Tectonic Evolution and Paleogeography of Pennsylvanian–Permian Strata in East-Central British Columbia (NTS 093I, O, P): Implications from Stratigraphy, Fracture Analysis and Sedimentology

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Introduction

The northwestern margin of Pangea during the late Paleozoic (Mississippian–Permian) is historically depicted as a passive margin (Barclay et al., 1990). However, there is evidence for active compressive tectonics during the Antler and Sonoma orogenies recorded in the western United States and into southern Canada (Dickenson, 2004). In addition, active tectonism during the Pennsylvanian–Permian has been interpreted to affect successions in the western United States (Snyder et al., 2002; Trexler et al., 2004). A very fundamental question concerns whether these tectonic events affected the North American margin or occurred during the process of amalgamation of a distant ribbon continent termed Rubia (Hildebrand, 2009). Research during the past fifteen years on the North American craton of west-central Alberta and east-central British Columbia (BC) has shown evidence for tectonic activity in the form of structural inversion of block faults during the Late Paleozoic (Fossenier, 2002; Henderson et al., 2002; Dunn, 2003; Henderson et al., 2010). These structural inversion events directly affect the paleogeography of this area and set some limits on the site of tectonic activity. Although the late Paleozoic paleogeography of west-central Alberta surrounding the Peace River Basin (PRB) is established (Dunn, 2003), the BC portion of the equivalent-aged units is still unresolved. This paper presents new data that show how tectonic and paleogeographic features had significant control on the environments of deposition of Pennsylvanian–Permian strata, as well as the inheritance of some of these tectonic and paleogeographic trends during the Late Cretaceous to Paleogene development of the fold-and-thrust belt. A new 'western paleo-high', located west of the Peace River Basin, is documented by significant differences in carbonate rock types, as well as an unconformity generated during uplift. The integration of sequence stratigraphy, biostratigraphy, sedimentology and fracture analysis helps to develop predictive models for the distribution of reservoir units within the study area.

Keywords: *biostratigraphy, Pennsylvanian, Permian, tectonics, carbonates, fractures, upwelling, western Pangea*

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Study Area and Methods

Field sites for this study are located in the Sukunka-Kakwa area of east-central BC, within NTS areas 93I, O and P (Figure 1). The outcrops are located southeast of Chetwynd and extend to south of Tumbler Ridge. They are part of a southeast-trending outcrop belt that represents the westernmost extent of the Western Canada Sedimentary Basin. Nine outcrops were studied in August of 2009 and 2010. They are, from north to south, Ursula Creek, Peck Creek, Mountain Creek, Watson Peak, Mount Palsson, Mount Crum, Fellers Creek, Mount Cornock and Ganoid Ridge. One exploration well (06-20-068-9W6, Figure 1) is used and labelled on the map to show the relationship between deposits in the study area and those farther east into the subsurface of west-central Alberta. Outcrops were accessed by helicopter due to the remote nature of the sites. Data collected and processed from fieldwork in 2009 (Henderson et al., 2010) are combined with new field observations obtained in August 2010 and presented in this summary.

Peck Creek, Mountain Creek, Fellers Creek and Mount Cornock were the focus of fieldwork in August 2010. Samples collected at Fellers Creek and Mountain Creek fill data gaps that were identified from the 2009 season (Henderson et al., 2010). Ursula Creek, Peck Creek and Mount Cornock represent new outcrops accessed in August 2010. Samples collected in 2010 included 49 large (5–10 kg) rock samples used for conodont analysis and 60 small samples for thin sections. In total, 260 thin sections and 140 conodont samples were analyzed from both field seasons. Conodont samples were processed following standard procedures outlined by Collinson (1963) and Stone (1987). Carbonate petrography was necessary for interpretation of depositional environments.

Fracture analysis was conducted only in August 2009, but new interpretations supplement preliminary results presented in Henderson et al. (2010). Both linear and circular scan lines were used to record the orientation and density of fractures found in Mississippian, Pennsylvanian and Permian rocks. In addition, large-scale lineament data were collected using digital elevation models overlain on geological maps of the study area. These fracture patterns were recognized and analyzed at the micro, meso and macro scales (Dean, 2010).

Geological Setting

The strata in question are equivalent to subsurface strata to the east in the PRB and to the southwest in the Alberta portion of the Rocky Mountains (Figure 2). The stratigraphic sequences in both outcrop and the subsurface are bounded by several major unconformities. Differences in the duration and timing of unconformities between east-central BC and the subsurface in Alberta provide insight into the paleogeographic details of both localities. The Pennsylvanian portion of the Belcourt Formation in east-central BC is equivalent to the lower Belloy Formation in the subsurface (PRB), while the Lower Permian portion of the Belcourt Formation is equivalent to the middle Belloy Formation. The Fantasque Formation is equivalent to the upper Belloy Formation from the PRB (Henderson et al., 1994).

Biostratigraphic data provide evidence that active tectonics in east-central BC coincided with the timing of tectonism recorded in Nevada (Snyder et al., 2002; Trexler et al., 2004); these tectonic events occured during an interval that falls between the Antler and Sonoma orogenies (Henderson et al., 2010). The Antler and Sonoma orogenies are recorded not only in the western United States, but also into the southern and central portions of western Canada (Root, 2001), providing a compelling argument that the Antler, Sonoma and Pennsylvanian–Permian tectonic events influenced the entire western margin of the supercontinent Pangea. Tectonic activity during this time period affected basin and sub-basin development, as seen by variable preservation of stratigraphic units and the compartmentalization of reservoir units (Fossenier, 2002; Dunn, 2003; Henderson et al., 2010).

These strata were deposited as sediments on the western margin of Pangea adjacent to the PRB at a paleolatitude of 20–30 N (Golonka and Ford, 2000), a setting that probably was influenced by easterly trade winds, causing varying degrees of upwelling along the western coast of North America (Levitus, 1988; Xie and Hsieh, 1995). The known paleogeographic features include the PRB, a fault-bounded basin representing marginal marine deposits of the Pennsylvanian and Permian (Douglas et al., 1970); and the Sukunka Uplift, a northeast-trending feature that underwent several structural inversions throughout the late Paleozoic and bounded the southwestern section of the PRB

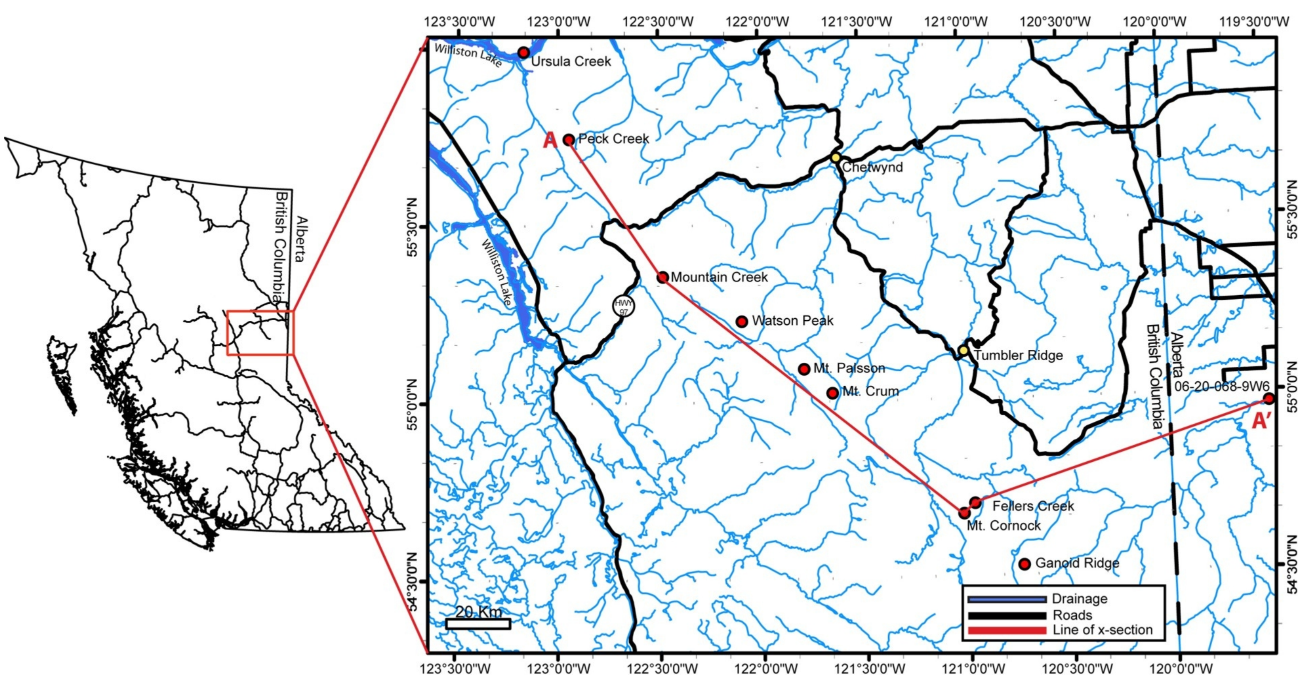


Figure 1. Study area in east-central British Columbia, showing the location of measured sections and the line of cross-section (A-A') detailed in Figure 5. Modified from Henderson et al. (2010).

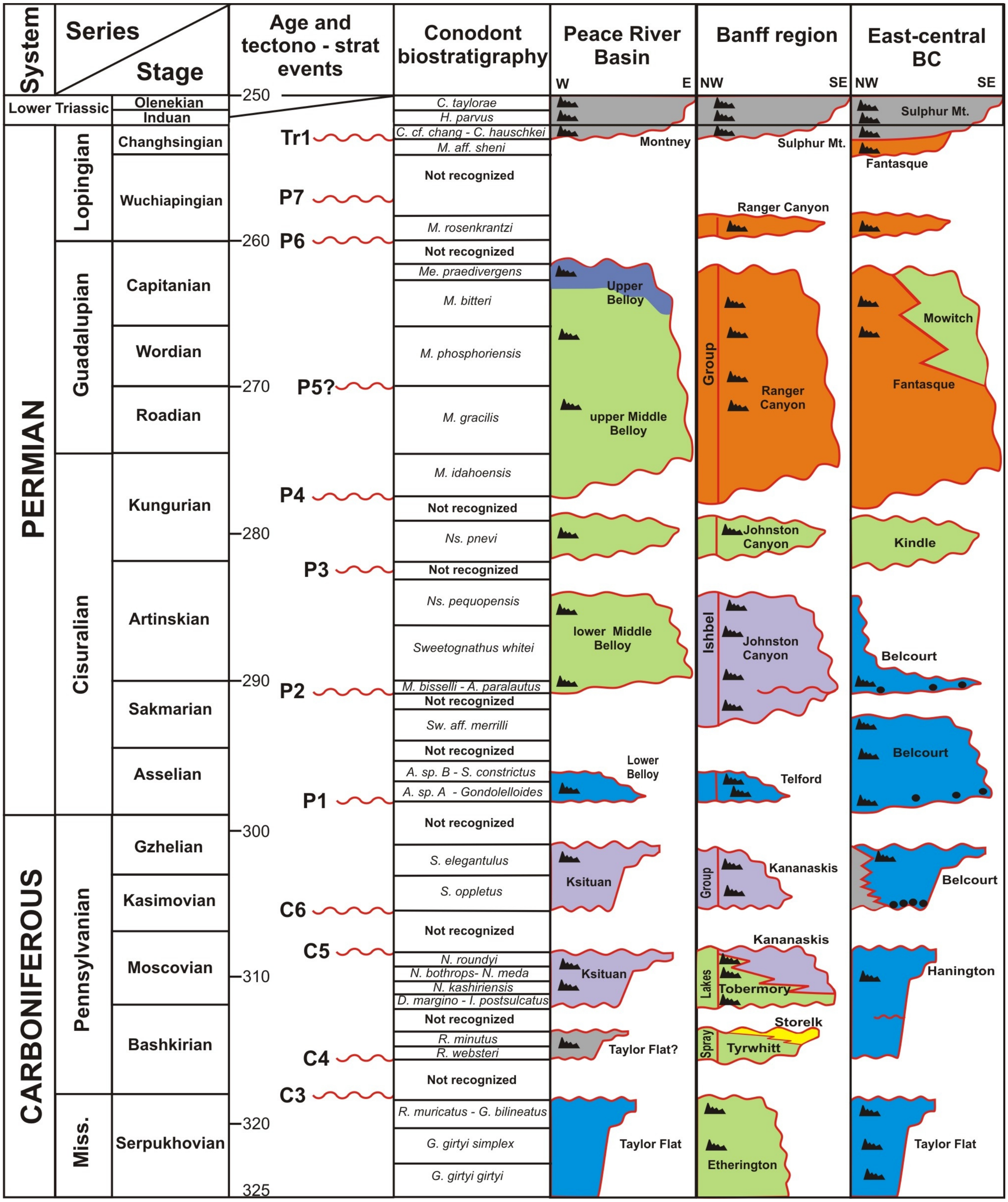


Figure 2. Stratigraphy and tectonostratigraphic sequences of east-central British Columbia correlated to the Peace River Basin of west-central Alberta and northeastern British Columbia, and the southwestern Alberta Rockies ('Banff region'). Tectonostratigraphic sequences are from Snyder at al. (2002), Trexler et al. (2004) and Henderson et al. (2010). Stratigraphy is modified from Henderson et al. (2010). Conodont symbols indicate control points. Colours represent primary lithology, including limestone (blue), dolostone (purple), chert (orange), quartz arenite (yellow), bioturbated and bioclastic sandstone (green) and silty shale (grey). Abbreviations: C, Carboniferous; P, Permian.

(Richards, 1989). The Beatton High is a structural element along the northwestern margin of the PRB, and the Ishbel Trough is the location of deeper marine deposition along the northwestern margin of Pangea (Henderson et al., 1993; Henderson et al., 1994; see inset on Figure 3).

Evidence for Pennsylvanian–Permian Tectonics

Stratigraphy

The identification and duration of unconformities in the Pennsylvanian–Permian of the study area is based on detailed conodont biostratigraphy and lithological contacts and characteristics. Several distinct stratigraphic packages are bounded by these unconformable surfaces, as illustrated in Figure 2. The middle to upper Pennsylvanian is present at Mountain Creek and Fellers Creek, bounded by a sub-Pennsylvanian unconformity below and a sub–upper Kasimovian unconformity above (Figure 2). Early Permian rocks (Asselian–Sakmarian) are present at Mountain Creek and Fellers Creek, bounded by a sub–late Early Permian unconformity at the base and a sub–middle Permian unconformity at the top. Middle Permian strata (Roadian–Wordian) are present at all of the outcrops except Watson Peak, where they are bounded by a sub–middle Permian unconformity at the base and a sub-Triassic unconformity at the top.

Unconformities

These unconformities are interpreted to have been generated largely by tectonic events, and may be correlated with events described in Nevada. This study adopts the nomenclature presented by Snyder et al. (2002) and Trexler et al. (2004) for late Paleozoic unconformities identified in northwestern Nevada. These events described from Nevada are a result of compressive tectonics during Pennsylvanian–Permian time that may have far-field influence from the Antler Orogeny, but are considered as separate tectonic events that created significant angular unconformities (Trexler et al., 2004). Two of the unconformities in east-central BC and Nevada are marked by prominent conglomerates found at the Fellers Creek section in the study area (Figure 4).

The first significant unconformity is sub–late Pennsylvanian in age and is equivalent to the C5 and C6 unconformities recognized in Nevada (Figure 2). It is recorded in outcrop at Fellers Creek as the erosional base of the first conglomerate, which, from conodont ages, is Moscovian in age. The second unconformity is equivalent to the P1 event (Figure 2), which is a sub–Early Permian (Artinskian–Kungurian) unconformity represented by the erosional base of the second conglomerate at Fellers Creek. The next youn-

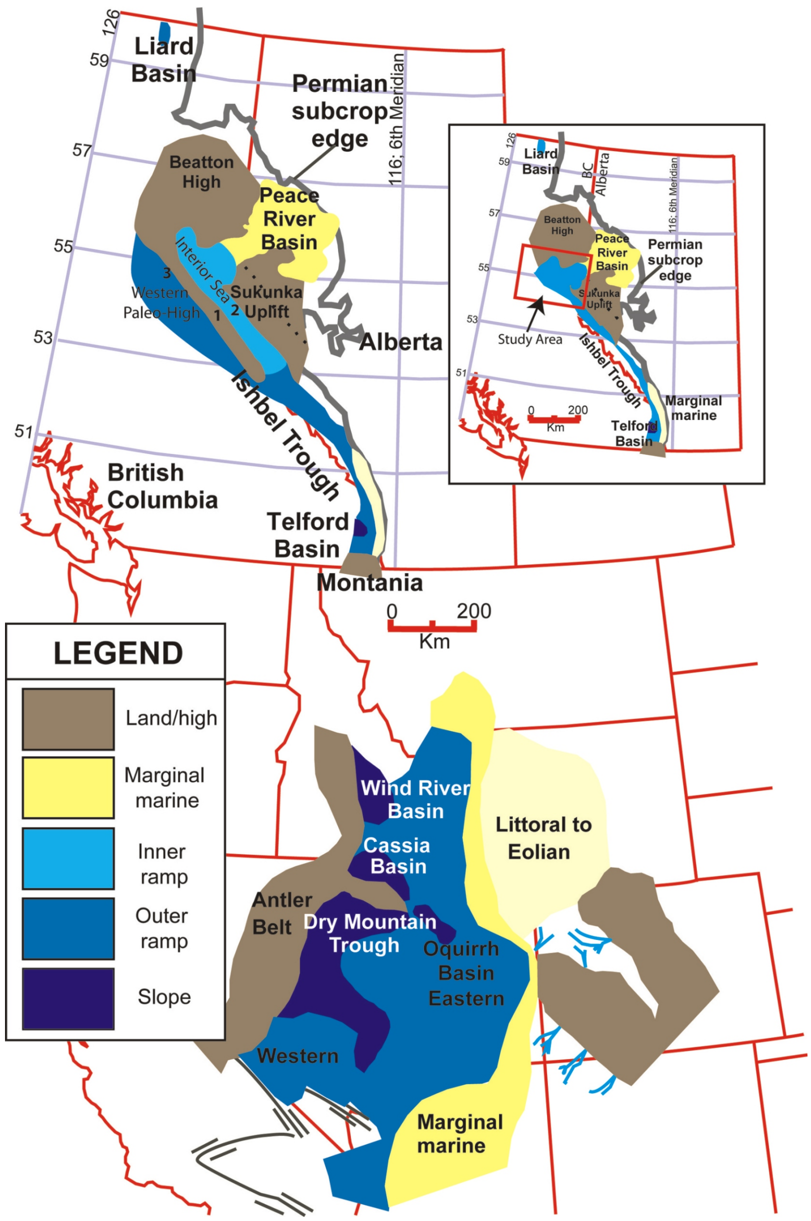


Figure 3. Simplified late Sakmarian paleogeography of western North America, showing significant tectonic elements and the interpreted location and configuration of the newly defined (this paper) western paleo-high, extending south from the Beatton High. Numbered features: 1, Mount Cornock; 2, Fellers Creek; 3, Mountain Creek. Paleogeographic features associated with the Antler Orogeny in the western United States are also labelled. Inset in upper right is of known and published simplified paleogeography in west-central Alberta, with study area outlined in red. Modified from Henderson et al. (2002).

gest event is the combined P3 and P4 (P3-P4) unconformity, which is sub–middle Permian in age (Figure 2). Artinskian and Kungurian strata are missing below this unconformity in the study area, whereas the late Artinskian is missing below the P3-P4 unconformity in the PRB. The P6/P7 event (Figure 2) recorded the removal of Late Permian strata in almost all of the outcrop sections.

The most prominent unconformity in the BC outcrops, the P3-P4, or the amalgamation of P4 through C3 unconformities, is a result of nondeposition or a structural high that was present from Late Mississippian through Early Permian (Figures 3, 5). The recognition of this unconformity delineates this feature in detail. Several outcrops in the study area, including Mount Cornock, Mount Crum, Watson Peak and Mount Palsson, have no Early Permian and little to no Middle Permian strata preserved, thus reflecting the P3/P4 event. These outcrops show a north-trending structure just to the west of outcrops containing thicker Early Permian deposits. Cross-section A–A' (Figure 5), from west to east, shows a paleogeographic high at Mount Cornock. This feature extends as far north as Ursula Creek, where Early Permian strata are also missing. In addition, the Pennsylvanian is thicker and contains deeper water deposits to the northwest at Mountain Creek. This outcrop is located on a different thrust sheet to the west of the one containing Peck Creek, Mount Cornock and Fellers Creek, and may record deposition in a deeper trough on the western side of this paleogeographic high (Figure 5).

Fractures

Nine main fracture orientations were observed in outcrop and from cores in east-central BC. Most fracture orientations are parallel and conjugate to the maximum principal stress direction (050 , $_1$) and regional structural trend (320 , $_2$). These fracture orientations include the 290 , 310 and 330 sets, which are parallel and conjugate to the regional structural trend. The 030 , 050 and 070 sets are roughly orthogonal to the regional fold axes. These are interpreted as being related to Laramide-age (Late Cretaceous–Early Paleogene) folding and thrusting. Fractures not consistent with these orientations, or oblique to the regional structural trend, include the 010 , 090 and 350 sets. These oblique orientations may be seen at the macro scale (map scale) as lineaments (Figure 6). These lineaments are erosional features developed along weak strata, thrust faults, tear faults and thrust- and fold-related fracture swarms during exhumation and glaciation.

The oblique sets of fractures that do not follow the regional Laramide structural trend may reflect structural inheritance of reactivated Pennsylvanian–Permian sub-basin boundaries. The 010 , 090 and 350 sets roughly parallel the orientations of Pennsylvanian–Permian sub-basin boundary faults (Figure 7). Structural features and orientations that

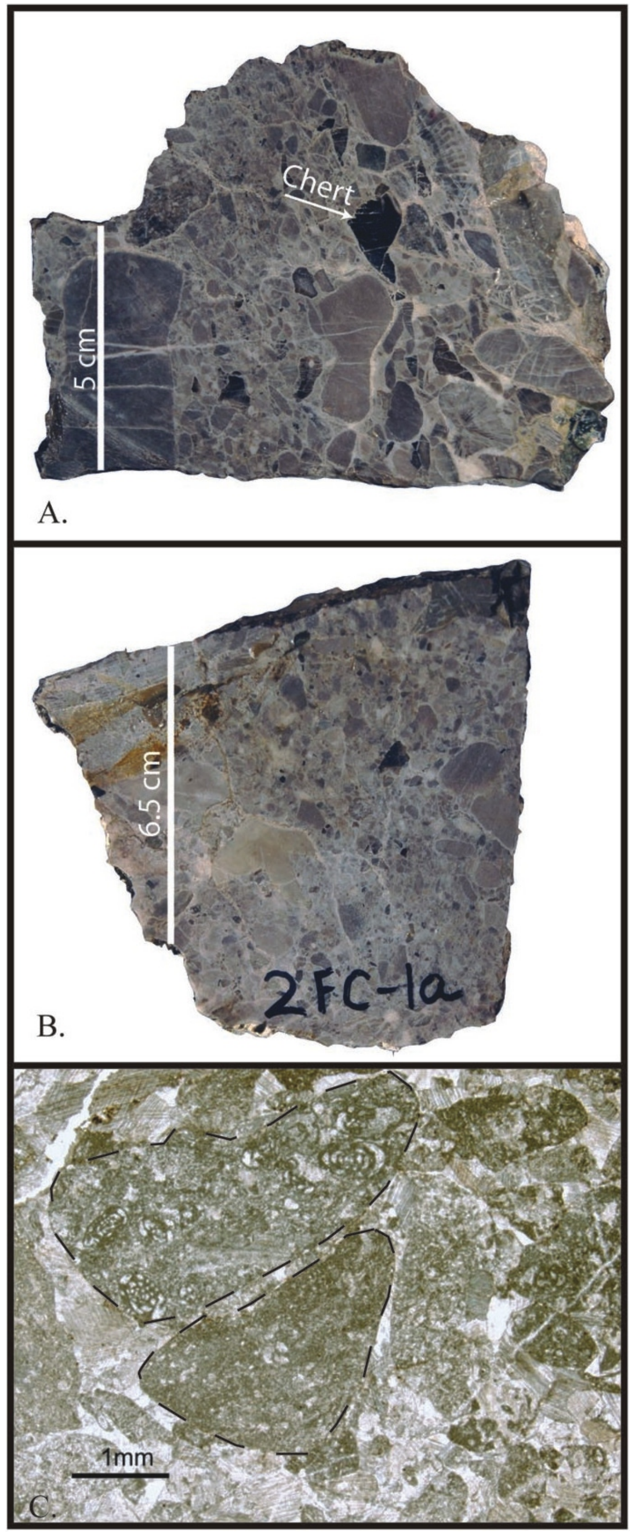


Figure 4. Photographs of cut slabs of conglomerate from Fellers Creek, east-central British Columbia: **A)** basal Belcourt conglomerate with chert clasts (27–27.7 m); **B)** second conglomerate from Fellers Creek (29.8 m); **C)** photomicrograph of top of second conglomerate from Fellers Creek (31.9 m), outlining subrounded carbonate clasts. All measurements are from the base of the section.

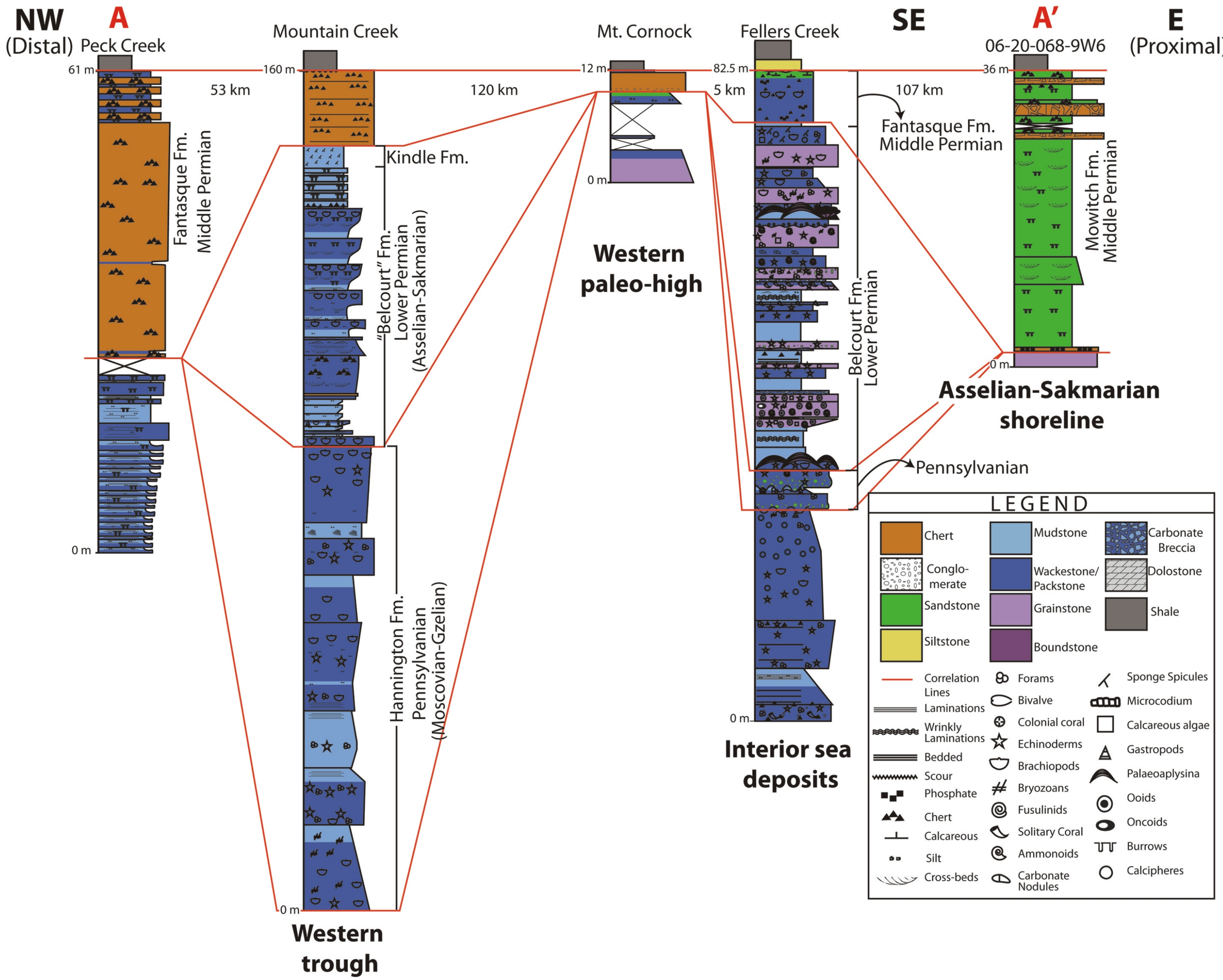


Figure 5. Cross-section A–A' (see Figure 1 for location), showing stratigraphic relationships between outcrops, rock types and formations. The western paleo-high and interior sea shown in Figure 3 are also labelled. Stratigraphic units include, in ascending order, Mississippian (below the lowest red line), Pennsylvanian Hannington Formation, Pennsylvanian–Early Permian Belcourt Formation, Early Permian Kindle Formation and middle Permian Fantasque Formation. The stratigraphic datum is the base of the Triassic Sulphur Mountain Formation.

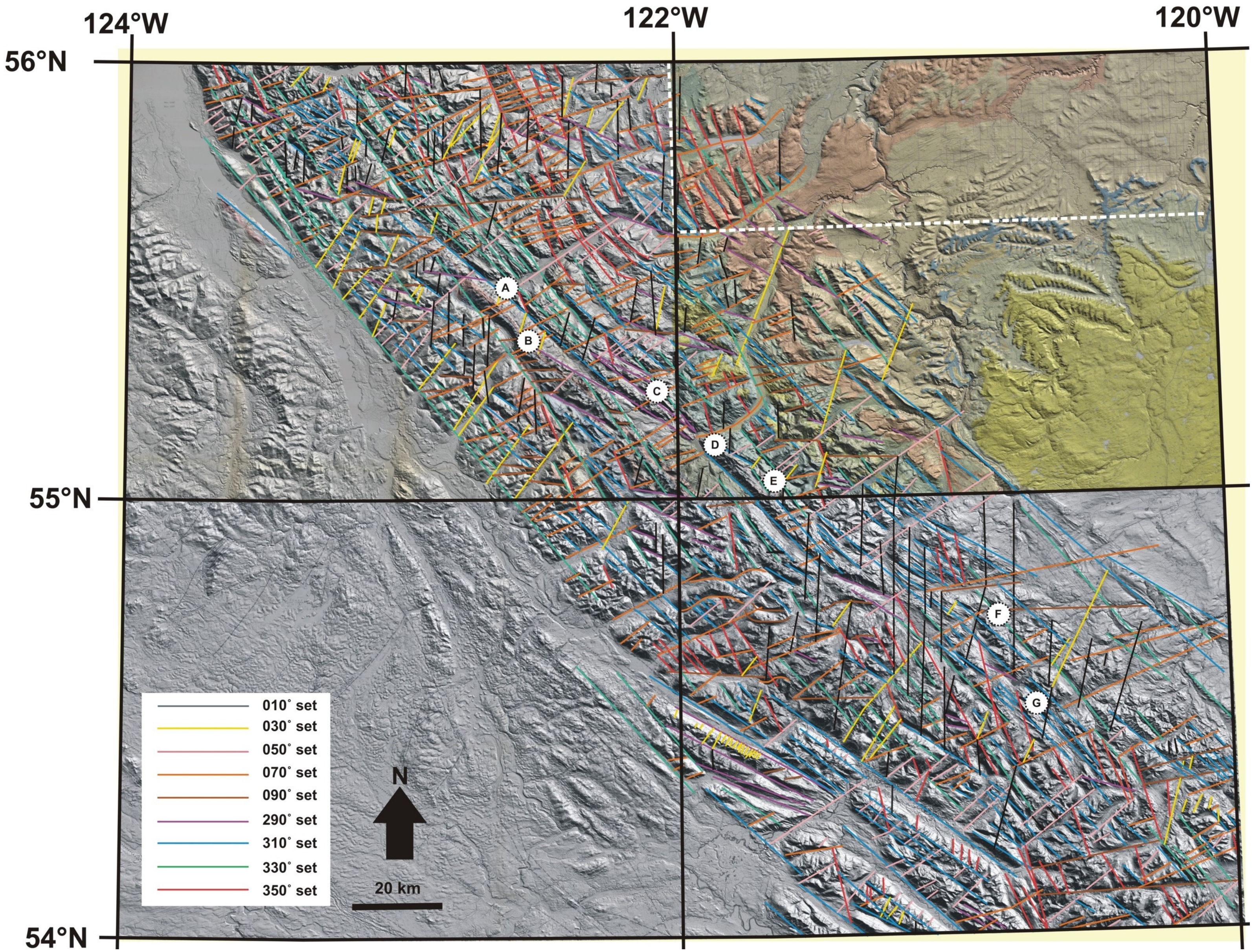


Figure 6. Digital elevation model (DEM; data from GeoBase) of the study area, illustrating macro-scale lineament orientations: **A)** Solitude Mountain, **B)** Mountain Creek, **C)** Watson Peak, **D)** Mount Palsson, **E)** Mount Crum, **F)** Fellers Creek, and **G)** Ganoid Ridge. Dashed white box denotes the Fort St. John block, an extension of Alberta townships and ranges into British Columbia between 55.65 and 56.65 N and 120 and 122 E (map adapted from Stott et al., 1983; McMechan and Thompson, 1989, 1994).

developed during the Pennsylvanian–Permian influenced the locations and orientation of Laramide-age structures and fractures. These fracture orientations imply that faults bounded sub-basins during and possibly subsequent to deposition during the Pennsylvanian–Permian.

Facies Descriptions and Interpretations

Facies described in this section do not include all rock types found in the study area, but are the principal facies that reflect the tectonic and environmental conditions. The two primary outcrops described in this study are Mountain Creek and Fellers Creek, and facies are described from these two outcrops. Mountain Creek contains more Pennsylvanian and deeper water facies, and represents deposition on the western side of the western paleo-high (Figures 3, 5). Fellers Creek contains the shallowest water facies found in the study area and represents deposition within the protected interior sea (Figures 4, 5). Photomicrographs of thin sections from Fellers Creek and Mountain Creek are illustrated in Figure 8.

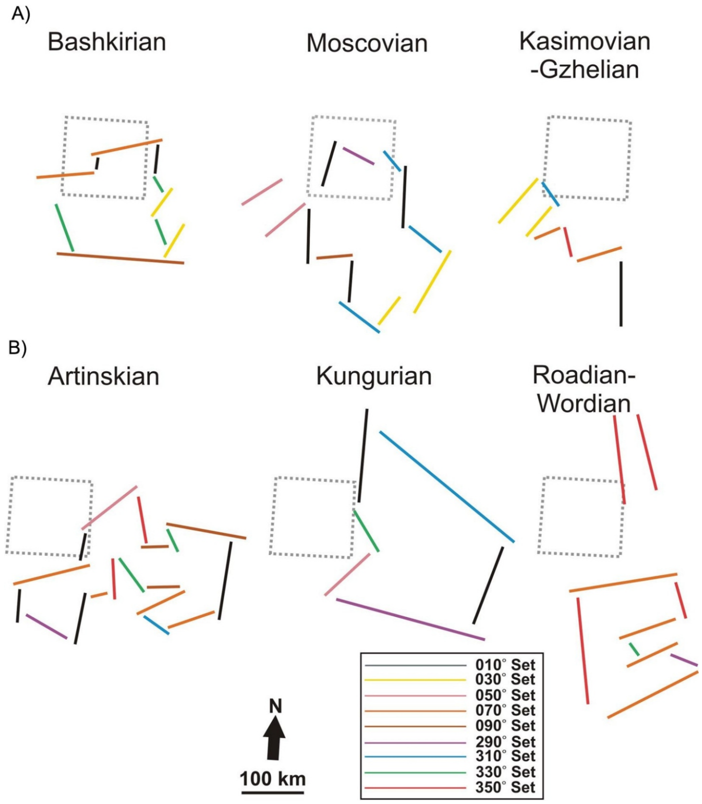


Figure 7. Schematic diagram illustrating the dominant sub-basin orientations (see legend) in the **A)** Pennsylvanian, and **B)** Permian. The dashed grey boxes denote the present-day position of the Fort St. John block. Adapted from Dunn (2003) and Dean (2010).

Conglomerate

Description

Several conglomerates with erosional bases occur throughout the study area and are composed of poorly sorted, rounded to subangular carbonate and chert clasts in a carbonate matrix. The most representative of these conglomerates is at Fellers Creek (Figures 4, 5).

Interpretation

These conglomerates are interpreted to record erosion as a result of tectonic uplift. Clasts are very poorly sorted and subrounded to angular, suggesting that the source of the clasts is fairly close to the location of deposition. Carbonate clasts often contain Mississippian foraminifera, indicating that uplift and subsequent erosion occurred between the Mississippian and early Permian (Figure 4C).

Photozoan[2] Carbonates Deposited East of the Western Paleo-High

Ooid Grainstone

Description

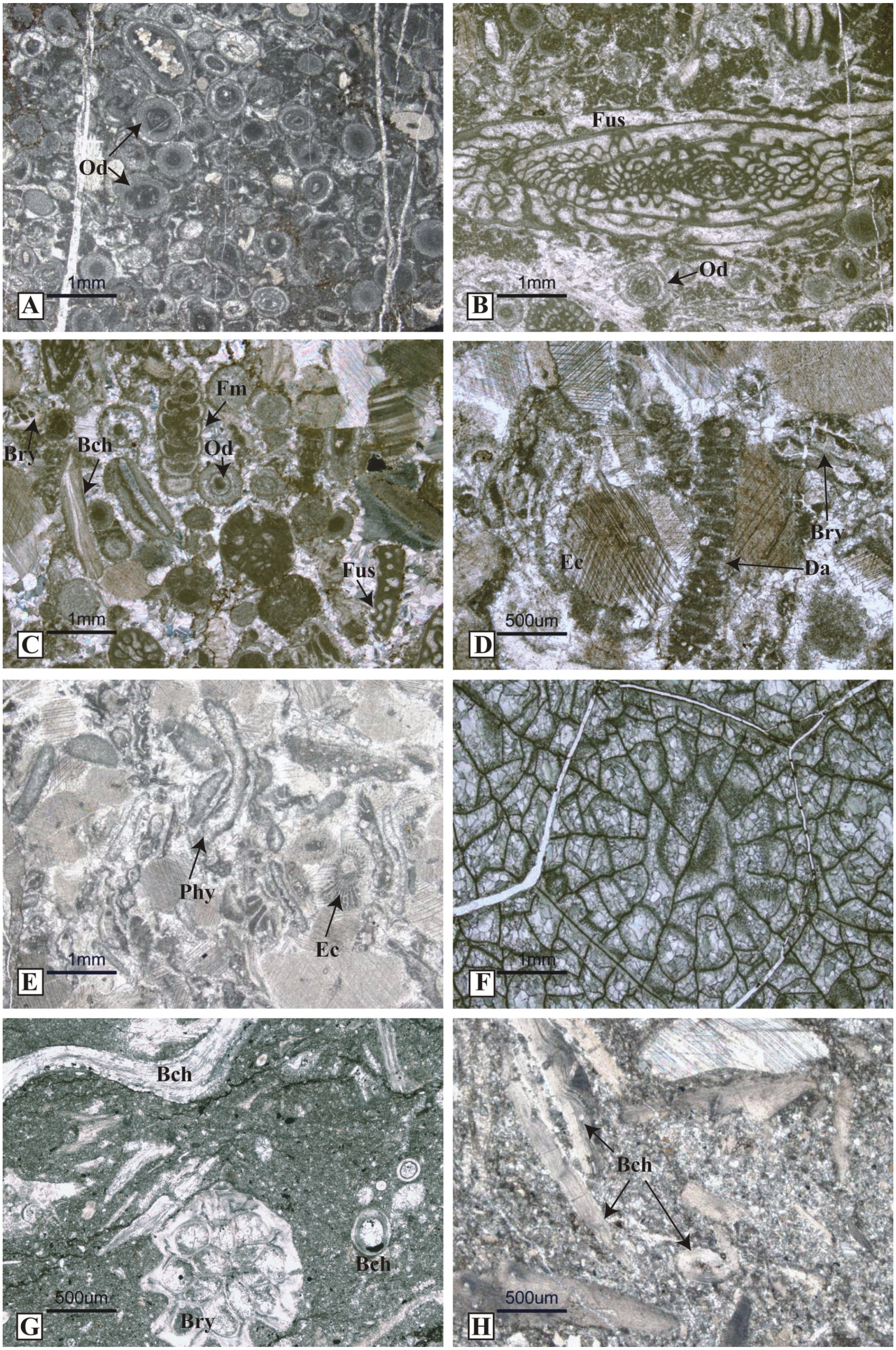
This facies is found at the Fellers Creek section and is characterized by ooids. It ranges from oolite consisting entirely of ooids to grainstone with abundant bioclasts and ooids. Bioclasts include echinoderms, brachiopods, bryozoans and common large fusulinids (Figure 8A–C).

Interpretation

This facies represents deposition in a high-energy environment close to a shoreline and forms an ooid shoal. Most of the constituents within the facies, especially the ooids and large fusulinids, imply deposition of a photozoan carbonate association, or a warm-water carbonate association (James 1997; Reid et al., 2007).

Figure 8. Photomicrographs of thin sections from Fellers Creek and Mountain Creek, east-central British Columbia: **A)** ooid grainstone, Fellers Creek (38.3 m); **B)** ooid grainstone with large fusulinid, Fellers Creek (38.3 m); **C)** bioclastic ooid grainstone with fusulinids and brachiopods, Fellers Creek (39.3 m); **D)** algal-bioclastic grainstone, Fellers Creek (45.1 m); **E)** algal-bioclastic grainstone, Fellers Creek (45.1 m); **F)** coral boundstone, Fellers Creek (66 m); **G)** brachiopod-bryozoan packstone-wackestone facies showing abundant ramose bryozoans, Mountain Creek (9 m); **H)** brachiopod-bryozoan packstone-wackestone facies showing abundant pseudopunctate brachiopods, Mountain Creek (91.4 m). All measurements are from the base of the section. Abbreviations: Bch, brachiopod; Bry, bryozoan; Da, Dasycladacean; Ec, echinoderm; Fm, foraminifera; Fus, fusulinid; Od, ooid; Phy, phylloid.

[2] *"An association of benthic carbonate particles including 1)skeletons of light-dependent organisms, and/or 2) non-skeletal particles (ooids, peloids etc.), plus or minus 3) skeletons from the heterozoan association" (James 1997, p. 4). Warm-water carbonates are composed of the photozoan association plus or minus the heterozoan association.*


Od
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1mm
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Algal-Bioclastic Grainstone

Description

This facies is recognized by the presence of green algae, including dasycladacean and phylloid algae. Other carbonate grains include echinoderms, bryozoans, brachiopods and foraminifers. Many grains have a micrite coating or are abraded, or both. The facies is found only at Fellers Creek.

Interpretation

This facies was deposited within the photic zone in a warm, high-energy environment. It probably represents deposition on a carbonate ramp, above fair-weather wave base. It also represents a photozoan or warm-water carbonate association.

Palaeoaplysina-Rugose Coral Boundstone

Description

This facies occurs at two levels in the Fellers Creek section. The first, just above the second Belcourt conglomerate, contains only *Palaeoaplysina*; the second has both *Palaeoaplysina* and colonial rugose corals (*Protowentzelella kunthi*: pers. comm., E.W. Bamber, 2010). This association shows both of these reef-building organisms forming biostromes that are closely related, span the entire length of the bed and are up to 1.5 m thick (Figure 5).

Interpretation

These carbonate constituents represent a classic photozoan or warm-water assemblage (James, 1997). In comparison to modern carbonate fauna, the *Palaeoaplysina* and colonial rugose corals would have flourished in a warm-, clear-water environment (Halfar et al., 2004).

Heterozoan[3] Carbonates Deposited West of the Western Paleo-High

Bryozoan-Brachiopod Packstone-Wackestone

Description

This facies consists primarily of ramose bryozoans and strophomenid brachiopods with a lime-mud matrix. Silt-sized quartz grains constitute 5–10% of the matrix and may be eolian in origin. The fossil abundance varies from grain supported to matrix supported with as little as 15% carbonate grains. Echinoderm fragments are occasionally present and small foraminifera occur sporadically.

Interpretation

This is the primary facies found at the Mountain Creek section and represents deposition in an outer ramp setting, below fair-weather wave base. The lack of any warm-water carbonate constituents suggests a deeper, cool-water environment (below the thermocline). This fossil assemblage is characteristic of a heterozoan carbonate association typical of water temperatures down to 13.7 C (James, 1997).

Bioturbated Silty Mudstone

Description

This facies was found primarily at the Mountain Creek section. It is an organic-rich carbonate mudstone with a low diversity of trace fossils. Subangular quartz silt constitutes up to 20% of the matrix.

Interpretation

This facies represents deposition on the outer ramp in deeper water than that represented by the bryozoan-brachiopod packstone-wackestone facies, with some possible eolian influence. The abundant organic material may be a result of dysoxic[4] waters, although trace fossils suggest the environment was not hostile enough to deter organisms from existing (Allison et al., 1995). Both water depth (below photic zone and thermocline) and clastic input would have deterred carbonate-producing organisms from growing.

Paleogeography: Discussion

Stratigraphic Implications

Recognition, correlation and dating of unconformities are important in interpreting the paleogeography of these deposits. Mapping the occurrence of units and facies shows the western paleo-high (Figure 5) extending north to Ursula Creek and postulated to extend as far south as the Meosin Mountain area (Figure 9). Thicker carbonate deposits are found both east and west of this linear structural feature (Figure 9). The most significant unconformity, which is an amalgamation of the P3-P4 through C3 unconformities (Figure 2), represents a paleo-high to the west of the opening of the PRB (Figure 3). This paleogeographic high, recorded by missing strata at Watson Peak, Mount Palsson, Mount Crum and Mount Cornock (Figures 5, 9), is a result of active tectonics that may be temporally correlated with tectonism in Nevada (Trexler et al., 2004). The Mountain Creek section is located in a thrust sheet to the west of outcrops that document this high, and records deep-water sediments that were deposited in a deeper, more distal trough to the west of the high (Figures 3, 5, 9). Thinner and shallower water carbonates measured to the east of the paleo-high are exposed at Fellers Creek and represent the more restricted, inner eastern side of the western paleo-high (more proximal; Figures 3, 9).

[3] *"An association of benthic carbonate particles produced by 1) organisms that are light independent, plus or minus 2) red calcareous algae" (James 1997, p. 4). Cool-water carbonates are composed of the heterozoan association.*

[4] *having a very low oxygen concentration (i.e., between anoxic and hypoxic)*

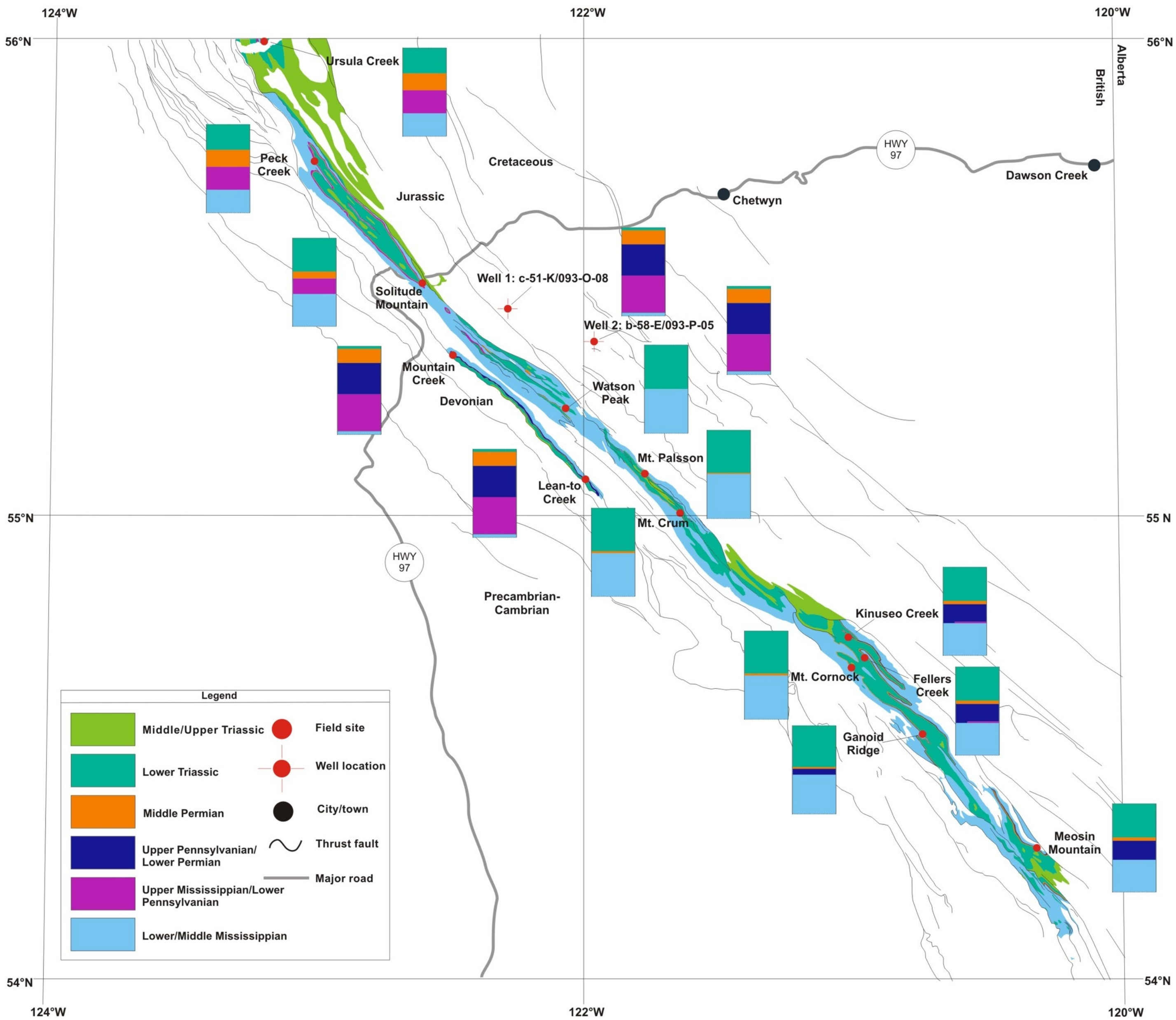

Figure 9. Geology of the east-central British Columbia study area, showing schematic summary columns of strata present at each outcrop. Note missing Early Permian strata at Watson Peak, Mount Palsson, Mount Crum and Mount Cornock, defining a southeast-trending linear paleo-high.

Paleoenvironmental Implications

Pennsylvanian and Permian warm-water carbonate rocks have been described before in east-central BC (Bamber and MacQueen, 1979). The apparent anomalous occurrence of this narrow belt of warm-water carbonate rocks in a region that should have been affected by cool upwelling currents has not been addressed. These deposits were located at a paleolatitude equivalent to the current latitude of the Baja California peninsula in Mexico, which, on the Pacific side, is subject to cool upwelling waters caused by easterly trade winds (Zaytsev et al., 2003). The tectonic elements recognized in this area are key to explaining the environment in which these warm-water organisms thrived. Early Permian photozoan carbonates are found in a narrow belt just to the east of outcrops that contain no Early Permian deposits and, in some cases, no Permian strata at all. It is proposed that the southeast-trending structural high (Figure 9) is a western land mass, much like Baja California today, that protected an inland sea where photozoan carbonates could grow.

Hydrocarbon Potential

The results of this study provide evidence for active tectonics creating paleogeographic highs that coincide temporally with Pennsylvanian–Permian events described in Nevada. The delineation of these paleogeographic features helps to explain and predict the distribution of Pennsylvanian–Permian sediments in east-central BC, and may have a bearing on the distribution and type of potentially porous lithofacies in the subsurface. Exploration efforts should be focused on the dolomitization of inner-ramp lithofacies that dominate the margins of the interior sea. Dolomitization appears to be associated with proximity to sub-basin defining faults, especially those that have trends of 010 , 090 and 350 , as revealed by macro-scale lineaments. These trends are not associated with regional stress patterns associated with the Laramide Orogeny and may be inherited from Pennsylvanian–Permian faults.

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