Chronostratigraphic and Tectonostratigraphic Summary of the Late Paleozoic and Early Triassic Succession in East-Central British Columbia (NTS 093I, O, P)

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Introduction

The northwest margin of Pangea during the late Paleozoic has been historically depicted as a relatively passive margin (Barclay et al., 1990), but there is increasing evidence for active compressive tectonics. The latest Devonian Antler orogeny is recognized in the Roberts Mountain allochthon in central Nevada (Dickinson, 2006), and evidence for this event is present within the pericratonic Kootenay terrane in southern British Columbia (Richards, 1989; Dickinson, 2004). The Sonoma orogeny is recorded in the western United States by latest Permian to earliest Triassic thrusting of the Havallah Basin succession over the Antler Belt (Brueckner and Snyder, 1985; Dickenson, 2006). Several additional deformation events are recognized between the Antler and Sonoman events in the western United States during the Mississippian to Permian (Trexler et al., 2003, 2004). Critical to our understanding of the evolution of the Cordilleran margin in Canada and the United States is whether these collision and assembly events affected the North American margin or occurred in the Panthalassic Ocean, as in the SAYBIA model of Johnston (2008) and RUBIA model of Hildebrand (2009). S. Johnston (2008) argued that the best evidence for a ribbon continent forming well away from the North American margin is the fact that there was no evidence of loading causing isostatic flexure of the lithosphere within the 'Rocky Mountain Platform' (i.e., the Front Ranges of the Canadian Rockies). Root (2001), however, proposed that a Middle Devonian (upper Eifelian) event mapped in southeastern BC resulted in the development of a peripheral bulge in the Front Ranges where Frasnian strata unconformably overlie Middle Cambrian units. He suggested that this was an early manifestation of the Antler event, but admitted that one problem with his interpretation was the lack of evidence for activity on this bulge during the Antler orogeny in latest Devonian to Early Carboniferous. However, D. Johnston et al. (2010), using a detailed isopach map based on both surface sections and subsurface wells, and supported by high-resolution conodont biostratigraphy, showed that the lack of Early Tournaisian strata of the upper Exshaw and middle Bakken formations in southwestern Alberta may indicate slight eastward migration of this same peripheral bulge. In addition, research during the past ten years on the North American craton of west-central Alberta and east-central British Columbia (BC) has shown evidence for structural inversion of block faults during the Late Paleozoic and earliest Triassic (Kendall, 1999; Panek, 2000; Fossenier, 2002; Henderson et al., 2002; Dunn, 2003; Henderson et al., 2010; Zubin-Stathopoulos et al., 2011) that significantly affects the paleogeography of the margin and the potential for hydrocarbon resources.

This paper builds on the initial stratigraphic framework of Bamber and Macqueen (1979), and represents a summary of three years of research in east-central BC that includes other evidence in support of tectonic controls on the cratonic platform succession during the Pennsylvanian and Permian. These effects, which are sometimes subtle, are now recognized because we re-examined, using high-resolution biostratigraphy, the timing of widespread unconformities that correlate all the way to Nevada. The complexity of the tectonostratigraphic framework means that this research summary is really only a beginning.

Study Area and Methods

Field sites for this study are located in the Sukunka-Kakwa area within NTS areas 093P, I and O (Figure 1), and have been described previously by Henderson et al. (2010) and Zubin-Stathopoulos et al. (2011). The outcrops are located southeast of Chetwynd, BC and are part of a southeast-trending outcrop belt that represents the westernmost extent of the Western Canada Sedimentary Basin. Outcrops were accessed by helicopter due to the remote nature of the sites. The approach was to combine high-resolution cono-

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Keywords: *Pennsylvanian, Permian, Lower Triassic, conodont biostratigraphy, tectonostratigraphic framework*

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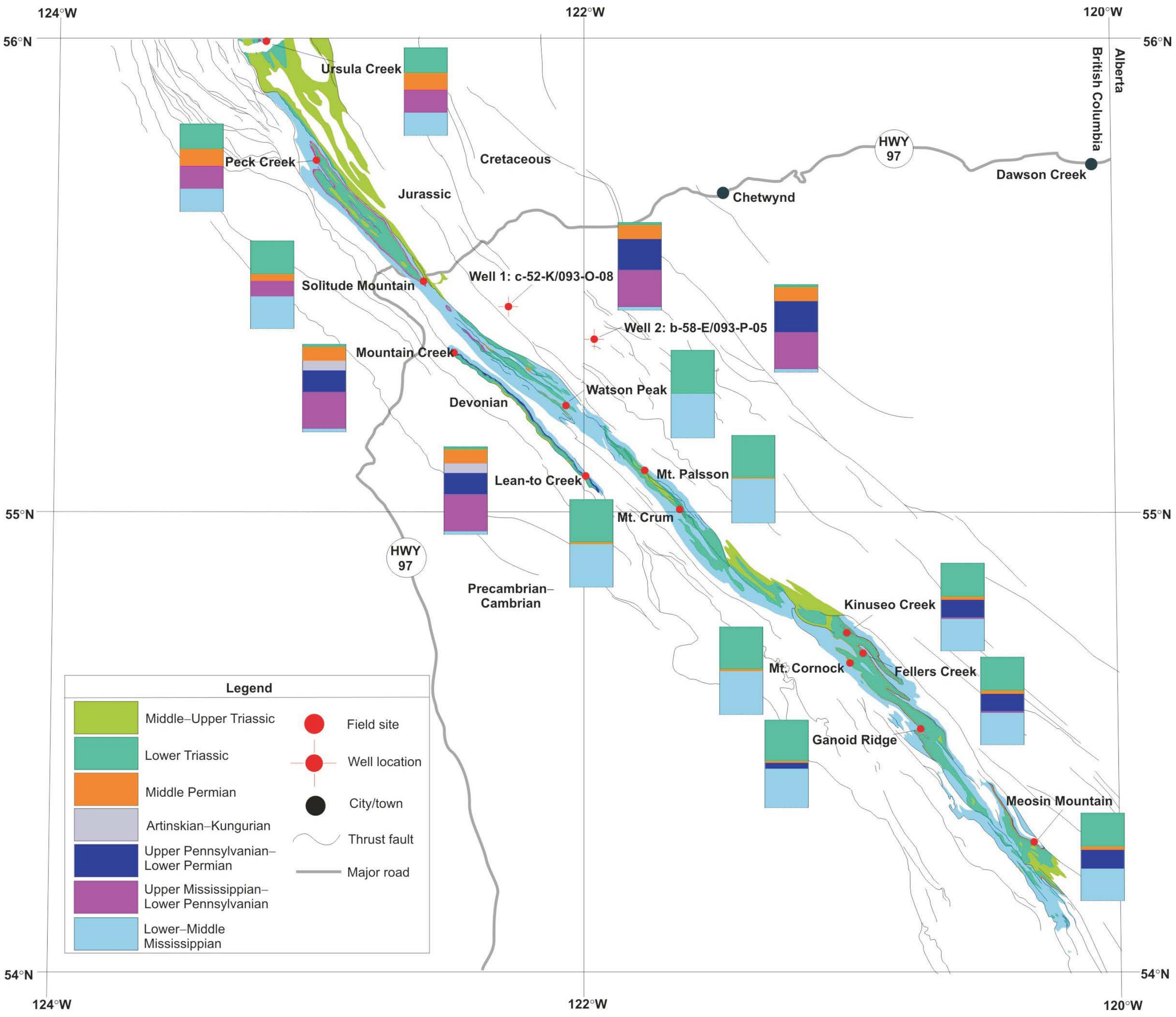

Figure 1. Study area showing studied sections and Mississippian to Triassic geology (not palinspastically restored). Schematic stratigraphic summary columns show that the overall preserved succession more or less parallels the individual thrust sheets, with the most complete succession in the westernmost sheet that includes the Mountain Creek and Lean-to Creek locations, which are the only locations in the region preserving Artinskian to Kungurian strata. Note missing Early Permian strata at Watson Peak, Mount Palsson, Mount Crum and Mount Cornock, defining a southeast-trending western paleohigh. Modified from Zubin-Stathopoulos et al. (2011).

dont biostratigraphy with detailed section measurement and some mapping.

Evidence for Pennsylvanian–Permian Tectonics

This section summarizes the evidence for several tectonic events and highlights some of the implications each has in terms of diagenesis, fracture distribution and unit preservation. The primary line of evidence is identification and duration of unconformities within the Pennsylvanian–Permian of the study area, as determined by detailed conodont biostratigraphy (Fossenier, 2002; Dunn, 2003; Zubin-Stathopoulos, 2011). The biozonation scheme for the area was previously provided in Zubin-Stathopoulos et al. (2011). Comparisons are made to tectonostratigraphic events documented in the southwestern United States.

C4/C5 Moscovian Event

The lower Belloy Carbonate Member (Halbertsma, 1959; type section in the 12-14-78-1W6 well) was later referred to as the Ksituan Member of the Belloy Formation (Henderson et al., 1994), and a paper is in preparation to name this unit as a new formation (see Zubin-Stathopoulos, 2011). It is a distinct unit that is separated from the rest of the Belloy Formation by an entire stratigraphic sequence (Figure 2). It is contemporaneous with a post–Taylor Flat extensional event in which a peritidal to open-marine carbonate succession is widely distributed from west-central Alberta to east-central BC (Porter, 2007). The peritidal succession in Alberta is generally dolomitized and represents an important hydrocarbon-bearing unit in a relatively simple stratigraphic-fault play (see Progress Field in Dunn, 2003). In BC, the unit is variably dolomitized and represents a very important gas play in a thrust structural play, but there are many complications (see 'Hydrocarbon Implications'). This event and overlying strata resulted in the Ely Basin in Nevada (Trexler et al., 2004).

C6 Kasimovian and P1 Asselian Events

The C6 event is one of the more prominent in Nevada that resulted in a major angular unconformity, which is especially well displayed at Carlin Canyon (Trexler et al., 2004) in the northwestern part of the Dry Mountain Trough (Figure 3). The C6 and P1 unconformities in Nevada truncate structures of two distinct events, including thrust faults and overturned folds in the C6 event and more open folds and high-angle normal faults just before the P1 unconformity (Trexler et al., 2004). We have not resolved such intense compression structures in east-central BC because the record is mostly in the subsurface and some units have been eroded. However, considerable local evidence points to this being an important tectonostratigraphic event in the region. In Alberta, the Ksituan Formation was subaerially exposed and accompanied by dolomitization and karst development (Porter, 2007). This could be attributed simply to a lowstand of sea level, but the development of highs and basins to the west suggests that it was more complex. Zubin-Stathopoulos et al. (2011) provided evidence that a western paleohigh and eastern interior sea developed during this event (Figure 2). Local uplift removed much of the previous record of Moscovian carbonate rocks (Figure 2) and some of these clasts are found within the Asselian to lower Sakmarian Belcourt Formation. These structures were large enough to affect carbonate sedimentation that included warm-water associations in the shallow interior sea (Belcourt Formation), cool-water associations west of the paleohigh in the newly defined Mountain Creek Formation (see paper in preparation in Zubin-Stathopoulos 2011) and a thick carbonate mudstone unit in well C-52-K (Figure 2).

P2 Artinskian Event

The P2 event is a major unconformity at the regional scale in Nevada that involved the development of the Dry Mountain Trough, but the deformation geometry is less clear (Trexler et al., 2004). This event may also correlate with the Melvillian Disturbance (Beauchamp, 1995) in the Sverdrup Basin of the Canadian Arctic. In east-central BC, rocks overlying the P2 unconformity are missing except for thin units of the Kindle Formation at Mountain Creek and Lean-to Creek in westernmost exposures. At the same time, to the east in the subsurface of west-central Alberta, a new basin developed in which Belloy Formation siliciclastic rocks and minor bioclastic carbonate were deposited (Figures 2, 3). Presumably, a broad high developed that restricted these Artinskian-age deposits to the Peace River Basin (Figure 3). Sandy carbonate rocks of this age are also present in the Telford Basin (Figure 3) to the south (MacRae and McGugan, 1977). This broad high in east-central BC appears to have resulted from the amalgamation of the Sukunka Uplift and the Beatton High, which were separate structures before the Artinskian (Henderson et al., 1994); it also encompasses the western paleohigh and interior sea generated by the C6-P1 event (Figure 2). Such an extensive structure may be interpreted as a peripheral bulge (Figure 3) and the Peace River Basin as a back-bulge basin (see 'Tectonostratigraphic Implications'). Dunn (2003) mapped Artinskian and Kungurian lithofacies that included braid deltas and what was interpreted as a barrier island with root traces paralleling the Alberta-BC border. With the interpretation of the peripheral bulge, these units can now be interpreted as a beach on the western margin of the Peace River Basin, with an adjacent braid delta indicating sediment sources from the south and west. The remainder of the marginal-marine facies in the Peace River Basin (Figure 3) includes carbonate-rich subtidal to supratidal bioclastic sandstone, with 'early' vadose cement locally forming beach rock.

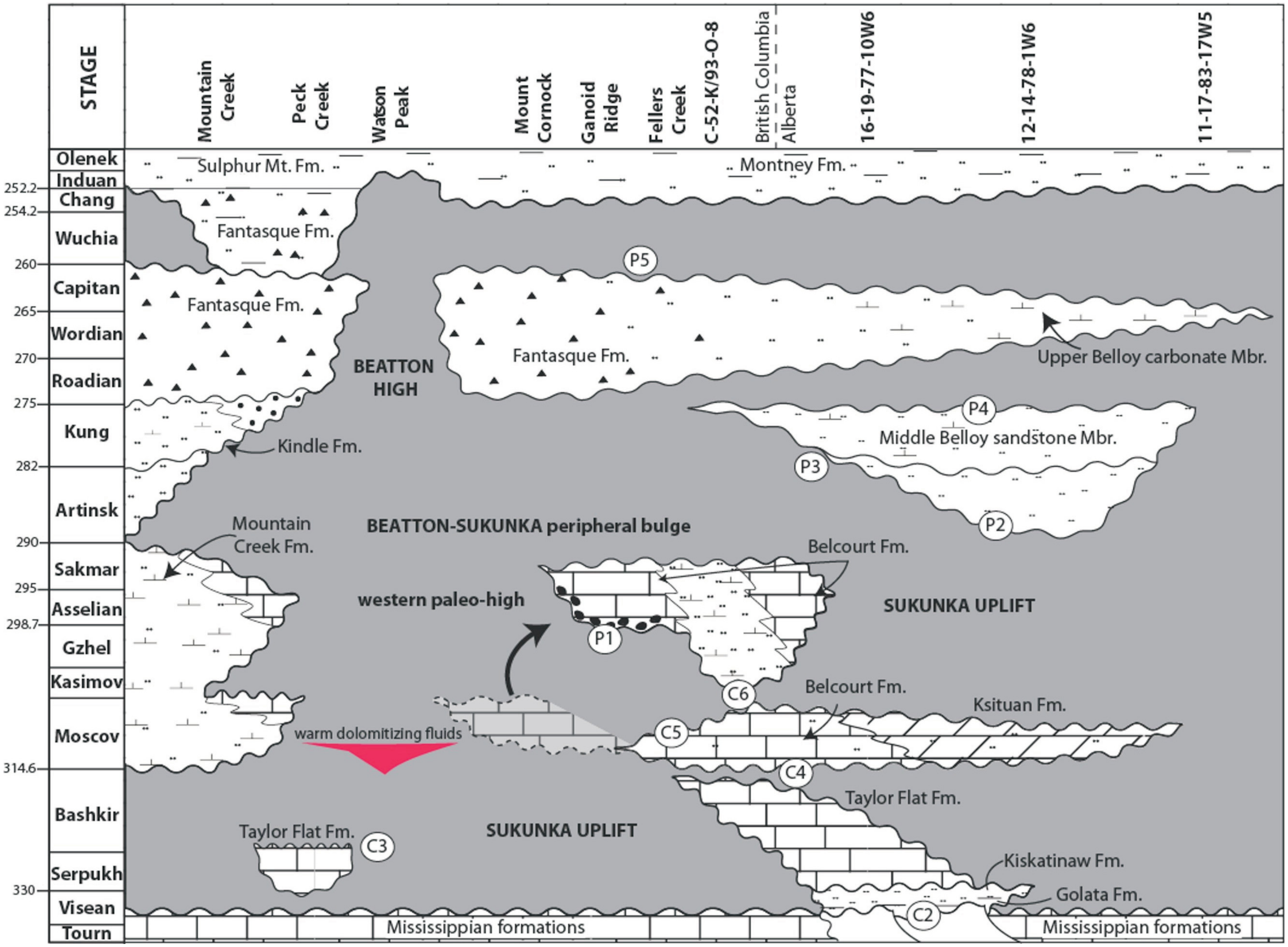

Figure 2. Chronostratigraphic diagram showing temporal and spatial distribution of major units in east-central British Columbia to west-central Alberta. The C6 event resulted in a western paleohigh that caused erosion of the underlying Moscovian succession and local deposition of Moscovian-age clasts within Early Permian sediments. The Beatton-Sukunka peripheral bulge is interpreted to have formed during P2 deformation, which also potentially drove warm dolomitizing fluids into the underlying succession. Abbreviations: Tourn, Tournaisian; Serpukh, Serpukhovian; Bashkir, Bashkirian; Moscov, Moscovian; Kasimov, Kasimovian; Gzhel, Gzhelian; Sakmar, Sakmarian; Artinsk, Artinskian; Kung, Kungurian; Capitan, Capitanian; Wuchia, Wuchiapingian; Chang, Changhsingian; Olenek, Olenekian. Modified from Zubin-Stathopoulos (2011). Locations of Alberta wells: 16-19-77-10W6 (55.6922°N, 119.5292°W; UTM Zone 11, 341025E, 6174721N); 12-14-78-1W6 (55.7614°N, 118.0491°W; UTM Zone 11, 434168E, 6180024N); 11-17-83-17W5 (56.1974°N, 116.6534°W; UTM Zone 11, 521504E, 6228001N).

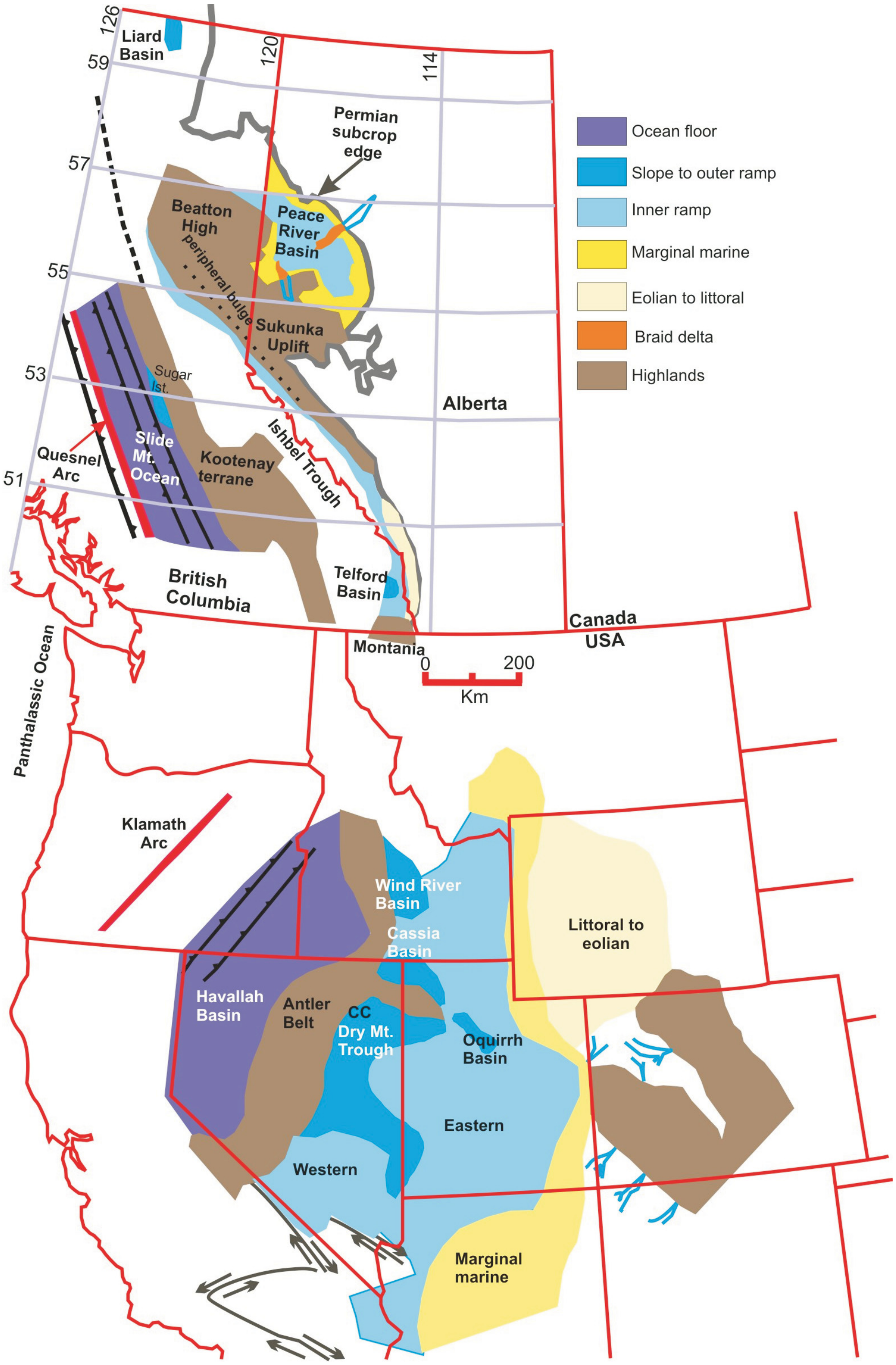

Figure 3. Schematic paleogeography of the western United States to northeastern British Columbia (BC) for the early Artinskian (modified from Zubin-Stathopoulos et al., 2011). Dotted line in Beatton High area represents former position of late Asselian interior seaway. Dashed line in northeastern BC represents southernmost position of younger dextral Tintina strike-slip fault. The geotectonic history for the succession south of this position is markedly different from that to the north. The Yukon-Tanana terrane (see several papers in Colpron and Nelson [2006], including Nelson et al. [2006]) may represent the western margin of the Slide Mountain Ocean that was later transported along strike-slip faults, including possible transfer of strike-slip motion to Permian westerly facing subduction-zone boundaries. The Lower Permian Sugar Limestone (Orchard and Struik, 1985) was deposited on the eastern margin of the Slide Mountain Ocean. The axis of the Devonian Peace River Arch and Carboniferous to Triassic Peace River Basin is perpendicular to this position as well. Position of tectonic elements is, in part, based on Gabrielse et al. (1991), Henderson et al. (1993), Wardlaw et al. (1995) and Nelson et al. (2006). Peace River Basin lithofacies from Dunn (2003). Tectonic nomenclature based on Snyder et al. (2002). Abbreviation: CC, Carlin Canyon.

P3 Kungurian Event

This is a relatively minor event in both Nevada and east-central BC, and may be attributed to a relative lowstand of sea level, as is characteristic of the Kungurian globally, or to reduced rates of subsidence and filling of the basin created by the P2 event. Artinskian and Kungurian inner-ramp facies of the Kindle Formation in east-central BC (Figure 3) and the Johnston Canyon Formation in southwestern Alberta have cool-water associations and typically are quite phosphatic.

P4 Roadian Event

This is a major event that represents the formation of the Phosphoria Basin, centred in northeastern Nevada and southern Idaho, and the development of an important intra-Permian unconformity in southeastern to east-central BC, which is overlain by a persistent thin-shelf deposit referred to as the Ranger Canyon and Fantasque formations. The Phosphoria Basin is widespread and overlaps many Early Permian tectonic basins. The Ranger Canyon Formation is also widespread (McGugan, 1965) and, in at least one locality (Crossing Creek in southeastern BC), overlies the Artinskian to Lower Kungurian Johnston Canyon Formation as an angular unconformity (McGugan and Rapson, 1962), with a phosphatic conglomerate at the base. McGugan (1965) suggested that such widespread but relatively thin deposits are more likely to be controlled by eustacy than by tectonics. The latest Kungurian to Early Roadian represents a global sea-level rise and may indicate a time of tectonic quiescence on the margin (see 'Tectonostratigraphic Implications').

P5 Capitanian Event

This event was a major lowstand of sea level that resulted in subaerial exposure of most of the margin. There is biostratigraphic evidence that the Fantasque Formation at Peck Creek and Ursula Creek in northeastern BC includes continuous deposition through the Late Permian (Figure 2) into the Early Triassic (Henderson, 2011). These sites were located on the down-faulted eastern margin of the Ishbel Trough.

P6 Late Changhsingian Event

This event is recognized as a combination of probable eustatic rise and tectonic-basin reorganization, including inversion of various structural elements, and requires further mapping. It coincides in timing with the Sonoman orogeny, which is better understood in the western United States, where the Havallah sequence is thrust upon coeval successions on the North American craton (Brueckner and Snyder, 1985). The Mount Crum section (Figure 1) was high during the Early Induan (Griesbachian), suggesting that collapse of the Beatton High north of this locality created a site for earliest Triassic deposition and the important shale-gas fairway of the Montney Formation north of about 55.5°N. Zonneveld et al. (2010) also suggested an earliest Triassic sub-basin in the Ring-Border to Kahntah River fields, at about 58°N on the BC-Alberta border.

Tr1 Late Induan Event

This event is also associated with inversion of various structural elements (Kendall, 1999; Panek, 2000) and requires further mapping. The fact that turbidite successions, which may be driven by tectonically controlled slope steepening, are diachronous (Late Induan through Olenekian) across the region (Kendall, 1999; Orchard and Zonneveld, 2009; Henderson, 2011) points to the need for detailed mapping and biostratigraphic analysis.

Discussion and Conclusion

Tectonostratigraphic Implications

Nelson et al. (2006) and Colpron and Nelson (2011) summarized a model in which the Slide Mountain Ocean was the locus for back-arc seafloor spreading from mid-Carboniferous to Middle Permian, followed by a reversal in which the North American continent advanced upon the frontal arc with the back-arc basin closure attributed to the Late Permian–Early Triassic Sonoman orogeny. It is possible that such 'accordion tectonics' had another beat to it, as evidence continues to emerge supporting episodic thin-skinned deformation affecting the North American margin between the Antler and Sonoman orogenies. This requires an active orogenic belt to the west that affects the North American (northwestern Pangea) margin from the latitude of at least northern Nevada to east-central BC. If the broad structure affected by the P2 event is a peripheral bulge, as interpreted herein, then there must have been active uplift to the west that provided sufficient load to cause isostatic flexure of undisputed North American margin rocks in east-central BC. It is interesting that imbricate thrusts mapped within the Antler Formation of the Slide Mountain terrane near Wells in central BC involve rocks no younger than Early Permian (Struik and Orchard, 1985). This event may then have been followed by renewal of back-arc spreading, with the Slide Mountain Ocean growing to a significant extent during the early Middle Permian when the thin, widespread Fantasque Formation was deposited across east-central BC as an overlap succession, much like the coeval Phosphoria Basin to the south. Using mean global seafloor-spreading rates of 40–70 km/m.y. (Seton et al., 2009) for comparison only (Slide Mountain Ocean rates are unknown) would create an ocean at least 600–1050 km wide during the Artinskian and Kungurian, and 1200–2100 km wide if spreading also continued through the Middle Permian. A second closure of this ocean during latest Permian would then have resulted in the obduction of Slide Mountain Ocean rocks onto the Kootenay terrane, resulting in the Sonoman orogeny.

These interpretations must be reconciled with the suggestions, based on faunal similarities, by Belasky et al. (2002) that the Stikine, Quesnel and Klamath arc terranes must have been 2000–3000 km away from their latitudinal equivalents on the North American craton during the Early Permian. The driving force for these tectonic events remains equivocal, but a new dimension has been added to the discussion. This new dimension is the fact that successions on undisputed North America (the Rocky Mountain Platform of Johnston, 2008) are affected by isostatic flexure in both extensional and compressional settings at different times. This means that the Ishbel Trough was a foreland basin at various times during the Late Paleozoic and at least semi-isolated from open Panthalassic Ocean. This would seem to negatively affect one line of evidence for a single SAYBIA collision during the Late Cretaceous, but the presence of phosphate-rich facies on the eastern margin of an isolated, narrow Ishbel Trough remains a problem.

Clearly the region from central BC to west-central Alberta is critical to resolve events associated with the evolution of the North American Cordillera during the Late Paleozoic and Early Mesozoic, so we initiated a restudy of the Barkerville terrane, including the Sugar Limestone, during the summer of 2011. Furthermore, increased resolution of Cordilleran evolution will lead to a better understanding of the events that affected reservoir quality and natural gas resources in east-central BC.

Hydrocarbon Implications

The results of this study provide evidence for active tectonics creating paleogeographic highs that confine some depositional units and result in the erosion of others. Overall, the Late Paleozoic and earliest Triassic stratigraphy in east-central BC is punctuated by numerous unconformities. Two of the most important tectonic events (C6 and P2) in the region may have significant hydrocarbon implications. The most important conventional-gas reservoirs in the region are Moscovian carbonate units, but preservation is strongly affected by the C6 event (Figure 2). The P2 event is interpreted to have formed a peripheral bulge in the region, suggesting compressive tectonics to the west that may have also driven warm dolomitizing fluids into the underlying sequences (Figure 2). Wamsteeker (2007) indicated that Moscovian shelf carbonate rocks were subjected to three major diagenetic events: eogenetic processes, hydrothermal dolomitization by about 150°C fluids enriched in ^{18}O relative to Pennsylvanian seawater, and calcite veins in Laramide fractures. Moscovian carbonate rocks may have dolomitized preferentially along pre-existing faults and fractures in the region, indicating that the best porosities in the area would be more predictable if paleostructures in the region were better known. The warm fluids may also account for the thermal-maturity anomaly (Ing and Henderson, 2009) in the region in which Pennsylvanian rocks have higher-than-expected CAI (Colour Alteration Index from Conodonts) values compared to values in the overlying Permian (especially of Artinskian and younger). Finally, there is likely a strong inheritance between the position of Pennsylvanian and Permian faults and the breakout of Late Cretaceous thrust faults that created the anticlinal structural traps (Dunn, 2003). Therefore, successful exploitation of these resources must consider the overall complicated tectonic history of the region that affected fracture distribution (Dean, 2010), as well as deposition, diagenesis, preservation and final-stage trap location. Finally, if the Sonoman orogeny turns out to be a significant event to the west in this region, then there is a high probability that westerly derived sedimentation may also affect distribution of reservoir characteristics in the Montney Formation shale-gas play, as well as younger Triassic units.

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