Boise State University
ScholarWorks

Geosciences Faculty Publications and Presentations

Department of Geosciences

11-26-2012

Variability of Pennsylvanian-Permian Carbonate Associations and Implications for NW Pangea Palaeogeography, East-Central British Columbia, Canada

K. D. Zubin-Stathopoulos
University of Calgary

B. Beauchamp
University of Calgary

V. I. Davydov
Boise State University

C. M. Henderson
University of Calgary

This is an author-produced, peer-reviewed version of this article. The final, definitive version of this document can be found online at *Geological Society, London, Special Publications,* published by Geological Society (UK). Copyright restrictions may apply. DOI: 10.1144/SP376.1

Variability of Pennsylvanian-Permian Carbonate Associations and Implications for Northwest Pangea Palaeogeography, East-Central British Columbia, Canada

K. D. Zubin-Stathopoulos
University of Calgary
Department of Geoscience
2500 University Dr. NW
Calgary, Alberta T2N 1N4
Canada
(kdzubins@ucalgary.ca)

B. Beauchamp
University of Calgary
Department of Geoscience
2500 University Dr. NW
Calgary, Alberta T2N 1N4
Canada
bbeaucha@ucalgary.ca

V.I. Davydov
Boise State University
Department of Geosciences
1910 University Drive
Boise, ID, USA 83725
vdavydov@boisestate.edu

C. M. Henderson*
University of Calgary
Department of Geoscience
2500 University Dr. NW
Calgary, Alberta T2N 1N4
Canada
charles.henderson@ucalgary.ca

5,943 Words,72 References, 1 Table, 10 Figures

Abstract

Different stages of Pennsylvanian-Permian carbonate sedimentation in east-central British Columbia record a complex history of changing environments influenced by evolving palaeogeography and climate. Newly recognized tectonically controlled features affected the distribution and variability of carbonate associations, providing new interpretations for this portion of the west coast of Pangea. Both a heterozoan (cool-water) and photozoan (warm-water) association were identified on either side of a palaeogeographic high here informally termed “Tipinahokan Peninsula”. Cool water carbonates were located outboard, or to the west of this high, an area influenced by upwelling waters. Inboard of this high, a warm, protected sea developed, here termed “Kisosowin Sea”. This configuration and palaeolatitude is similar to that of Baja California, Mexico and the Sea of Cortéz, providing a good modern analog for these deposits where warm water carbonates grow at latitudes otherwise dominated by cool water deposits. The warm sea provided a place for a photozoan association to develop during the Permian when the low latitude NW coast of Pangea was dominated by cool water carbonates.

Key Words: Palaeoclimate, carbonate associations, western Pangea, ocean circulation, Pennsylvanian, Permian, upwelling, biostratigraphy.

Pennsylvanian-Permian strata in east-central British Columbia, western Canada, consist of carbonate rocks with a small siliciclastic component and are predominantly skeletal wackestone and packstone (Bamber & Macqueen 1979). Localized occurrences of grainstone and boundstone that record warm water carbonate deposition also occur in the eastern and southern portion of the area. This occurrence is unusual because it is present in an area that is otherwise dominated by cool water limestone, dolostone and phosphatic siltstone. This aspect of western Pangean sedimentation has not been addressed in previous studies (Bamber & Macqueen 1979; McGugan & Rapson-McGugan 1976). This paper explains the anomalous occurrence of these warm water carbonates by the emergence of a Late Pennsylvanian topographic high that separated and protected a warm inland sea to the east from a significantly cooler open ocean affected by upwelling to the west.

Pennsylvanian and Lower Permian carbonate reefs and mounds typical of tropical to sub-tropical settings have been well documented in the Western United States and the Canadian Arctic (Davies *et al.* 1989; Beauchamp & Desrochers 1997; Morin *et al.* 1994; Wahlman 2002). The Pennsylvanian-Permian basins of the western U.S. were located near the palaeo-equator where warm shallow water prevailed (Blakey 2008). At higher latitudes, tropical to sub-tropical seas also developed, such as in the Sverdrup Basin of the Canadian Arctic, an area that was bathed by warm waters originating from the Tethyan Ocean prior to the closure of the Uralian seaway (Reid *et al.* 2007). The reef-building organism *Palaeoaplysina*, as well as colonial rugose corals and calcareous green algae have been documented in British Columbia (Bamber & Macqueen 1979). These fossils form a photozoan biotic association, which is typical of shallow warm water tropical-like conditions (James 1997).

This paper documents the facies variability of Pennsylvanian-Lower Permian carbonates in east-central British Columbia focusing on differences in biotic associations and other sedimentological attributes. Such differences are often attributed to climate change over time (e.g. Beauchamp 1994). However, this study shows that distinctive warm and cool water shallow water shelf deposits accumulated at the same time while remaining unaffected by the major climatic shift that occurred across the Asselian-Sakmarian boundary associated with the thawing of Gondwana glaciers. We here present an alternative interpretation whereby the significant difference in carbonate associations is explained by the existence of a protected sea that allowed warm water carbonates to grow in the western portion of the Peace River Basin. The name Kisosowin Sea (Kisosowin means “warm” in Cree) is here informally ascribed to this palaeogeographic feature. The Kisosowin Sea was protected by a Late Pennsylvanian-Early Permian topographic high, herein termed the Tipinahokan Peninsula (Tipinahokan means “shelter from the cold” in Cree), that acted as a barrier sheltering the area of warm water sedimentation to the east from an area cooled by upwelling to the west.

Geological Setting

Study Area and Methods

Pennsylvanian-Permian strata from the westernmost portion of the Western Canada Sedimentary Basin (WCSB) crop out in a NW-SE trending belt in eastern British

Columbia and western Alberta. This study focuses on outcrops in map sheets 93I, P, O and 94B where the succession is relatively well exposed in a series of Laramide thrust sheets of the Rocky Mountains (Fig. 1). The eight measured sections include Peck Creek, Mountain Creek, Watson Peak, Mount Palsson, Mount Crum, Fellers Creek, Mount Cornock and Ganoid Ridge. In addition to new outcrop data collected in 2009 and 2010, our study incorporates published field descriptions of Bamber & Macqueen (1979) and McGugan & Rapson-McGugan (1976). Mountain Creek and Fellers Creek, which are the most complete sections we measured, are described in greater detail. Exploration wells are also used for correlation to the eastern Peace River Basin where the biostratigraphy and sedimentology is better understood.

In total, 116 conodont samples and 203 thin sections were processed from the eight measured sections. This paper relies on biostratigraphic data and age interpretations outlined in Zubin-Stathopoulos (2011). Facies analysis was conducted using thin sections, cut slabs, outcrop photographs and field notes. Standard procedures for petrographic analysis were used for identifying and imaging carbonate constituents. Gamma readings were taken at Fellers Creek, Mountain Creek, Ganoid Ridge, Watson Peak, Mount Crum and Mount Palsson using a hand held scintillometer. The carbonate classification scheme of Dunham (1962) is used as well as modifiers for carbonate associations including the terms “photozoan” and “heterozoan” to qualify the environmental controls (temperature, nutrients, etc.) of carbonate constituents (James 1997). In addition, assemblages specific to late Palaeozoic biota (bryonoderm, bryonoderm-extended) were used (Beauchamp 1994).

Stratigraphic Setting

Compared to the Mississippian succession, which consistently ranges in the hundreds of metres from the US-Canada border to the Northwest Territory, the Pennsylvanian-Permian succession of Alberta and eastern British Columbian is relatively thin, quite variable in composition and recorded a complex stratigraphic-sedimentological history at a time of ongoing tectonic activity in the WCSB. In east-central British Columbia, Pennsylvanian-Permian rocks are dominated by shallow water carbonate and chert with varying siliciclastic proportions that generally increase upward (Bamber & Macqueen, 1979). This succession comprises eight relatively thin unconformity-bounded low order sequences that can be correlated from the Rocky Mountains in the west to the subsurface areas in the east (Fig. 2) (Bamber & Macqueen 1979; McGugan & Rapson-McGugan 1976; Zubin-Stathopoulos 2011). In the study area, these sequences are represented by the Kindle, Belcourt, Fantasque and Mowitch formations (Bamber & Macqueen 1979). Pennsylvanian strata in the area are equivalent to the Ksituan Formation of Henderson *et al.* (1994). The Upper Pennsylvanian-Lower Permian sequences in east-central BC are equivalent to part of the Belloy Formation in the subsurface to the east (Dunn 2003; Naqvi 1972) while the Middle Permian units are equivalent to the upper Belloy Formation (Dunn 2003). While they differ lithologically, these units are equivalent in age to formations in southeast British Columbia and southwest Alberta (MacRae & McGugan 1977; McGugan & Rapson 1962 1963).

The studied succession is part of three low-order sequences of Moscovian, Kasimovian-Gzhelian and Asselian-Sakmarian respectively (Figs. 2 and 3). The three sequences are contained within the Belcourt Formation. The sequence boundaries are sharp, erosive and unconformable surfaces associated with intraformational conglomerates of probable near-shore origin (Fig. 4). The Pennsylvanian portion of the Belcourt Formation (Moscovian) is correlative to the Ksituan Formation. The Belcourt Formation is a unit of fossiliferous carbonate that recorded moderately deep water to shallow shelf or ramp cyclic sedimentation (Bamber & Macqueen 1979). In the study area, the formation varies in thickness (Fig. 3), ranging from zero at Mt. Cornock up to 127 m at Mountain Creek (Fig. 3). Southern and eastern outcrops display typical Belcourt facies, *i.e.* grainstone (ooid and skeletal), boundstone and lesser amounts of skeletal wackestone and packstone, a suite of facies that is best preserved at Fellers Creek (Fig. 4). The western section displays a different composition, which consists dominantly of lime-mudstone, skeletal wackestone and packstone, and minor amounts of skeletal grainstone. This succession is best exemplified at Mountain Creek (Fig. 5). We are of the opinion that a new formation could be erected to reflect this basic and mappable lithological difference within the Belcourt Formation. For the purpose of this paper, however, we will refer to the Fellers Creek Assemblage (FCA) (eastern and southern area) and the Mountain Creek Assemblage facies (MCA) (western area) of the Belcourt Formation as shown in Figure 2.

Peace River Basin and Tectonic Highs

The deposits described in this study are located in the western part of the Peace River Basin. The Peace River Basin is a down-warped and down-faulted portion of the interior cratonic platform (Henderson *et al.* 2002) of North America that became an area of carbonate and clastic deposition during the Pennsylvanian-Permian interval (Henderson *et al.* 1994). The Peace River Basin is a complex tectono-stratigraphic element at the convergence of multiple tectonic interactions and was the locus of both differential subsidence and uplift that occurred at varying rates and time in different areas. The location of the Peace River Basin was in part determined by tectonically-controlled palaeogeographic elements such as the Beatton High and Sukunka Uplift (Henderson *et al.* 2002). In addition, it is now apparent that the Peace River Basin and adjacent Ishbel Trough to the west (Richards *et al.* 1993) are divided into discrete sub-basins (Henderson *et al.* 2002).

In the study area, a prominent tectonic high, the NW-SE axis of which is intersected at Mt. Cornock (Fig. 3), separated two distinct depositional areas to the west and east. While the Belcourt Formation is absent on the crest of the high, such as Mt. Cornock (Fig. 3), it thickens markedly to the east and west of the high. The high also constitutes the physical boundary between the area dominated by the Mountain Creek facies assemblage of the Belcourt Formation to the west and the Fellers Creek facies assemblage to the east (Fig. 3). Evidence of recurrent tectonic activity along the high is shown by several horizons with intraformational conglomerates, some of which contain clasts derived from the immediately underlying succession (Fig. 4).

Palaeolatitudinal Setting

Various palaeogeographic reconstructions of Pangea places the study area in eastern British Columbia between 20 and 25° N during the Moscovian-Kasimovian and 25 to 30°

N during the Asselian-Kungurian (Blakey 2008; Golonka & Ford 2000; Vai 2003). These estimates are based on published reconstructions that rely on palaeomagnetism, palaeobiogeography, best global fit of tectonic plates and comparisons with modern latitudinal gradients and corresponding facies (Golonka & Ford 2000). Contemporaneous deposits in the southwestern United States (Texas to Utah) are interpreted to be equatorial, ranging from 0 to 10˚ N and having migrated 10˚ northward during the Kasimovian to Kungurian interval (Tabor *et al.* 2008). The Sverdrup Basin of the Canadian Arctic is interpreted as being located at about 25-30˚ N in the latest Pennsylvanian (Gzhelian) to Early Permian (Asselian-Sakmarian), based on extensive warm-water photozoan carbonates, and to have migrated to approximately 40˚ N by the Middle Permian as suggested by dominance of cool- to cold-water heterozoan carbonates (Beauchamp 1994; Bensing *et al.* 2008). This significant oceanic cooling has been associated with the closure of Uralian seaway during the Artinskian that prevented warm Tethyan-derived waters from reaching NW Pangea (Reid *et al.* 2007). Based on these considerations, east-central British Columbia may have been at a slightly lower latitude than suggested by some global reconstructions, possibly ranging from 15 to 20˚ N during the Early Permian, which would coincide with the modern distribution of warm water carbonates (Halfar *et al.* 2004a) and place the area well within the range of Coriolis-driven Ekman transport and upwelling along the western margin of Pangea.

Shelf Cyclicity and Palaeoclimatic Setting

The Pennsylvanian-Early Permian interval was characterized by relatively high sea level with cyclic influence from glacial eustasy (Golonka & Ford 2000) at a time of widespread glaciation in Gondwana (Wanless & Shepard, 1936). Cyclothems are well known and described from the western United States where the climate was wet-equatorial (Heckel 1986; Wanless & Shepard 1936). These cyclothems classically consist of deep marine shale, followed by regressive marine limestone and capped by shallow marine or terrestrial (coal) deposits (Heckel 2008). Arid cyclothems are less well known, but are shown to be present in higher latitude deposits of western and northern Canada (Ford *et al.* 2009; Heckel 2002; Moore 2002; Morin *et al.* 1994). Some of these cyclothems commonly contain evaporites as their capping unit (ex. sabkha-type dolostone and sulfate evaporites). Aeolian-sourced silt is pervasive throughout these deposits (Heckel 2002).

Arid conditions persisted throughout the Pennsylvanian in the Western United States, Canada and Russia (Francis 1994) and continued during the Permian resulting in widespread evaporitic and desert environments. These conditions also led to abundant aeolian silt deposition within Pennsylvanian to Middle Permian marine carbonates (Francis 1994; Soreghan *et al.* 2008). The end of widespread Gondwana glaciation roughly coincides with the Asselian-Sakmarian boundary, above which high amplitude-high frequency sequences or cycles are not as well developed as in older Pennsylvanian-Early Permian sediments (Beauchamp & Henderson 1994). Sea level was at a near minimum toward the end of the Kungurian (Golonka & Ford 2000; Soreghan *et al.* 2008). During the Middle Permian, arid conditions coupled with cool water deposition prevailed all along the northwestern margin of Pangea at a time of global warming (Beauchamp & Baud 2002; Clapham 2010).

As observed around the world, the Pennsylvanian-Lower Permian succession of east-central British Columbia displays a series of high-order cycles as recorded by fluctuations in carbonate facies representing environments ranging from outer shelf (or ramp) to shoreline (see descriptions below). This is shown by fluctuations from lime mudstone to packstone to grainstone in the Asselian succession at Fellers Creek (Fig. 4), and from lime mudstone to wackstone and packstone in the Moscovian to Asselian succession at Mountain Creek (Fig. 5). Cycles average 5-10 m in thickness, which is similar to contemporaneous cyclothems in the mid-continent (Heckel 2002) and in the Arctic (Morin *et al.* 1994). However, the number of observed cycles varies greatly from section to section and is considerably smaller than the number of cycles observed elsewhere. This reflects the incomplete nature and highly variable preservation of the Pennsylvanian-Permian succession in east-central British Columbia, which attests for erosion and/or non-deposition at time of active differential tectonic uplift and subsidence. The Sakmarian succession at Fellers Creek displays only 2-3 shelf cycles, which may also reflect an incomplete stratigraphic record. However, only a few shelf cycles are observed in the Sakmarian succession of the Sverdrup Basin, at a time of widespread global transgression contemporaneous with the thawing of Gondwana glaciers.

Facies Descriptions, Interpretations and Depositional Models

The Moscovian to Sakmarian succession of east-central British Columbia comprises 12 carbonate microfacies (MF), the content and interpretation of which is summarized in Table 1. The microfacies are illustrated in Figs. 6 and 7. The interpreted depositional environments range from relatively deep (below storm wave base) low energy outer shelf or ramp (MF-09), to storm-influenced middle ramp (MF-03, MF-08), to high energy shallow inner ramp/shoreface (above fair weather wave base) (MF-01 to MF-03; MF-07, MF-10, MF-12). Most facies represent open marine sedimentation, except for MF-05 (protected inner ramp), and MF-04 that represents potentially inter- to supra-tidal, back-ramp deposition.

Both photozoan and heterozoan biotic associations were observed. Photozoan biota includes telltale indicators of shallow, warm-water tropical-like conditions such as dasycladacean algae, colonial rugose corals, *Palaeoaplysina* and ooids. *Palaeoaplysina* is an organism with unknown biological affinity that may belong to the class hydrozoa (Davies & Nassichuk, 1973), though it has also been interpreted to be closely related to calcareous algae (Watkins & Wilson, 1989). It is usually found in shallow water, high productivity environments where photosynthesizing organisms are common (Davies & Nassichuk, 1973). It is considered to be part of the photozoan association and formed bioherms in a moderate to low energy environment on the inner to outer ramp.

Heterozoan biota are far less diversified and dominated by sponge spicules, bryozoan, echinoderm and brachiopods, a typical Late Palaeozoic cool-water assemblage also known as Bryonoderm (Beauchamp 1994). Cool-water conditions reflect deeper depositional settings (MF-08 and MF-09) or shallow –water deposition in an area bathed by cool to cold waters (MF-10 to MF-12). In the latter case, it is not the biota that indicates shallow water deposition, but different lines of evidence such as the dominance of grainstones or presence of cross-beddings or ripples. One of the most distinctive aspects of the studied succession is the dominance of photozoan carbonates in the eastern and southern sections, as seen at Fellers Creek (Fig. 4) (Fellers Creek facies assemblage). In contrast, heterozoan carbonates dominate the western sections as exemplified at Mountain Creek (Fig. 5) (Mountain Creek facies assemblage).

Various combinations of the twelve facies occur recurrently in the study area and can be found at various stratigraphic levels of the Belcourt Formation. The recurrence of facies sets attest for shifts in relative sea level in response to ongoing high-frequency glacio-eustatic fluctuations. While the entire spectrum of facies is never present within a single vertical cycle, facies variations do suggest bathymetric shifts in the order of 30 to 50 m on average for each cycle as environments shifted from offshore, distal outer shelf sedimentation below storm wave base to high energy nearshore, shoreline and even supra-tidal sedimentation and erosion.

While it is impossible to correlate individual cycles from section to section due to the extreme lateral and vertical variations in the number of cycles, we can analyze the spectrum of microfacies through the prism of the three low-order sequences in the area, the Moscovian, Kasimovian-Gzhelian, and the Asselian-Sakmarian sequences. Each of these sequences, which represent the grouping of an undetermined number of high-order cycles, has its own set of depositional characteristics as described below (Fig. 8).

Moscovian

The Moscovian portion of the Belcourt Formation consists of bioturbated silty mudstone (MF-08), bryozoan-brachiopod wackestone-packstone (MF-09) and fine grained packstone/grainstone (MF-12) (Fig. 4). These three facies alternate in a cyclic fashion, shallowing up from MF-09 to MF-08 and capped by MF-12. The capping facies progressively gets muddier upwards, and the mudstone portion of the cycle becomes thicker indicating overall deepening upward succession for these cycles. The Moscovian portion of the Fellers Creek section consists of conglomerate-containing chert and carbonate clasts (Fig. 4). The bryozoans and brachiopods require normal marine salinity and circulation in order to develop indicating that these sediments represent deposition in an open marine environment (Fig. 8A). The Moscovian found elsewhere in the Peace River Basin is mostly assigned to the Ksituan Formation, which is predominantly composed of finely crystalline dolostone and is interpreted as shallow tidal flat deposits in sabkhas and lagoons (Dunn 2003; Wamsteeker 2007).

Conodont taxa recovered from the Moscovian interval include *Adetognathus lautus*, *Diplognathodus edentulus, Neognathodus bothrops* and *Idiognathodus expanses* (Zubin-Stathopoulos 2011). This sequence starts at the conglomerate at the base of the Belcourt Formation at Fellers Creek and Mountain Creek section (Figs. 4 and 5). The sequence displays extreme thickness variations ranging from zero at some outcrops (Mount Palsson, Mount Cornock, etc.) to 164 m in the subsurface in the Peace River Basin. The Moscovian portion of the Mountain Creek section coarsens upward (shallowing upward) with up to 6 shallowing-upward cycles (Fig. 4).

Thicknesses are controlled in part by palaeogeographic features that caused both erosion and non-deposition of this sequence (Zubin-Stathopoulos 2011). Localized palaeogeographic highs were present, which resulted in the deposition of Moscovian aged conglomerates containing Mississippian clasts at Fellers Creek. Palaeogeographic highs that were uplifted from the Late Pennsylvanian through Early Permian resulted in the erosion of this sequence, but the preservation of Moscovian aged conodonts (*Neognathodus bothrops*) within carbonate clasts found in a lag indicates that Moscovian rocks were more pervasive than what is seen at many outcrops (Zubin-Stathopoulos 2011).

This sequence is characterized by overall open marine conditions (Fig. 8A) with no indication of a restricted or protected marine environment, except in back ramp environments suggested by facies of the Ksituan Formation. The alternation of dominantly lime mudstone beds with periodic wackestone and packstone beds containing chaotically organized brachiopod and bryozoan fragments indicates an overall deep, low energy environment below storm wave base with shallowing upward cycles that end in storm influenced beds at the tops. Mountain Creek is located in the westernmost thrust sheet of all of the outcrops studied. The facies and location within this thrust sheet imply that these are the most distal sediments. The carbonate association indicates deposition on a relatively deep to shallow cool water carbonate ramp (Fig. 8A).

Kasimovian-Gzhelian

Rocks representing these two Late Pennsylvanian stages are not prominent in the study area, but are present at Mountain Creek and West Sukunka. The Kasimovian-Gzhelian portion of the Belcourt Formation consists of bioturbated silty mudstone (MF-

04) and bryozoan-brachiopod wackestone-packstone (MF-09). The carbonate association indicates cool, moderately deep water. The facies and location within the westernmost thrust sheet imply that these are the most distal sediments deposited on the outer ramp. The correlation of these stages is based on the occurrence of *Adetognathus lautus* and *New Genus A sp.* (Kasimovian) (Zubin-Stathopoulos 2011). This succession is up to 70 m in the outcrop belt, though it is usually not present. Our limited data set for this sequence prevents us from suggesting a sequence-specific interpretation. The range of depositional environments was likely similar to that of the Moscovian (Fig. 8A).

Asselian-Sakmarian

The Asselian-Sakmarian succession is bounded by prominent unconformities and is therefore believed to constitute a single low-order sequence. However, an additional erosion surface associated with conglomerates and potentially representing an unconformity occurs at Fellers Creek and is viewed as representing the Asselian-Sakmarian boundary (Fig. 4). It also likely represents the boundary between two higher-order sequences within the lower order Asselian-Sakmarian sequence. Because of this, we here describe the Asselian part of this sequence first, and then the Sakmarian part below. This makes sense considering that the Asselian was still a time of Gondwana glaciations while glacial thaw and retreat occurred during the Sakmarian.

The Asselian portion of the Belcourt Formation consists of ooid-foraminifer grainstone (MF-01), *Palaeoaplysina* packstone/boundstone (MF-06), algal-bioclastic grainstone (MF-02), rugose coral wackestone-packstone (MF-05), microbial mudstone/dolostone (MF-04) and bryozoan-echinoderm packstone-grainstone (MF-03). These light- and warm temperature-dependent organisms constitute a Photozoan Association (James 1997). The Asselian portion of the Mountain Creek section consists largely of MF-02 (bryozoan-brachiopod wackestone-packstone) with some alternation with MF-01 (silty bioturbated mudstone). Some levels contain brachiopod hash in a lime-mud matrix and represent brachiopod banks.

Conodont taxa in this sequence include *Adetognathus n.sp. B*, *Streptognathodus verus*, and *Streptognathodus fusus* (Zubin-Stathopoulos 2011). The Asselian part of the sequence ranges from 0 to 20 m in the outcrop belt. It is not recognized in the eastern Peace River Basin, possibly due to low global sea level resulting in non-deposition or poor preservation (Golonka & Ford 2000). Distinct shallowing-upward cycles are present at both the Fellers Creek (Fig. 4) and Mountain Creek sections (Fig. 5). Active tectonism during this interval created a palaeogeographic high between the western sections and the eastern sections (Fig. 3). This high formed during the Asselian just to the west of Fellers Creek. Deposits at the Fellers Creek section represent a photozoan carbonate ramp that fostered the growth of temperature dependent organisms such as *Palaeoaplysina* and fusulinaceans as well as abiotic constituents such as ooids (Fig. 8B). Deposits at the Mountain Creek section represent a heterozoan carbonate ramp that contained only heterozoan elements including brachiopod and bryozoan (Fig. 8B). The Sakmarian facies (Fig. 8C) found at Fellers Creek include *Palaeoaplysina* boundstone (MF-06), colonial rugose coral boundstone (MF-07) algal-bioclastic grainstone (MF-02), and echinoderm-brachiopod packstone-grainstone (MF-03). These facies are part of the photozoan carbonate association (James 1997; Reid *et al.* 2007). Facies found at

Mountain Creek include bryozoan-brachiopod wackestone-packstone (MF-08), cross bedded silty mudstone-wackestone (MF-11), and hummocky cross-stratified mudstone (MF-10). These belong to a heterozoan carbonate association (James 1997; Reid *et al.* 2007) of the bryonoderm variety (Beauchamp & Desrohers 1997).

Biostratigraphically significant fossils in this sequence include the conodont *Sweetognathus binodosus* (Zubin-Stathopoulos 2011) and the coral *Protowentzelella kunthi* (E.W. Bamber, pers. comm. 2010). Two closely spaced samples with fusulinaceans at 37.5 and 39.5 were recovered in the Fellers Creek section. The fusulinaceans are quite abundant in the samples, but their taxonomy is rather poor. Three species are identified in both samples (Fig. 9): *Schubertella* ex gr. *kingi* Dunbar & Skinner, *Pseudofusulina attenuata* Skinner & Wilde and *Ps. acuta* Skinner & Wilde. The first species is an opportunistic schubertellid that is widely distributed globally and occurs in latest Gzhelian through entire Lower Permian (Davydov, 2011). The other two species were originally described from the McCloud Limestone in Shasta Lake area (Skinner & Wilde, 1965). *Pseudofusulina attenuata* has also been found in Nevada in a stratigraphically very narrow horizon (Stevens et al., 1979; Davydov et al., 1997). In Nevada the horizon with *Pseudofusulina attenuata* yields the conodonts *Mesogondolella* aff. *striata* Chernykh near the bottom and *Sweetognathus* aff. *merrilli* Kozur near the top (Wang 1993; V. Chernykh 2008 pers. comm.) suggesting late Asselian to early Sakmarian age for this unit (Chernykh, 2005). The Sakmarian is not recognized in the subsurface of the eastern Peace River Basin. Only a 15 m thick interval occurs at Fellers Creek (Fig. 4), which is correlated to other Sakmarian occurrences at Kinuseo Creek and

Meosin Mountain. Sakmarian aged rocks are also found at Mountain Creek. This part of the sequence developed at a time of global sea level rise and active tectonism.

The palaeogeographic high that was present during the Asselian persisted through the Sakmarian (Figs. 8B-C) and probably into the Artinskian and Kungurian. This high continued to separate photozoan carbonates to the east from heterozoan carbonates to the west throughout the Sakmarian. Sediments on the flanks of this high were deposited on a carbonate ramp with bioherms. Sediment more distal to the flanks were deposited on a ramp that more closely resembles a siliciclastic ramp, where carbonate producing organisms did not build mounds or wave resistant structures (Figs. 8B-C).

Discussion: Significance of Distribution of Carbonate Associations

Western Pangean Climate and Oceanic Currents

The occurrence of warm-water photozoan associations in east-central British Columbia could be attributed to a climatic warming event. However, it has been suggested that a southward cool boundary current existed along the entire west coast of Pangea creating increasing cool water conditions starting in the Early Permian with most pronounced effects in the Middle Permian (Beauchamp & Baud 2002; Clapham 2010). Northern and northwestern Pangea was cooling and decoupled from a broader global warming trend (Clapham 2010). The Middle Permian basin of west Texas was experiencing warmer water temperatures, while just north in the Phosphoria Sea, cool water deposits prevailed (Clapham 2010). The Guadalupian of east central British Columbia also records a similar climatic story to that of the Sverdrup Basin and the basins of the western United States. Cool water deposits are recorded along the entire western coast of Pangea, dominantly consisting of spiculite and chert indicative of this cooling episode (Beauchamp & Baud, 2002; Clapham, 2010).

Carbonate reefs that are typical of photozoan associations are well documented in the western United States within tectonically controlled sub-basins such as the Wood River Basin (Wahlman 2002). There is an abundance of cool water deposits in British Columbia including the spiculitic and phosphatic siltstone of the Johnston Canyon Formation in southeastern British Columbia and southwestern Alberta located within the southern portion of the Ishbel Trough (MacRae & McGugan 1977). This also indicates that this cool boundary current had a control on the fauna of the Early Permian in east-central British Columbia. In addition, the palaeolatitude indicates that at least seasonal upwelling influenced these deposits, creating an environment conducive only to a heterozoan carbonate production. Despite the existence of a cool boundary current that became progressively more pronounced through the Permian, patch reefs and mounds typical of the photozoan or warm water carbonate associations were able to develop in this isolated area on the northwestern coast of Pangea.

Warm to cool carbonate deposition and palaeogeography

Warm water carbonate associations (photozoan) are defined as a group of benthic carbonate particles including light dependent organisms and/or non-skeletal particles (ooids) plus or minus non-light dependent components (James 1997). Other examples of constituents found within the photozoan association include warm water corals, green algae and fusulinaceans. The Fellers Creek facies assemblage of the Belcourt Formation predominantly consists of skeletal packstone and grainstone containing many of these constituents. It occurs in an isolated area within the outcrop belt in the central and southern portion of the study area. The Belcourt Formation can generally be characterized as deposited in a warm shallow sea where carbonate producing organisms were protected from cool upwelling ocean currents that would have prevented photozoan carbonates from growing. These organisms would have also required clear, oligotrophic waters in order to develop (Halfar *et al.* 2004a).

Several outcrops within the study area have no Pennsylvanian to Early Permian deposits. In contrast, the Fantasque Formation (Middle Permian) is present nearly everywhere, though it is missing at Watson Peak. This series of outcrops are interpreted as the location of a tectonic high that was active from the Late Pennsylvanian through the Early Permian, located to the west of outcrops that represent deposition in the Kisosowin Sea (Fig. 10). This high developed during the Kasimovian C6 tectonic episode (Fig. 2) and may have extended into the Early Permian P1 event, described from Nevada (Snyder *et al.* 2002; Trexler *et al.* 2004) and outlined in detail in Zubin-Stathopoulos (2011) for east-central British Columbia (Fig. 10). *Microcodium* found in shallow water deposits within the Asselian and Sakmarian sequences indicates that this high may have been host to the development of soil and vegetation (Kosir 2004). It was centred approximately at 20˚ N palaeolatitude.

The fusulinacean assemblage with *Pseudofusulina attenuata* and *Ps. acuta* can be attributed to the McCloud province (Ross, 1995), where the fusulinaceans and coral faunas at certain horizons include significant Tethyan warm-water elements (Ross, 1995;

Fedorowsky et al., 2007). The occurrence of this exotic for North American province assemblage in central Nevada and in east-central British Columbia 1800 km to the north suggests a warming episode along the North American margin during early Sakmarian time as well as a linkage with Klamath/Quesnel arc rocks (Fig. 10) to the west. Belasky et al. (2002) suggested, based on faunal similarities that the Quesnel and Klamath terranes must have been 2000-3000 km away from their latitudinal equivalents on the NA craton during the Early Permian. Models developed by Nelson et al. (2006) suggest that the Slide Mountain Ocean (and therefore also the Havallah Basin) was the locus for back-arc sea floor spreading and would have been distant from the NA craton. Henderson et al. (in press) highlighted the importance of timing and suggested the development of a peripheral bulge that closed the Kisosowin Sea in the early Artinskian points to terrane interaction with the NA craton. This would suggest a narrower Slide Mountain Ocean and Havallah Basin, which seems to be supported by the fusulinacean assemblage. It is apparent that the climatic warming suggested by the occurrence of these McCloud tethyan warm-water elements in east-central British Columbia is insufficient by itself to account for this association given the prevailing cool-water currents affecting the margin at these palaeolatitudes. The Kisosowin Sea clearly represents a protected embayment that was able to foster these warm water organisms during the Early Permian (Fig. 10).

Cool-water carbonate associations, or heterozoan associations, are defined as a group of benthic carbonate particles produced by organisms that are light-independent plus or minus red calcareous algae (James 1997). Common carbonate producing organisms found within this association include brachiopods, bryozoans, mollusks, echinoderms and some foraminifers. The Mountain Creek facies assemblage of the Belcourt Formation predominantly consists of wackestone and packstone with minor grainstone that are part of the Heterozoan association with no indication of photozoan elements. This assemblage occurs at outcrops in the westernmost thrust sheet in the study area located west of outcrops that represent the Tipinahokan Peninsula.

Baja California: Modern Anologue for the Tipinahokan Peninsula

Baja California is a southward extending peninsula on the west coast of Mexico that protects a gulf, or sea (Sea of Cortéz/Gulf of California) with the opening to this embayment to the south. The peninsula is located between 22 and 32˚ N latitude and experiences seasonal upwelling along the Pacific coast (Walsh *et al.* 1977). Upwelling directly affects food chain dynamics, with marked changes when upwelling is slow or even at times when the current reverses and downwelling occurs along this coast (Walsh *et al.* 1977). Upwelling is at its maximum from February to June. The Sea of Cortéz is considered to be "a mostly isolated, distinct body of water" with different biological populations on the Pacific coast of the Baja peninsula (Lluch-Belda *et al.* 2003). Despite this, the California Current reaches the mouth of the Sea of Cortéz, allowing some interchange between the Pacific Ocean and the opening of the gulf (Lluch-Belda *et al.* 2003). This brings not only cool water, but nutrients to the sediments at the mouth of the Sea of Cortéz.

The most northern occurrence of reef-forming hermatypic corals occur within the southern portion of the Sea of Cortéz near an area called La Paz, which is at 24˚ N latitude (Halfar *et al.* 2004a). This area is characterized as a warm-temperate carbonate realm with a mixed heterozoan-photozoan association (Halfar *et al.* 2004b). Mean sea surface temperature is at 24° C, allowing the growth of photozoan carbonates (James 1997). Farther north in the Sea of Cortéz, the majority of carbonate producing organisms consists of mollusks and rodoliths, with occasional, and often older, reworked coral indicating a heterozoan carbonate association (Halfar *et al.* 2004b). This occurrence of reef-forming corals is due to the protected oceanographic conditions that allow for warm water and oligotrophic to mesotrophic conditions necessary for photozoan carbonate production (Halfar *et al.* 2004b).

The configuration of the Sea of Cortéz with protected photozoan carbonates on the inside of the peninsula is a good analogue for the late Palaeozoic of east-central British Columbia. It not only occurs at comparable latitude on the west coast of a continent, but modern climate is representative of an interglacial period, similar to that of the many interglacials during the Asselian-Sakmarian. This presence of a palaeogeographic high with warm-water carbonates to the east and cool water carbonates to the west within latitudes that experiences at least seasonal upwelling resembles the geographic configuration and biotic distribution of Baja California (see inset in Fig. 2). Photozoan carbonates within the Sea of Cortéz are characterized as warm-temperate because of the lack of green algae and extensive reef-forming carbonates (Halfar *et al.* 2004b). Photozoan carbonates within the Kisosowin Sea can be characterized as subtropical because of the presence of calcareous green algae, hermatypic coral and ooids (James *et al.* 1999). This difference in the carbonate organisms between the Sea of Cortéz and the Kisosowin Sea despite the similarity in latitude and geography may be due to several factors including warmer global temperatures during the Permian and basin configuration that would promote more oligotrophic conditions allowing photozoan carbonates to develop.

Conclusions

The emergence of the Tipinahokan Peninsula during the Late Pennsylvanian created a protected sea that emulated the conditions found in tropical to subtropical Pennsylvanian-Permian basins of the western United States such as the Midland, Orogrande, Paradox and Wood River basins as well as the tethyan McCloud limestone of the Klamath arc. The warm-water carbonates of the Kisosowin Sea were situated in a palaeolatitude that should have experienced cool water sedimentation from upwelling, indicating important linkages between climate, oceanic currents and tectonically controlled basins. In particular, our study demonstrates the existence of a Moscovian open ocean embayment with little restriction except in back-ramp lagoon and sabkha environments. This was followed by the emergence of the Tipinahokan Peninsula, which began during the Late Pennsylvanian C6 event and later climaxed during the Early Permian P1 event. The Tipinahokan Peninsula was fully emergent by the Asselian through the Sakmarian allowing a photozoan carbonate ramp to develop in the protected Kisosowin Sea to the east. A cool-water heterozoan carbonate ramp influenced by nutrient-rich upwelling waters existed to the west of the Tipinahokan Peninsula.

This study thus demonstrates the presence of a cool upwelling system along the northwest margin of Pangea at a time when substantially warmer water carbonate sedimentation occurred well over a 1000 kms to the north in the Sverdrup Basin (Arctic

Canada) and to the south in Nevada. Finally, our study shows that the major global climatic shift across the Asselian-Sakmarian boundary, which is associated with the thawing of Gondwana ice sheets, did not solely affect carbonate sedimentation in our study area.

Acknowledgements: Geoscience BC and Talisman Energy Inc. provided financial support that made this research in a remote area possible. This project was also financially supported by Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery grants held by Charles M. Henderson and Benoit Beauchamp.

References

Aretz, M., Herbig, H.G., Somerville, I.D., & Cûzar, P., 2010. Rugose coral biostromes in the late Viséan (Mississippian) of NW Ireland: Bioevents on an extensive carbonate platform. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **292**, 488-506.

Bamber, E.W., & Macqueen, R.W., 1979. Upper Carboniferous and Permian stratigraphy of the Monkman Pass and Southern Pine Pass areas, northeastern British Columbia. Bulletin *Geological Survey of Canada*, **301,** 27.

Beauchamp, B., 1994. Permian climatic cooling in the Canadian Arctic. Special Paper - *Geological Society of America*, **288**, 229-246.

Beauchamp, B., & Baud, A., 2002. Growth and demise of Permian biogenic chert along northwest Pangea: evidence for end-Permian collapse of thermohaline circulation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **184**, 37-63.

Beauchamp, B., & Desrochers, A., 1997. Permian warm- to very cold-water carbonates and cherts in Northwest Pangea. Special Publication, *Society for Sedimentary Geology*, **56**, 327-347.

Beauchamp, B., & Henderson, C.M., 1994. The Lower Permian Raanes, Great Bear Cape and Trappers Cove formations, Sverdrup Basin, Canadian Arctic: stratigraphy and conodont zonation. *Bulletin of Canadian Petroleum Geology*, **42**, 562-597.

Belasky, P., Stevens, C.H., & Hanger, R.A., 2002. Early Permian location of western North American terranes based on brachiopod, fusulinid and coral biogeography. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **179**, 245-266.

Bensing, J.P., James, N.P., & Beauchamp, B., 2008. Carbonate Deposition During a Time of Mid-Latitude Ocean Cooling: Early Permian Subtropical Sedimentation in the Sverdrup Basin, Arctic Canada. *Journal of Sedimentary Research*, **78**, 2-15.

Blakey, R.C., 2008. Pennsylvanian-Jurassic Sedimentary Basins of the Colorado Plateau and Southern Rocky Mountains, *in* Andrew, D.M., (ed) *Sedimentary Basins of the World*, **5**, 245-296.

Boyd, R., 2010. Transgressive wave-dominated coasts, *in* James, N.P., & Dalrymple, R.W., (eds) *Facies Models 4*, CSPG, 265-294.

Chernykh, V.V., 2005. Zonal methods in biostratigraphy: zonal conodont scale of the Lower Permian in the Urals. (In Russian) *Institute of Geology and Geochemistry, Uralian Branch of the Russian Academy of Sciences Ekaterinburg*, 217.

Clapham, M.E., 2010. Faunal evidence for a cool boundary current and decoupled regional climate cooling in the Permian of western Laurentia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **298**, 3-4.

Coates, A.G., & Jackson, J.B.C., 1987. Clonal Growth, Algal Symbiosis, and Reef Formation by Corals. *Paleobiology*, **13**, 363-378.

Davies, G.R., & Nassichuk, W.W., 1973. The Hydrozoan? Palaeoaplysina from the Upper Paleozoic of Ellesmere Island, Arctic Canada. *Journal of Paleontology*, **47**, 251-265.

Davies, G.R., Richards, B.C., Beauchamp, B., & Nassichuk, W.W., 1989. Carboniferous and Permian Reefs in Canada and Adjacent Areas. *Canadian Society of Petroleum Geologists*, **13**, 565-574.

Davydov, V.I., 2011. Taxonomy, nomenclature and evolution of the early schubertellids (Fusulinida, Foraminifera). *Acta Palaeontologica Polonica*, **56 (1)**, 181-194.

Davydov, V.I., Snyder, W.S., Spinosa, C., Ross, C.A., Ross, J.R.P., & Brenckle, P.L., 1997. Permian foraminiferal biostratigraphy and sequence stratigraphy of Nevada. *Special Publications - Cushman Foundation for Foraminiferal Research*, **36**, 31-34.

Dunham, R.J., 1962. Classification of carbonate rocks according to depositional texture. *Memoir American Association of Petroleum Geologists*, **1**, 108-121.

Dunn, L., 2003. *Sequence biostratigraphy and depositional environmental modeling of the Pennsylvanian-Permian Belloy Formation, northwest Alberta and northeast British Columbia*. Ph.D. thesis, University of Calgary.

Embry, A.F., III, & Klovan, J.E., 1971. A late Devonian reef tract on northeastern Banks Island, N.W.T. *Bulletin of Canadian Petroleum Geology*, **19**, 730-781.

Federowski, J., Bamber, E.W., & Stevens, C.H., 2007. Lower Permian colonial rugose corals, western and northwestern Pangaea; taxonomy and distribution. *National Research Council of Canada, Ottawa, Ont., Canada.*

Ford, C.M., Henderson, C.M., Hubbard, S.M., Soreghan, G.S., Hathaway, K., Soreghan, M., & Davydov, V.I., 2009. Geologic Record of Arid Climate Cyclothems in the Upper Pennsylvanian and Lower Permian Tobermory and Kananaskis Formations of Fortress Mountain Ridge Section. *CSPG CSEG CWLS Convention*: Calgary, Alberta, 771-774.

Francis, J.E., 1994. Paleoclimates of Pangea; geological evidence: Memoir, *Canadian Society of Petroleum Geologists*, **17**, 265-274.

Frey, R.W., 1990. Trace fossils and hummocky cross-stratification, Upper Cretaceous of Utah. *Palaios*, **5,** 203-218.

Frisia, S., 1994. Mechanisms of Complete Dolomitization in a Carbonate Shelf: Comparison between the Norian Dolomia Principale (Italy) and the Holocene of Abu Dhabi Sabkha, *In* Purser, B., Tucker, M., & Zenger, D., (eds) *Dolomites*, Blackwell Publishing Ltd., 55-74.

Golonka, J., & Ford, D., 2000. Pangean (Late Carboniferous-Middle Jurassic) paleoenvironment and lithofacies. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **161**, 1-34.

Halfar, J., Godinez-Orta, L., Mutti, M., Valdez-Holguin, J.E., & Borges, J.M., 2004a. Nutrient and temperature controls on modern carbonate production: An example from the Gulf of California, Mexico. *Geology*, **32**, 213-216.

Halfar, J., Ingle, J.C., & Godinez-Orta, L., 2004b. Modern non-tropical mixed carbonate-siliciclastic sediments and environments of the southwestern Gulf of California, Mexico. *Sedimentary Geology*, **165**, 93-115.

Heckel, P.H., 1986. Sea-level curve for Pennsylvanian eustatic marine transgressive-regressive depositional cycles along Midcontinent outcrop belt, North America. *Geology*, **14,** 330-334.

—, 2002. Overview of Pennsylvanian cyclothems in Midcontinent North America and brief summary of those elsewhere in the world. Memoir, *Canadian Society of Petroleum Geologists*, **19**, 79-98.

—, 2008. Pennsylvanian cyclothems in Midcontinent North America as far-field effects of waxing and waning of Gondwana ice sheets. *Geological Society of America*, Special Papers, **441**, 275-289.

Henderson, C.M., Dunn, L., Fossenier, K., & Moore, D., 2002. Sequence biostratigraphy and paleogeography of the Pennsylvanian-Permian Belloy Formation and outcrop equivalents in Western Canada: Memoir, *Canadian Society of Petroleum Geologists*, **19**, 934-947.

Henderson, C.M., Richards, B.C., Barclay, J.E., Mossop, G.D., & Shetsen, I., 1994. Permian strata of the Western Canada Sedimentary Basin, *In* Mossop, G.D., & Shetsen, I., (eds) *Geologic Atlas of the Western Canada Sedimentary Basin*, Geological Survey of Canada, 251-258.

Henderson, C.M., Zubin-Stathopoulos, K.D., & Dean, G.J., in press. Chronostratigraphic and tectonostratigraphic summary of the Late Paleozoic and Early Triassic succession in east-central British Columbia. *In Geoscience BC summary of activities 2011*, Geoscience BC, Report 2012-1.

Hubert, J.F., 1978. Paleosol caliche in the New Haven Arkose, Newark Group, Connecticut. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **24**, 151-168.

James, N.P., 1997. The cool-water carbonate depositional realm. Special Publication, *Society for Sedimentary Geology*, **56**, 1-20.

James, N.P., Collins, L.B., Bone, Y., & Hallock, P., 1999. Subtropical carbonates in a temperate realm; modern sediments on the Southwest Australian shelf. *Journal of Sedimentary Research*, **69**, 1297-1321.

James, N.P., Frank, T.D., & Fielding, C.R., 2009. Carbonate sedimentation in a Permian high-latitude, subpolar depositional realm; Queensland, Australia. *Journal of Sedimentary Research*, **79**, 125-143.

Jones, B., 2010. Warm-water neritic carbonates, *In* James, N.P., & Dalrymple, R.W., (eds) *Facies Models 4*, CSPG, 341-369.

Kepper, J.C., 1966. Primary dolostone patterns in the Utah-Nevada Middle Cambrian. *Journal of Sedimentary Research*, **36**, 548-562.

Klappa, C.F., 1978. Biolithogenesis of *Microcodium*: elucidation. *Sedimentology*, **25**, 489-522.

Kosir, A., 2004, *Microcodium* Revisited: Root Calcification Products of Terrestrial Plants on Carbonate-Rich Substrates. *Journal of Sedimentary Research*, **74**, 845-857.

Lluch-Belda, D., Lluch-Cota, D.B., & Lluch-Cota, S.E., 2003. Baja California's Biological Transition Zones: Refuges for the California Sardine. *Journal of Oceanography*, **59**, 503-513.

MacRae, J., & McGugan, A., 1977. Permian stratigraphy and sedimentology-southwestern Alberta and southeastern British Columbia. *Bulletin of Canadian Petroleum Geology*, **25**, 752-766.

Mastandrea, A., Perri, E., Russo, F., Spadafora, A., & Tucker, M., 2006. Microbial primary dolomite from a Norian carbonate platform: northern Calabria, southern Italy. *Sedimentology*, **53**, 465-480.

McGugan, A., & Rapson, J.E., 1962. Permo-Carboniferous stratigraphy, Crowsnest area, Alberta and British Columbia. *Journal of the Alberta Society of Petroleum Geologists*, **10**, 352-368.

—, 1963. Permo-Carboniferous stratigraphy between Banff and Jasper, Alberta. *Bulletin of Canadian Petroleum Geology*, **11**, 150-160.

McGugan, A., & Rapson-McGugan, J.E., 1976. Permian and Carboniferous stratigraphy, Wapiti Lake area, northeastern British Columbia. *Bulletin of Canadian Petroleum Geology*, **24**, 193-210.

Moore, D., 2002. *The Stratigraphy of the Pennsylvanian and Lower Permian Tobermory, Kananaskis and Johnston Canyon Formations of the Front Ranges of the Southern Canadian Rocky Mountains, Alberta and British Columbia*. Masters thesis, University of Calgary.

Morin, J., Desrochers, A., & Beauchamp, B., 1994. Facies analysis of Lower Permian platform carbonates, Sverdrup Basin, Canadian Arctic Archipelago. *Facies*, **31**, 105-130.

Naqvi, I.H., 1972. The Belloy Formation (Permian), Peace River area, northern Alberta and northeastern British Columbia. *Bulletin of Canadian Petroleum Geology*, **20**, 58-88.

Nelson, J.L., Colpron, M., Piercey, S.J., Dusel-Bacon, C., Murphy, D.C., & Roots, C.F., 2006. Paleozoic tectonic and metallogenic evolution of the pericratonic terranes in

Yukon, northern British Columbia and eastern Alaska. *Geological Association of Canada Special Paper*, **45**, p. 323-360.

Rapson-McGugan, J.E., 1970. The diagenesis and depositional environment of the Permian Ranger Canyon and Mowitch formations, Ishbel Group, from the southern Canadian Rocky Mountains. *Sedimentology*, 15**,** 363-417.

Reid, C.M., James, N.P., Beauchamp, B., & Kyser, T.K., 2007. Faunal turnover and changing oceanography: Late Palaeozoic warm-to-cool water carbonates, Sverdrup Basin, Canadian Arctic Archipelago. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **249**, 128-159.

Richards, B.C., Barclay, J.E., Bryan, D., Hartling, A., Henderson, C.M., Hinds, R.C., Trollope, F.H., Mossop, G.D., & Shetsen, I., 1994. Carboniferous strata of the Western Canada Sedimentary Basin, *In* Mossop, G.D., & Shetsen, I., (eds) *Geologic Atlas of the Western Canada Sedimentary Basin*, Geological Survey of Canada, 221-250.

Ross, C.A., 1995. Permian fusulinaceans. *In*: P.A. Scholle, T.M. Peryt, & D.S. Ulmer-Scholle (eds.), *Permian of Northern Pangea*. Vol. **1**: Paleogeography, Paleoclimate, Stratigraphy, Springer-Verlag, Berlin, 167-185.

Saxena, S., & Betzler, C., 2003. Genetic sequence stratigraphy of cool water slope carbonates (Pleistocene Eucla Shelf, southern Australia). *International Journal of Earth Sciences*, **92**, 482-493.

Skinner, J.W. & Wilde, G.L., 1965. Permian biostratigraphy and fusulinid faunas of the Shasta lake area, Northern California. *University of Kansas Paleontological Contributions*, Paper Article **6**, p. 1-98.

Soreghan, G.S., Soreghan, M.J., & Hamilton, M.A., 2008. Origin and significance of loess in late Paleozoic western Pangaea; a record of tropical cold? *Palaeogeography, Palaeoclimatology, Palaeoecology*, **268**, 234-259.

Stevens, C.H., Wagner, D.B., & Sumsion, S.R., 1979. Permian Fusulinid Biostratigraphy, Central Cordilleran Miogeosyncline. *Journal of Paleontology*, **53 (1)**, 29-36.

Sun, D., Bloemendal, J., Rea, D.K., Vandenberghe, J., Jiang, F., An, Z., & Su, R., 2002. Grain-size distribution function of polymodal sediments in hydraulic and aeolian environments, and numerical partitioning of the sedimentary components. *Sedimentary Geology*, **152**, 263-277.

Tabor, N.J., Montanez, I.P., Scotese, C.R., Poulsen, C.J., & Mack, G.H., 2008. Paleosol archives of environmental and climatic history in paleotropical western Pangea during the latest Pennsylvanian through Early Permian. Special Paper, *Geological Society of America*, **441**, 291-303.

Vai, G.B., 2003. Development of the palaeogeography of Pangaea from Late Carboniferous to Early Permian. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **196**, 125-155.

Wahlman, G.P., 2002. Upper Carboniferous-Lower Permian (Bashkirian-Kungurian) mounds and reefs. Special Publication, *Society for Sedimentary Geology*, **72**, 271-338.

Walsh, J.J., Whitledge, T.E., Kelley, J.C., Huntsman, S.A., & Pillsbury, R.D., 1977. Further Transition States of the Baja California Upwelling Ecosystem. *Limnology and Oceanography*, **22**, 264-280.

Wamsteeker, M.L., 2007. *Diagenetic and geochemical characterization of the Ksituan Member of the Belloy Formation, east central British Columbia Foothills.* Bachelors thesis, University of Calgary.

Wang, D., 1993. *Conodont biostratigraphy of the Carbon Ridge Formation, Secret Canyon, Fish Creek Range, Nevada.* Idaho State University, Pocatello, ID, Boise, 59.

Wanless, H.R., & Shepard, F.P., 1936. Sea level and climatic changes related to late Paleozoic cycles. *Geological Society of America Bulletin*, **47**, 1177-1206.

Watkins, R., & Wilson, E.C., 1989. Paleoecologic and biogeographic significance of the biostromal organism Palaeoaplysina in the Lower Permian McCloud Limestone, eastern Klamath Mountains, California. *Palaios*, **4**, 181-192.

Wells, J.W., 1963. Coral Growth and Geochronometry. *Nature*, **197**, 948-950.

Wray, J.L., 1977. *Calcareous Algae*. Elsevier Scientific Publishing Company, Amsterdam, 185.

Zubin-Stathopoulos, K.D. 2011. *Tectonic Evolution, Paleogeography and Paleoclimate of Pennsylvanian–Permian Strata in East-Central British Columbia: Implications from Conodont Biostratigraphy and Carbonate Sedimentology*. Masters thesis, University of Calgary.

Figure captions

Fig. 1. Study area, east-central British Columbia. The line of cross sections of figures 3 and 8 are also indicated. Modified from Zubin-Stathopoulos et al., 2011.

Fig. 2. Stratigraphy and tectonostratigraphic sequences of east-central British Columbia, Peace River Basin and the 'Banff Region' of the southwestern Alberta Rockies. The focus of this study is highlighted in grey. Colours represent primary lithology. Blue=limestone, purple=dolostone, orange=chert, yellow=quartz arenite, green=bioturbated/bioclastic sandstone and grey=silty shale. C=Carboniferous, P=Permian. Tectonostratigraphic sequences modified from Snyder et al., 2002 and Trexler et al., 2004. Stratigraphy modified from Zubin-Stathopoulos et al*.,* 2011.

Fig. 3. Cross section A-A' as indicated on Figs. 1 and 9. Correlations are based on ages obtained from conodonts, foraminifers and coral.

Fig. 4. (a) Fellers Creek litholog indicating age based on conodont biostratigraphy, formations, conglomerates (red areas) and microfacies (MF) occurrence, modified from Zubin-Stathopoulos et al., 2011. Key to symbols and lithologies is shown in Fig. 5. (b) Conglomerate within the Sakmarian sequence containing reworked Pennsylvanian conodonts; 36.45 m. (c) 2.85 m. Second Belcourt Conglomerate. (d) Basal Belcourt conglomerate; 0 m.

Fig. 5. (a) Mountain Creek litholog indicating age based on conodont biostratigraphy, formations present and facies occurrence. The upper portion was re-measured at a slightly different location and logged as a separate section; the equivalent level is indicated by a red line. Field occurrences of (b) MF-11 (49.5 m), (c) MF-08 (43.7 m) and (d) MF-10 (41.0 m) are shown.

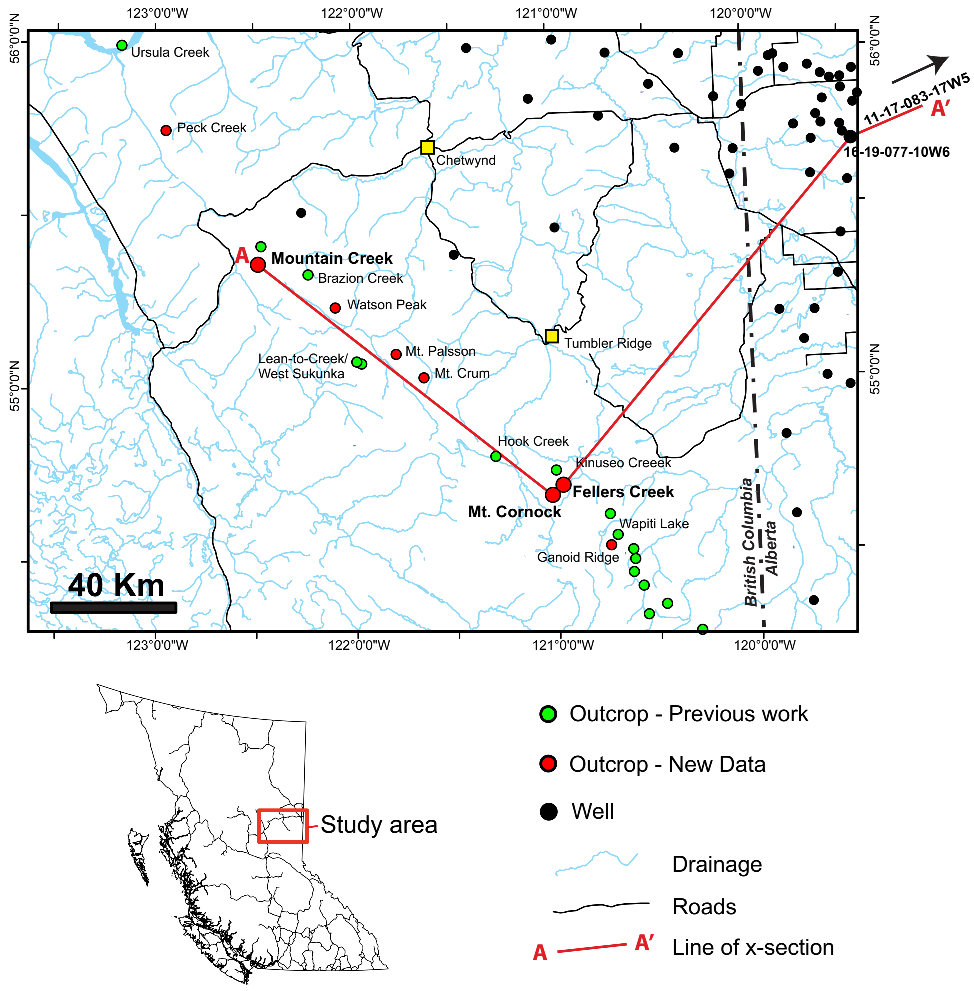
Fig. 6. Belcourt Formation microfacies (Fellers Creek Facies Assemblage) photomicrographs taken in plain polarized light. All measurements are from the base of the Belcourt Formation (basal conglomerate) at the Fellers Creek section. (a) MF-01, Fellers Creek at 12.35 m (b) MF-01, 11.25 m. (c) MF-02, 18.15 m. (d) MF-03, 40.95 m. (e) MF-04, 27.75 m. (f) Outcrop photograph, knife is 10 cm long, MF-05, 26.25 m. (g) MF-06, 5.9 m. (H) MF-07, 39.1 m. Ech=echinoderm, Bch=brachiopod, Bry=bryozoan, Fus=Fusulinacean, Da=Dasycladacean algae, Paleo=*Palaeoaplysina*.

Fig. 7. Belcourt Formation microfacies (Mountain Creek Facies Assemblage) photomicrographs taken in plain polarized light. All measurements are from the base of the Mountain Creek section. (a) MF-08, 9 m. (b) MF-08, 104.5 m (c) MF-09, abundant sponge spicules at 107 m (d) MF-10, 140 m (e) MF-10, 140 m, from the same thin section indicating possible storm event (f) Outcrop photograph, finger tips for scale, MF-11. (g) MF-12, 80.7 m. (h) MF-12, 6.35 m. Ech=echinoderm, Bch=brachiopod, Bry=bryozoan

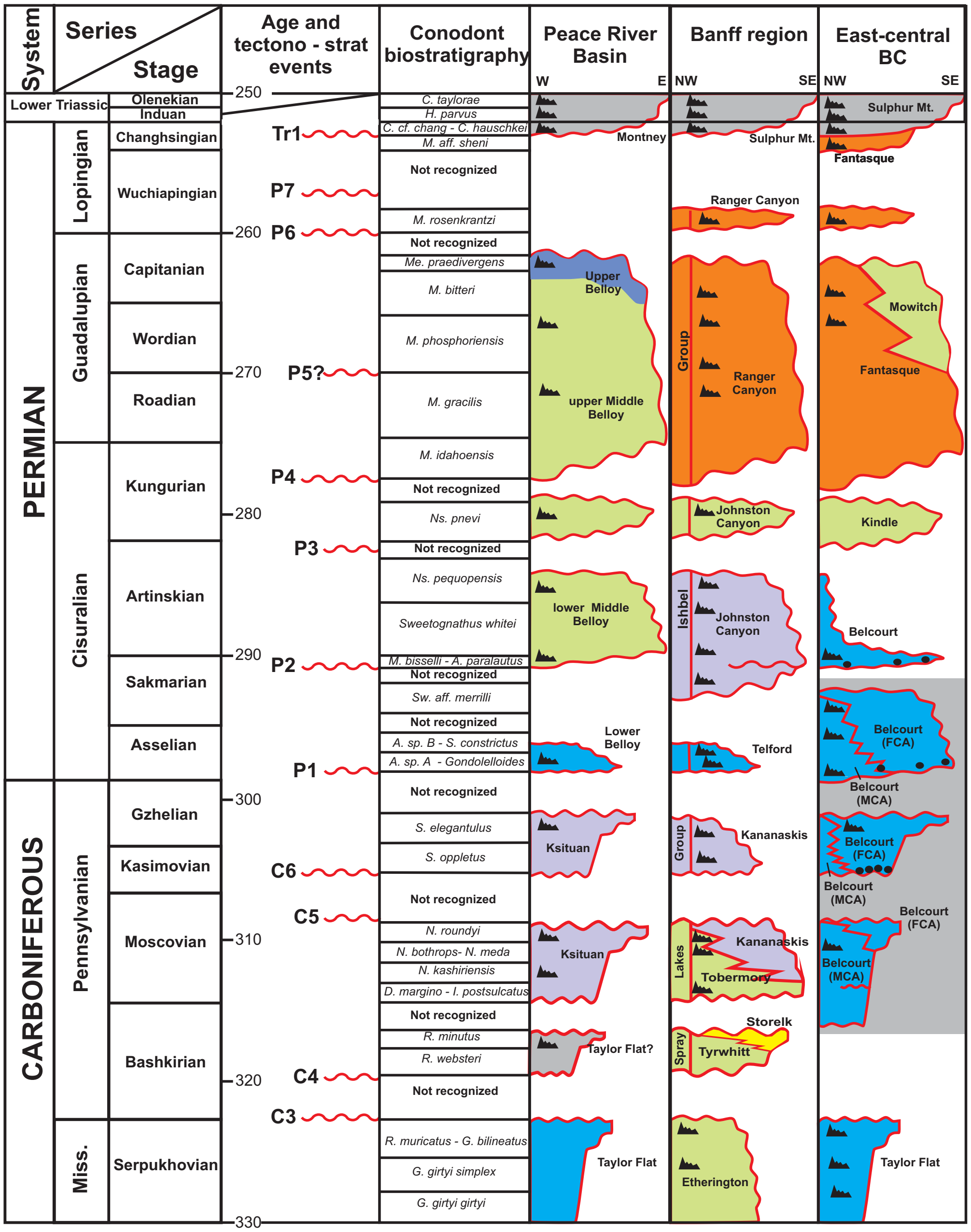
Fig. 8. Deposition model of time slices roughly based on cross section of Fig. 1 as shown in inset map. FWWB=Fair weather wave base, SWB=Storm wave base. Facies locations are indicated by facies number. (a) Moscovian profile. The occurrence and distribution of shallow water deposits on the right side of the diagram are based on data from Wamsteeker (2007). K=Extensive supratidal to shallow subtidal dolostone succession (Ksituan Formation) occurs east of the back-ramp setting. (b) Asselian profile showing the Tipinahokan Peninsula and Kisosowin Sea. Known facies are shaded in solid colours (see legend) and interpreted location of facies are slightly transparent. (c) Sakmarian profile. Known facies are shaded in solid colours (see legend) and interpreted location of facies are slightly transparent.

Fig. 9. Fusulinaceans from Fellers Creek section. 1, *Schubertella* sp. Fel_37.5_6c, 0.1mm. 2, *Schubertella* ex gr. *king*i Fel_39.5_1d, 0.1mm. 3, *Pseudofusulina attenuata* Skinner and Wilde Fel_37.5_1a, 1mm. 4, *Pseudofusulina attenuata* Skinner and Wilde Fel_37.5_2b, 1mm. 5, *Pseudofusulina attenuata* Skinner and Wilde Fel_37.5_8a, 1mm. 6, *Pseudofusulina attenuata* Skinner and Wilde Fel_37.5_1b, 1mm. 7, *Pseudofusulina attenuata* Skinner and Wilde Fel_39.5_1a, 1mm. 8, *Pseudofusulina attenuata* Skinner and Wilde Fel_37.5_5a, 1mm. 9, *Pseudofusulina acuta* Skinner and Wilde Fel_37.5_4a, 1mm. 10, *Pseudofusulina acuta* Skinner and Wilde Fel_37.5_1d, 1mm. 11, *Pseudofusulina acuta* Skinner and Wilde, Fel_37.5_5b, 1mm.

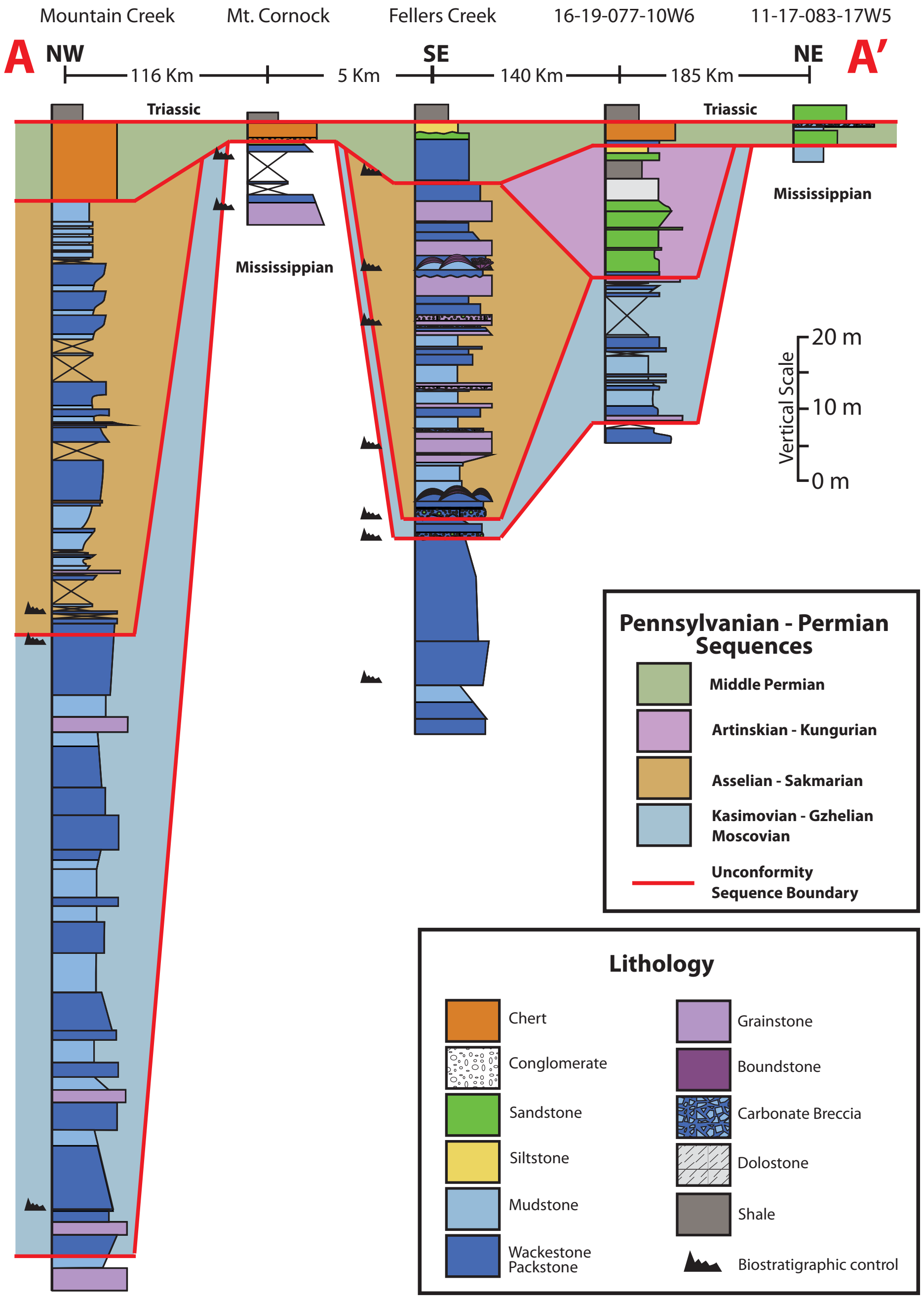
Fig. 10. Asselian-Sakmarian paleogeography and tectonic elements for British Columbia, Alberta and western United States, modified from Henderson et al. (2001). Configuration is based on the contouring function in ArcGIS and the predicted thickness distribution. This is a non-palinspastic reconstruction, so the Kisosowin Sea would be approximately 20 km wider than shown (Richards et al., 1994). The width of the Slide Mountain Ocean and Havallah Basin is speculative. F1 to F3 indicates the location of Fusulinacean assemblages discussed in the text.



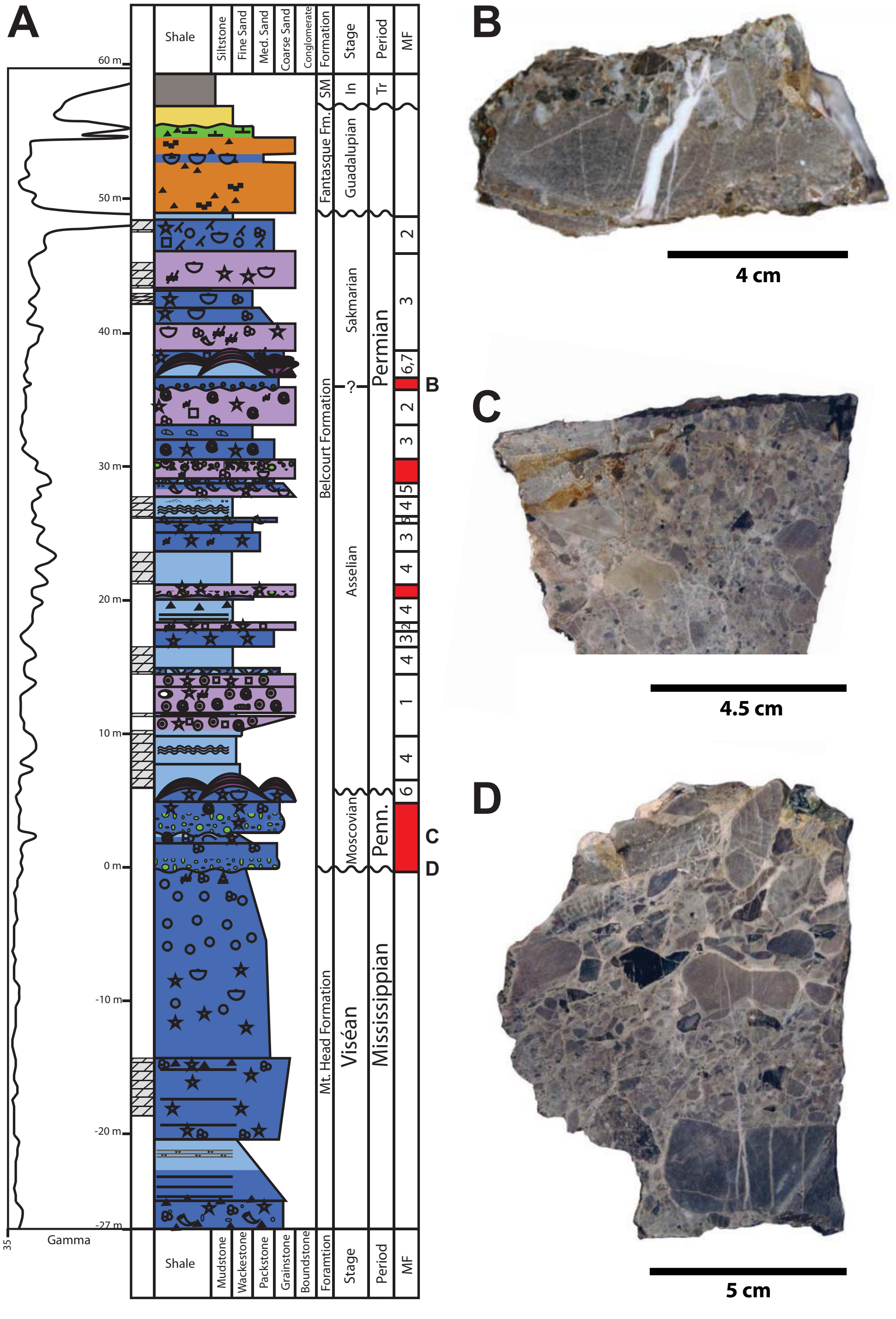
Zubin-Stathopoulos et al._Figure 01



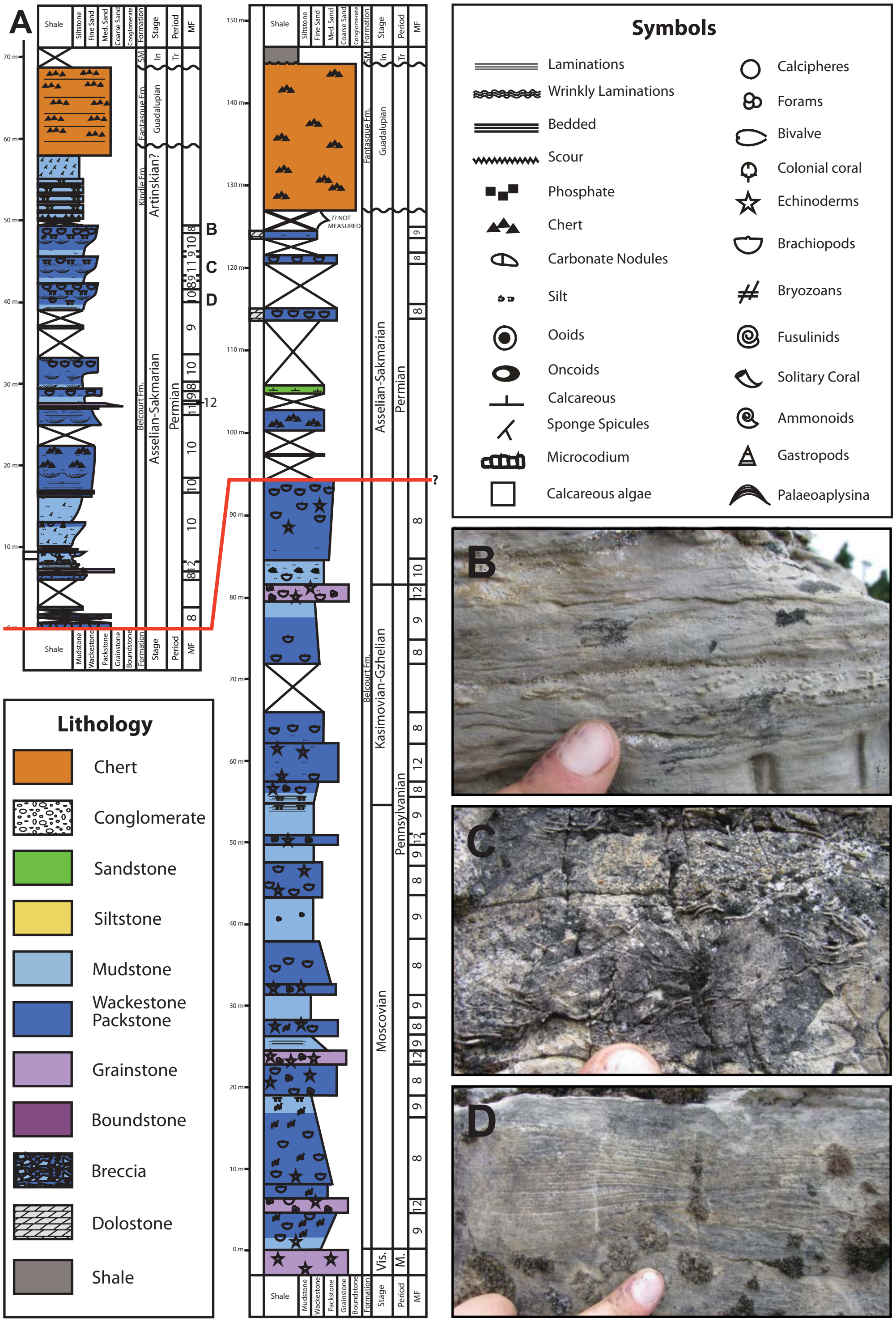
Zubin-Stathopoulos et al._Figure 02



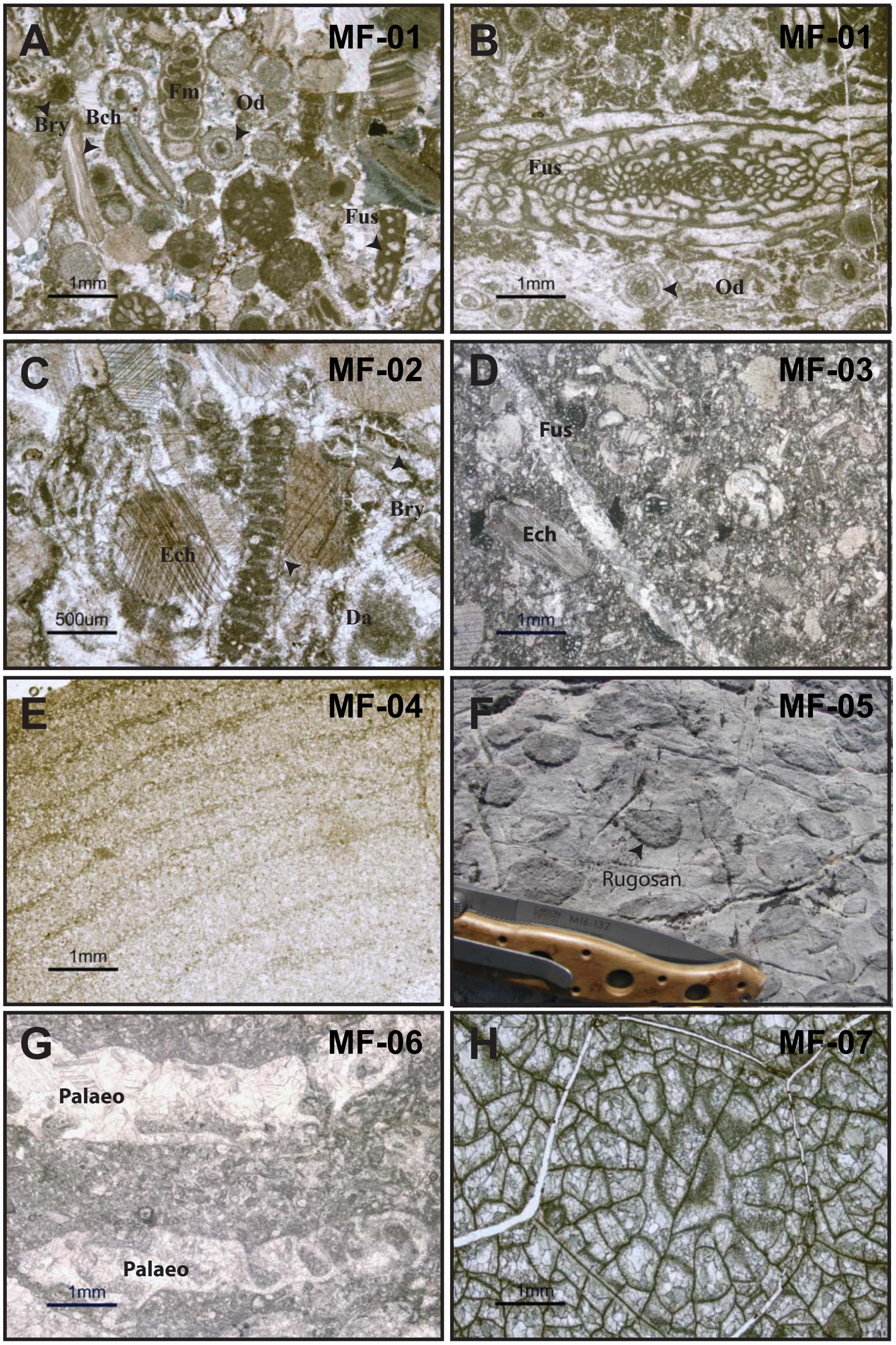
Zubin-Stathopoulos et al._Figure 03



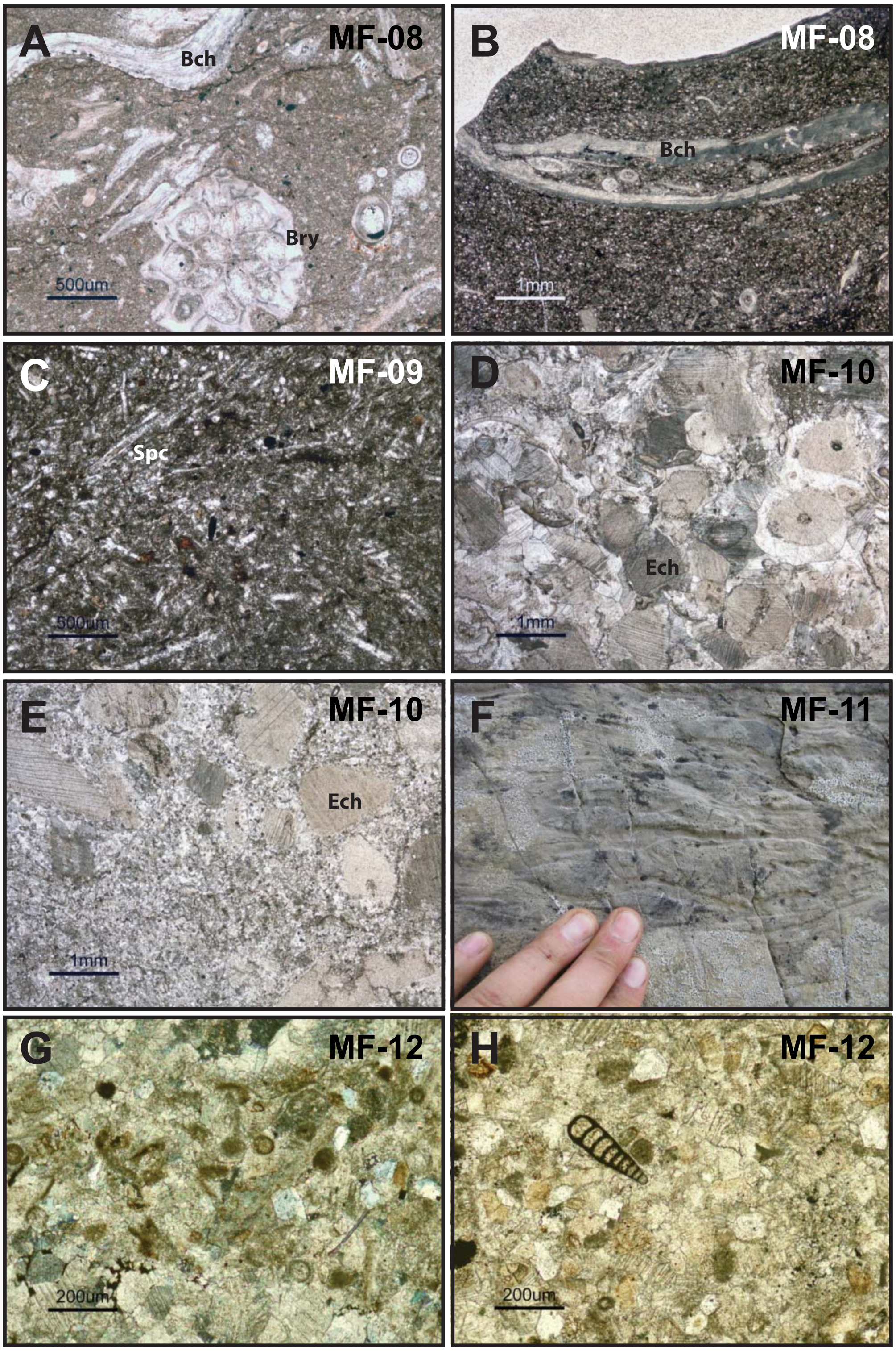
Zubin-Stathopoulos et al._Figure 04



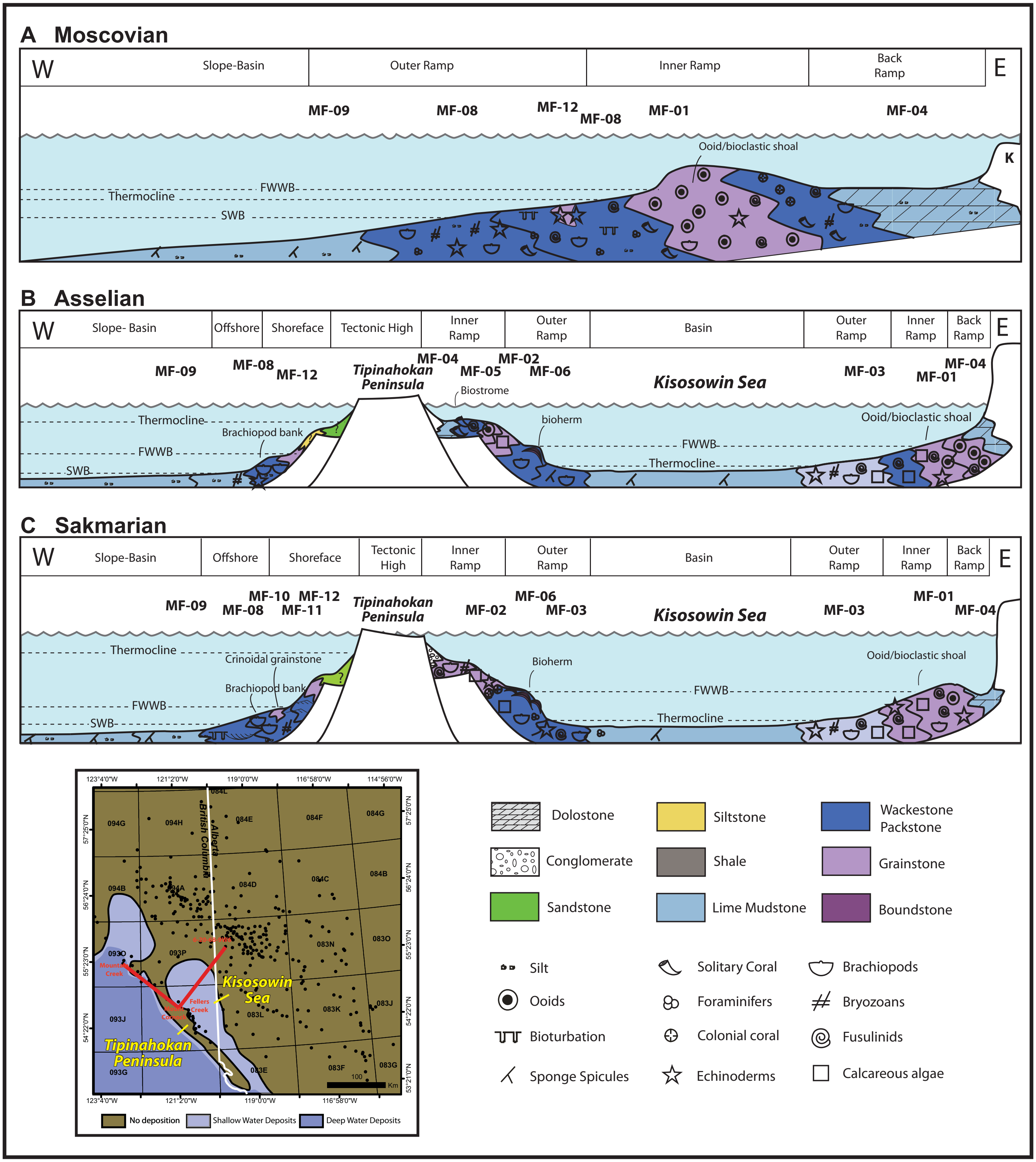
Zubin-Stathopoulos et al._Figure 05



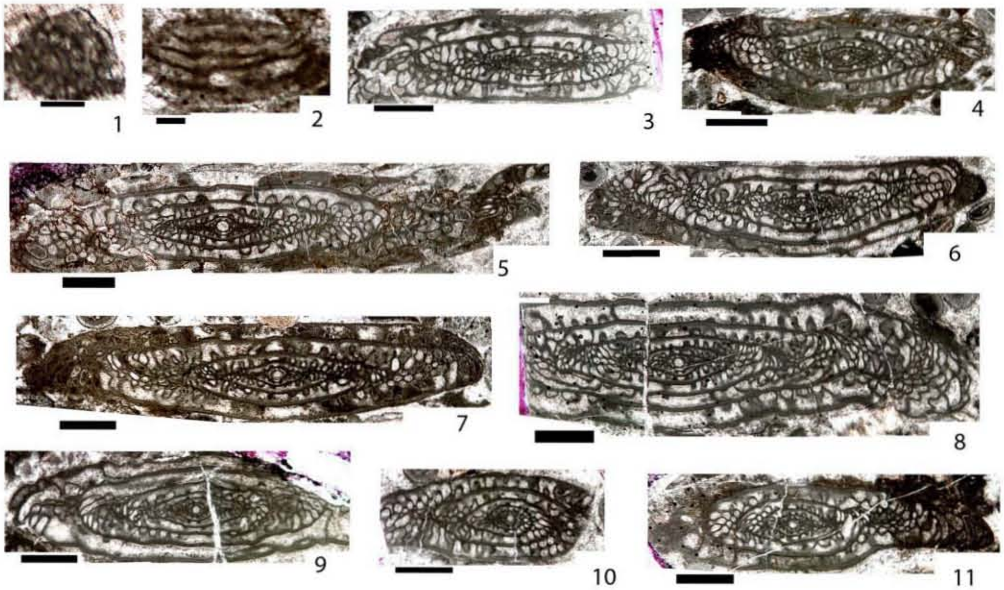
Zubin-Stathopoulos et al._Figure 06



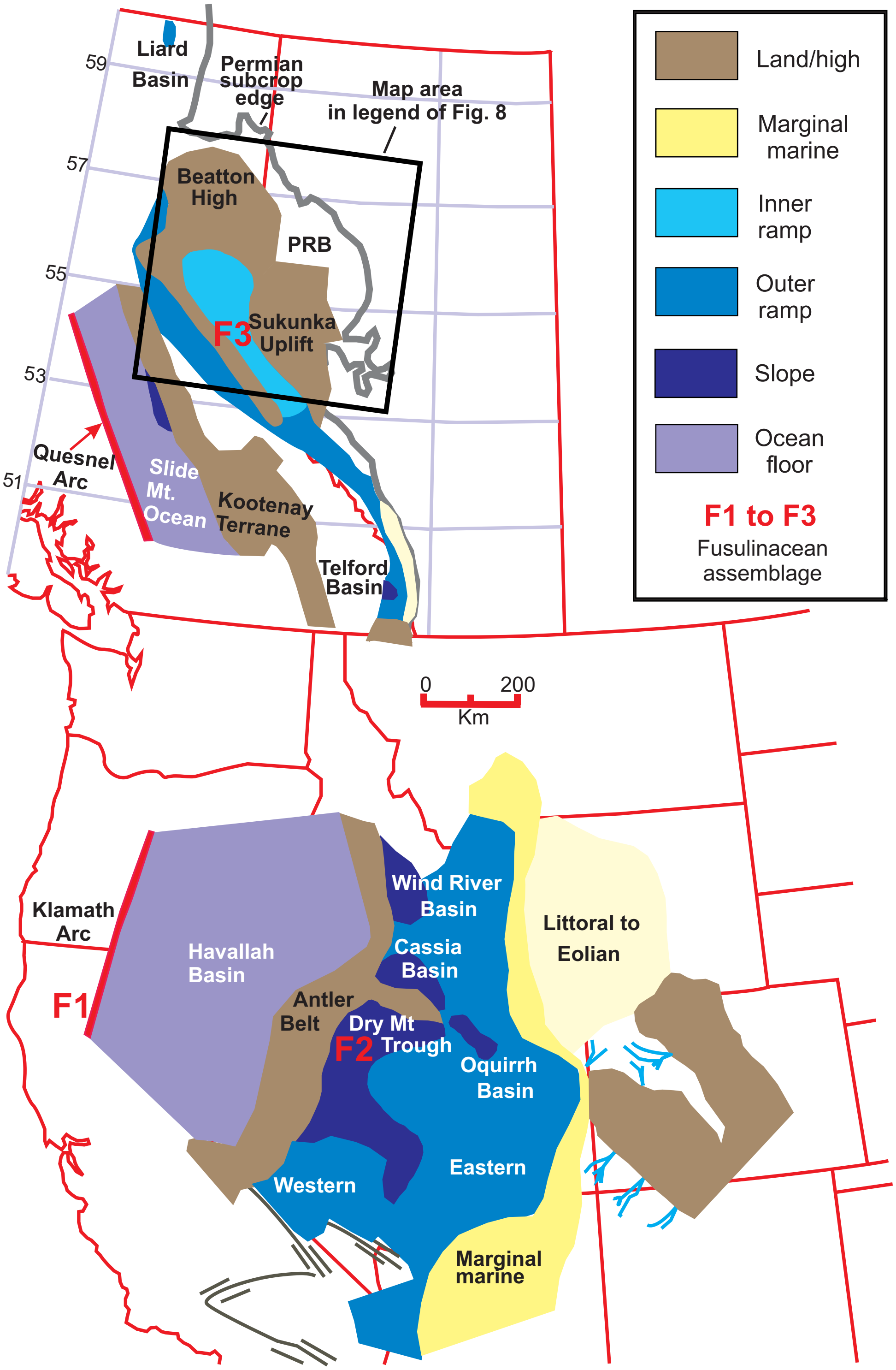
Zubin-Stathopoulos et al._Figure 07



Zubin-Stathopoulos et al._Figure 08



Zubin-Stathopoulos et al._Figure 09



Zubin-Stathopoulos et al._Figure 10

Table 01. *Carbonate microfacies of Moscovian to Sakmarian Belcourt Formation, east-central British Columbia, Canada.*

FWB=Fairweather Wave Base. SWB=Storm Wave Base. FCA=Fellers Creek facies assemblage. MCA=Mountain Creek facies assemblage. References are: (1) Bamber and Macqueen, 1979, (2) Wamsteeker, 2007 (3) McGugan and Rapson-McGugan, 1976, (4) Kepper, 1966, (5) Mastandrea et al., 2006, (6) Frisia, 1994, (7) Aretz et al., 2010, (8) Coates and Jackson, 1987, (9) Wells, 1963, (10) Mastandrea et al., 2006, (11) *Protowentzelella kunthi* (pers. comm., E.W. Bamber 2010), (12) Soreghan et al., 2008, (13) Sun et al., 2002, (14) Frey, 1990, (15) Boyd, 2010, (16) Jones, 2010, (17) James et al., 2009, (18) Saxena and Betzler, 2003

Name	**ASSOCIATION Main biota**	**Figured elements**	**Petrographic attributes**	**Relevant field observations**	**Occurrence**	**Depositional environment**
MF-01 Ooid-Foraminifer Grainstone (Fig. 6A, 6B)	PHOTOZOAN foraminifera Fusulinid Endothyrid paleotextularid echinoderm brachiopod	ooids (60-90%) bioclasts (10-40%) broken fossils *Microcodium*	Tangential ooids former aragonite recrystalization		east & south outcrops (FCA) Fellers Creek Kinuseo Creek Meosin Mountain Mount Hannington well c-52-K/93-O-8(1) surface-subsurface NE BC(2)	INNER RAMP (SHOAL) proximity to shoreline warm shallow high energy (FWB) oligotrophic subaerial exposure
MF-02 Algal-Bioclastic Grainstone (Fig. 6C)	PHOTOZOAN Calcareous alga Dasycladacean phylloid foraminifera echinoderm brachiopod bryozoan	broken fossils (30-70%) bioclasts (30-70%)	Little to no mud		east & south outcrops (FCA) Fellers Creek Kinuseo Creek Meosin Mountain Mount Hanington (1)	INNER RAMP proximity to shoal warm shallow high energy (>FWB) oligotrophic
MF-03 Bryozoan-Echinoderm Packstone-Grainstone (Fig. 6D)	HETEROZOAN-EXTENDED Bryonoderm-ext. foraminifera Fusulinid paleotextularid rugose coral solitary echinoderm brachiopod bryozoan trepostome fenestrate	bioclasts (0-30%) fossils whole & broken (0-100%)	Bryozoans branches intact <1 cm in diameter		east & south outcrops (FCA) Fellers Creek Kinuseo Creek (1,3) Meosin Mountain (1,3) Mount Hanington (1,3)	INNER TO MIDDLE RAMP cool shallow moderate to high energy (<FWB) oligotrophic
MF-04 Microbial Lime- to Dolomudstone (Fig. 6E)		chert clasts Rare 1-2 cm Sub-angular	Dolomitization Partial to complete Uniform Finely crystalline 5-10 μm rhombs Laminations Light & dark bands Grade into one another	Recessive >0.5 m units Poorly exposed Laminated	east & south outcrops (FCA) Fellers Creek Kinuseo Creek (?)	INTERTIDAL BACK-RAMP low energy suspension settling high energy events microbial stabilization (4,5) stressed environment evaporative arid climate (6,7) primary to early diagenetic dolomitization

			Fabric Patchy Locally brecciated			
MF-05 Rugose Coral Wackestone Packstone (Fig. 6F)	PHOTOZOAN(?) rugose coral colonial solitary	whole fossils (100%)	dark micritic matrix	30-50 cm beds Rugose corals distribution not uniform along bedding plane not in life position not broken or abraded corallite diameter: 1-3cm	east & south outcrops (FCA) Fellers Creek	INNER RAMP (PROTECTED) biostromes protected areas >FWB rugose corals knocked over & buried quickly photic zone limitation (8-10) no Zooxanthellae-type symbionts light and depth dependent because photic zone food source (7-9)
MF-06 *Palaeoaplysina* Packstone Boundstone (Fig. 6G)	PHOTOZOAN Calcareous alga *Tubiphytes* Foraminifera encrusting echinoderm brachiopod bryozoan	fossils whole & broken (100%)	heavy recrystalization of *Palaeoaplysina* plates Lime mudstone and wackestone matrix fills space in between *Palaeoaplysina* plates	massively bedded units beds are 0.2-1 m thick irregular upper and lower contacts *Palaeoaplysina* plates are 2-5 mm thick and 2-5 cm long Plates parallel to bedding	east & south outcrops (FCA) Fellers Creek (two levels) Kinuseo Creek (1) western outcrops (MCA) West Sukunka (1)	OUTER RAMP bioherms moderate to low energy Aassociated with colonial rugose coral bioherms and grainstone (MF-07 and MF-03) that formed within high-energy environments
MF-07 Colonial Rugose Boundstone (Fig. 6H)	PHOTOZOAN rugose coral colonial (11)	fossils whole (100%)		Irregular patches on top of and in sharp contact with *Palaeoaplysina* Boundstone Coralites approx. 1 cm in diameter Ceroid growth form	east & south outcrops (FCA) Fellers Creek (one level)	INNER RAMP isolated bioherms high-energy environment constant wave agitation photic zone hard (lithified) substrate
MF-08 Bryozoan- Brachiopod Wackestone Packstone (Fig. 7A, 7B)	HETEROZOAN Bryonoderm echinoderm brachiopod bryozoan trepostome fenestrate foraminifera endothyrid paleotextularid	fossils broken (100%)	matrix mixed argillaceous – lime mud sometimes dolomitic	Broken fossils preserved in multiple different orientations	western outcrops (MCA) Mountain Creek West Sukunka (1)	MIDDLE RAMP Relatively shallow Just below FWB Low energy (most of the time) Cool water
MF-09 Bioturbated Silty Lime Mudstone (Fig. 7C)	HETEROZOAN Bryonoderm sponge spicule brachiopod bryozoan foraminifera protonodosarid	fossils whole & broken (100%)	Terrigenous component is sub-angular coarse, quartz silt up to 20%. Sponge spicules commonly found in burrow fills.	Variably bioturbated feeding and dwelling traces *Chondrites* *Helminthopsis* *Palaeophycus* Planar laminae	western outcrops (MCA) Mountain Creek West Sukunka (1)	OUTER RAMP Relatively deep Below FWB and SWB Low energy Sporadic high-energy events Suspension settling Aeolian silt in arid climate (12-13) Oxic sea floor conditions Cool to cold water

				often disrupted by bioturbation		
MF-10 Hummocky Cross-Stratified Silty Packstone Grainstone (Fig. 7D, 7E)	HETEROZOAN Bryonoderm echinoderm brachiopod bryozoan ostracod	fossils broken silt-size (100%)	Microgranular fabric	Small-scale hummocky cross-stratified silty Crinoidal packstone/grainstone single bed grades upwards from grainstone to a packstone overlain by *Zoophycos*(?)-rich beds	western outcrops (MCA) Mountain Creek West Sukunka(?) (1)	SHOREFACE TO OFFSHORE TRANSITION Relatively shallow water below FWB, above SWB Regular storms Storm-related lag deposition Cool water Opportunistic organisms (14)
MF-11 Silty Cross-Bedded Packstone Grainstone (Fig. 7F)	HETEROZOAN Bryonoderm brachiopod bryozoan	fossils bioclasts silt-size (100%)	silty (as least 20%) and argillaceous microgranular	Ripples	western outcrops (MCA) Mountain Creek West Sukunka(?) (1)	SHOREFACE shallow water above FWB Cool, eutrophic(?) water (15, 16)
MF-12 Bioclastic Grainstone Packstone (Fig. 7G, 7H)	HETEROZOAN Bryonoderm echinoderm brachiopod (rare) bryozoan (rare) foraminifera endothyrid paleotextularid	fossils bioclasts silt-size (70-100%) Broken (10-30%) peloid	Matrix is mixed argillaceous and micrite		western outcrops (MCA) Mountain Creek (upper part) West Sukunka(?) (1)	INNER RAMP Relatively shallow water > FWB, above SWB High energy, constant agitation Periodic storms Cool water Sediment-starved environment(?) (17,18)