Structural constraints for oil and gas assessment in the Whitehorse Trough: New results from seismic profiling[1]

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ABSTRACT

The Whitehorse Trough is a Mesozoic sedimentary basin in south-central Yukon that has been identified as an immature, gas-prone basin, based on a limited geoscience database. A total of 170 km of regional, multi-channel, multi-component Vibroseis seismic reflection data were acquired in 2004 across the northern Whitehorse Trough in order to improve understanding of its structural architecture. The shallow seismic images appear to depict broad antiformal and synformal structures, truncated by relatively steep faults. Strata interpreted as the Lewes River and Laberge groups seem to attain a maximum thickness of 6000-7000 m toward the west side of the Trough, with interpreted Laberge Group accounting for up to ~3000 m of this total. Maximum vertical relief of the structures is ~4000 m.

RÉSUMÉ

Le basin de Whitehorse est un bassin sédimentaire d'âge Mésozoïque dans le centre-sud du Yukon. Il fût identifié, sur la base de données géoscientifiques limitées, comme étant un bassin immature ayant un potentiel pour le gaz naturel. Des données de levé sismique Vibroseis régional multicanal et multicomposante ont été acquises sur 170 kilomètres en 2004 sur la partie septentrionale de la cuvette de Whitehorse, dans le but d'améliorer notre compréhension de son architecture structurale. Les images sismiques à faible profondeur semblent révéler des structures antiformes et synformes de grande amplitude recoupées par des failles de fort pendage. Les strates interprétées comme étant les groupes de Lewes River et de Laberge atteignent une épaisseur maximale de 6000 à 7000 mètres vers le côté ouest du basin, le Groupe de Laberge représentant jusqu'à 3000 mètres de cette épaisseur totale. L'extension maximale de ces structures suivant la verticale est d'environ 4000 mètres.

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INTRODUCTION

The Whitehorse Trough is an elongated, northwest-trending Mesozoic marine sedimentary basin which extends some 650 km from just north of Carmacks, Yukon, to near Dease Lake, British Columbia (Fig. 1). It originated as a forearc basin in the Middle to Late Triassic, adjacent to the emerging Lewes River Arc, and had received more than 7000 m of clastic deposits by Middle Jurassic time (e.g., Wheeler, 1961; Tempelman-Kluit, 1979). It is underlain by late Paleozoic and early Mesozoic arc volcanic 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 mid- to late Paleozoic rocks of the Yukon-Tanana Terrane.

The Whitehorse Trough has been identified as an immature, gas-prone basin in which potential source rocks, reservoirs and seals occur (National Energy Board, 2001). Potential for some 7.3 trillion cubic feet (Tcf) (210 billion m^3) of gas, and possibly some oil, is estimated for the basin, with 2.6 to 4.8 Tcf (74 to 140 billion m^3) in Yukon (K. Ozadetz, pers. comm., 2004). Structural traps associated with clastic or carbonate reservoirs (Lewes River and Laberge groups) are proposed as having significant hydrocarbon potential with surface-defined anticlines posing the best primary drilling targets (National Energy Board, 2001). However, current assessments of hydrocarbon potential in the Whitehorse Trough rely on limited stratigraphic studies and are based on conceptual plays. No private seismic surveys or wells have been completed in this region. A recent Lithoprobe seismic survey crosses the central part of Whitehorse Trough near the Yukon-British Columbia boundary (SNORCLE line 3, Fig. 1; Cook *et al.*, 2004) and provides an interpretation of the crustal structure in the area. However, the Lithoprobe survey was designed primarily to image deep crustal features and offers limited information about the upper crust, and thus is of little use for hydrocarbon potential assessment. In 2004, the Yukon Geological Survey and Geological Survey of Canada commissioned a regional, multi-channel, multi-component Vibroseis seismic reflection survey across the northern part of Whitehorse Trough and into adjacent terranes (Fig. 2), with the aim of enhancing the geoscience database of the area for use in future hydrocarbon potential assessments. The survey comprises two seismic profiles, totaling 170 km in length, acquired along the Robert Campbell and North Klondike highways (Fig. 2). An initial interpretation of the shallow part of these crustal sections is presented here.

GEOLOGICAL SETTING

The Canadian Cordillera consists of a collage of terranes that were accreted to the western margin of the North American craton between late Paleozoic and early

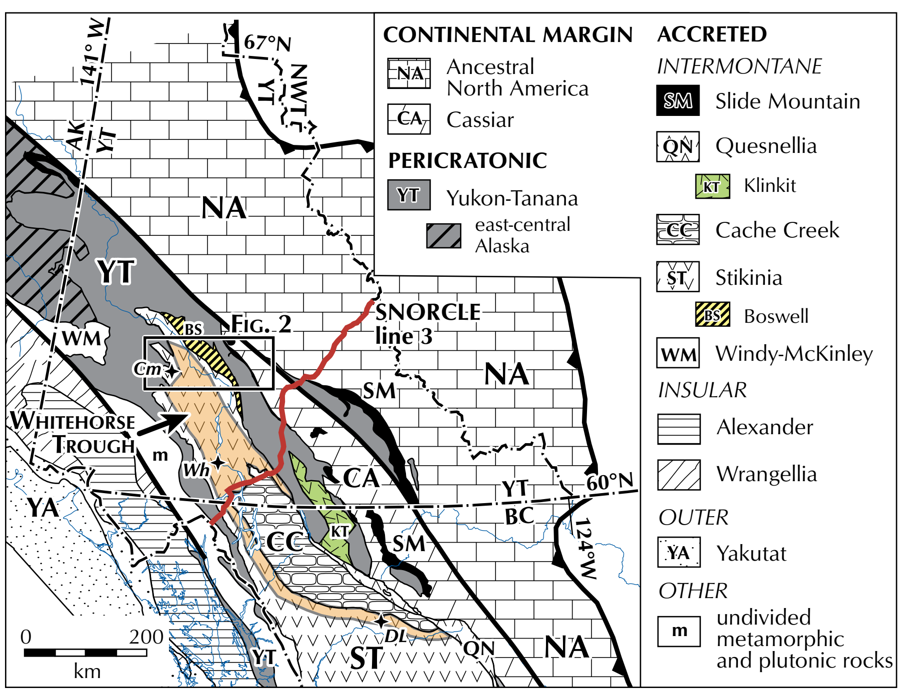

Figure 1. *Terrane map of Yukon and adjacent northern British Columbia. The grey-shaded area in northern Stikinia indicates regional distribution of the Whitehorse Trough. Cm = Carmacks, DL = Dease Lake, Wh = Whitehorse.*

Cenozoic time (Coney *et al*., 1980; Gabrielse *et al*., 1991; Price and Monger, 2000 and references therein). The largest of these terranes, Stikinia, comprises Late Devonian to Middle Jurassic volcanic and sedimentary strata, as well as comagmatic plutonic rocks (Monger *et al*., 1991). Paleozoic assemblages are mostly known in northern British Columbia (e.g., Logan *et al*., 2000). The northern portion of Stikinia is composed of Upper Triassic arc volcanic and sedimentary rocks of the Lewes River Group and Lower to Middle Jurassic sedimentary strata of the Laberge Group (e.g., Wheeler, 1961; Fig. 3). Sedimentary facies of the Lewes River (Aksala formation) and Laberge groups define the Whitehorse Trough in Yukon (e.g., Wheeler, 1961; Hart, 1997). The Lewes River Group at its base comprises calc-alkaline basalts, andesites and agglomerates of the Povoas formation (Tempelman-Kluit, 1984; Hart, 1997). The Povoas locally overlies Paleozoic greenstones of the Takhini assemblage west of Whitehorse (Hart, 1997). The Povoas is comformably overlain by heterogeneous clastic strata (mainly sandstone, greywacke and argillite), limestone and minor conglomerate of the Aksala formation (Tempelman-Kluit, 1984; Hart, 1997).

The Laberge Group consists of conglomerate, sandstone, siltstone, argillite and tuff. In the northern Whitehorse Trough, near Carmacks (Fig. 2), the Laberge Group

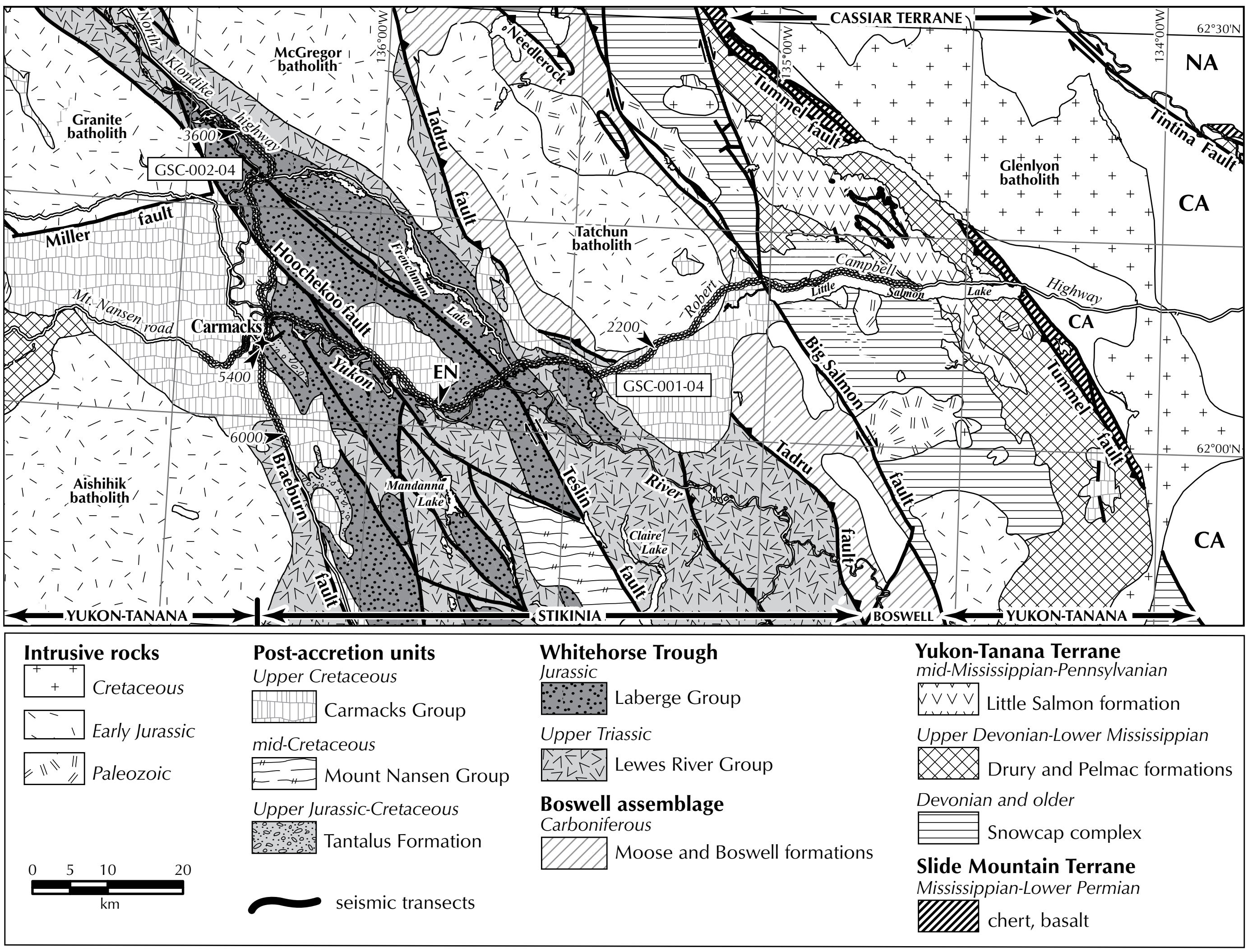

Figure 2. *Geological map of the northern Whitehorse Trough and surrounding region compiled from Tempelman-Kluit (1984) and Colpron et al. (2002). Heavy black lines show location of seismic transects along the Robert Campbell (GSC-001-04, Line 1) and North Klondike highways (GSC-002-04, Line 2). Numbers and arrows along transects indicate station numbers near end-points for parts of the sections shown in Figure 4. "EN" points to location of Eagle's Nest Bluff along Line 1. NA = Ancestral North America; CA = Cassiar Terrane.*

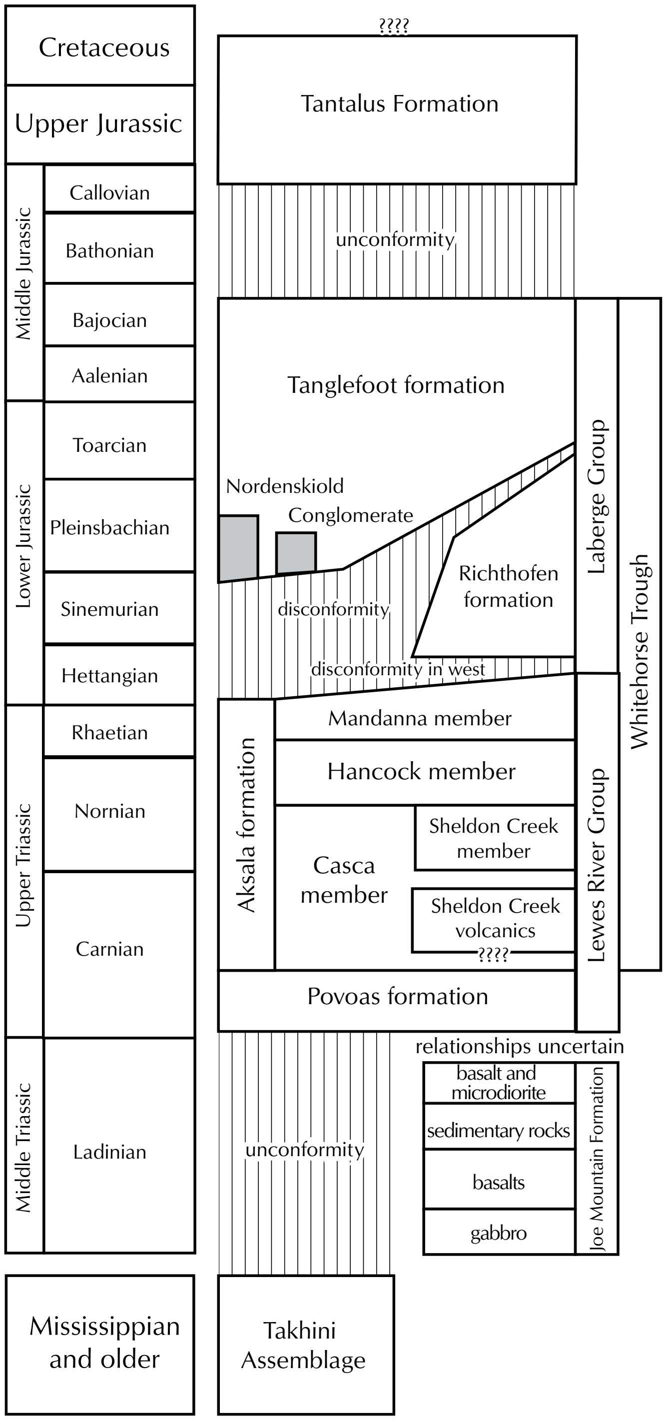

Figure 3. *Stratigraphic relations of northern Stikinia, modified from Hart (1997) to accommodate revisions to the Laberge Group stratigraphy suggested by Lowey (2004).*

consists primarily of coal-bearing interbedded sandstone and mudstone of the Tanglefoot formation, which includes subordinate amounts of conglomerate, pebbly sandstone and tuffaceous rocks (Lowey, 2004). At this latitude, the Tanglefoot formation unconformably overlies the Lewes River Group. To the south, in the central Whitehorse Trough, the Richthofen formation, dominated by thin-bedded sandstone-mudstone couplets (turbidites) and clast-supported conglomerates (but no coal), unconformably overlies the Lewes River Group (Lowey, 2005).

The Laberge Group is unconformably overlain by the Upper Jurassic to Lower Cretaceous Tantalus Formation (Fig. 3; Bostock, 1936; Tempelman-Kluit, 1984; Long, 2005), which consists primarily of fluvial sandstone and chert-pebble conglomerate representing a molasse deposit that marks the end of deposition in the Whitehorse Trough. In the northern Whitehorse Trough, occurrences of the Tantalus Formation are primarily restricted to the western edge of the Trough near Carmacks (Fig. 2), where significant coal resources have historically been mined, and in isolated exposures north of Claire Lake and beneath the Carmacks Group basalts along the Robert Campbell Highway (Tempelman-Kluit, 1984; Colpron *et al.*, 2002).

At the latitude of Carmacks, the northern Whitehorse Trough is bounded on the west by the Braeburn fault, a dextral strike-slip fault with an estimated 8-km of displacement, which projects underneath the Upper Cretaceous Carmacks Group (Fig. 2; Tempelman-Kluit, 1984). To the west, granodiorite gneiss of the Yukon-Tanana Terrane, intruded by Early Jurassic granitic batholiths, dips to the east beneath the Whitehorse Trough. The eastern margin of the Whitehorse Trough is defined by the Tadru fault, a southeast-dipping thrust fault that places mid- to late Paleozoic rocks of the Boswell assemblage onto Upper Triassic strata of the Lewes River Group (Colpron *et al.*, 2002, 2003). Boswell assemblage rocks consist of basalt and limestone of the Late Devonian to Early Mississippian Moose formation and volcanic, volcaniclastic and sedimentary rocks of the Boswell formation (Simard, 2003; Fig. 2).

North of the Tatchun batholith (Fig. 2), metasedimentary rocks of the Snowcap complex, the oldest unit in Yukon-Tanana Terrane (Devonian and older), structurally overlie greenstone of the Moose formation along the Needlerock thrust (Fig. 2). Along Robert Campbell Highway, the Boswell assemblage and Yukon-Tanana Terrane are juxtaposed along the Big Salmon fault, a strike-slip fault with up to 56 km of Late Cretaceous(?) dextral displacement (Colpron *et al.*, 2003; Fig. 2).

The Yukon-Tanana Terrane comprises a metasedimentary basement complex (Snowcap complex), intruded by Mississippian plutons, and unconformably overlain by Carboniferous arc-derived metaclastic rocks (Drury and Pelmac formations) and mafic metavolcanic rocks (Little Salmon formation). To the east, Yukon-Tanana Terrane is juxtaposed with Cassiar Terrane along the Tummel fault, a ~3 km-wide zone of imbricate fault slices of Slide Mountain Terrane (chert, basalt, serpentinite) and synorogenic metaclastic rocks (Colpron *et al.*, 2005; Fig. 2).

Rocks of Yukon-Tanana Terrane, Boswell assemblage and Lewes River Group are intruded by large Early Jurassic batholiths (Fig. 2) that are, in part, coeval with deposition of Laberge Group strata in the Whitehorse Trough. Cretaceous plutons intrude rocks of Stikinia near Whitehorse, but are absent from the northern Whitehorse Trough (Gordey and Makepeace, 2001). In this region, Cretaceous plutons are mainly restricted to Yukon-Tanana and Cassiar terranes (Fig. 2).

Rocks of the northern Whitehorse Trough are extensively faulted and folded by broad, open to southwest-vergent folds (Fig. 2; Tempelman-Kluit, 1984). The overall structure is that of a broad anticlinorium, occupied by strata of the Lewes River Group, flanked by two synclinoria of the Laberge Group. These structures are dissected by an array of brittle faults with a complex kinematic history.

Basalt and agglomerate of the Upper Cretaceous Carmacks Group overlie all terranes along the transect area (Fig. 2; Tempelman-Kluit, 1984). The Carmacks Group occurs as a series of erosional remnants, along the survey transect, which are typically only a few hundred metres thick, with the thickest accumulation (~800 m) west of Carmacks. The Carmacks Group clearly postdates some of the major faults in the area (Tadru and Braeburn faults, Fig. 2), but is possibly affected by late brittle deformation along some of the other faults (e.g., Big Salmon, Hoochekoo and Miller faults).

SURVEY DESIGN

The seismic survey was designed to transect three distinct geological terranes: the Yukon-Tanana Terrane, the Boswell assemblage, and Stikinia, which envelop the Whitehorse Trough. Two regional profiles were acquired in the winter, 2004: Line GSC-001-04 (Line 1) is a 117-km east-west transect across the northern Whitehorse Trough, along the Robert Campbell Highway, beginning at the midpoint of Little Salmon Lake, and ending 13 km west of the town of Carmacks on Mt. Nansen road (Fig. 2). 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. Line GSC-002-04 (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. 2). A 2.64-km section on the North Klondike Highway is common to both lines. Data recording parameters were chosen to obtain optimal resolution in the upper 5 km, while allowing sufficient depth penetration to image crustal-scale features.

RECORDING PARAMETERS

During the survey, standard operating procedures were followed which precluded vibrating in the immediate vicinity of buildings, wells or other infrastructure. While traversing the town of Carmacks, data receivers were deployed to record reflections from vibration points located outside of town, but no vibration operations were conducted through the town. This expectantly reduced data quality somewhat near Carmacks. However, due to low population density this approach was necessary only once per line and did not affect the overall data acquisition integrity. Acquisition parameters are summarized in Table 1, with Table 2 providing the sequence of processes applied to obtain the seismic images presented here. In addition to the processes listed in Table 2, tests of prestack partial migration (or dip-moveout processing) and prestack time migration were made but without significant improvement of the seismic images.

PRELIMINARY INTERPRETATION

The preliminary interpretation of the seismic reflection profiles presented here focuses on the shallow structures of the Whitehorse Trough (upper 3 seconds (s); Fig. 4). An example of the migrated seismic data for the centre of the Whitehorse Trough is shown in Figure 5, overlain with a preliminary geological interpretation. Summary interpretation schematics for Lines 1 and 2 are included in Figure 4.

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	100 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: 750 m, replacement velocity: 4800 m/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)

Interpretation of the seismic lines is complicated by the variable orientation of the profiles relative to the regional strike of the regional geology in this area which is approximately southeast. 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 may in some cases be caused by changes in the direction of the seismic lines.

The interpretations presented in Figure 4 hinge on observations made along the central part of Line 1 (Fig. 5) where the seismic data correlate very well with observed surface geology. A seismically defined antiform corresponds with a geologically mapped anticline, and a highly reflective package projects up-dip to exposed Upper Triassic limestone of the Lewes River Group at Eagle's Nest bluff. 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 composition 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 (Fig. 5). The shallow seismic images depict broad antiformal and synformal structures punctuated by relatively steep faults where reflectivity is abruptly truncated (e.g., Teslin fault in Fig. 5). The vertical extent of interpreted strata of Lewes River and Laberge groups attains a maximum thickness of 6000-7000 m toward the west side of the Trough, with interpreted Laberge Group accounting for up to ~3000 m of this total. Maximum vertical relief is ~4000 m as indicated by the amplitude of the interpreted fold structures, with less structural relief observed along-strike on Line 2 (Fig. 4).

Several prominent fault zones within or along the boundaries of the Whitehorse Trough are crossed along Lines 1 and 2, including the Tadru, Teslin, Hoochekoo and Braeburn faults. These faults have variable expression on the seismic sections. The Tadru fault does not have a distinct shallow expression, but the interpreted location of this fault in the seismic data is based primarily on the surface projection of a prominent east-dipping zone of reflectivity that can be followed to mid-crustal depths (not shown). The Teslin fault is identified by truncation of a prominent package of west-dipping reflections (Fig. 5), defining a relatively steep fault trace to a two-way traveltime of ~2 s. At greater depth, it is interpreted to dip

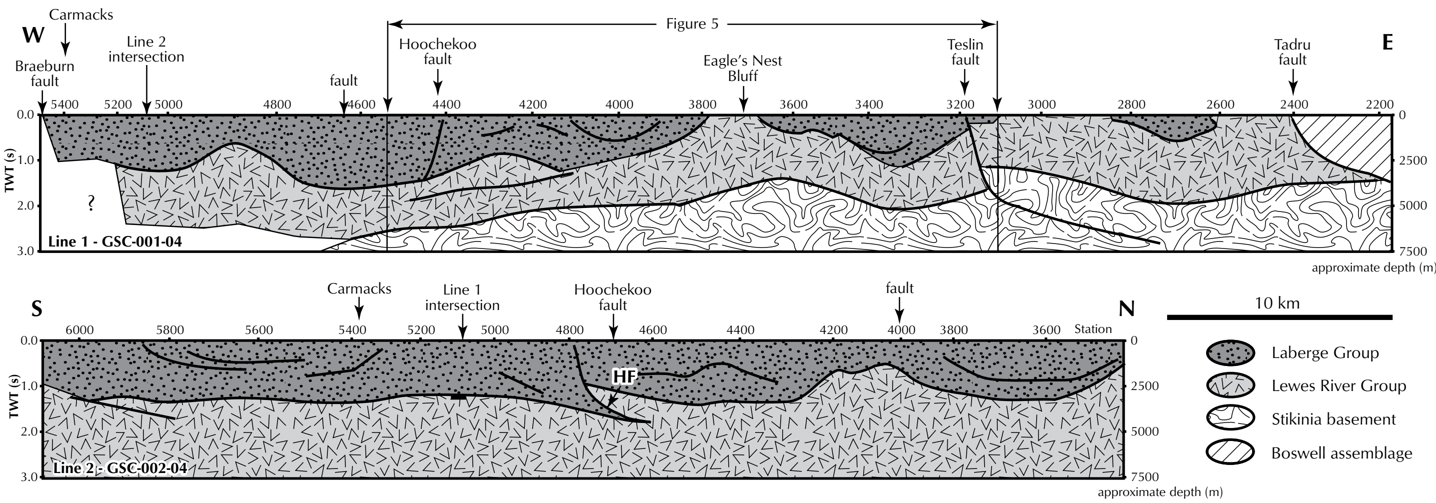

Figure 4. *Schematic interpretations for Lines 1 and 2. The surface locations of major faults are indicated. Also shown are the locations of the town of Carmacks, Eagle's Nest Bluff and point of intersection of the two lines. Detailed image for the central part of Line 1 is shown in Figure 5. "HF" on Line 2 points to subsurface expression of the Hoochekoo fault. 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. TWT = two-way traveltime (in seconds).*

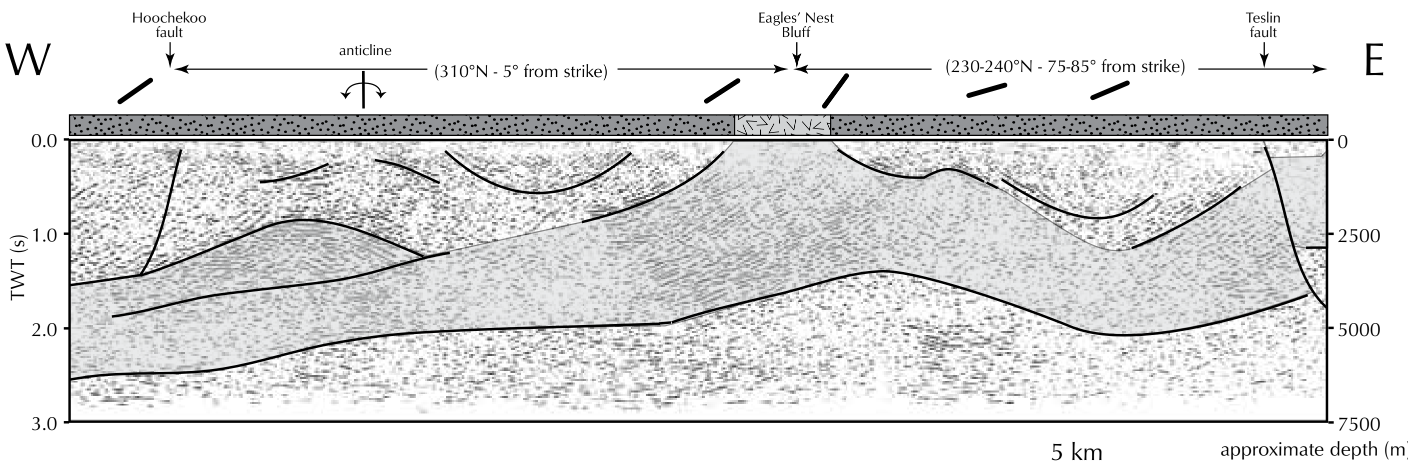

Figure 5. *Preliminary interpretation of migrated seismic data from the central segment of Line 1. Indicated along the top of the plot are the following: 1) the distribution of rock types as mapped at the surface (patterns correspond to legend in Fig. 4); 2) apparent dip of bedding measured on outcrops near the profile (solid bars); 3) orientation of the seismic line with respect to regional strike of structures in Whitehorse Trough (~315°N); 4) surface location of major faults; 5) surface projection of an anticlinal structure mapped north of the profile (Tempelman-Kluit, 1984); and 6) location of Eagle's Nest Bluff, where Upper Triassic limestone of the Lewes River Group is exposed. Note that the road takes a 90° bend near the bluff (Fig. 2). Grey-shaded area in subsurface shows distribution of interpreted Lewes River Group extrapolated from surface exposure. The approximate depth scale indicated on the right vertical axis assumes a mean subsurface seismic velocity of 5000 m/s. TWT = two-way traveltime (in seconds).*

eastward to at least the middle crust and perhaps deeper (Fig. 4). The interpreted subsurface trajectory of the Hoochekoo fault is based primarily on the image from Line 2 (not shown) where a prominent zone of reflectivity projects at the surface to near the location of the fault as indicated by the surface geology (Figs. 2, 4). This fault extends to 2 s two-way traveltime where it appears to sole out. It should be noted that the seismic interpretation of Line 2 suggests that the surface location of the Hoochekoo fault is actually several kilometres south of its currently mapped position (Fig. 4). The nature of the Braeburn fault is not obvious in the seismic data, due largely to the crooked nature of the profiles where this fault is crossed.

SUMMARY

Preliminary images from the Whitehorse Trough seismic survey provide a first look at the crustal architecture of the region. Preliminary interpretation of the shallow seismic images indicates broad antiformal and synformal structures truncated by relatively steep faults. Interpreted strata of the Lewes River and Laberge groups attain a maximum thickness of 6000-7000 m toward the west side of the Trough, with interpreted Laberge Group accounting for up to ~3000 m of this total. Maximum vertical relief of the structures is ~4000 m. Interpreted results will be studied against current geological models to assess the hydrocarbon potential of the Whitehorse Trough and advance the understanding of the tectonic history and structural framework of central Yukon.

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