

Seismic and geological constraints on the structure and hydrocarbon potential of the northern Whitehorse trough, Yukon, Canada

Abstract

The Whitehorse trough is an Early to Middle Jurassic underexplored and undrilled sedimentary basin in the northern Canadian Cordillera that is prospective for oil and gas. It records deposition in a collapsing forearc that evolved to become a synorogenic piggyback basin within the nascent Cordilleran orogen. The basin developed atop the Triassic and older arc terranes of Stikinia and Quesnellia, and locally overlaps the Cache Creek accretionary complex. A regional seismic survey and bedrock mapping across the northern Whitehorse trough in Yukon indicate that Jurassic strata of the Laberge Group are up to 3000 m thick and were deformed by southwest-verging folds and thrust faults. These structures have an overall *en échelon*, sigmoidal pattern that is consistent with dextral transpression associated with strike-slip displacement along the Teslin and Braeburn faults. The structures likely began developing in Middle to Late Jurassic and were further enhanced during the mid-Cretaceous. Fold-and-thrust structures of the northern Whitehorse trough present suitable structural plays in areas where Jurassic strata with good source rock potential and adequate thermal maturity are most prospective.

Résumé

Bassin sédimentaire du Jurassique précoce et moyen sous-explorée et non-sondée de la Cordillère canadienne septentrionale, la dépression de Whitehorse représente un potentiel gazier et pétrolier. Les roches qui y sont contenues montrent les dépôts d'un avant-arc d'effondrement devenu un bassin transporté synorogénique dans l'orogène naissante de la Cordillère. Le bassin a pris forme sur des terranes d'arc du Trias et d'autres plus anciennes de Stikinie et de Quesnellie et il chevauche localement le complexe d'accrétion de Cache Creek. Après avoir procédé à un levé sismique et à une cartographie du substrat rocheux de la dépression septentrionale de Whitehorse dans le Yukon, les données indiquent que les strates du Jurassique du groupe de Laberge ont jusqu'à 3000 mètres d'épaisseur et sont déformées par des plissements et des failles chevauchantes orientés sud-ouest. En accord avec la transpression dextre associée au déplacement en coulissement le long des failles de Teslin et de Braeburn, dans l'ensemble, ces structures ont une forme *en échelon* et sigmoïdale. Ces structures ont probablement commencé à prendre forme durant le Jurassique moyen à tardif et à ressortir plus amplement au cours du Crétacé moyen. Les plissements et failles chevauchantes de la dépression septentrionale de Whitehorse présentent des thèmes structuraux convenables dans les régions où les strates du Jurassique ayant une roche mère potentielle et une maturité thermique adéquate se révèlent les plus prometteuses.

Michel Ory

Don White

Geological Survey of Canada
615 Booth Street
Ottawa, ON K1A 0E9
Canada
don.white@nrcan.gc.ca

Maurice Colpron

Yukon Geological Survey
P.O. Box 2703 (K-14)
Whitehorse, YT Y1A 2C6
Canada
maurice.colpron@gov.yk.ca

Grant Buffett¹

Geological Survey of Canada
615 Booth Street
Ottawa, ON K1A 0E9
Canada

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¹ Present address: Institute of Earth Sciences 'Jaume Almera', C/ Lluis Sole Sabaris s/n., Barcelona, E-08028, Spain, gbuffett@ija.csic.es

Introduction

The Whitehorse trough is an elongated, northwest-trending, predominantly marine sedimentary basin of Mesozoic age that extends some 650 km from northern British Columbia to just north of Carmacks in central Yukon (Fig. 1). It originated as a forearc basin in the Late Triassic, adjacent to the emerging Lewes River arc (Stikinia), and had received more than 7000 m of clastic deposits by Middle Jurassic time (Wheeler, 1961; Tempelman-Kluit, 1979). It is underlain by upper Paleozoic and lower Mesozoic arc rocks of Stikinia and is structurally overlain, in southern Yukon and northern British Columbia, by the oceanic Cache Creek terrane (Fig. 1). The Whitehorse trough overlies Stikinia at its northern apex, where it is bounded on three sides by polydeformed and metamorphosed middle to upper Paleozoic rocks of the Yukon-Tanana terrane. It has been identified as an immature, gas-prone basin in which potential source rocks, reservoirs, seals and traps occur (National Energy Board, 2001). A mean assessed hydrocarbon resources of $82.3 \times 10^9 \text{ m}^3$ (2920 billion cubic feet or BCF) of gas and $17.1 \times 10^6 \text{ m}^3$ (107 million barrels or MMBO) of oil is estimated for the Yukon portion of the basin (Hayes, 2012). Structural traps associated with clastic or carbonate reservoirs (Laberge and Lewes River groups) are proposed as having the greatest hydrocarbon potential, with surface-defined anticlines posing the best drilling targets (National Energy Board, 2001; Hayes, 2012). Current assessments of hydrocarbon potential in the Whitehorse trough, however, rely on limited stratigraphic, structural and thermal maturation studies (English et al., 2005; Lowey et al., 2009), and are based on conceptual or speculative plays.

In 2004, the Yukon Geological Survey and Geological Survey of Canada commissioned a regional Vibroseis seismic reflection survey across the northern part of Whitehorse trough and into adjacent terranes (Fig. 1) with the objective of enhancing the geoscience database of the area for use in hydrocarbon potential assessment. The survey comprises two seismic profiles totaling 170 km in length acquired along major roads near the town of Carmacks (Fig. 1; White et al., 2006; Buffett et al., 2006). Acquisition of this survey was followed by bedrock mapping of the northern Whitehorse trough in 2006 in order to improve the surface control on regional structures and stratigraphy (Colpron et al., 2007). We present here a structural interpretation of the northern Whitehorse trough as derived from both bedrock mapping and the shallow part of the seismic crustal sections.

Geological Setting

Stikinia is the largest of the allochthonous terranes of the Canadian Cordillera (Wheeler et al., 1991; Colpron and Nelson, 2011). It comprises Upper Devonian to Middle Jurassic volcanic and sedimentary strata, as well as comagmatic plutonic rocks (Monger et al., 1991). Stikinia and its eastern twin, Quesnellia, are primarily characterized by regionally extensive Upper Triassic augite-phyric basalt, basaltic andesite and volcanoclastic rocks. In British Columbia, arc sequences of Stikinia and Quesnellia are separated by oceanic rocks of the intervening Cache Creek terrane (Fig. 1 inset). In Yukon, the Cache Creek

terrane does not extend north of Whitehorse and similar volcanic and volcanoclastic rocks of Stikinia and Quesnellia are juxtaposed along the Teslin fault (Fig. 1). Stikinia and Quesnellia are interpreted to have formed part of a single, continuous arc system that developed along the western edge of the North American plate in Late Triassic (Fig. 2; Mihalynuk et al., 1994). In Early to Middle Jurassic, oroclinal collapse of this arc system entrapped part of the adjacent subduction complex with exotic Tethyan elements (Cache Creek terrane) and marked the onset of orogenic activity along western North America (Mihalynuk et al., 1994, 2004). Although alternatives have been proposed (e.g. Wernicke and Klepacki, 1988; Gehrels et al., 1991; Dostal et al., 2009), no other model better explains the geological relationships and concentric distribution of terranes in the northern Cordillera (Fig. 1), a topic beyond the scope of this paper. Importantly, this evolving geodynamic setting provided the environment for deposition of the sedimentary strata of the Whitehorse trough (Fig. 2).

Stratigraphy

Both Stikinia and Quesnellia include sporadically exposed Paleozoic arc 'basement' rocks. In Stikinia these correspond to the Stikine assemblage of northwestern British Columbia, a volcanic-sedimentary sequence of Devonian to Lower Permian age (Logan et al., 2000; Gunning et al., 2006). Correlative rocks in Yukon are the metamorphosed volcanic, volcanoclastic and minor carbonate rocks of the upper Paleozoic Takhini assemblage, exposed west of Whitehorse (Figs. 1 and 3; Hart, 1997). In Quesnellia, upper Paleozoic arc and backarc assemblages are found in central and southern British Columbia (Ferri, 1997; Beatty et al., 2006). In south-central Yukon the Boswell assemblage is an upper Paleozoic volcanic-sedimentary sequence assigned to Quesnellia (Colpron et al., 2006, and unpublished data). It consists of a lower unit of Upper Devonian to Lower Mississippian basalt (normal and enriched mid-ocean ridge basalt [MORB]) and limestone, and an upper unit of Upper Mississippian to Lower Permian arc volcanic, volcanoclastic and sedimentary rocks (including Pennsylvanian-Permian fossiliferous limestone; Simard, 2003; Simard and Devine, 2003). These rocks are unconformably overlain by Upper Triassic volcanic and volcanoclastic strata of the Semenof formation on Boswell Mountain (Fig. 1; informal stratigraphic nomenclature of Tempelman-Kluit, 1984, 2009; Simard, 2003). Paleozoic rocks of the Takhini and Boswell assemblages are inferred to be the depositional basement to Mesozoic arc rocks of Stikinia/Quesnellia beneath the Whitehorse trough.

In Yukon, Mesozoic Stikinia is represented by volcanic and sedimentary strata of the Middle Triassic Joe Mountain Formation and the Upper Triassic Lewes River Group (Fig. 3; Hart, 1997; Wheeler, 1961). The Joe Mountain Formation consists of a mafic-ultramafic intrusive complex, basalt and volcanoclastic rocks of Ladinian (Middle Triassic) age and of MORB to back-arc basin basalt geochemical affinity (Hart, 1997; Piercey, 2005). The Upper Triassic Lewes River Group includes a lower formation of Carnian augite-phyric basalt, basaltic andesite and volcanoclastic rocks (Povoas formation; informal nomenclature of Tempelman-Kluit, 1984, 2009) and an upper formation of Carnian to Rhaetian epiclastic, volcanogenic sedimentary rocks and limestone (Aksala formation, *ibid.*; Fig. 3). Volcanic rocks

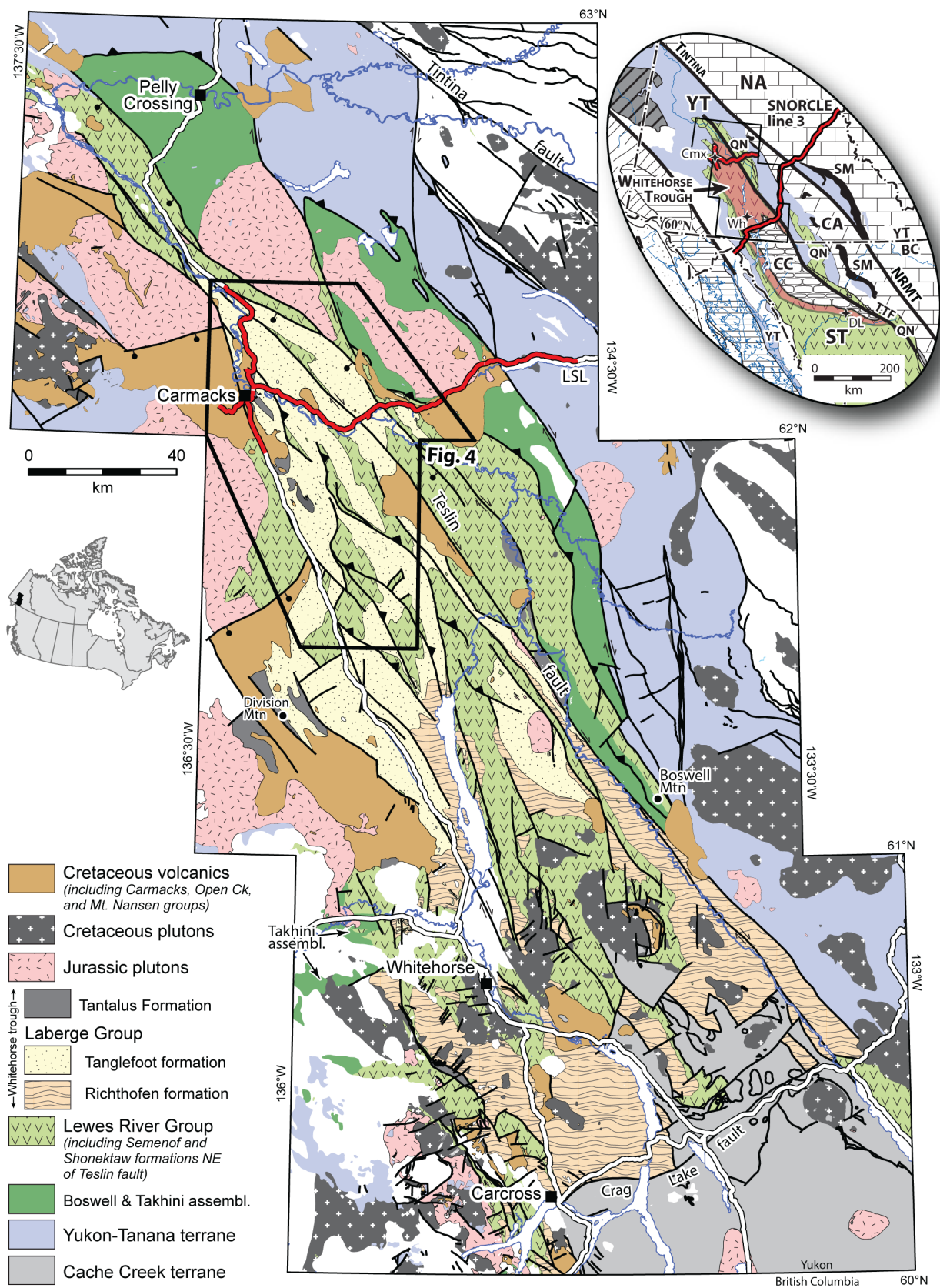


Figure 1. Regional geology of Stikinia and the Whitehorse trough in south-central Yukon (after Colpron, 2011). Inset shows the location of Whitehorse trough (red shading) with respect to terranes of the northern Cordillera (after Colpron and Nelson, 2011). Location of the 2004 Carmacks seismic survey reported here is shown by red lines on the map and in inset; location of Line 3 of the 1999 SNORCLE Lithoprobe transect (Cook et al., 2004) is also indicated in inset. Abbreviations: CA – Cassiar terrane (derived from ancestral North America); CC – Cache Creek terrane; Cmx – Carmacks; DL – Dease Lake; LSL – Little Salmon Lake; NA – rocks of ancestral North America; NRMT – Northern Rocky Mountain Trench fault; QN – Quesnellia; SM – Slide Mountain terrane; ST – Stikinia; TTF – Teslin-Thibert fault; Wh – Whitehorse; YT – Yukon-Tanana terrane.



Figure 4. Geological map of the northern Whitehorse trough (after Colpron et al., 2007) showing the locations of the two seismic lines. In the vicinity of Carmacks, seismic lines 1 and 2 are co-located from just north of Carmacks to the junction with the Robert Campbell Highway. Seismic station numbers are not shown for this segment to avoid clutter. Upper Triassic volcanic and volcanoclastic rocks northeast of Teslin fault are part of the Semenof formation (Quesnellia). For simplicity they are grouped here (and in seismic sections) with the correlative Povoas formation (Stikinia). Based on regional considerations, the Teslin fault is interpreted to have a compound history of thrust and strike-slip faulting (see text). Sections A, B and C are depicted in Figure 5. ENB – Eagle’s Nest Bluff.

The Laberge Group comprises a southern unit of deep-water turbidite (sandstone-siltstone-mudstone) and mass-flow conglomerate, the late Hettangian(?) to Bajocian Richthofen formation (informal nomenclature of Tempelman-Kluit, 1984, 2009; equivalent to the Inklin Formation of northern British Columbia; Souther, 1971; Johannson et al., 1997; Mihalynuk, 1999), and a northern, in part coeval, unit of shallow marine to fluvial sandstone, conglomerate and minor shale with coal seams, the Sinemurian to Bajocian Tanglefoot formation (Fig. 3; informal nomenclature of Tempelman-Kluit, 1984, 2009; Hart, 1997; Lowey, 2004, 2008; Takwahoni Formation in northern British Columbia). A crystal-lithic tuff unit, the Pliensbachian (ca. 186–188 Ma) Nordenskiöld formation (informal nomenclature of Tempelman-Kluit, 1984, 2009), occurs at multiple stratigraphic levels and is common to both the Richthofen and Tanglefoot formations (Fig. 3; Colpron and Friedman, 2008). In the northern Whitehorse trough, conglomerate and sandstone of the Tanglefoot formation commonly occur as massive units that generally lack well-defined bedding planes.

The Laberge Group is disconformably overlain by the Middle Jurassic to Lower Cretaceous Tantalus Formation (Fig. 3; Bostock, 1936; Tempelman-Kluit, 1984, 2009; Long, 2005), a coal-bearing sequence of fluvial chert-pebble conglomerate and sandstone that marks the end of deposition in the Whitehorse trough. Near Whitehorse, the Whitehorse trough is intruded by numerous Early Cretaceous plutons (Fig. 1); a single Early Cretaceous pluton is mapped in the northern Whitehorse trough near Carmacks (Fig. 4; Colpron et al., 2007; Colpron and Friedman, 2008). Late Cretaceous volcanic rocks of the Mount Nansen and Carmacks groups unconformably overlie Jurassic and older strata throughout south-central Yukon

(Fig. 4). The ca. 70 Ma Carmacks Group consists mainly of high-Mg, shoshonitic columnar basalts (Johnston et al., 1996b) that likely formed valley fills and blanketed parts of the northern Whitehorse trough; the present exposures being erosional remnants of once larger basalt floods. Predominance of gabbro in Carmacks exposures near Eagle's Nest Bluff (ENB on Fig. 4; Colpron et al., 2007) suggests proximity to a volcanic centre.

Structure

The structure of the northern Whitehorse trough is characterized by northwest-trending open folds and southwest-verging thrust faults (Figs. 4 and 5). Outcrop-scale structures are rarely observed and the rocks generally lack cleavage development. Fold geometry is determined by variations in bedding plane attitudes and the scale of folding is on the order of 3–5 km (wavelength). Folds of the Nordenskiöld formation are particularly well defined in the regional aeromagnetic data south of the Robert Campbell highway (Figs. 4 and 6). Southwest-verging thrust faults are evidenced by stratigraphic truncations. These structures are well-defined south of the highway where they juxtapose Lewes River strata against the Tanglefoot formation (Coghlan, Chain and Hoochekoo faults; Fig. 4). They are not recognized north of the highway where the Whitehorse trough strata are primarily the Tanglefoot formation. In general, the limited exposures and massive character of lithologies in this region prevent accurate definition of structures north of the highway.

Northeast-trending structures near Braeburn and Coghlan Lake are primarily defined by distribution of Lewes River Group and probably reflect the presence of structures that predate (at least in part) deposition of the Jurassic Laberge Group (Fig. 4). This interpretation is supported by the observation that Laberge Group sandstone and conglomerate overlie various Lewes

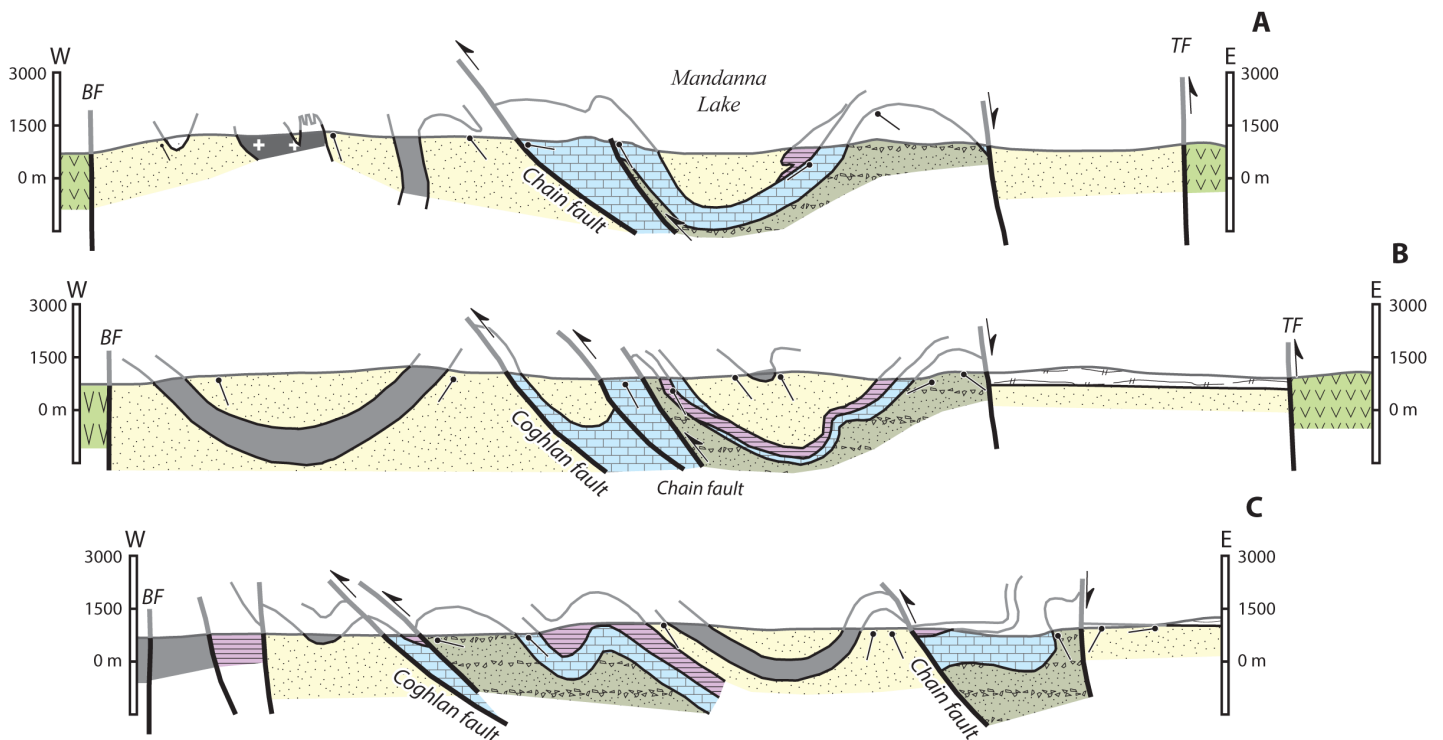


Figure 5. Schematic structural cross-sections across the northern Whitehorse trough, based on field observations. Lines of section and legend are shown on Figure 4. BF – Braeburn fault; TF – Teslin fault.

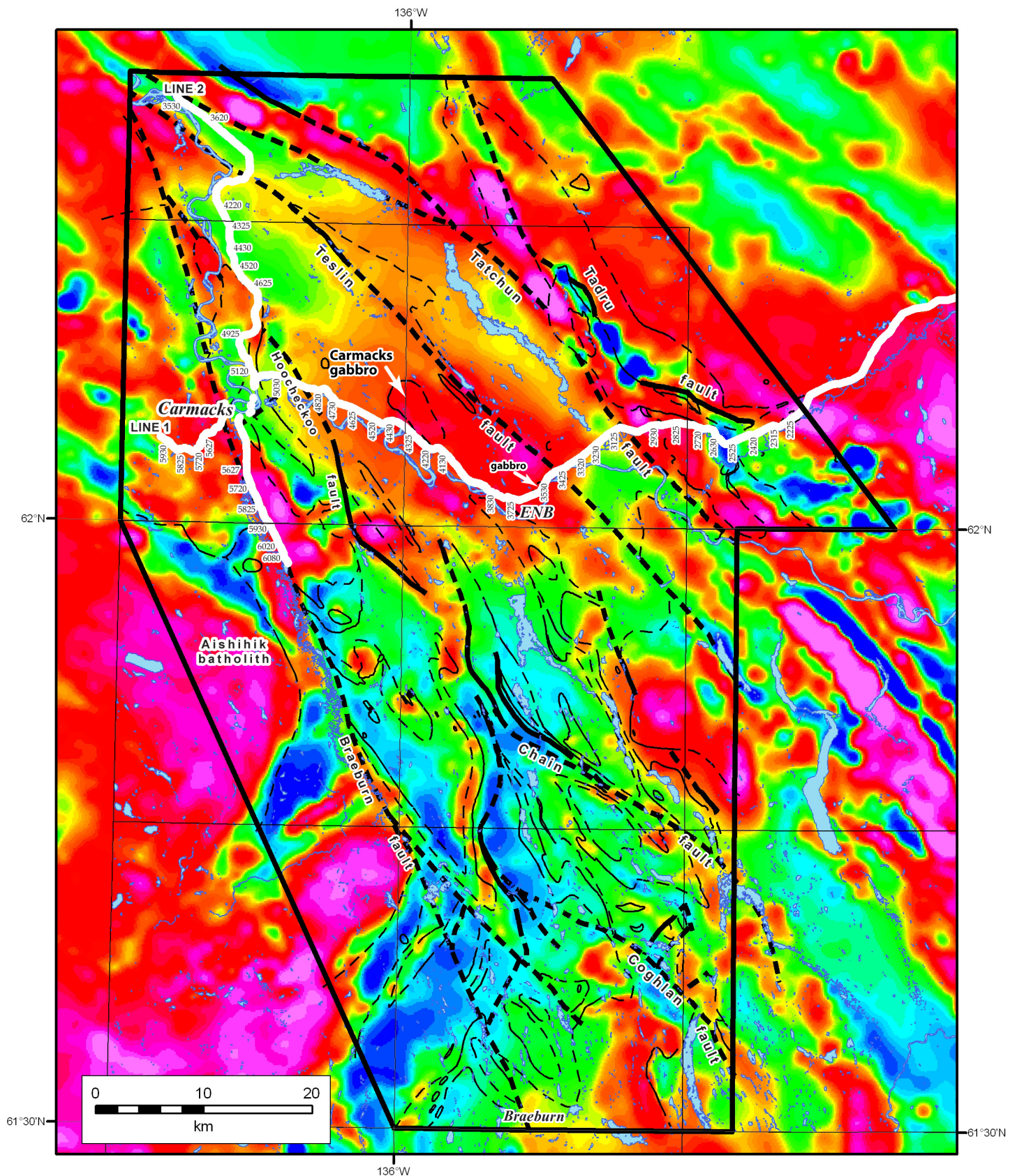


Figure 6. Residual total field aeromagnetic map of the northern Whitehorse trough. The area of the geological map (Fig. 4) is outlined; faults and geological contacts are shown for reference. Bold white lines indicate location of seismic profiles described in this paper. The seismic and magnetic data are available from the Geological Survey of Canada. ENB – Eagle's Nest Bluff.

River units throughout the northern Whitehorse trough. The Laberge Group typically rests on the Hancock and Mandanna members of the Aksala formation throughout much of the map area, but locally overlies the older Povoas formation southeast of Carmacks and southeast of Frenchman Lake (Fig. 4).

At the latitude of the Robert Campbell Highway, the northern Whitehorse trough is bounded on the east by the Tadru fault, a northeast-dipping thrust fault that places upper Paleozoic rocks of the Boswell assemblage onto Upper Triassic strata of the Lewes River Group (Fig. 4; Colpron et al., 2002, 2003). In the hangingwall of the fault, rocks of the Boswell assemblage are penetratively foliated, greenschist facies greenstone, metavolcaniclastic rocks, metasilstone and metarhyolite. Volcanic and carbonate rocks of the Lewes River Group are penetratively foliated in the immediate footwall of the Tadru fault, but fabric development decreases rapidly to the west. Lewes River rocks in the footwall of the Tadru fault locally contain shear bands with top-to-the-southwest kinematics. The fault is congruent with an upright to southwesterly overturned syncline cored by sandstone and conglomerate of the Early to Middle Jurassic Tanglefoot formation that occurs in its immediate footwall, south of Robert Campbell Highway (Fig. 4). The Tadru fault is clearly onlapped by basalt flows of the Upper Cretaceous Carmacks Group.

To the west, the Braeburn fault delimits the Whitehorse trough near Carmacks (Fig. 4). The fault trace is defined by truncations of stratigraphic units (Fig. 4) and trends observed in the regional aeromagnetic map (Fig. 6) along the Nordenskiöld valley. Structural features directly related to the Braeburn fault are not recognized in the field. Tempelman-Kluit (1984, 2009; and unpublished notes) estimated approximately 8 km of dextral strike-slip displacement along Braeburn fault based on apparent offset of stratigraphic markers north of Braeburn (Fig. 4). However, exact matches of stratigraphic markers across the fault are uncertain as Lewes River and Laberge strata are repeated within the triangular fault wedge that occurs east of Braeburn fault south of Twin Lakes (Fig. 4). It is also uncertain whether the Braeburn fault cuts the Upper Cretaceous Carmacks Group near the town of Carmacks, or whether the basalts overlap the fault.

The Teslin fault runs through the east-central portion of the northern Whitehorse trough, northeast of Eagle's Nest Bluff (ENB, Fig. 4). It locally juxtaposes Lewes River strata on the east against the Tanglefoot formation on the west. However, for much of its length, the fault has no apparent stratigraphic expression and is wholly contained within the Laberge Group (Figs. 1 and 4); its exact location is poorly constrained. The Teslin fault is the northwestern extension of the Thibert-Kutcho fault system of northern British Columbia, which juxtaposes rocks of Quesnellia on the east to the Cache Creek terrane on the west (Fig. 1). In the SNORCLE seismic reflection survey, near the Yukon-British Columbia border, the Teslin fault is the surface expression of a series of east-dipping reflectors that extend to mid-crustal level (Cook et al., 2004; Snyder et al., 2005). The dip of this structure is congruent with southwest-verging thrust faults imbricating Cache Creek and Laberge Group strata to the west (e.g. English et al., 2005), and thus may suggest, in part, a history of southwest-verging thrusting along Teslin fault, possibly in Early to Middle Jurassic time

(Mihalynuk et al., 2004). Gabrielse et al. (2006) estimated a dextral offset of approximately 130 km on the Thibert fault in northern British Columbia. They considered strike-slip faulting to have been in part coeval with mid-Cretaceous magmatism in the northern Cordillera (ca. 95–115 Ma), but development of dextral C/S fabrics in a Paleocene pluton near the Yukon-British Columbia boundary suggests that deformation persisted locally at least until early Cenozoic time (Mihalynuk et al., 2006). In the northern Whitehorse trough, the Teslin fault appears to affect rocks as young as the mid-Cretaceous Mount Nansen Group, but is overprinted by the magnetic anomaly ascribed to probable intrusion related to Upper Cretaceous Carmacks Group north of the Robert Campbell highway (Figs. 4–6).

Late brittle faults are locally evident in the northern Whitehorse trough. The Tatchun fault down-drops Laberge Group strata against topographically higher Lewes River rocks northwest of Tatchun Lake (Fig. 4; Colpron et al., 2007). Slickenlines and stepped-fibers in sandstone and volcaniclastic rocks of the Laberge Group indicate down-to-the south, normal displacement along the fault. A splay of the Tatchun fault is also inferred to juxtapose Lewes River strata against Early Jurassic granodiorite to the north (Fig. 4). The Tatchun fault is inferred to be onlapped by basalt of the Upper Cretaceous Carmacks Group east of Frenchman Lake.

To the south, east of Mandanna Lake, a down-to-the-east normal fault is inferred from map relationships (Fig. 4; Colpron et al., 2007). The fault juxtaposes Upper Triassic Lewes River strata on the west to Early and Middle Jurassic sandstone of the Tanglefoot formation on the east. This fault could be related to emplacement of the felsic volcanic rocks of the Mount Nansen Group adjacent to it (Fig. 4).

A detailed analysis of brittle faults in an outcrop near Eagle's Nest Bluff indicates a complex kinematic history for the region that is dominated by a dextral strike-slip component (Kennedy, 2006). The relationship between brittle faulting near Eagle's Nest Bluff and regional faults in the northern Whitehorse trough is uncertain, but the overall dextral strike-slip kinematic history documented at Eagle's Nest Bluff is consistent with the late deformation history inferred along the Teslin-Thibert fault system in northern British Columbia (Gabrielse et al., 2006; Mihalynuk et al., 2006).

2004 Seismic Survey

The seismic survey was designed to meet several objectives. Primarily, we wished to better define the internal structural architecture of the northern Whitehorse trough. Toward this end, data acquisition parameters were chosen to optimize resolution in the upper 5 km of the crust. The secondary objective was to place the Whitehorse trough in a broader regional and crustal-scale context. Survey lines were chosen to transect the three distinct geological terranes that underlie the Whitehorse trough (Yukon-Tanana terrane, Boswell assemblage and Stikinia) and acquisition parameters were selected to allow sufficient depth penetration to reveal crustal scale features.

Two regional profiles were acquired in the winter of 2004 along roads in the area. Line 1 is a 117 km east-west transect along the Robert Campbell Highway beginning at the midpoint

of Little Salmon Lake, 104 km east of the town of Carmacks, and ending 13 km west of the town on Mt. Nansen road (Figs. 1 and 4). This line transects all terranes generally at a high angle to the regional structures. It starts well to the east of the Whitehorse trough in order to test whether Mesozoic strata extend in the subsurface beneath Paleozoic rocks of the Boswell assemblage and Yukon-Tanana terrane. We present here only the westernmost 88 km of Line 1, where it crosses strata of the northern Whitehorse trough (Fig. 4). Detailed interpretations of the uppermost 3 s of these data and those from Line 2 are shown in Figure 7. Also shown in Figure 7 are overlays of the stacking velocities used for processing. These velocities are included as an additional aid to interpretation while recognizing that their reliability varies spatially according to the quality and abundance of reflections, and that stacking velocities are affected by factors other than lithology, particularly in regions of structural complexity (e.g. Sheriff and Geldart, 1995). Line 2 is 53 km in length, starting 35 km north of Carmacks and ending 18 km south of the town, entirely along the western edge of the Whitehorse trough on the North Klondike Highway (Fig. 4).

The data acquisition and processing parameters are summarized in Tables 1 and 2. In addition to the processes listed in Table 2, tests of prestack partial migration (or dip-moveout processing) and prestack time migration were made, without significant improvement of the seismic images.

Seismic Interpretation

The interpretation of the seismic reflection profiles presented here focuses on the shallow structure of the northern Whitehorse trough (upper 3 s; Fig. 7). Interpretation of these images is complicated by the variable orientation of the seismic profiles relative to the approximately northwesterly regional strike of structures in this area. Recognizing this, it is important to keep in mind that the dips observed on the seismic sections are apparent dips and that changes in apparent attitude in the images may in some cases be caused by changes in the direction of the seismic lines. Line 1 is oriented at a relatively high angle to strike (approximately 70°–80°) along the eastern half of the profile from the Tadru fault to near Eagle's Nest Bluff (stations 2300–3700), but runs at a low angle (approximately 10°–30°) to strike to the intersection with line 2 (station 5100) after which it is very crooked to the terminus of the line (station 6000). Line 2 is oriented within 20° of strike along most of its length, and for 20 km at its southern end it follows the trace of the Braeburn fault. In regions where the seismic lines are locally very crooked (e.g. around Carmacks), only relatively flat-lying structures are amenable to imaging based on the data processing as applied in this study.

In the absence of drillhole information in this area, interpretation of the seismic images is based on the characteristics of the observed reflectivity constrained by surface geological mapping including the distribution of tectonostratigraphic units, location of fault boundaries, measured structural attitudes, and qualitative projection of fold axes into the plane of the seismic section. In general, the structural style inferred from geological mapping is adopted in the seismic interpretation wherever it is compatible. The following principles guide the interpretation of the seismic data: 1) Subsurface fault geometry is defined either where dipping reflections associated with the fault itself, or the

truncation of reflectors abutting the fault, project to the surface location of the fault; 2) Subsurface lithologic units are identified where characteristic reflectivity can be directly correlated with known surface lithology; 3) Structural relief is interpreted based on the observed vertical variations in depth to laterally continuous reflectivity; 4) Consistency with mapped geological structure is made qualitatively by approximately projecting regional structures into the seismic section. Time-to-depth conversion of the seismic images was done using a velocity of 5000 m/s which is representative of stacking velocities in the upper 3 s. This velocity, and thus the depth estimates, could be in error by $\pm 15\%$.

A variety of structural geometries is defined by the seismic reflection images including broad antiforms/synforms, homoclinal bands of reflectivity, discrete dipping reflections and zones where reflectivity is abruptly truncated. With few exceptions, the dipping reflections do not extend deeper than approximately 3s, where they are either apparently truncated or flattened.

The reflection fabrics observed in the upper 5–6 km are interpreted as primarily representing original stratigraphic layering as rocks of the Whitehorse trough have experienced relatively low-grade metamorphism. Based on correlation with outcrops (along the central part of Line 1 and the northern end of Line 2), and the more diverse lithostratigraphy of the Lewes River Group relative to the Laberge Group, as a general rule the zones of higher subsurface reflectivity are interpreted as Lewes River Group.

Line 1

Line 1 traverses surface rocks that are primarily ascribed to the Laberge Group comprising a heterogeneous mix of sandstone, conglomerate and minor shale that are generally poorly stratified and thus provide limited means of directly correlating the subsurface images with known lithologies. An exception to this occurs along the central part of the profile where the seismic image is relatively clear and carbonate of the Upper Triassic Lewes River Group (Hancock member) is exposed (stations 3750–3800) immediately adjacent to the line at Eagle's Nest Bluff (Fig. 4). The top of a reflective homoclinal panel (B_1 , Fig. 7) projects to the surface at the western boundary of the carbonate outcrop. This panel is approximately 4000 m thick as measured orthogonal to layering, and defines dipping strata with predominant westward apparent dips at depths greater than 1000 m. Accounting for the change in orientation of the profile at this point, the true dip of these strata is northwestward. This is consistent with measured bedding planes in nearby outcrops and the northwesterly plunge of a regional anticline mapped along-strike to the south (Fig. 4; Colpron et al., 2007). This correlation of prominent reflectivity and exposed Lewes River Group rocks, in addition to the compositional diversity of Lewes River Group rocks, forms the primary basis for making this a more general correlation for interpretation. Further eastward the apparent dips observed on the seismic image change to shallowly east-dipping as the Teslin fault is approached.

To the west of Eagle's Nest Bluff, an antiform of comparably reflective rocks is observed (A_1 , Fig. 7). However, reflective zones A_1 and B_1 are separated by a relatively transparent zone where A_1 and B_1 are truncated (T_1 , Fig. 7). This occurs in a location

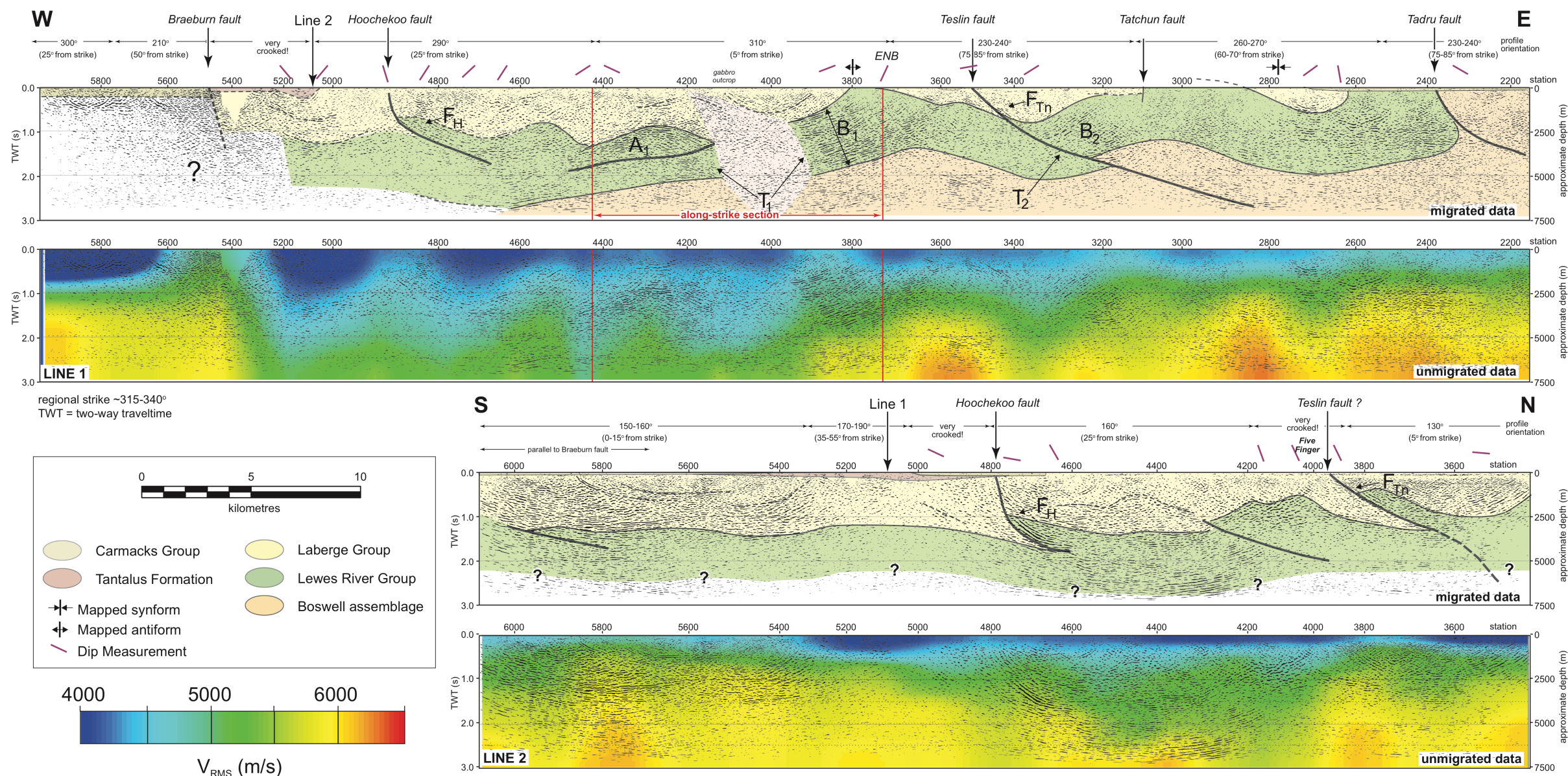


Figure 7. Migrated seismic profiles are shown with overlays of schematic interpretations (above) and smoothed stacking velocities (below) for seismic lines 1 and 2. Indicated along the top of the interpretations are: 1) apparent dip of bedding measured on outcrops near the profile (solid purple bars); 2) orientation of the seismic line with respect to regional strike of structures in Whitehorse trough (approximately 315°N); 3) surface location of major faults; 4) surface projection of an anticline-syncline pair mapped north of the profile (Tempelman-Kluit, 1984); and 5) location of Eagle's Nest Bluff (ENB), where Upper Triassic limestone of the Lewes River Group is exposed. Labels on the seismic sections are referred to in the text. Note that the depth of the bottom of the Lewes River Group along Line 2 is uncertain although it is shown continuing to 7500 m depth. The approximate depth scale indicated on the right vertical axis assumes a mean subsurface seismic velocity of 5000 m/s. TWT = two-way travelttime (in seconds).

where outcrops of gabbroic rocks associated with basalts of the Upper Cretaceous Carmacks Group project onto the seismic line (stations 4160–4170, Figs. 4 and 6). This T_1 feature in the seismic image is interpreted as a young intrusion that cuts through the reflective strata. There does not appear to be any corroborating manifestation of this feature in the corresponding stacking velocities shown in Figure 7, although as noted earlier, stacking velocities are not always representative of lithologic variations. If the generally high values of the total magnetic field observed in this vicinity (see Fig. 6) are attributed to related gabbroic intrusions, then the subsurface extent of intrusive rocks associated with Carmacks volcanics in this region may be

significantly greater than their surface exposure. Occurrence of another small exposure of gabbro north of Eagle's Nest Bluff near station 3530 (Figs. 4 and 6) could support this interpretation. Alternatively, the high magnetic field values may be associated with rocks forming structural basement (e.g. Povoas formation of the Lewes River Group).

Along the eastern half of Line 1, the interpreted structure is depicted as a thin layer of Laberge Group rocks that have been gently folded and faulted with the underlying Lewes River Group. The Teslin fault is identified in the shallow subsurface by a prominent east-dipping reflection (F_{Tn}), and then at greater depth by the truncation (T_2) of a prominent package of

Table 1. Data Acquisition Parameters

Field Crew	Kinetex Inc., Calgary.
Date	February-April, 2004
Clients	Geological Survey of Canada/Yukon Geological Survey
Instrumentation	I/O Vectorseis® System IV
Traces/Record	600
Record Length	33 seconds (extended correlation)
Sample Rate	2 ms
Anti-alias Filter	½ Nyquist
Nominal CDP Fold	100
Vibroseis Source Parameters	
Source Type	4 Vibrators (IVI Y2400 Buggy Mount)
Source Array	4 Vibrators In-line
Pattern Length	12000 m
VP Interval	60 m
# Sweeps/VP	6 or 10 (with 3 vibrators operational)
Sweep Length	24 seconds
Sweep Type	Linear upsweep
Sweep Frequency	10-84 Hz
Receiver Array Parameters	
Group Interval	20 m
Geophones/group	1 (3C Sensor Buried)

Table 2. Data Processing Flow

Data Preparation Diversity stacking of unstacked sweeps Vibroseis self-tapering extended correlation Crooked line geometry application First Breaks manually picked
Pre-Stack Processing AGC: 500ms mean window Top mute application Velocity analysis: semblance and constant velocity stack Refraction statics correction: final datum elevation: 750m, replacement velocity: 4800m/s Normal moveout correction: Stretch mute tolerance of 50% Residual statics correction CDP Stack: Method for trace summing: mean
Post-Stack Processing Phase-shift migration Semblance smoothing Amplitude threshold applied (values <1.5*RMS are set to zero)

west-dipping reflections (B_2 ; Lewes River Group), thus defining a shallowly east-dipping fault trace to the bottom of the section (Fig. 7). The east-side-up sense of displacement along this fault is inferred from along-strike exposures of Lewes River rocks in the hanging wall juxtaposed to Laberge Group strata in the footwall (Fig. 4). The Tatchun fault as shown is based on geological constraints; it is not apparent on the seismic image. The Tadru fault defines the eastern boundary of the Whitehorse trough. It does not have a distinct shallow seismic expression, although there is a change in shallow reflectivity to either side of the surface-mapped fault. The interpreted geometry of the Tadru fault in the shallow seismic data is based primarily on the surface projection of a prominent zone of east-dipping mid-crustal reflectivity observed on a seismic section extending to 12 s two-way travel time (not shown). The steep-to-overtaken limb of the

fold just to the west of the fault is based on high angle dip of bedding observed during mapping.

The western Whitehorse trough along Line 1 is characterized by reflections that predominantly have apparent dips to the west. As well, the depth to relatively reflective rocks is greater than in the east, suggesting a westward increase in thickness of the Laberge Group strata. The westward thickening of the Laberge Group strata is also supported by the westward deepening of low stacking velocities (<5000 m/s) as seen in the lower panel of Figure 7. The interpreted subsurface trajectory of the Hoochekoo fault is based on the observed east-dipping reflections (F_H in Line 1, Fig. 7) and the geometry as imaged along Line 2 (see below). The nature of the Braeburn fault is not obvious in the seismic data, likely the result of the crooked nature of the profiles where this fault is intersected.

Line 2

Seismic Line 2 is poorly oriented for the purposes of imaging shallow crustal structure. In the north, it is oriented within 20° degrees of strike, and south of Carmacks it is aligned with the interpreted surface trace of the Braeburn fault. As a result, the structure interpreted in Figure 7 south of Carmacks is highly speculative. However, several features along Line 2 are noteworthy. The Hoochekoo fault is identified by a moderately north-dipping zone of prominent reflectivity (F_H in Line 2, Fig. 7) that abuts against a less reflective zone immediately to the south. A north-over-south sense of displacement on the fault is inferred from the seismic image as reflective rocks (Lewes River Group) in the hanging wall shallow southward above less reflective rocks (Laberge Group). At surface, the trace of the Hoochekoo fault is masked by Carmacks Group basalt near station 4800; its location on the geological map is based on the seismic survey (Fig. 4). The Teslin fault appears to be north-dipping, based on the change in reflector dips from shallowly north-dipping in the hanging wall to sub-horizontal in the immediate footwall (F_{Tn} in Fig. 7). Approaching the northern terminus of the line, reflectors in the upper 2500 m shallow northward and project up-dip to the surface location of the Laberge/Lewes River contact. In general, Line 2 reveals less structural relief than Line 1 which is oriented across the regional strike.

Petroleum Systems

Whitehorse trough is an undrilled, frontier intermontane basin that is prospective for oil and gas from both conventional and unconventional reservoirs. A recent resource assessment by Hayes (2012) identified nine plays that are prospective for gas, including three plays that are also prospective for oil. Of these, five plays are conceptual and for conventional reservoirs. These include stratigraphic and structural plays in strata of the Lewes River Group, and the Tanglefoot and Tantalus formations. Speculative unconventional plays include potential coal-bed methane in the Tanglefoot and Tantalus formations, and possible tight/shale gas in the Richthofen formation (Hayes, 2012). Hayes (2012) also speculated that conventional reservoirs may exist in areas of structural overlap by the Cache Creek terrane, near the Yukon-British Columbia boundary (Fig. 1).

Lowey et al. (2009) summarized the results of RockEval analyses, thermal alteration indices of palynomorphs and conodonts, and vitrinite reflectance for over 600 samples from the Whitehorse trough in Yukon. They concluded that the Richthofen formation was a poor source rock that has reached high thermal maturity and thus has low potential for gas. The Tanglefoot formation, found in the northern part of Whitehorse trough, is gas-prone, with possible minor oil; it is immature to early mature and locally a good source rock. Lowey et al. (2009) selected the Five Finger area (Figs. 4 and 7), the Tantalus Butte area (Figs. 4 and 7), and the Division Mountain area (Fig. 1) as the most prospective Tanglefoot strata. The Tantalus Formation in these areas is also locally a good source rock and gas prone. It is thermally immature to early mature.

Geological mapping and the seismic surveys confirm the existence of structural plays such as large-scale anticlines and

thrust overlaps which could provide suitable geometries for the trapping of hydrocarbons (Figs. 4, 5 and 7). A number of these structures are well defined near areas identified as most prospective by Lowey et al. (2009). Geological mapping clearly indicates that regional folds are non-cylindrical with variable shallow plunges to the south and north (Figs. 1 and 4). Anticlines with significant thicknesses of Laberge Group strata are observed on Line 1, west of the Teslin fault, and between Hoochekoo and Teslin faults along the northern half of Line 2 (i.e. between Five Finger rapids and Tantalus Butte; Fig. 7). Both the Hoochekoo and Teslin faults display significant thrust overlaps and truncation of upward-dipping strata in seismic sections (Fig. 7). However, the interpreted thickness of Laberge Group strata near the Teslin fault is less than 1000 m.

A maximum burial of 3–4 km is indicated for Tanglefoot and Tantalus strata in the northern Whitehorse trough based on stratigraphic estimates and the homogenization temperature of petroleum fluid inclusions (Lowey, 2008; Lowey et al., 2009). Lowey (2008) estimated that maximum burial and oil generation probably started in Late Jurassic and was terminated by folding and faulting in Early Cretaceous. Overlying volcanic strata of the Mount Nansen and Carmacks groups indicate that strata of the Whitehorse trough were exhumed by mid- to Late Cretaceous.

Discussion

Development of the Whitehorse trough began after cessation of Late Triassic volcanism in Stikinia and Quesnellia (Fig. 3) and was coincident with onset of orogenic activities in the Canadian Cordillera (e.g. Murphy et al., 1995; Mihalynuk et al., 2004). Deposition of the Laberge Group was apparently preceded by faulting (extensional?) of the Triassic (and older) Stikinia basement, and was concurrent with rapid exhumation of the basin shoulders in Early Jurassic, as indicated by:

- 1) the petrology of Early Jurassic batholiths surrounding the northern Whitehorse trough (Fig. 1) which record approximately 15 km of exhumation during emplacement between ca. 200–185 Ma (Johnston et al., 1996a; Tafti, 2005). These batholiths represent the exhumed roots of the Early Jurassic arc of Stikinia and Quesnellia.

- 2) Early Jurassic $^{40}\text{Ar}/^{39}\text{Ar}$ mica cooling ages for much of the Yukon-Tanana terrane in Yukon and Alaska which suggest exhumation of the metamorphic infrastructure from mid- to upper crust by ca. 185 Ma (Dusel-Bacon et al., 1995, 2002; Berman et al., 2007; Breitsprecher and Mortensen, 2004).

- 3) the unroofing of the Late Triassic–Early Jurassic arc(s) recorded by clast compositions in conglomerate of the Laberge Group, with abundant volcanic and sedimentary clasts lower in the stratigraphic section and predominantly plutonic clasts higher up (Dickie and Hein, 1995; Johannson et al., 1997).

Development of the Whitehorse trough was coeval with renewed arc volcanism and a period of extension and subsidence in Stikinia recorded by the Hazelton Group in north-central British Columbia (Monger et al., 1991; Evenchick and Thorkelson, 2005; Gagnon et al., 2009, 2012). The pyroclastic deposits of the Nordienskiold formation in the northern

Whitehorse trough were probably derived from northern equivalents of the Hazelton arc.

The Laberge Group is interpreted to overlap Stikinia, Cache Creek and Quesnellia. A forearc setting has been proposed for the Laberge Group, based in part on the predominance of arc detritus in the basin and the local occurrence of ultra-high pressure minerals in Upper Pliensbachian strata (Dickie and Hein, 1995; Hart et al., 1995; Johannson et al., 1997; English et al., 2005; Canil et al., 2006). However the rapid exhumation of the basin shoulders and transition from deep to shallow marine and fluvial deposits by Middle Jurassic is consistent with a transition between a forearc environment and a synorogenic, intermontane piggyback basin. The latter setting was invoked for the Bowser basin of north-central British Columbia (Evenchick et al., 2007). The introduction of chert clasts in Middle Jurassic (Bajocian) strata of the Whitehorse trough (Tanglefoot, Takwahoni and Tantalus formations; Mihalynuk et al., 2004; Long, 2005) is a similar phenomenon to that which occurred at the onset of deposition in the Bowser basin, which reflects exhumation of the Cache Creek terrane (the source of the chert), imbrication with Stikinia, and convergence with the ancestral North American margin (Ricketts et al., 1992; Evenchick and Thorkelson, 2005; Evenchick et al., 2007). Regional constraints from British Columbia indicate that convergence of these allochthonous terranes and their eastward translation had begun by late Early Jurassic (e.g. Murphy et al., 1995) therefore supporting the interpretation that Whitehorse trough developed at least in part as a piggyback basin.

Previous thickness estimates for the Laberge Group in northern British Columbia and southern Yukon range from approximately 1500 to 3500 m (e.g. Wheeler, 1961; Souther, 1971; Dickie and Hein, 1995; Hart, 1997; Johannson et al., 1997; Mihalynuk, 1999). Based on an incomplete section at Division Mountain (Fig. 1), Lowey et al. (2009, p. 354) suggested a minimum thickness of approximately 600 m for the Tanglefoot formation. In contrast, seismic sections show that the vertical extent of interpreted Lewes River and Laberge strata attains a maximum thickness of 6000–7000 m toward the west side of the Whitehorse trough (Fig. 7). Interpreted Laberge Group (Tanglefoot formation) may account for up to approximately 3000 m of this total, which is in agreement with earlier estimates but substantially thicker than what Lowey et al. (2009) proposed south of Carmacks. The different thickness estimates could result from:

- 1) underestimation of the true thickness of the Tanglefoot formation by Lowey et al. (2009) who based their estimate on an incomplete section;
- 2) apparent overthickening of the Laberge Group by duplication along bedding plane detachments. The presence of bedding-plane faults has been noted locally, but the importance of these structures remains unknown;
- 3) or these estimates may reflect variations in thickness in different parts of the basin;
- 4) or inherent uncertainty in the seismic interpretation.

The structure of the northern Whitehorse trough is characterized by northwest-trending, southwest-verging folds and thrust faults that are dissected by northwest and north-striking strike-slip faults (Figs. 1, 4, 5 and 7). The shallow

seismic images depict broad anticlinal and synclinal structures punctuated by relatively steep faults where reflectivity is abruptly truncated (e.g. Teslin fault in Fig. 7). Maximum vertical relief is approximately 4000 m as indicated by the amplitude of the interpreted fold structures, with less structural relief observed along-strike on Line 2 (Fig. 7). The overall structural style is similar to recent interpretations of the Whitehorse trough in northern British Columbia, including interpretations of the SNORCLE seismic profiles (Mihalynuk, 1999; Gabrielse, 1998; Cook et al., 2004; Evenchick et al., 2005; English et al., 2005; Schiarizza, 2012).

The seismic data from Line 1 (Fig. 7) can be compared with an analogous section of SNORCLE line 3 (stations 18500 to 21000 in Cook et al., 2004) which transects the northern Cache Creek terrane and Whitehorse trough near Carcross (Fig. 1). Generally, the upper 4 s of this segment of the SNORCLE line 3 section are weakly reflective, with most significant reflectivity in this zone restricted to discontinuous bands in the upper 2 s. This general lack of reflectivity may in part be due to a focus on the deeper crustal section during processing of the SNORCLE data. It should also be noted that the seismic profile follows the trace of the northeast-striking Crag Lake fault for much of this segment of the SNORCLE line 3 (Fig. 1). Nonetheless, the shallow structural interpretation of seismic lines 1 and 2 presented here (Fig. 7) is generally consistent with that presented by Cook et al. (2004) along SNORCLE line 3, where the uppermost crust of the Cache Creek terrane is shown to be “deformed into broad, open folds with wavelengths of 20–25 km”. Both the Cache Creek terrane and Whitehorse trough are also bounded by northeast-dipping (southwest-verging) thrust faults on SNORCLE line 3, similar to structures shown in seismic line 1 in this study (Fig. 7).

Fold and thrust structures in the northern Whitehorse trough are generally gentle and record approximately 15–20% shortening based on cross-section estimates (Figs. 5 and 7). However, these estimates are only loosely constrained because of the lack of stratigraphic markers, the unknown importance of bedding-plane detachment, and the effect of transcurrent displacement along strike-slip faults. English et al. (2005) estimated approximately 35% shortening in the Whitehorse trough of northern British Columbia, but acknowledged similar limitations. In northern British Columbia the rocks of Whitehorse trough are typically pervasively cleaved, unlike correlative strata to the north in Yukon which generally lack a cleavage. Therefore shortening should be less in the northern Whitehorse trough in Yukon compared to its southern, more highly strained extent in British Columbia. English et al. (2005) also noted a decrease in overall shortening from south to north in northern British Columbia.

In southern Yukon, the fold and thrust structures of the northern Whitehorse trough display an overall sigmoidal, *en échelon* pattern (Colpron, 2011) that is consistent with a dextral transpressive regime (Figs. 1 and 8). This sigmoidal fold-and-thrust belt is bounded on the northeast by Teslin fault and on the southwest by Braeburn fault (Fig. 8). Both of these structures are inferred to include a component of dextral strike-slip displacement (Gabrielse, 1998; Gabrielse et al., 2006; Tempelman-Kluit, 2009) and therefore it is likely that

at least part of the fold-and-thrust structures of the northern Whitehorse trough were related to development of these major dextral structures.

The timing of regional southwest-verging fold and thrust structures is generally considered to be Middle Jurassic (Toarcian-Bajocian) in the northern Cordillera (Gabrielse, 1998; Mihalynuk et al., 2004; English and Johnston, 2005; English et al., 2005). In the northern Whitehorse trough, southwest-verging structures affect strata as young as Middle to Upper Jurassic (Bajocian-Tithonian), and possibly also Lower Cretaceous (Aptian-Albian) strata of the Tantalus Formation (Colpron et al., 2007; Colpron, 2011), but appear to be overlapped by Upper Cretaceous volcanic rocks of the Mount Nansen and Carmacks groups (Fig. 4). The timing of dextral strike-slip displacement along Teslin and related faults is estimated at ca. 115–95 Ma (Gabrielse et al., 2006) and it is likely that some of the displacement along folds and thrust faults of the northern Whitehorse trough is of this age as well. Regional southwest-verging contractional deformation therefore began during the later stages of deposition in the northern Whitehorse trough and was further enhanced during mid-Cretaceous dextral transpression (Fig. 8). Displacement along the Teslin fault apparently continued until (or was reactivated in) the Paleocene as evidenced by ductile fabrics in a ca. 57 Ma pluton near the BC-Yukon boundary (Mihalynuk et al., 2006).

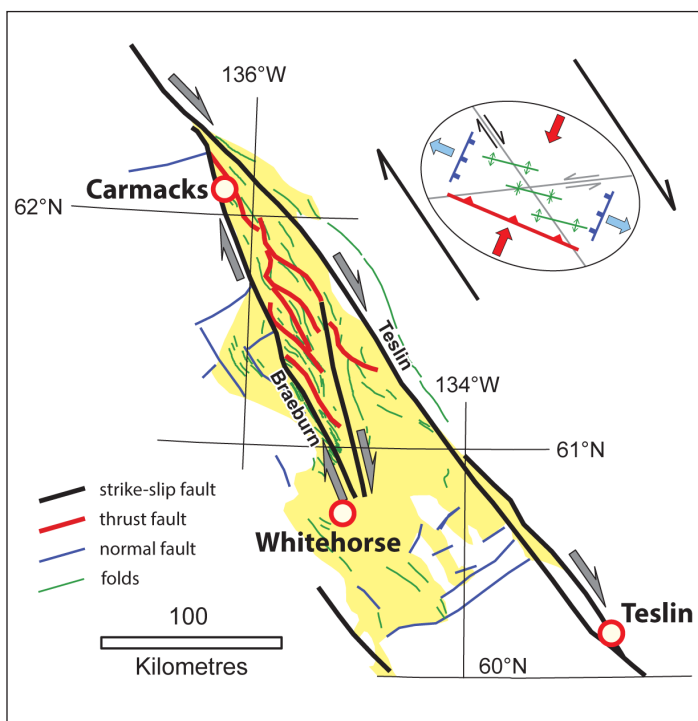


Figure 8. Simplified structure map of the northern Whitehorse trough showing the sigmoidal, *en échelon* distribution of folds and thrust faults with respect to northwest-trending dextral strike-slip bounding faults such as the Teslin and Braeburn faults. The overall pattern of structures is consistent with a dextral transpressive regime. Inset in upper right shows conceptual geometry of folds and faults in a dextral strike-slip system. Normal faults surrounding the Whitehorse trough are likely not related to the dextral system. Area underlain by Whitehorse trough strata is shown in yellow. Structural trends were selected from Colpron (2011).

Conclusions

Early to Middle Jurassic strata of the Laberge Group (Whitehorse trough) were deposited in a rapidly evolving geodynamic setting, marking the transition from forearc to a synorogenic piggyback basin in the nascent Cordilleran orogen. Seismic reflection transects and geological mapping across the northern Whitehorse trough in Yukon indicate that as much as 3000 m of Jurassic strata were deposited in the basin. The structure of the northern Whitehorse trough is dominated by southwest-verging folds and thrust faults that are dissected by northwest-trending strike-slip faults. The overall structural geometry is consistent with a dextral transpressive regime. These structures probably began in Middle to Late Jurassic and were enhanced during mid-Cretaceous dextral transpression associated with the Teslin fault system. This structural style offers suitable hydrocarbon plays in large-scale anticline and thrust overlaps, and several of these were seismically imaged north of Carmacks.

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