Tectonic History, Biostratigraphy and Fracture Analysis of Upper Paleozoic and Lowest Triassic Strata of East-Central British Columbia (NTS 093I, O, P): Preliminary Report

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Introduction

The British Columbia portion of the Western Canada Sedimentary Basin (WCSB) is far less developed than the Alberta portion. During the past decade, however, this area has experienced tremendous growth, particularly in natural-gas exploration. Pennsylvanian and Permian strata are among BC's important reservoir intervals (Bird et al., 1994), as they are underexplored and have considerable potential to yield new natural-gas supplies in addition to the already-discovered producing fields. One area that has been identified as having particularly high potential for undiscovered conventional natural-gas resources is the southern Foothills and adjacent Deep Basin in the Sukunka-Kakwa area (Figure 1; National Energy Board, 2006). Despite strong industry interest in Pennsylvanian and Permian strata (Hanington, Ksituan, Belcourt, Fantasque and Belloy formations, including the Ksituan Member of the Belloy Formation), no detailed stratigraphic and sedimentological studies of upper Paleozoic strata have been conducted in the Sukunka-Kakwa area. This study seeks to address this gap by developing detailed predictive sedimentary-facies and diagenetic models within a sequence biostratigraphic framework for known and potential reservoir intervals in upper Paleozoic and Lower Triassic strata within the Sukunka-Kakwa area (Figure 1) of east-central BC (1:250 000 NTS areas 093I, O and P; latitude 54–55.75ºN; longitude 120–122ºW). Data from outcrop sections will be integrated with all available subsurface data; in particular, wireline logs will be compared to gamma-ray scintillometer curves generated at each outcrop location.

Fieldwork was conducted in August 2009, so the results provided in this report are very preliminary. Additional fieldwork is planned in 2010. This paper will also identify some of the essential objectives, methods and expected outcomes, and provide an initial assessment of how this research will benefit the exploration community.

Geological Setting

The strata in question were deposited on what has generally been interpreted as a relatively passive western North American cratonic margin during the Pennsylvanian to Early Triassic, with possible far field and relatively minor effects associated with the Antler (latest Devonian to earliest Mississippian) and Sonoman (latest Permian and earliest Triassic) orogenies (Henderson et al., 1994; Richards et al., 1994). However, increasing evidence (Fossenier, 2002; Dunn, 2003) is demonstrating that this region experienced significant tectonism in the form of block faulting and possible foreland-basin development similar to northern Nevada (Trexler et al., 2004).

The key to unravelling upper Paleozoic tectonostratigraphic history is the identification of unconformities that separate genetically related stratigraphic successions developed by a combination of eustatic and tectonic influences. These tectonostratigraphic events have been identified in Nevada as C1–C6, P1–P5 and Tr1 (Snyder et al., 2002; Trexler et al., 2004), and they mostly correlate with unconformities in Western Canada (Figure 2). Since standard lithostratigraphy and low-resolution biostratigraphy are insufficient to identify these discrete packages, high-resolution biostratigraphy and geochemical tools are required to reveal the position and duration of the uncon-

Keywords: *Pennsylvanian, Permian, Lower Triassic, stratigraphy, biostratigraphy, conodonts, structure, fractures, petroleum exploration*

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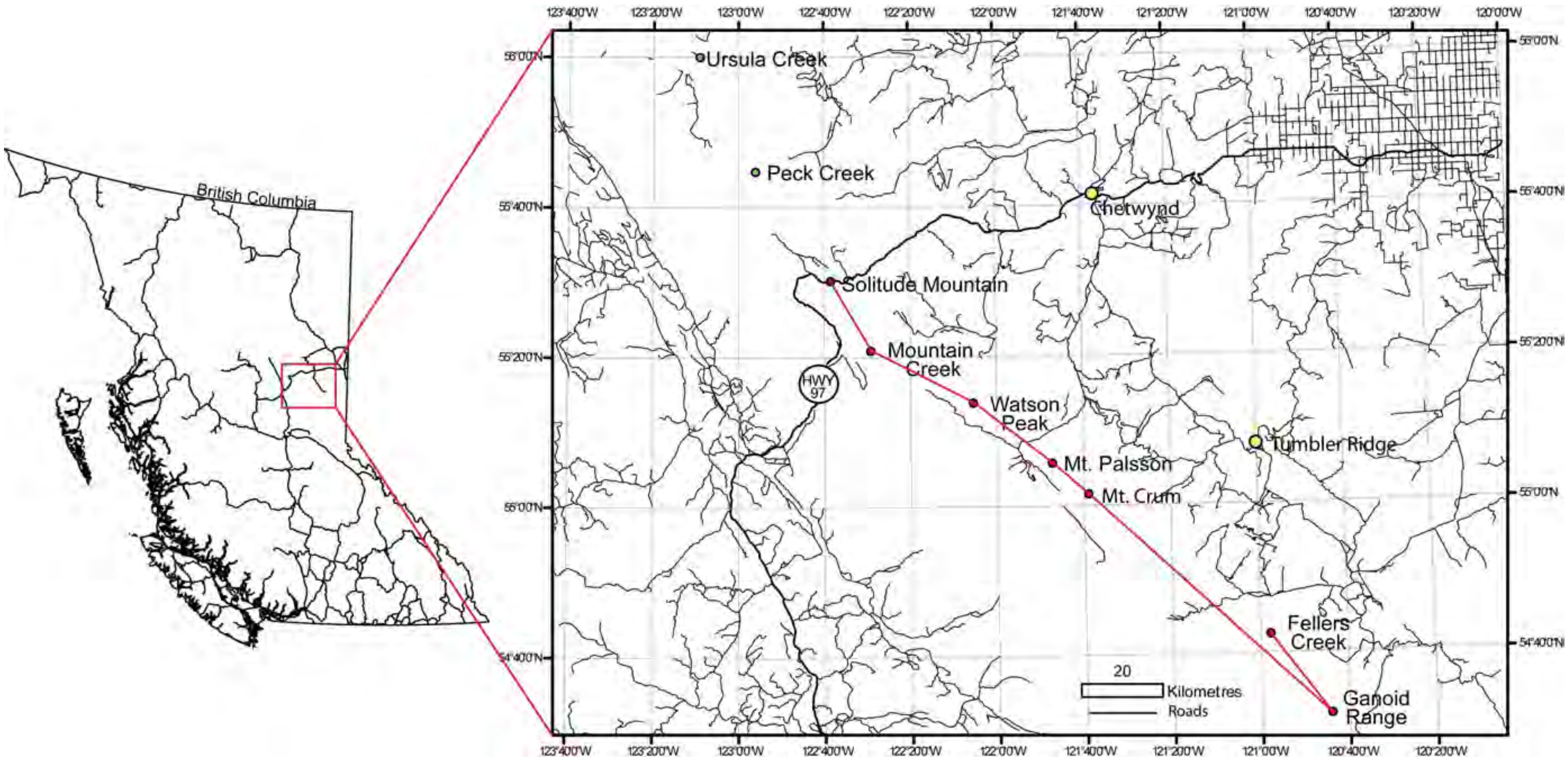

Figure 1. Sukunka-Kakwa study area of east-central British Columbia, showing sections measured and line (red) of cross-section depicted in Figure 3.

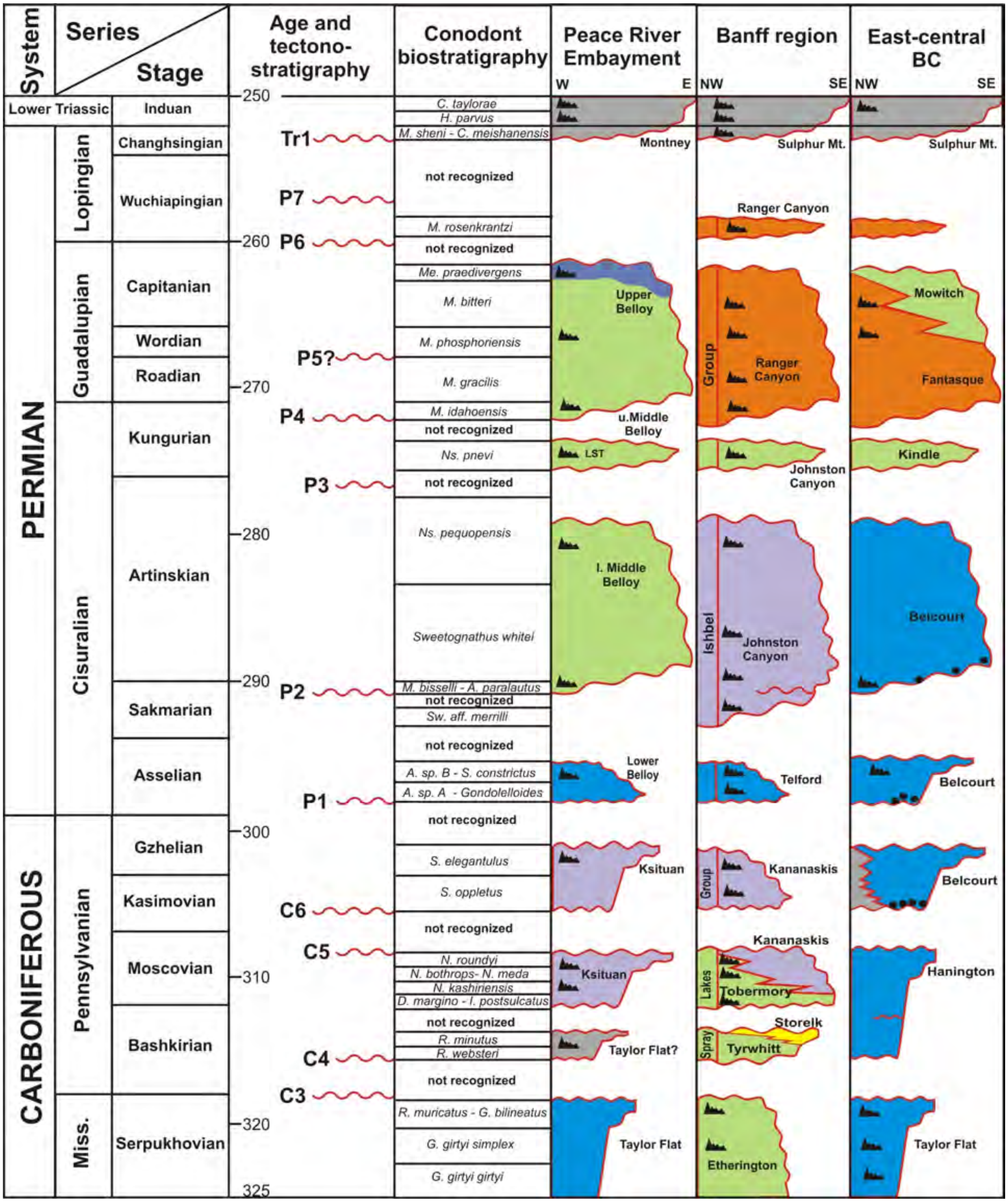

Figure 2. Stratigraphy and tectonostratigraphic sequences correlated among the southwestern Alberta Rocky Mountains, the Peace River Embayment of west-central Alberta and northeastern British Columbia, and the study area in east-central BC. Tectonostratigraphic sequences C1–C6, P1–P5 and Tr1 are after Snyder et al. (2002) and Trexler et al. (2004); P6 and P7 are new. Ages are from the 2009 International Commission on Stratigraphy Time Scale, with some modifications based on new ages (Henderson et al., 2009). Stratigraphy is modified from Henderson et al. (2002). Conodont symbols indicate control points in correlations: *G.*, *Gnathodus*; *R.*, *Rhachistognathus*; *D.*, *Declinognathodus* (including *D. marginodosus*); *I.*, *Idiognathoides*; *N.*, *Neognathodus* (including *N. medadultimus*); *S.*, *Streptognathodus*; *A.*, *Adetognathus*; *Sw.*, *Sweetognathus*; *M.*, *Mesogondolella*; *Ns.*, *Neostreptognathodus*; *Me.*, *Merrillina*; *C.*, *Clarkina*; *H.*, *Hindeodus*. The Hanington Formation is comparable to the Belcourt Formation in facies and there has been a recommendation to abandon the term; however, there is a distinct Moscovian age unit in the area and the name has been retained in this study. The basal conglomerate of the Belcourt has Upper Pennsylvanian and Lower Permian above and mid-Pennsylvanian (Moscovian) or Mississippian below. The upper Belloy Formation carbonate is primarily a caliche (Dunn, 2003). Colours depict dominant generalized lithology, including limestone (blue), dolostone (purple), chert (orange), quartz arenite (yellow), bioturbated and bioclastic sandstone (green), and silty shale (grey).

formities. Based on previous work (Higgins et al., 1991; Henderson et al., 2002) and preliminary results from this study, the authors have interpreted 10 unconformity-bound sequences from Serpukhovian to Induan (Figure 2). The succession of these discrete phases of sedimentary-basin development has resulted in variable preservation of the different stratigraphic units and compartmentalization of reservoir units.

Description and Geological Significance of Units (Pennsylvanian to Lowest Triassic)

Hanington Formation or Ksituan Member of the Belloy Formation

The Mountain Creek and Solitude Mountain sections might be the only outcrop locations studied that contain significant Pennsylvanian strata, although their presence is postulated at Fellers Creek (Figures 3, 4). Solitude Mountain contains similar facies and is correlative with the Mountain Creek section (Figure 3). Although the Mountain Creek section contains several discrete units, including the Belcourt and Fantasque formations, in its upper portion, most of it may represent the Ksituan Member of the Belloy Formation described by Fossenier (2002) as shallow- to open-marine shoaling-upward cycles. In outcrop, this succession is equivalent to the Hanington Formation (Bamber and Macqueen, 1979) and represents the most important reservoir target in the subsurface immediately to the east of the studied sections. Detailed conodont biostratigraphy, based on the numerous samples collected during fieldwork, will be necessary to resolve questions about age, thickness (0–100 metres in the study area) and distribution of this unit.

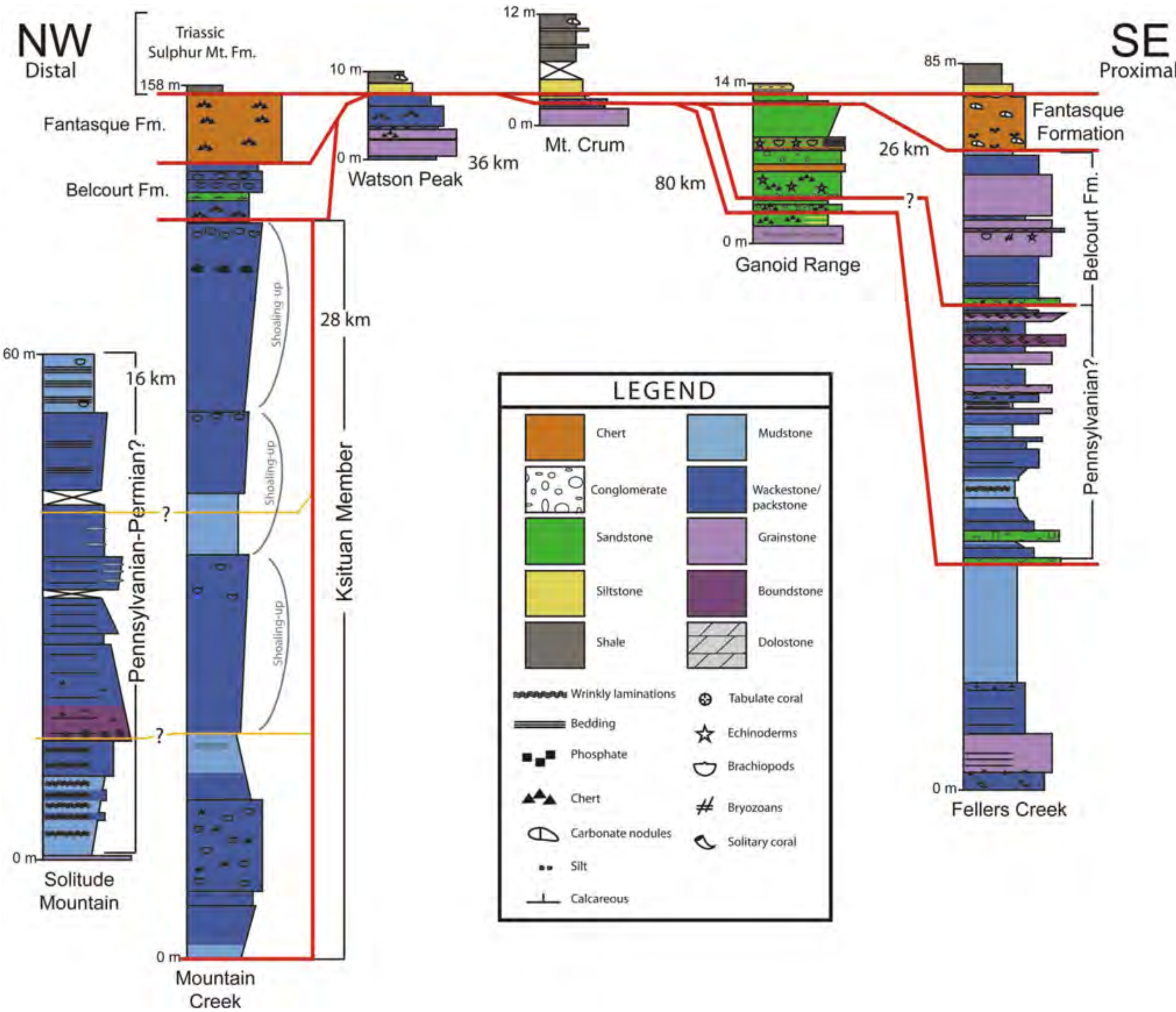

Figure 3. Cross-sections showing stratigraphic relationships in the Sukunka-Kakwa study area, east-central British Columbia. Stratigraphic units, in ascending order, are Mississippian (below lowest red line), Pennsylvanian Ksituan Member (Belloy Formation) or Hanington Formation, latest Pennsylvanian to Lower Permian Belcourt Formation, and Middle to Upper Permian Fantasque Formation. Base of the Triassic Sulphur Mountain Formation (Montney Formation in the subsurface) represents the datum.

The units at the Mountain Creek section are predominantly laminated mudstone and wackestone, with some brachiopod packstone representing the shallowest facies (Figure 5). The Solitude Mountain section consists of wackestone to packstone with some occasional coarser material (coral boundstone) in shoaling-upward packages (Figure 3). Assuming this is equivalent to the Mountain Creek section, it probably represents a shallower water facies.

Belcourt Formation

The Belcourt Formation is easily identified by a basal conglomerate in the Fellers Creek and Ganoid Range sections. This conglomerate consists of poorly sorted, subangular to rounded clasts in a carbonate matrix (Figures 3, 5) and has previously been described only as Permian in age (Bamber and Macqueen, 1979). The Belcourt Formation regionally contains some Pennsylvanian (part of Kasimovian and Gzhelian). Several conglomerate horizons were identified, and the exact age relationships at the Fellers Creek section will be determined by detailed conodont biostratigraphy. Each of these conglomerate levels may represent the product of erosion associated with discrete uplift events. Regionally, the sub–lower Kasimovian unconformity is the most significant. Several shoaling-upward cycles deposited on a gentle ramp occur at the Fellers Creek section. These consist initially of packstone to dolomitic mudstone. Up-section, these cycles grade into grainstone containing brachiopods, bryozoans, crinoids and, in some cases, coral boundstone (Figures 3, 5). The Belcourt Formation at the Ganoid Range is predominantly fine- to coarse-grained calcareous sandstone (Figure 5). The same basal conglomerate is identified, although it is much thinner than at Fellers Creek (Figures 3, 5). This succession represents a much shallower environment compared to Fellers Creek, and the siliciclastic sediments may have been delivered by erosion of uplifted portions of the Sukunka High, across which Pennsylvanian and Permian units thin or disappear in the area (Richards, 1989); the Belcourt Formation ranges in thickness from 0 to 50 m in the current study area.

Fantasque Formation

The Fantasque Formation is identified in four of the six sections described in this study, recognizable by the strong gamma kick at the base. At Fellers Creek, the Fantasque Formation is a 10 m thick unit with abundant phosphate and chert nodules at the base. It thins to approximately 1.2 m at Ganoid Range, where there are some phosphate and chert clasts, although the unit still appears nodular. The Fantasque at Mount Crum is represented by approximately 50 cm of nodular chert and phosphate. The formation may also be present at the Mountain Creek section, where there is an 18 m thick unit of nodular chert, although no apparent gamma kick exists (Figure 3). This is a condensed unit that is equivalent to the Ranger Canyon Formation in southwestern Alberta (Henderson et al., 1994). The Fantasque Formation is absent at Watson Peak.

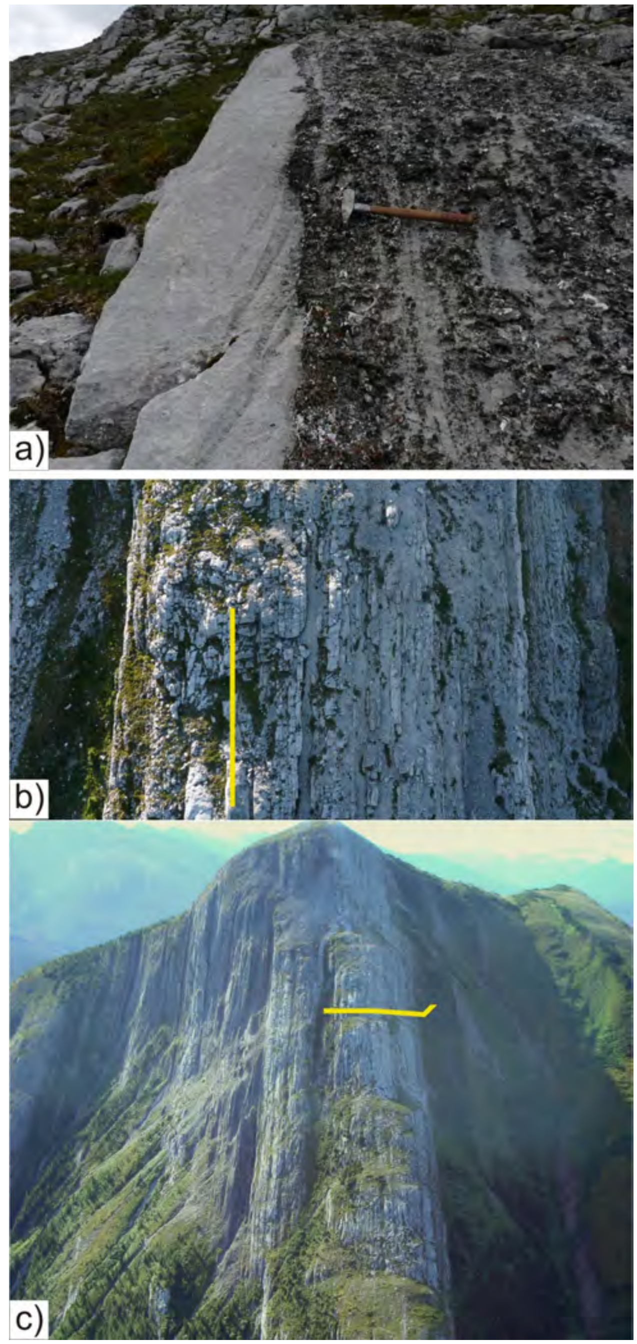

Figure 4. Photographs of Fellers Creek section, Sukunka-Kakwa area, east-central British Columbia: a) conglomerate unit representing the contact (just below 45 cm long hammer) between the Mississippian below and the Ksituan Member (Belloy Formation) and/or Belcourt Formation above; b) close-up aerial view of section; yellow line marks the contact between the Mississippian on the left and the Pennsylvanian–Permian Ksituan Member (Belloy Formation) and/or Belcourt Formation to the right; c) aerial view of section looking south; yellow line marks the measured section depicted in Figure 3 (section is 85 m thick).

Lower Sulphur Mountain (Montney) Formation

Shale and siltstone of the Lower Triassic Montney Formation and surface equivalents in BC were deposited in a ramp setting on the margin of the North American craton (Davies, 1997). Samples were collected from Fellers Creek, Ganoid Range, Mount Crum, Watson Peak and Mount Palsson; however, only the basal part of the formation was measured, so thicknesses are not available. The most significant sampling was at Mount Crum, where approximately 50 m of mainly shale was sampled sequentially at intervals of about 1 m. In addition, gamma-ray scintillometer readings were run on the same section at 0.5 m intervals. The following analyses are currently planned on this suite of samples: 1) total organic carbon analysis, 2) carbon isotope analysis, 3) carbon and oxygen isotope analysis on limestone nodules, 4) x-ray diffraction on shale samples, 5) Sr isotope analysis on conodont elements, 6) thin-section petrology of siltstone and limestone nodules, and 7) detrital zircon analysis of sandy/silty interbeds.

Total organic carbon analysis will be used to determine the values and range of total organic carbon in shale of the basal Triassic as a potential source rock. X-ray diffraction will be used to determine the bulk mineralogy of the shale, as well as any deep-burial diagenesis effects. Thin-section petrology will also aid in the determinations of composition and diagenetic process. Zircon analysis may determine the source of siliciclastic sediment in siltstone beds. Carbon isotopic analysis to determine ^{13}C shift in carbon isotopic signature across the Permian–Triassic boundary and Sr isotopes in conodont elements are important tools to facilitate correlation. The results of the latter analyses will be compared to the global secular Sr isotope curve to obtain an approximate age. The same analysis will be applied to conodont elements collected from the Middle to Upper Permian section (Fantasque Formation) in an attempt to establish the regional time break between the top of the Paleozoic and the basal Triassic, which is essential for recognizing the position of uplifted blocks and the diachronism of the latest Permian to lowest Triassic transgression.

Upper Paleozoic Tectonics

Trexler et al. (2004) documented a number of tectonic events in northern Nevada. Their C3 event represents the development of the Ely Basin and a transition from siliciclastic-dominated to carbonate-dominated deposition without a major break in sedimentation near the Mississippian–Pennsylvanian boundary. Preliminary results from the current study and previous studies (Henderson et al., 2002) suggest that this event in east-central BC coincides with the base of the Ksituan Member (Belloy Formation) or Hanington Formation. The schematic cross-section in Figure 6 suggests possible early foreland-basin development at this time in east-central BC, with a separate sub-basin developed to the east of the Sukunka High. The C6 event of Trexler et al. (2004) appears to correlate with the major conglomerate that typically forms the base of the Belcourt Formation, although multiple conglomerate units at Fellers Creek are problematic. These correlations suggest that the tectonics affecting northern Nevada extended at least as far

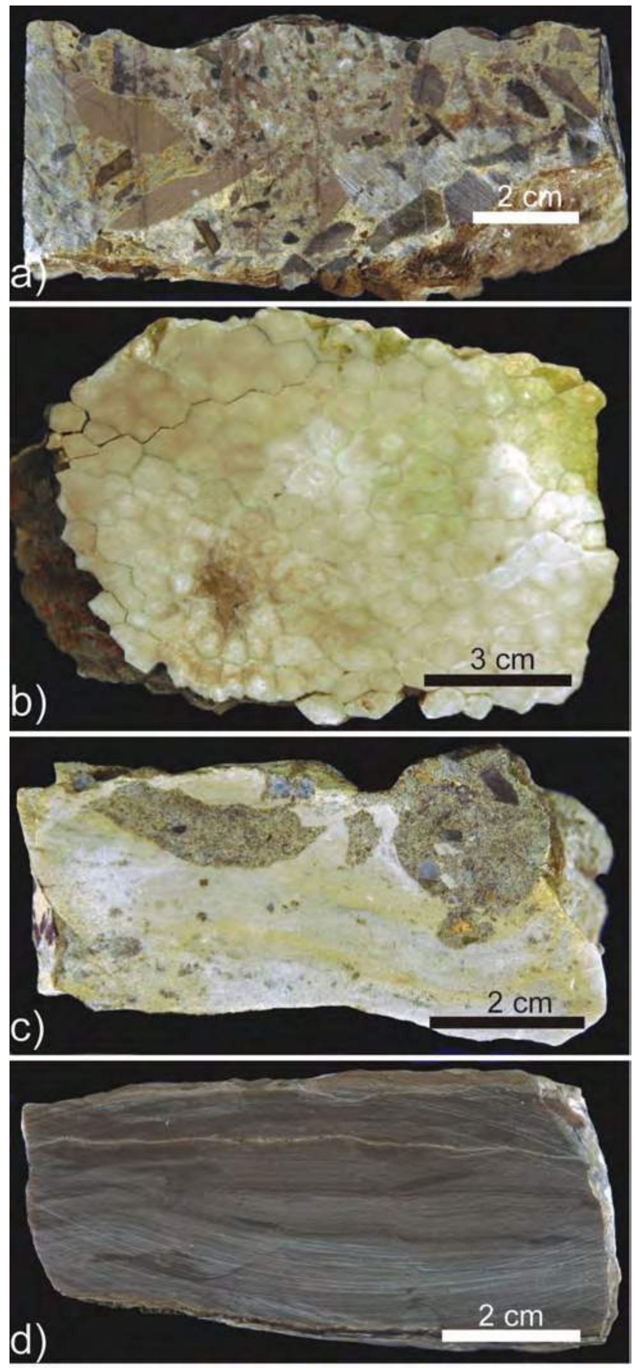

Figure 5. Selected rocks from Sukunka-Kakwa study area, east-central British Columbia: a) Belcourt Formation conglomerate from Ganoid Range at 3.5 m above base; b) coral boundstone from Fellers Creek at 66 m above base; c) fine-grained calcareous sandstone mixed with coarse sand from Ganoid Range at 1.7 m above base; d) laminated mudstone from Mountain Creek at 35.3 m above base.

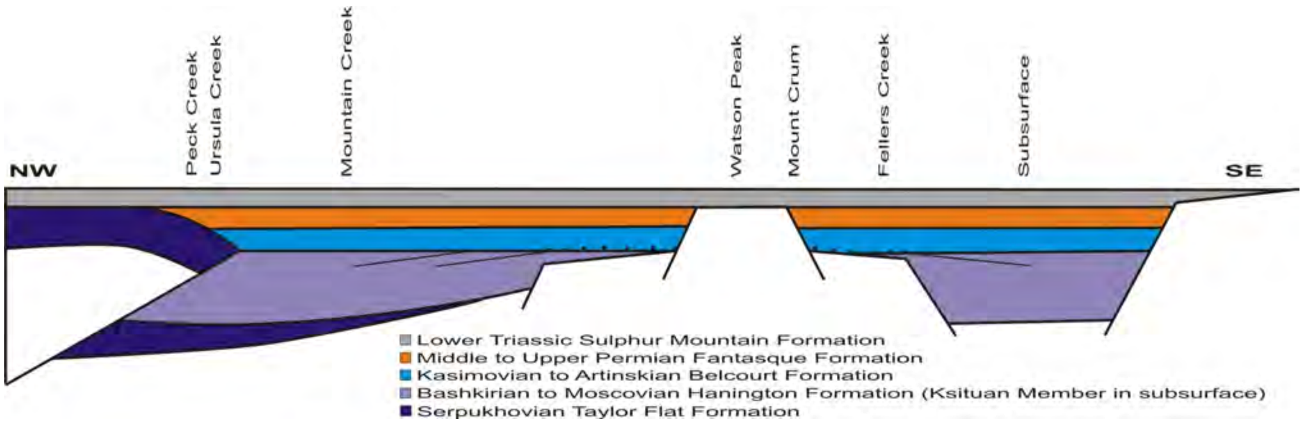

Figure 6. Schematic cross-section of the Sukunka-Kakwa, east-central British Columbia that suggests possible early foreland-basin development during the early Pennsylvanian. The high to the northwest is recognized only as a profound uniformity, with the Middle Permian Fantasque Formation overlying the Serpukhovian Taylor Flat Formation (actual fault relationships and origin are unknown). East of this area, there is a thick Pennsylvanian section that thins dramatically toward the Sukunka Uplift, where, at Watson Peak, Lower Triassic strata overlie mid-Mississippian strata. This high area acts somewhat like a peripheral bulge and probably saw several episodes of differential uplift, especially at level C6 (see Figure 2), indicated by truncation and basal conglomerate. Evidence of postulated erosion from this high and proximity to it is provided by the siliciclastic succession at the Ganoid Range (see Figure 3). East of this area, in the subsurface, is a sub-basin in which Ksituan Member rocks are thick and represent the primary exploration target.

north as east-central BC, and that these events are therefore intimately linked to large-scale structural events on the North American margin. Evidence indicates that Pennsylvanian block faulting led to thickness variations and preferential preservation of reservoir facies in local sub-basins (Figure 3). For example, the Moscovian interval is absent or restricted to a feather-edge (Hanington Formation) throughout much of the outcrop belt, especially adjacent to the Sukunka Uplift, whereas this unit is thick (>200 m) and gas prone in the subsurface to the east. The Fantasque Formation and equivalent units are the most widespread strata in the area that presumably point to a stable setting at a time when the Slide Mountain Ocean was at its widest and most distant from the North American margin (Nelson et al., 2006; Orchard, 2006 for ages).

Laramide Orogeny Structural Interpretation

Upper Paleozoic and Lower Triassic strata in the area were subjected to several discrete syndepositional tectonic events, as indicated above. However, the major structures that represent the structural traps in the subsurface were generated by thin-skinned thrusting during the latest Cretaceous and early Paleogene. In addition, it is very probable that some of these ancient block faults have affected the position of later Laramide-age structures (Dunn, 2003); certainly, individual thrust sheets display very different stratigraphic successions, with thick Pennsylvanian in westernmost sections studied (Mountain Creek), dramatic thinning of Pennsylvanian and Permian in a range to the east (Mount Crum, Watson Peak), and then thickening again of the upper Paleozoic in a range even farther east (Ganoid Range and Fellers Creek).

Understanding the influence of fractures generated within this Laramide-age fold-and-thrust belt on reservoir quality is of vital significance. Fractures are the representation of a surface or zone of failure by any non-sedimentary mechanical discontinuity. The use of outcrop data (orientation, size, density and intensity) for analysis of these features aids in their characterization (Dershowitz and Einstein, 1988).

Preliminary fracture results from linear scanlines show domination by six main fracture sets in the Ganoid Range (Figures 7–11). Set 1 is oriented parallel to the regional fold-axis trend (154) and the local fold-axis trend (162), implying that these fractures are Stearns Type 2 and formed as a result of increased curvature of bedding during folding. Set 2, oriented oblique to set 1, may have formed as a conjugate to the first set. Fracture sets 4 and 5 are conjugate to the principal stress direction ($_1$) and oriented perpendicular to the regional fold axis, implying that these are Stearns Type 1 fractures and formed as a result of regional compression. Fracture sets 4 and 5 (Stearns Type 1) generally appear in the hinge zones of the folds, whereas sets 1 and 2 (Stearns Type 2) dominate in the limbs. Set 3 fractures formed as conjugates to the dominant set 1 fractures at the Ganoid Range. Fracture sets 2 and 6 also formed as a conjugate pair, oblique to the fold-axis trend (Feltham, 2005).

Fracture density and intensity were calculated from circular window scanlines using equations derived from Mauldon et al. (2001). The fracture density is highest in the hinge zone of the folds, where bedding curvature is greatest (GR2–CSL2), and decreases on the limbs of the structure away from the hinge. The Terzaghi correction was applied to the data from linear scanlines to calculate the true fracture density and normalized against densities from circular window scanlines. The same analysis will be completed for fracture data collected at the remaining field sites to find dominant sets and calculate fracture properties.

Fracture data collected from east-central BC will be of vital significance to hydrocarbon exploration. Analyzing the fractures will aid in refining the tectonic history and calculating optimal drilling directions for reservoir units. Creating a regional fracture model for the area will lead to enhanced methods of recovery in addition to more efficient exploration techniques in this upper Paleozoic gas play.

The small-scale structures observed at Mountain Creek (Figure 12) are disharmonic folds that may have developed as leading-edge structures above a thrust that dies out beneath them. These folds are disharmonic because the lower unit (Mississippian package) is more susceptible to deformation than the overlying units.

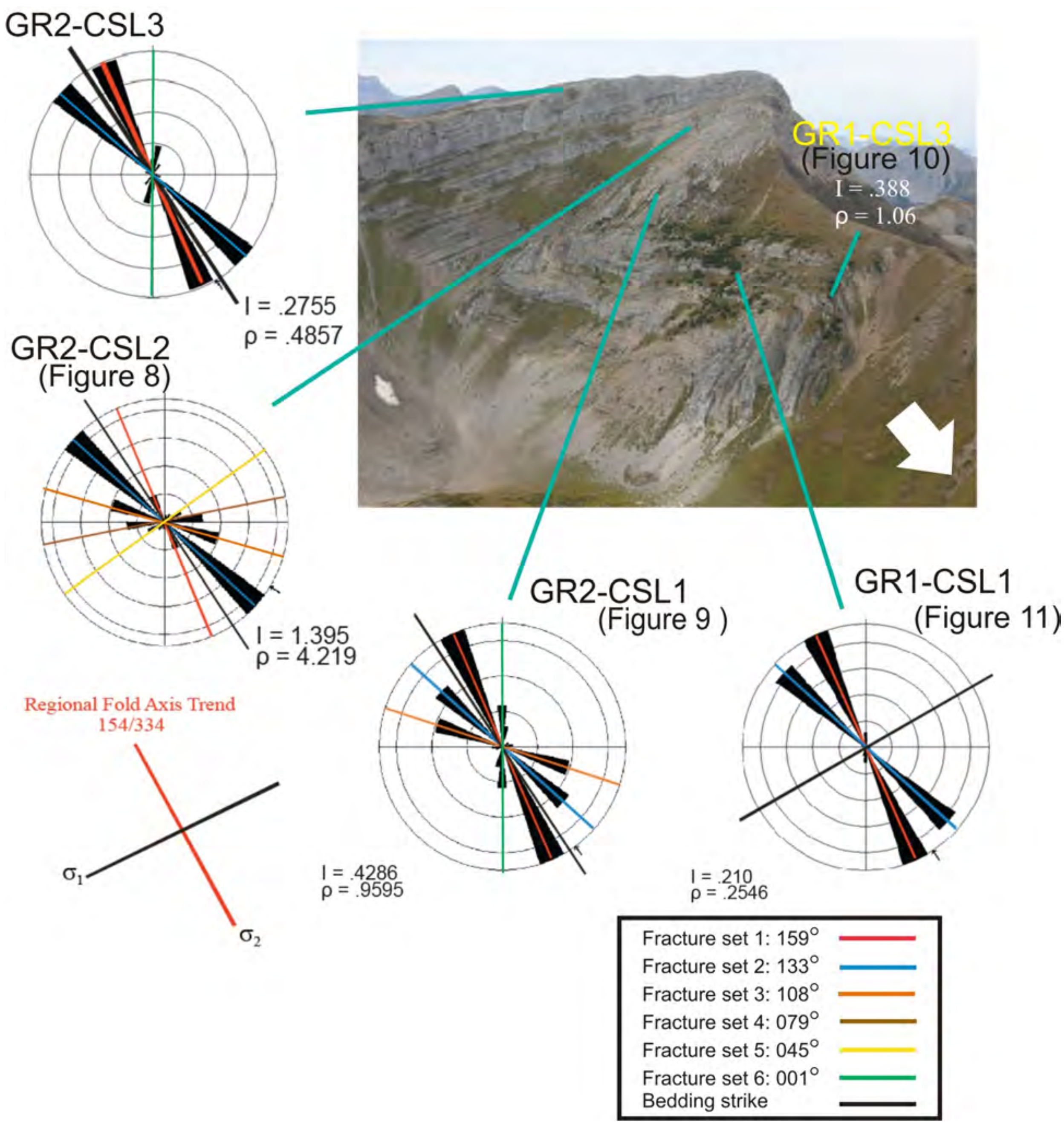

Figure 7. Ganoid Range, Sukunka-Kakwa area, east-central British Columbia: photograph of structure in the field area (white arrow points north), with orientations of linear scanline fractures and circular-window scanline calculated densities. Note the regional fold-axis trend of 154 and the principal stress direction of 064 .

Tectonostratigraphic Implications for Petroleum Exploration

The Ksituan Member (Belloy Formation) in east-central BC has the greatest potential as a reservoir unit for this area because of the distribution of hydrocarbon-bearing lithofacies and structural traps (Fossenier, 2002). There are several major Pennsylvanian, Permian and Triassic gas fields (i.e., Brassey, Brazion, Bullmoose-Sukunka, Grizzly, Ojay) within the study area (Barss and Montandon, 1981; BC Oil and Gas Commission, 2001). Despite the size and quality of these reservoirs, it was believed until recently that much of the upper Paleozoic and Triassic interval in the study area was too 'tight' (i.e., too low in permeability) to allow economic production of hydrocarbons. Recent drilling, combined with the use of new technologies, has shown this to be incorrect. In the view of the authors, the complex nature of the stratigraphy and deformation, and the paucity of detailed geological studies in these intervals have delayed the discovery of new pools and hindered the accurate delineation of resources in discovered pools. Most of the study area is characterized by widely spaced wells and a paucity of available core.

A major problem for hydrocarbon exploration in Pennsylvanian, Permian and Lower Triassic strata in the Sukunka-Kakwa region is the absence of an existing integrated lithostratigraphic and biostratigraphic framework. The study interval encompasses up to 500 m of stratigraphic section and spans approximately 75 million years (ca. 325–250 Ma) of Earth history. Regionally consistent unit subdivision and mapping are essential for effective hydrocarbon exploration. Preliminary studies have shown that optimum reservoir horizons occur in discrete chronostratigraphic units in the study interval (e.g., Moscovian for Ksituan Member). Throughout much of the study interval, these units are laterally inconsistent on a regional scale owing to numerous erosional unconformities and regional tectonism coeval with sediment accumulation. Thus, the production of an accurate, integrated chronostratigraphic-sequence stratigraphic framework for this succession is essential to develop effective exploration models for conventional and 'tight gas' resources.

Dolomitized shallow-water carbonate is the primary reservoir facies in the late Paleozoic (Pennsylvanian–Permian) and Belloy Formation, including the Ksituan Member. These units have proven to be highly important but exceptionally elusive reservoir successions in the Sukunka-Kakwa region. Major shifts in depositional setting and climate throughout the evolution of this succession signifi-

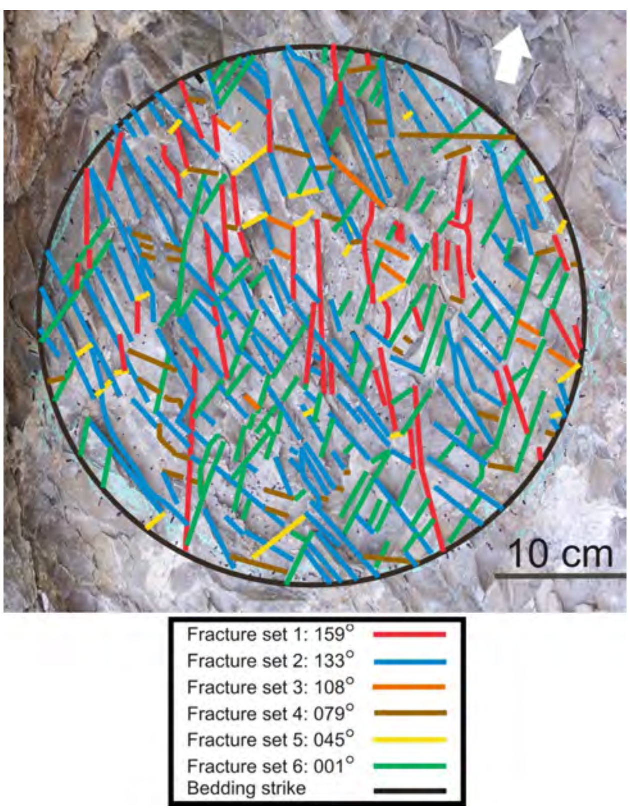

Figure 8. Ganoid Range, Sukunka-Kakwa area, east-central British Columbia: circular-window scanline 2-2 (GR2–CSL2), with fracture orientations; white arrow points north.

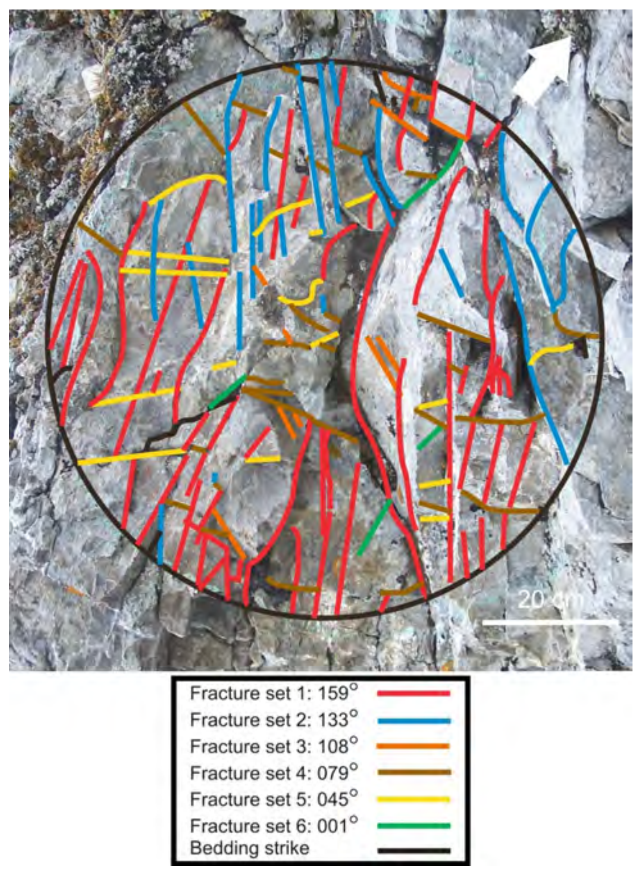

Figure 9. Ganoid Range, Sukunka-Kakwa area, east-central British Columbia: circular-window scanline 2-1 (GR2–CSL3), with fracture orientations; white arrow points north.

cantly complicate facies distribution. Furthermore, controls on dolomitization and other diagenetic changes are poorly constrained.

The Montney Formation represents a major shale-gas target in northeastern BC because it consists of very fine to fine-grained turbidite sandstone successions encased in organic-rich silty shale. Preliminary analyses, including conodont biostratigraphy, suggest that the turbidite facies are similar in age across the region. However, the age of the base of the Montney Formation varies regionally, probably because of onlap onto late Paleozoic highs; grain size also varies around these structures. This diachronism at the base of the Montney Formation will help in the mapping of late Paleozoic structures and may have some bearing on distribution of reservoir facies. Age differences between the underlying Permian section and the earliest Triassic, determined using strontium isotope analysis of conodonts, tied to the secular strontium isotope curve may provide insights into the degree of erosion and structural elevation of upper Paleozoic strata prior to Triassic deposition, and/or provide evidence of the influence of the Sukunka High on Early Triassic and even Middle Triassic (Caplan and Moslow, 1997) sedimentation.

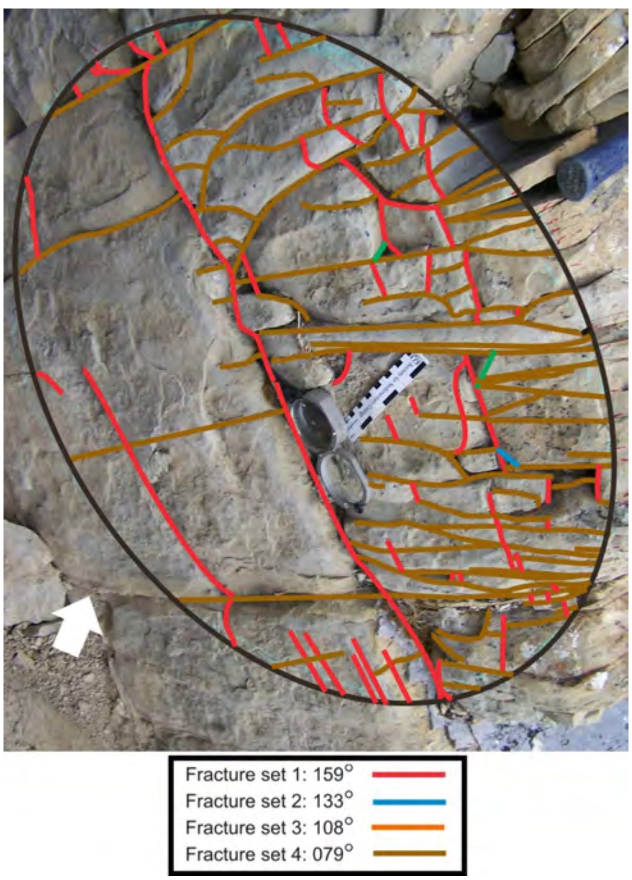

Figure 10. Ganoid Range, Sukunka-Kakwa area, east-central British Columbia: circular-window scanline 3 (GR2–CSL3), with fracture orientations (photo taken oblique to scanline); white arrow points north.

As Western Canada Sedimentary Basin exploration continues to mature, the focus of many hydrocarbon exploration companies will expand to encompass stratigraphic intervals with moderate to low porosity and microdarcy permeabilities. Ideally these horizons contain organic-rich rocks to provide the gas, and either coarser sedimentary rock types or sufficient fractures to provide reservoir- and flow-conduits. Identifying these characteristics, as this research continues, is the primary goal of the project.

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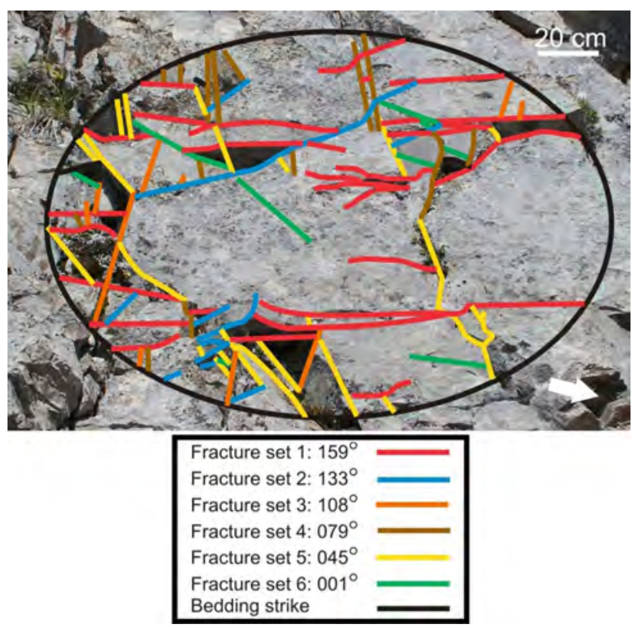

Figure 11. Ganoid Range, Sukunka-Kakwa area, east-central British Columbia: circular-window scanline 1 (GR1–CSL1), with fracture orientations; white arrow points north.

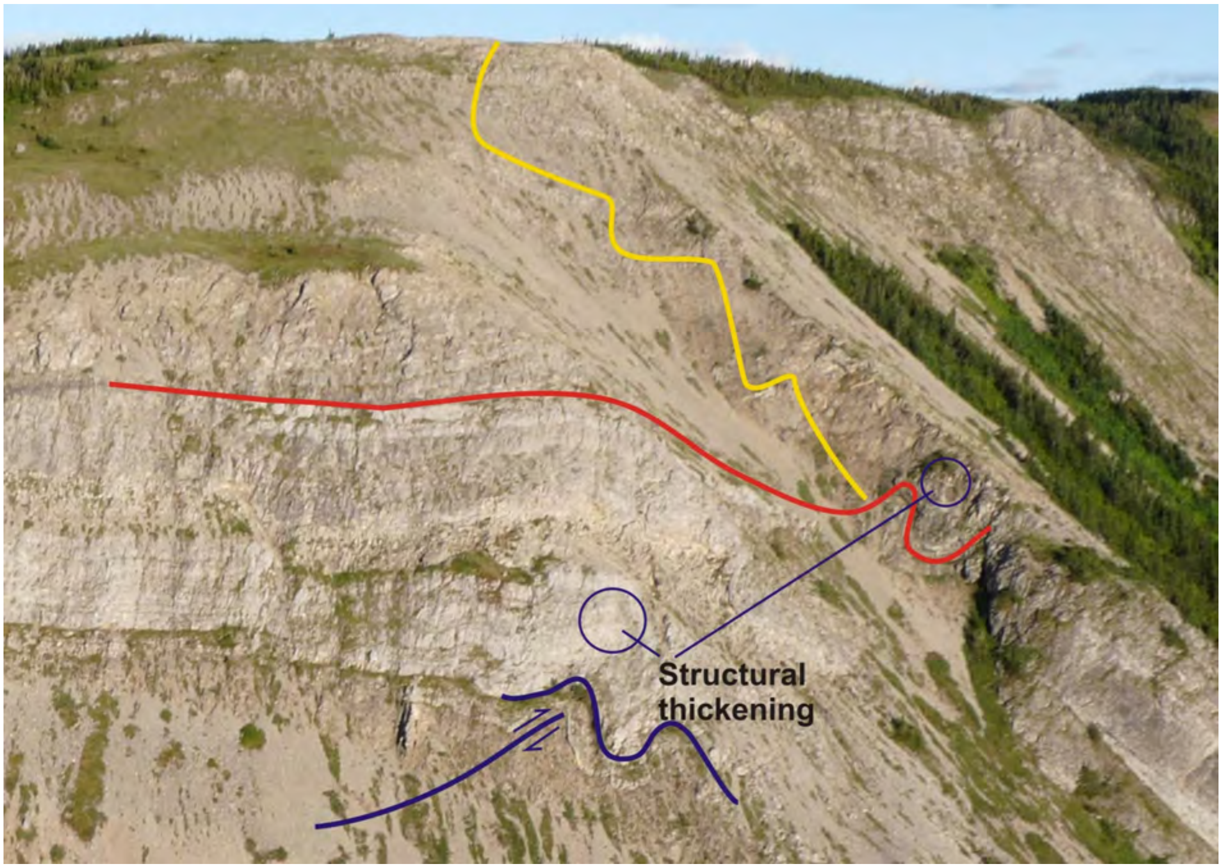

Figure 12. Small-scale disharmonic folding in the Mississippian at the Mountain Creek section, Sukunka-Kakwa area, east-central British Columbia. Red line represents approximate top of Mississippian. Purple lines depict structural features. Yellow line represents approximate line of section for the Hanington and Belcourt formations; jogs in the line of section are near cycle boundaries in the succession. Most of the Pennsylvanian and Permian succession does not display any folding.

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