. 4.** Clay indicator profiles for well 16-17-083-25W6. Depths are in metres. Chemofacies are numbered from 1 to 13 (right). Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. 5.** Mineralogical indicator profiles for well 16-17-083-25W6. Depths are in metres.

Chemofacies are numbered from 1 to 13 (right). Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. 6.** Line of cross-section illustrating the correlation between all sample sets used in this study: (A) Ursula Creek Outcrop; (B) 16-17-083-25W6; (C) c-74-G/94-B-9; (D) d-48-A/94-B-9; (E) 11-20-082-02W6; and (F) 2-30-070-24W5. The Spathian/Anisian (Lower/Middle Triassic) boundary was chosen as the datum as it is a chronostratigraphic boundary definitively present in all data sets. Gamma ray logs and Zr/La profiles are shown. Zones of correlated conodont horizons are indicated by stars. Of note is the loss of upper chemofacies in wells C and D and in the two Alberta wells (E and F; chemofacies 9 to 13 are not observed). This can be explained by a combination of erosion and clinoform deposition. Also of interest is the thickening of the lower chemofacies in wells E and F, further supporting a clinoform model of deposition.

**Fig. 7.** Eigenvector plots of e1 versus e2 for all data sets. (A) Eigenvector plot of well 16-17-083-25W6. Elemental clusters are indicated by black polygons: the MgO cluster (top), the heavy element cluster (central), REE+Y cluster (right) and Al<sub>2</sub>O<sub>3</sub> cluster (left). (B) Eigenvector plot of well 11-20-082-02W6. (C) Eigenvector plot of well Ursula Creek. (D) Eigenvector plot of well d-48-A/94-B-9. (E) Eigenvector plot of well 2-30-070-24W5, and (F) Eigenvector plot of well c-74-G/94-B-9.

**Fig. 8.** Geochemical plots showing the distribution of light rare earth elements (LREE; y axis) versus heavy rare earth elements (HREE; x axis), after Plank and Langmuir (1998). (A) The influence of hydrothermal input, continental detritus, arc volcanics and clay sequestration are illustrated in the plot for well 16-17-083-25W6 sorted by chemofacies. (B) Plot for well 11-20-082-02W6. (C) Plot for Ursula Creek. (D) Plot for well d-48-A/94-B-9. (E) Plot for well 2-30-070-24W5. and (F) Plot for well c-74-G/94-B-9.

**Fig. 9.** Geochemical plot of the data from well 16-17-083-25W6 illustrating the influence of felsic (Th/Sc) versus mafic (Cr/Th) input (after Bracailli *et al.*, 2007). Felsic, mafic and ultramafic trends are illustrated. Data points are coloured based on chemofacies (legend on the right). Doig samples (chemofacies 13), Belloy samples (chemofacies 1), and chemofacies 8 samples all show mafic, and ultramafic input. Additionally, felsic content increases stratigraphically upward (note change in facies colour along the y-axis).

**Fig. 10.** Geochemical plots illustrating the influence of felsic (Th/Sc) versus mafic (Cr/Th) input (after Bracailli *et al.*, 2007) for data sets: (A) 11-20-082-02W6; (B) Ursula Creek; (C) d-48-A/94-B-9; (D) 2-30-070-24W5; and (E) c-74-G/94-B-9.

**Fig. 11.** Cross-plot of Sr versus Mg values for the well 16-17-083-25W6. Biotic and abiotic trends are shown from Carpenter & Lohmann (1992). Biotic and abiotic trends are shown from Carpenter & Lohmann (1992).

**Fig. 12.** Oxide, Sr and Ba profiles for well 16-17-083-25W6 with calcite cementation zones indicated by red and dolomite-rich zones highlighted in grey. Peaks in Sr correlate with calcite-rich zones. The gamma ray profile is given on the left.

**Fig. 13.** Depth-plot illustrating the variation in the ratio of Fe/S, P/Fe (samples showing MREE depletion are shown) and Cu for well 16-17-083-25W6. Zones of high P/Fe are indicated by red bars. Depth is in metres (*y*-axis). Within the plot of Fe/S, at depth 2400 m, the character of the ratio value changes from low to high, suggesting a switch in the dominant iron-bearing phase from pyrite to iron oxyhydroxide.

**Fig. 14.** Phosphorus/iron values for wells 2-30-070-24W5, 11-20-082-02W6, c-74-G/94-B-9, d-48-A/94-B-9 and Ursula Creek. Intervals with values greater than 0.12 (the lower limit of hydrothermal influence) are highlighted in green.

**Fig. 15.** Rare earth element (REE) plots showing the typical pattern observed in the sample set compared to anomalous patterns observed at 2367.6 m and 2368 m: REE data are normalized to chondrite values and MREE deletion is clearly illustrated for depths of 2367.6 m and 2368 m.

**Fig. 16.** Interpreted sea-level change based off of changes in detrital input proxies and clay indicators. This data set has been biostratigraphically dated (Golding *et al.*, 2014).

Additionally, relative sea-level curves from Davies *et al.* (1997) have been incorporated along the left. These inferred shoreline shifts (central) agree with that of Davies *et al.*

(1997), with the exception of two additional shoreline shifts within the present data during the Griesbachian and Dienerian. Ratio values of Sc/Zr, Lu/Hf, and Zr/La are indicated by log-scale along the top of the figure.

**Figure 17** Idealized cross-section highlighting Montney stratigraphy from British Columbia to Alberta (west to east). The clinoform model of Montney deposition is not new, but was first proposed by Davies *et al.* (1997). However, this new model highlights surfaces of significant erosion, missing from earlier models. These surfaces (such as surface 1) are often associated with sequence boundaries, first described by Davies *et al.* (1997). Additionally, what is often referred to in Alberta as the 'basal Doig siltstone' is here shown to be equivalent to the upper Montney in British Columbia and is equivalent to chemofacies 8 to 12. The mid-Montney boundary varies across provincial boundaries. Within British Columbia, the mid-Montney boundary corresponds to the Smithian/Spathian boundary, while in Alberta, the mid-Montney boundary occurs at the Dienerian/Smithian transition. Thinning of the upper Montney (denoted by the Smithian/Spathian boundary) eastward results in the loss of Spathian deposits in Alberta. Within this cross-section the following boundaries of interest are depicted: (1) Alberta mid-Montney sequence boundary – associated with Montney turbidites and Coquinal Dolomite Middle Member; (2) British Columbia mid-Montney sequence boundary / Alberta top-Montney – basal Doig siltstone boundary. This boundary is the Hood Creek Road Cut sequence boundary with the large *Thalassinoides*; (3) Unconformity below the 'Anisian wedge'; (4) boundary between the Montney and Doig phosphate zone. The rough extent of the Basal Doig siltstone (which marks the presence of Spathian deposits, chemofacies 8 to 12) in Alberta is indicated bottom right.

**Table 1.** Summary of the variables used in PCA/cluster analysis.

**Table 2.** Summary table illustrating high (>0.8) and low (<-0.8) Pearson product-moment correlation values for certain elements. High correlation values are indicated in green; negative correlation is identified by red.

**Table 3.** Mineral occurrence of elements discussed in Pearce *et al.* (2010), who also referred to the work of Morton *et al.* (2005) and Pearce *et al.* (2005).

**Table 4.** X-ray diffraction (XRD) analysis for select intervals of well 2-30-070-24W5. The limit of detection varies from 0.5 to 2.0% depending on crystallinity.

**Table 5.** Calculated values for detrital proxy data within each chemofacies, from the type data set (16-17-083-25W6), including maximum, minimum and average values. These values were compared with the overall average values for this data set ( $\text{TiO}_2/\text{Al}_2\text{O}_3 = 0.0657$ ,  $\text{Sc}/\text{Zr} = 0.0353$ ,  $\text{Lu}/\text{Hf} = 0.0632$  and  $\text{TiO}_2/\text{K}_2\text{O} = 0.192$ ). Values above the overall average appear in green; values below the overall calculated average appear in red.

**Table 6.** Calculated values for clay proxy data within each chemofacies from the type data set (16-17-083-25W6), including maximum, minimum and average values. These values were compared with the overall average values for this data set ( $\text{Ga}/\text{Rb} = 0.14$ ,  $\text{K}/\text{Rb} = 330.75$ ,  $\text{Rb}/\text{Al} = 0.0017$ ,  $\text{Cr}/\text{Sc} = 7.629$ ,  $\text{Zr}/\text{La} = 9.40$ ,  $\text{Zn}/\text{Sc} = 19.1453$ ,  $\text{K}_2\text{O}/\text{Al}_2\text{O}_3 = 0.347$  and  $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3 = 0.129$ ). Values above the overall average appear in green; values below the overall calculated average appear in red.

**Table 7.** Calculated values for mineralogical proxy data within each chemofacies, from the type data set (16-17-083-25W6), including maximum, minimum and average values. These values were compared with the overall average values for this data set ( $P_2O_5/Al_2O_3 = 0.074$ ,  $Cr/Nb = 6.86$ ,  $Lu/Zr = 0.0016$  and  $Cr/Zr = 0.275$ ). Values above the overall average appear in green; values below the overall calculated average appear in red.

**Table 8.** Calculated values for provenance proxy data within each chemofacies, from the type data set (16-17-083-25W6), including maximum, minimum and average values. These values were compared with the overall average values for this data set ( $Cr/Al = 0.0015$ ,  $Ni/Al = 0.000812$ ,  $Th/Sc = 0.952$ ,  $MgO/Al_2O_3 = 0.523$ ,  $Ti/Nb = 332.45$  and  $Ti/Zr = 13.58$ ). Values above the overall average appear in green; values below the overall calculated average appear in red.

**Table 9.** Interpretation of each chemofacies using the average values generated in Table 5. Interpretation is based on the literature cited in the text.

#### *Supplementary Tables and Figures*

**Table S1.** Pearson product-moment values for well 16-17-083-25W6. Table values greater than 0.8 are highlighted in green while values below -0.8 are highlighted in red.

**Table S2.** Pearson product-moment values for Ursula Creek. Table values greater than 0.8 are highlighted in green while values below -0.8 are highlighted in red.

**Table S3.** Pearson product-moment values for well 2-30-070-24W5. Table values greater than 0.8 are highlighted in green while values below -0.8 are highlighted in red.

**Table S4.** Pearson product-moment values for well 11-20-082-02W6. Table values greater than 0.8 are highlighted in green while values below -0.8 are highlighted in red.

**Table S5.** Pearson product-moment values for well d-48-A/94-B-9. Table values greater than 0.8 are highlighted in green while values below -0.8 are highlighted in red.

**Table S6.** Pearson product-moment values for well c-74-G/94-B-9. Table values greater than 0.8 are highlighted in green while values below -0.8 are highlighted in red.

**Table S7.** Summary of the first ten principal components used for statistically defining the chemofacies.

**Fig. S1.** Clay indicator profiles for well d-48-A/94-B-9. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S2.** Detrital indicator profiles for well d-48-A/94-B-9. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S3.** Mineralogical indicator profiles for well d-48-A/94-B-9. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S4.** Provenance indicator profiles for well d-48-A/94-B-9. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S5.** Clay indicator profiles for well c-74-G/94-B-9. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S6.** Detrital indicator profiles for well c-74-G/94-B-9. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S7.** Mineralogical indicator profiles for well c-74-G/94-B-9. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S8.** Provenance indicator profiles for well c-74-G/94-B-9. Depths are in metres.

Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S9.** Clay indicator profiles for well 11-20-082-02W6. Depths are in feet. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S10.** Detrital indicator profiles for well 11-20-082-02W6. Depths are in feet. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S11.** Mineralogical indicator profiles for well 11-20-082-02W6. Depths are in feet. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S12.** Provenance indicator profiles for well 11-20-082-02W6. Depths are in feet. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S13.** Clay indicator profiles for well 2-30-070-24W5. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S14.** Detrital indicator profiles for well 2-30-070-24W5. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S15.** Mineralogical indicator profiles for well 2-30-070-24W5. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S16.** Provenance indicator profiles for well 2-30-070-24W5. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S17.** Clay indicator profiles for the outcrop Ursula Creek. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S18.** Detrital indicator profiles for the outcrop Ursula Creek. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S19.** Mineralogical indicator profiles for the outcrop Ursula Creek. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S20.** Provenance indicator profiles for the outcrop Ursula Creek. Depths are in metres. Chemofacies are numbered on the right. Simplified interpretations of concentrations are labelled at the base with arrows. For references, refer to the *Elemental Indicators* section in the text.

**Fig. S21.** Comparison of select detrital and clay indicators between wells 2-30-070-24W5 (right) and 16-17-083-25W6 (left) illustrating the identification and correlation of chemofacies in well 2-30-070-24W5.

**Fig. S22.** Comparison of select detrital and clay indicators between wells 11-20-082-02W6 (right) and 16-17-083-25W6 (left) illustrating the identification and correlation of chemofacies in well 11-20-082-02W6.

**Fig. S23.** Comparison of select detrital and clay indicators between wells c-74-G/94-B-9 (right) and 16-17-083-25W6 (left) illustrating the identification and correlation of chemofacies in well c-74-G/94-B-9.

**Fig. S24.** Comparison of select detrital and clay indicators between wells d-48-A/94-B-9 (right) and 16-17-083-25W6 (left) illustrating the identification and correlation of chemofacies in well d-48-A/94-B-9.

**Fig. S25.** Comparison of select detrital and clay indicators between the outcrop Ursula Creek (right) and 16-17-083-25W6 (left) illustrating the identification and correlation of chemofacies in outcrop Ursula Creek.

**Fig. S26.** Litholog for well 16-17-083-25W6. See legend for explanation of symbols used.

**Fig. S27.** Litholog for well d-48-A/94-B-9. See legend for explanation of symbols used.

**Fig. S28.** Litholog for well c-74-G/94-B-9. See legend for explanation of symbols used.

**Fig. S29.** Litholog for the outcrop Ursula Creek.

**Fig. S30.** Graph of the number of clusters vs. similarity between clusters. An inflection point occurs at 12, which is why 12 statistical divisions were chosen. The Belloy Formation, defined by Golding et al. (2014) within this study's data set, was divided out as an additional subdivision (although the division is not statistically significant).

<b>Category</b>	<b>Number of Variables</b>
<b>Oxides</b>	10
<b>Oxide Elements</b>	10
<b>Trace Elements</b>	40
<b>Clay Indicators</b>	7
<b>Provenance Indicators</b>	5
<b>Detrital Indicators</b>	4
<b>Mineral Indicators</b>	6
<b>Grain Size Indicators</b>	2
<b>ALL DATA</b>	<b>84</b>

Element	SiO2	Al2O3	TiO2	K2O	CaO	Na2O	Ta	Zr
Th	Green	Green	Green	Green	Red			
Ta	Green	Green	Green	Green	Red		Black	
Nb	Green	Green	Green	Green	Red		Green	
Rb	Green	Green	Green	Green	Red		Green	
Ga	Green	Green	Green	Green	Red		Green	
Sc	Green	Green	Green	Green	Red		Green	
Co		Green	Green	Green			Green	
Cs		Green						
Be		Green		Green				
Hf						Green		Green
Zr								Black
Ni				Green				Black
Ba				Green				Black
Ce				Green				Black
SiO2	Black	Green	Green	Green	Red			
Al2O3	Green	Black	Green	Green	Red			
TiO2	Green	Green	Black	Green	Red			
K2O	Green	Green	Green	Black	Red			
MgO					Green			

<b>Element</b>	<b>Mineral affinity</b>
Si	Quartz
Al	Clay minerals, mica, kaolinite, gibbsite, bauxite
Ti, Nb, Ta	heavy minerals such as rutile, anatase and Ti-bearing minerals (leucoxene and ilmenite)
Fe	Fe oxyhydroxides (goethite and hematite), ferroan dolomite, pyrite, siderite
Ca, Mn, Mg, Sr	siderite, dolomite, calcite, clays (Mg associated with chlorite)
Na	clay minerals, halite
K, Rb, Cs	illite, mica, K-feldspar
P	clays (illite), mica, siderite (in association with Fe, Mn and REEs), biogenic phosphate (associated with U, Mo, Ca and Ce)
Zr and Hf	zircon
Co, Ni, Zn, V, Cu	clay minerals and mica; Ni can be associated with Fe-oxyhydroxides
Th	weathered kaolinite (in association with Al, Ga and Sc), zircon, clay minerals, mica, apatite
U	organics, zircon (associated with Th and Zr)
REE	clay and mica, kaolinite or gibbsite (associated with high Al), Fe-oxyhydroxides, diderite, zircon and garnet
Sc and Ga	kaolinite (in association with Al)
Be, W, and Sn	heavy minerals (beryl and cassiterite), tonstein
Ba	clay and drilling fluid

	1715.8 m	1717.5 m	1719.85 m	1721.5 m	1723.86 m	1725.5 m	1727.35 m	1728.46 m	1730.43 m	1732.1 m
<b>Mineral</b>	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)
Quartz	34.7	43.9	54.8	71.8	71.5	50.9	57.6	61.3	73.5	42.4
Dolomite	21.7	18.2	11.3	12.4	10.2	15.1	12.8	11.9	0.6	48.6
Microcline	17.8	8.1	15.1	6.3	5.1	13.1	10.1	8.9	1.1	-
Muscovite	9.1	12.4	5.2	1.9	3.2	6.7	5.4	1.6	2.0	-
Calcite	3.5	5.8	2.1	0.7	1.1	1.1	4.5	6.1	5.3	0.6
Diopside	2.8	3.2	3.1	1.4	1.7	3.1	1.9	2.6	-	-
Albite	2.0	1.5	1.4	1.4	2.0	1.7	2.4	2.7	0.9	1.0
Pyrite	2.8	2.2	2.0	0.5	0.7	2.9	1.0	0.6	3.8	0.3
Clinocllore	1.0	1.6	1.3	0.7	1.1	1.0	1.7	1.4	-	-
Ankerite	0.9	0.8	0.9	0.8	1.0	0.9	0.9	1.0	-	2.3
Kaolinite	2.0	0.3	0.8	0.2	0.3	1.7	0.3	0.4	0.3	-
Chlorapatite	0.5	0.6	0.7	1.0	1.2	0.7	0.5	0.7	-	-
Kutnohorite	0.4	0.7	0.5	0.4	0.3	0.5	0.5	0.5	-	0.8
Brookite	0.4	0.4	0.4	0.3	0.3	0.4	0.3	0.2	-	-
Siderite	0.5	0.3	0.2	0.2	0.2	0.3	0.2	0.2	1.4	0.4
Fluorapatite	-	-	-	-	-	-	-	-	5.2	-
Marcasite	-	-	-	-	-	-	-	-	5.0	-
Calcite magnesian	-	-	-	-	-	-	-	-	0.9	-
Fluorapatite	-	-	-	-	-	-	-	-	-	3.5
TOTAL	100	100	100	100	100	100	100	100	100	100

Chemofacies		Ti/Al	Sc/Zr	Lu/Hf	Ti/K
13	max	0.080849	0.043779	0.173555	0.170706
	min	0.059138	0.005979	0.029456	0.127007
	avg	0.064859	0.031454	0.092964	0.145504
12	max	0.074222	0.030399	0.084082	0.198194
	min	0.063336	0.011721	0.039973	0.165484
	avg	0.068147	0.02187	0.051852	0.179885
11	max	0.076006	0.037303	0.062728	0.18926
	min	0.06199	0.021035	0.047911	0.161212
	avg	0.070189	0.027035	0.054473	0.176587
10	max	0.068321	0.042413	0.087519	0.186066
	min	0.063022	0.026862	0.049446	0.159848
	avg	0.064733	0.033378	0.05982	0.17563
9	max	0.072897	0.039814	0.070306	0.208827
	min	0.060782	0.024184	0.047167	0.178039
	avg	0.0666	0.03026	0.054408	0.197164
8	max	0.071875	0.040722	0.078009	0.201467
	min	0.063023	0.021032	0.047175	0.163489
	avg	0.067303	0.031435	0.057197	0.178699
7	max	0.073922	0.053382	0.120945	0.243106
	min	0.053016	0.016499	0.041868	0.169261
	avg	0.063546	0.033181	0.064096	0.203927
6	max	0.07461	0.049462	0.067065	0.2409
	min	0.062391	0.024333	0.049591	0.175265
	avg	0.069363	0.033184	0.055683	0.221709
5	max	0.068878	0.057641	0.094791	0.24838
	min	0.053437	0.030539	0.055284	0.172797
	avg	0.062174	0.043994	0.06734	0.205108
4	max	0.065819	0.067887	0.074359	0.238807
	min	0.057334	0.037093	0.056949	0.201989
	avg	0.061495	0.04671	0.064463	0.21512
3	max	0.069375	0.056266	0.080454	0.239093
	min	0.059928	0.026031	0.051332	0.206833
	avg	0.066101	0.041434	0.063167	0.224788
2	max	0.06739	0.07577	0.107734	0.2096
	min	0.055197	0.039477	0.061322	0.177362
	avg	0.062575	0.052278	0.073085	0.194342
1	max	0.040829	0.064328	0.118158	0.119407
	min	0.040829	0.064328	0.118158	0.119407
	avg	0.040829	0.064328	0.118158	0.119407

Chemofacies		Ga/Rb	K/Rb	Rb/Al	Cr/Sc	Zr/La	Zn/Sc	K/Al	Na/Al
13	max	0.143721	447.1661	0.002095	27.0123	34.03326	256.8932	0.501256	0.208801
	min	0.11274	336.8972	0.001549	9.426651	3.325384	5.362664	0.391936	0.081105
	avg	0.124387	383.7705	0.001835	16.78576	8.952996	86.80913	0.447062	0.128345
12	max	0.158361	431.9538	0.001658	9.953695	17.63911	55.77653	0.395282	0.200057
	min	0.137179	357.9692	0.001402	5.623236	3.811868	2.442895	0.358246	0.117733
	avg	0.147251	394.7814	0.00151	6.68064	11.8819	6.694111	0.379022	0.145489
11	max	0.161331	429.3171	0.00169	7.216126	12.43012	47.05129	0.427444	0.165247
	min	0.141334	337.661	0.001456	5.381372	7.386836	3.145944	0.363704	0.114875
	avg	0.150456	401.2225	0.001556	6.291306	10.76913	14.56291	0.397867	0.144111
10	max	0.161511	406.3616	0.001606	6.886009	11.44016	88.21825	0.394261	0.138733
	min	0.147946	348.6106	0.001379	4.760351	5.077812	3.897445	0.345093	0.081716
	avg	0.154281	387.0522	0.001498	5.86343	9.482	19.74178	0.369222	0.126461
9	max	0.156148	365.6342	0.001775	8.013681	12.59312	72.27645	0.357709	0.164609
	min	0.14279	310.5874	0.001454	4.635608	7.80944	3.236714	0.321905	0.119659
	avg	0.148344	336.7473	0.001578	6.207366	10.40401	21.79454	0.337878	0.13732
8	max	0.169069	410.8626	0.001877	10.79284	13.55448	121.1066	0.40682	0.17951
	min	0.136376	310.1469	0.001458	5.274246	4.878766	2.680357	0.35415	0.104558
	avg	0.148075	356.5648	0.001667	7.379145	9.950678	34.14526	0.377362	0.135034
7	max	0.155409	380.0742	0.001757	6.860339	13.8056	49.99996	0.374848	0.242245
	min	0.1358	257.8504	0.001459	4.866671	3.586812	2.722726	0.247776	0.1242
	avg	0.146077	305.9059	0.001622	5.982422	8.915995	9.136538	0.315692	0.158982
6	max	0.147924	349.1123	0.00185	7.454226	11.99854	102.0715	0.391681	0.183252
	min	0.128235	261.1168	0.001508	5.726949	6.983901	2.207871	0.295087	0.102822
	avg	0.138522	294.5231	0.001675	6.469519	10.26135	7.895225	0.31384	0.147736
5	max	0.158948	322.8516	0.001827	7.189465	10.25548	33.83281	0.321791	0.208736
	min	0.125228	257.0505	0.001516	4.887892	5.392277	3.200026	0.27117	0.087282

	avg	0.137639	287.0996	0.001665	6.030078	7.830425	7.40361	0.303945	0.129007
4	max	0.148307	277.1773	0.001821	6.681185	9.828208	12.21662	0.296667	0.141206
	min	0.127914	247.7709	0.001632	5.15183	6.630656	2.376812	0.272759	0.089285
	avg	0.133818	260.103	0.001725	5.999295	8.288536	6.640891	0.285709	0.11043
3	max	0.143752	313.7154	0.00189	8.334991	11.43834	23.26896	0.30733	0.173565
	min	0.118853	236.9108	0.001496	5.616258	6.609984	2.241635	0.281845	0.074249
	avg	0.127163	258.9895	0.001789	6.690059	8.627507	9.621217	0.29415	0.097089
2	max	0.131944	298.7012	0.001862	10.64945	9.230741	15.66155	0.33304	0.085097
	min	0.113769	262.1804	0.001695	6.436096	4.89438	1.910621	0.303859	0.046013
	avg	0.121041	284.3407	0.001777	7.147973	7.126561	5.578249	0.322007	0.066654
1	max	0.152673	262.0636	0.002047	83.4203	1.287697	3.344827	0.341931	0.122736
	min	0.152673	262.0636	0.002047	83.4203	1.287697	3.344827	0.341931	0.122736
	avg	0.152673	262.0636	0.002047	83.4203	1.287697	3.344827	0.341931	0.122736

Chemofacies		P2O3/Al2O3	Cr/Nb	Lu/Zr	Cr/Zr
13	max	2.36943706	30.15989	0.004026	1.000416
	min	0.03037241	7.493004	0.000711	0.07288
	avg	0.52630791	17.57344	0.002212	0.538475
12	max	1.36807648	7.943239	0.002026	0.214815
	min	0.02091007	4.533239	0.000977	0.085984
	avg	0.10384847	5.1276	0.001343	0.143382
11	max	0.07377165	5.623304	0.001688	0.211382
	min	0.01811236	4.107049	0.001226	0.134706
	avg	0.03213233	4.562836	0.001425	0.169215
10	max	0.04308528	5.175084	0.002334	0.217686
	min	0.01845087	4.220701	0.001251	0.165229
	avg	0.02669023	4.602506	0.001551	0.19396
9	max	0.0303379	5.624254	0.001886	0.258933
	min	0.01595749	4.372693	0.001228	0.145316
	avg	0.01931425	4.820874	0.001442	0.18593
8	max	0.16003218	9.515539	0.002052	0.394119
	min	0.01197805	4.48655	0.001272	0.128549
	avg	0.03224329	5.997805	0.001532	0.232964
7	max	0.1059192	6.692056	0.00328	0.302098
	min	0.01863884	4.499245	0.001084	0.103786
	avg	0.03880327	5.303066	0.001662	0.194837
6	max	0.04269826	5.897517	0.001705	0.31278
	min	0.01734135	4.57523	0.00123	0.162611
	avg	0.02498563	5.07693	0.001408	0.214048
5	max	0.04443363	6.289217	0.002503	0.339965
	min	0.01384167	4.527507	0.001419	0.186581
	avg	0.02240069	5.387552	0.001737	0.264026
4	max	0.01719659	6.095687	0.00202	0.361694
	min	0.01202611	4.76272	0.001496	0.204941
	avg	0.01452501	5.393587	0.001709	0.279008
3	max	0.02954884	6.688537	0.002132	0.329148
	min	0.01272907	4.693517	0.001284	0.166474
	avg	0.01623657	5.717874	0.001641	0.273501
2	max	0.02746657	9.970311	0.002806	0.569048
	min	0.01136381	6.134519	0.001482	0.271479
	avg	0.01511607	6.895471	0.001821	0.372473
1	max	0.14226455	125.4367	0.002883	5.36628
	min	0.14226455	125.4367	0.002883	5.36628
	avg	0.14226455	125.4367	0.002883	5.36628

Chemofacies		Cr/Al	Ni/Al	Th/Sc	Mg/Al	Ti/Nb	Ti/Zr
13	max	0.0062634	0.003836	1.83846	2.9647	381.107	14.24579
	min	0.00183892	0.000379	0.736019	0.327647	344.0334	3.628724
	avg	0.00352918	0.002332	0.930637	1.052833	361.2772	10.80156
12	max	0.00156774	0.001385	1.565226	1.668002	385.6654	12.55644
	min	0.0009492	0.000179	1.05759	0.187812	334.4731	6.367101
	avg	0.00110512	0.000719	1.17332	0.547279	356.9861	10.01036
11	max	0.00124826	0.001443	1.14847	2.044979	352.8925	15.16116
	min	0.00098372	0.000424	0.869347	0.27982	304.4002	10.17989
	avg	0.00110716	0.000867	1.04351	0.479136	326.6818	12.12023
10	max	0.00112522	0.00102	1.056328	2.114342	336.2982	15.57039
	min	0.00097965	0.000417	0.720012	0.235856	306.8697	11.75176
	avg	0.00104771	0.000669	0.93533	0.570821	321.9305	13.57095
9	max	0.00130002	0.001418	1.108614	1.018683	344.772	15.12734
	min	0.00103571	0.000615	0.777588	0.254361	295.1303	10.88209
	avg	0.00113099	0.00091	0.978671	0.464452	321.07	12.33868
8	max	0.00197769	0.001555	1.274315	2.546412	368.6934	15.66317
	min	0.00106367	0.000396	0.790063	0.184036	315.0913	9.330922
	avg	0.00134462	0.000885	1.039495	0.453648	337.5308	13.07144
7	max	0.00126011	0.000698	1.230906	1.650217	379.5571	14.75287
	min	0.00101253	0.000466	0.690601	0.275305	286.5369	7.520041
	avg	0.00112946	0.000577	0.96342	0.616601	336.803	12.20157
6	max	0.00137507	0.001177	1.149434	1.012248	342.0687	18.46911
	min	0.00116471	0.000457	0.823138	0.22756	297.907	10.782
	avg	0.00124966	0.000602	0.920702	0.379105	318.5856	13.37896
5	max	0.00128589	0.000721	0.954107	3.140037	335.6338	19.16005
	min	0.00107518	0.000306	0.679658	0.192336	284.6911	11.97982
	avg	0.00118573	0.000513	0.831798	0.668878	318.8622	15.57781
4	max	0.00127369	0.000623	0.930612	0.605206	344.8781	20.46371
	min	0.00111979	0.000437	0.671276	0.244649	307.79	13.24425
	avg	0.00116571	0.000498	0.834602	0.354241	322.2233	16.63752
3	max	0.00146115	0.000681	1.11241	0.652266	347.6538	19.04447
	min	0.00117232	0.000435	0.753515	0.199414	313.157	11.10733
	avg	0.00129579	0.000553	0.912867	0.269725	329.9038	15.76012
2	max	0.001939	0.000816	0.919536	2.277989	368.5659	24.7
	min	0.00129262	0.000109	0.75019	0.169892	302.3913	14.80423
	avg	0.00140523	0.000568	0.82467	0.353145	346.8148	18.64866
1	max	0.02554976	0.000939	0.919344	0.315262	227.0059	9.711491
	min	0.02554976	0.000939	0.919344	0.315262	227.0059	9.711491
	avg	0.02554976	0.000939	0.919344	0.315262	227.0059	9.711491

<b>Chemofacies</b>	<b>Provenance signal</b>	<b>Clay Content</b>	<b>Detrital input</b>	<b>Mineralogy</b>	<b>Formation</b>	<b>Relative Sea Level</b>
<b>13</b>	-igneous, mafic/ultramafic sediment input -submature sediment	lower than average clay content -higher than average chlorite and illite -lower than average smectite and kaolinite content	-Low detrital input -High pelagic input -Weathered material and clays present	-high Phosphate -high heavy mineral content (garnet, spinel, rutile)	Doig	Higher than average, Sharp sea level rise
<b>12</b>	-igneous, felsic sediment input -dolomite present -mature sediment	lower than average clay content -higher than average smectite and kaolinite -lower than average chlorite and illite content	-high detrital input with sediment recycling -high continental input and influx of weathered material	-high phosphate -minor heavy mineral content	Montney	Lower than average, sea level fall
<b>11</b>	-mature sediment with mixed mafic/felsic signature	lower than average clay content -higher than average smectite and kaolinite -lower than average chlorite and illite content	-high detrital input with sediment recycling -high continental input and influx of weathered material	-low phosphate -minor heavy mineral content	Montney	Lower than average, sharp sea level fall
<b>10</b>	-dolomite present -low mafic/felsic signature -submature sediment	lower than average clay content -higher than average kaolinite -lower than average	-minor detrital input with sediment recycling - continental	-low phosphate -minor heavy mineral content	Montney	Higher than average, sea level rise

		chlorite, illite and smectite content	input and weathered material present			
9	-mature sediment with mixed mafic/felsic signature	lower than average clay content -higher than average kaolinite and smectite -lower than average chlorite and illite content	-high detrital input -high continental input with sediment recycling -low amounts of weathered material/clay	-low phosphate -minor heavy mineral content	Montney	Lower than average, sea level fall
8	-mature sediment with mixed ultramafic/felsic, igneous signature	lower than average clay content -higher than average smectite and kaolinite -lower than average chlorite and illite content	--high detrital input with sediment recycling -high continental input and influx of weathered material	-low phosphate -minor heavy mineral content	Montney	Lower than average, rising sea level
7	-igneous, felsic sediment input -dolomite present -mature sediment	higher than average clay content -higher than average smectite and kaolinite -lower than average chlorite and illite content	-Low detrital input with some evidence of sediment recycling -High pelagic input -low amounts of weathered	-low phosphate -low heavy mineral content (garnet present)	Montney	Higher than average, sharp rise, then fall

			material			
<b>6</b>	-mixed felsic/mafic signatures (low signal strength) -submature sediment	lower than average clay content -higher than average smectite and illite -lower than average chlorite and kaolinite content	-high detrital input -high continental input with sediment recycling -low amounts of weathered material/clay	-low phosphate -minor heavy mineral content	Montney	Lower than average, sea level fall
<b>5</b>	-submature sediment with dolomite present -mixed felsic/mafic signatures (low signal strength)	higher than average clay content -higher than average smectite and illite -lower than average chlorite and kaolinite content	-low detrital input and sediment recycling -high pelagic input -low amounts of weathered material	-low phosphate -low heavy mineral content (garnet present)	Montney	Higher than average, rise and fall
<b>4</b>	-immature sediment with mixed mafic/felsic signature (low signal strength)	higher than average clay content -higher than average illite -lower than average chlorite, smectite and kaolinite content	-low detrital input and sediment recycling -high pelagic input -low amounts of weathered	-low phosphate -low heavy mineral content (garnet and spinel present)	Montney	Higher than average, falling

			material			
<b>3</b>	-immature sediment with mixed mafic/felsic signature (low signal strength)	higher than average clay content -higher than average illite -lower than average chlorite, smectite and kaolinite content	-mixed detrital and pelagic input -low sediment recycling, continental material or weathered material	-low phosphate -low heavy mineral content (garnet present)	Montney	Lower than average, rising
<b>2</b>	-igneous input, mixed mafic/felsic signature -immature sediment	higher than average clay content -higher than average illite -lower than average chlorite, smectite and kaolinite content	-low detrital input and sediment recycling -high pelagic input -low amounts of weathered material	-low phosphate -high heavy mineral content (spinel, garnet, rutile)	Montney	-higher than average but falling
<b>1</b>	mafic/ultramafic input -sediments submature	-higher than average clay content -higher than average chlorite and illite -lower than average smectite and kaolinite content	-low detrital input and sediment recycling -high pelagic input -some weathered material present	-high Phosphate -high heavy mineral content (garnet, spinel, rutile)	Belloy	Higher than average































