# Summary of the stratigraphy, sedimentology and hydrocarbon potential of the Laberge Group (Lower-Middle Jurassic), Whitehorse trough, Yukon

***Grant W. Lowey*[1]**
*Yukon Geological Survey*

Lowey. G.W., 2008. Summary of the stratigraphy, sedimentology and hydrocarbon potential of the Laberge Group (Lower-Middle Jurassic), Whitehorse trough, Yukon. *In:* Yukon Exploration and Geology 2007, D.S. Emond, L.R. Blackburn, R.P. Hill and L.H. Weston (eds.), Yukon Geological Survey, p. 179-197.

## ABSTRACT

Whitehorse trough is a northwestward-tapering belt of Upper Triassic to Lower Cretaceous volcanic and sedimentary rocks extending ~650 km from the British Columbia–Yukon border, north to the vicinity of Carmacks in south-central Yukon. It consists of three main stratigraphic units (*i.e.*, the Lewes River Group, Laberge Group and Tantalus Formation) representing three sedimentary basins, partially overlapping in space and time. The Laberge Group (Lower-Middle Jurassic), informally subdivided into the Richthofen, Tanglefoot and Nordenskiold formations, was deposited in the Laberge basin, a collapsing fore-arc basin in which the arc was undergoing uplift and erosion. The Richthofen formation consists of conglomerate, massive sandstone, sandstone-mudstone couplets, volcaniclastic rocks and minor limestone interpreted as submarine fan systems. The Tanglefoot formation consists of coal-bearing sandstone, mudstone, conglomerate, volcaniclastic rocks and minor limestone interpreted as delta systems and shallow marine deposits. The Richthofen and Tanglefoot formations are the same age (*i.e.*, Sinemurian to Bajocian), but the Richthofen formation is restricted to the southern half of the basin, whereas the Tanglefoot formation occurs in the northern half. The Nordenskiold formation consists of subaerially erupted, resedimented volcaniclastics deposited mainly during Pliensbachian time. The Richthofen formation is interpreted as a spent source rock and the Nordenskiold formation is not a source rock. The Tanglefoot formation is interpreted as a potential source rock and possibly an effective source rock. It contains petroleum fluid inclusions (mainly 23°- 32° and 40°- 44° API gravity) indicating a minimum trapping temperature of 110-115°C. The Tanglefoot formation is also a potential reservoir rock.

## RÉSUMÉ

La dépression de Whitehorse consiste en une ceinture de roches sédimentaires et volcaniques datant du Trias supérieur au Crétacé inférieur, qui s'effile vers le nord-ouest et s'étend sur quelque 650 km depuis la frontière entre la Colombie-Britannique et le Yukon jusqu'à Carmacks, dans le centre sud du Yukon. Elle est constituée de trois unités stratigraphiques principales, soit le Groupe de Lewes River, celui de Laberge et la Formation de Tantalus, qui représentent trois bassins sédimentaires qui se chevauchent partiellement sur le plan spatial et chronologique. Le Groupe de Laberge, qui se compose des formations informelles de Richthofen, de Tanglefoot et de Nordenskiold, a été mis en place dans le bassin de Laberge, qui consiste en un bassin d'avant-arc en effondrement dont l'arc était soumis à un soulèvement et à une érosion au moment de la mise en place. La Formation de Richthofen est constituée de conglomérat, de grès massif et de couples de grès-mudstone, ainsi que de roches volcanoclastiques et de quantités moindres de calcaire, lesquels sont interprétés comme des réseaux d'éventails sous-marins. La Formation de Tanglefoot est composée de grès renfermant du charbon, de mudstone, de conglomérat, et de roches volcanoclastiques, ainsi que de petites quantités de calcaire, lesquels sont interprétés comme des réseaux deltaïques et des dépôts épicontinentaux. Bien que les formations de Richthofen et de Tanglefoot aient le même âge (du Sinémurien au Bajocien), celle de Richthofen est circonscrite à la moitié sud du bassin, alors que celle de Tanglefoot repose dans sa moitié nord. La Formation de Nordenskiold est formée de roches volcanoclastiques produitent par des éruptions subaériennes et resédimentées principalement pendant le Pliensbachien. La Formation de Richthofen est interprétée comme une roche mère épuisée, alors que celle de Nordenskiold n'en est pas une. Celle de Tanglefoot est interprétée comme une roche mère possible ou peut-être même comme une roche mère réelle. Elle renferme des inclusions fluides de pétrole d'une densité allant principalement de 23 à 32 degrés API et de 40 à 44 degrés API, ce qui témoigne d'une température de piégeage minimale de 110 à 115 °C. La Formation de Tanglefoot pourrait également constituer une roche réservoir.

---

[1] *grant.lowey@gov.yk.ca*

# INTRODUCTION

Whitehorse trough is one of eight oil and gas basins identified in the Yukon (Fig. 1). It forms a northwestward-tapering belt of Upper Triassic to Lower Cretaceous volcanic and sedimentary rocks extending ~650 km from the British Columbia–Yukon border, north to the vicinity of Carmacks in south-central Yukon. It is the northernmost of four 'Interior Cordilleran' basins in northwestern Canada (*i.e.*, from south to north, Quesnel, Nechako, Bowser and Whitehorse; Teitz and Young, 1982) that exhibit similar patterns of sedimentary history and tectonic evolution and have corresponding oil and gas potential (Teitz and Young, 1982). Koch (1973) described occurrences of oil shale, gas odours and oil seeps in the central part of Whitehorse trough, and Petro-Canada concluded that Jurassic rocks throughout the basin have the potential to generate gas and possibly oil, whereas Cretaceous rocks have the potential to generate gas (Gilmore, 1985; Gunther, 1985). Beaton *et al.* (1992a) determined that coal seams from the Whitehorse trough have a low potential to generate oil and gas, and Allen (2000) provided new data that Jurassic rocks in the central part of the basin have the potential to generate gas and possibly oil. The National Energy Board (2001) concluded that the Whitehorse trough was an "immature, mainly gas-prone" basin and identified potential source rocks (*i.e.*, Triassic carbonates, Jurassic mudstones and Cretaceous mudstones), reservoirs (*i.e.*, Triassic carbonates, and Jurassic and Cretaceous sandstones), seals (*i.e.*, Jurassic mudstones and volcaniclastic rocks) and traps (*i.e.*, anticlines and pinch-outs). It is estimated that up to 4.8 Tcf (140 million cubic metres) of gas and possibly some oil may occur in the Whitehorse trough (K. Ozadetz, pers. comm., 2004). This paper summarizes the stratigraphy, sedimentology and hydrocarbon potential of the Lower and Middle Jurassic rocks (*i.e.*, the Laberge Group) in Whitehorse trough.

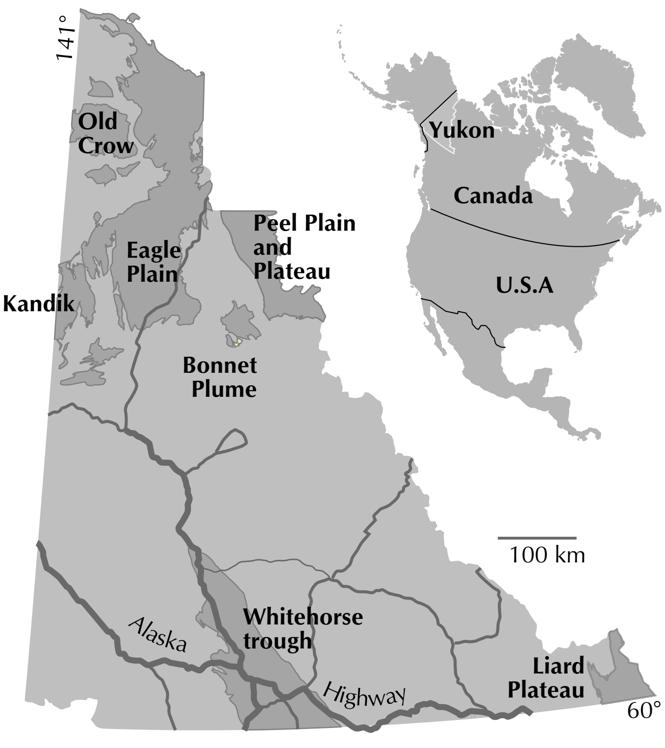


***Figure 1.*** *Petroleum basins in the Yukon (from Oil and Gas Branch, Yukon Government, 2007).*

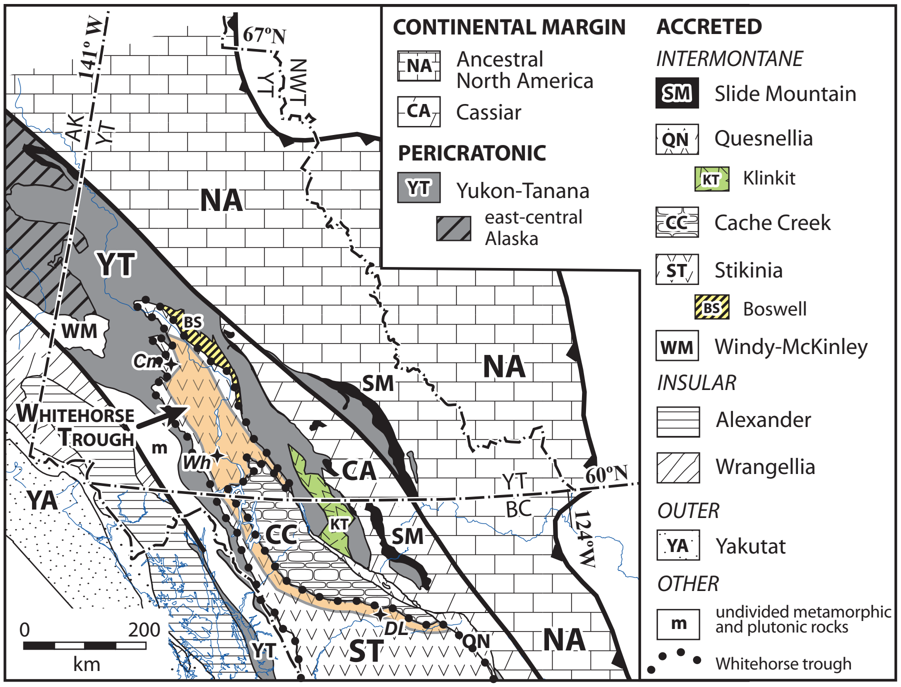
# GEOLOGIC SETTING

Wheeler (1961) introduced the name "Whitehorse trough" for a Late Triassic to early Cretaceous volcanic and sedimentary depocentre extending from northwestern British Columbia, northwestwards to south-central Yukon. It forms part of Stikinia (Fig. 2), which is flanked to the west and east by Yukon-Tanana terrane, and is bordered on the south by Cache Creek terrane (Wheeler and McFeely, 1991).

Although the early history of the Whitehorse trough is obscure, its origin is best explained by the 'oroclinal entrapment' model of Mihalynuk *et al.* (1994). In this model, the Quesnellia and Stikinia volcano-plutonic arcs impinged on the ancient margin of North America (*i.e.*, the Yukon-Tanana terrane) in Latest Permian to Middle Triassic time, followed by indentation and beginning of closure of the oceanic Cache Creek terrane in Late Triassic time; subsequently, Stikinia was rotated into an east-facing arc (locally referred to as the Lewes River arc), resulting in isolation of the Cache Creek terrane in the Early Jurassic, culminating with final closure and uplift in Middle Jurassic time (Mihalynuk *et al.*, 1994). The Whitehorse trough is preserved as a northwest-trending synclinorium characterized by southwest-verging fold-and-thrust belts (Wheeler, 1961; White *et al.*, 2006; Colpron *et al.*, 2007).

In the Yukon, the Whitehorse trough consists of three main stratigraphic units: the Lewes River Group (Upper Triassic), the Laberge Group (Lower-Middle Jurassic), and the Tantalus Formation (Middle Jurassic-Lower Cretaceous). These units represent three sedimentary basins partially overlapping in space and time. The Lewes River basin is interpreted as a fore-arc basin associated with westward subduction (Tempelman-Kluit, 1979; Souther, 1991); the Laberge basin is interpreted as a

***Figure 2.*** *Location map and geologic setting of the Whitehorse trough, Yukon (modified from Colpron et al., 2007). Wh=Whitehorse, Cm=Carmacks, DL=Dease Lake.*



collapsing fore-arc basin in which the Lewes River arc was being uplifted and eroded (Wheeler, 1961; Lowey and Hills, 1988); and the Tantalus basin represents mainly isolated, terrestrial basins (Wheeler, 1961; Long, 1986; Lowey and Hills, 1988).

## STRATIGRAPHY

The Laberge Group (Lower-Middle Jurassic) is underlain by the Lewes River Group and overlain by the Tantalus Formation (Fig. 3). Note that these are lithostratigraphic units (*i.e.*, defined on the basis of lithic characteristics and stratigraphic position, North American Commission on Stratigraphic Nomenclature, 2005). The Lewes River Group (Upper Triassic) is informally divided into the Povoas and Aksala formations, the later of which is informally subdivided into the Casca, Hancock and Mandanna members (Tempelman-Kluit, 1984). The Povoas formation consists of basalt, volcanic breccia, tuff and agglomerate; the Casca member consists of mudstone, sandstone and limestone with minor conglomerate; the Hancock member consists of limestone; and the Mandanna member consists of sandstone, limestone, volcaniclastic rocks and minor conglomerate. The Tantalus Formation (Middle Jurassic-Lower Cretaceous) is a formal unit consisting of conglomerate and coal-bearing sandstone and mudstone (Long, 1986; Lowey and Hills, 1988; Lowey, 2004).

## HISTORICAL BACKGROUND

Cairnes (1910) first described and named the Laberge strata in the Lewes and Nordenskiold coal district as the "Laberge series" and "Nordenskiold dacites". Lees (1934), working in the Laberge map area, and Bostock (1936) working in the Carmacks map area, adopted this nomenclature. Bostock and Lees (1938) subsequently described the Nordenskiold unit as the Nordenskiold formation. Wheeler (1961) mapped the Whitehorse area and renamed the Laberge series the "Laberge group". Souther (1971), working in northern British Columbia, subdivided the Laberge Group into the relatively coarser grained Takwahoni Formation and the relatively finer grained Inklin Formation. Tempelman-Kluit (1984) remapped the Carmacks and Laberge areas and subdivided the Laberge Group (from oldest to youngest) into the Richthofen, Conglomerate, Nordenskiold Dacite and Tanglefoot formations. Hart (1997) remapped parts of the Whitehorse area and redefined the Laberge Group (and all strata in the Whitehorse trough) as "time-rock" units. However, the Glossary of Geology (Bates and Jackson, 1987, p. 688) states that a time-rock unit is an "undesirable term for chronostratigraphic unit", and both the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005) and the International Stratigraphic Guide (International Subcommission on Stratigraphic Classification, 1994) refer to chronostratigraphic units, in order of decreasing rank, as eonothem, erathem, system, series and stage, whereas

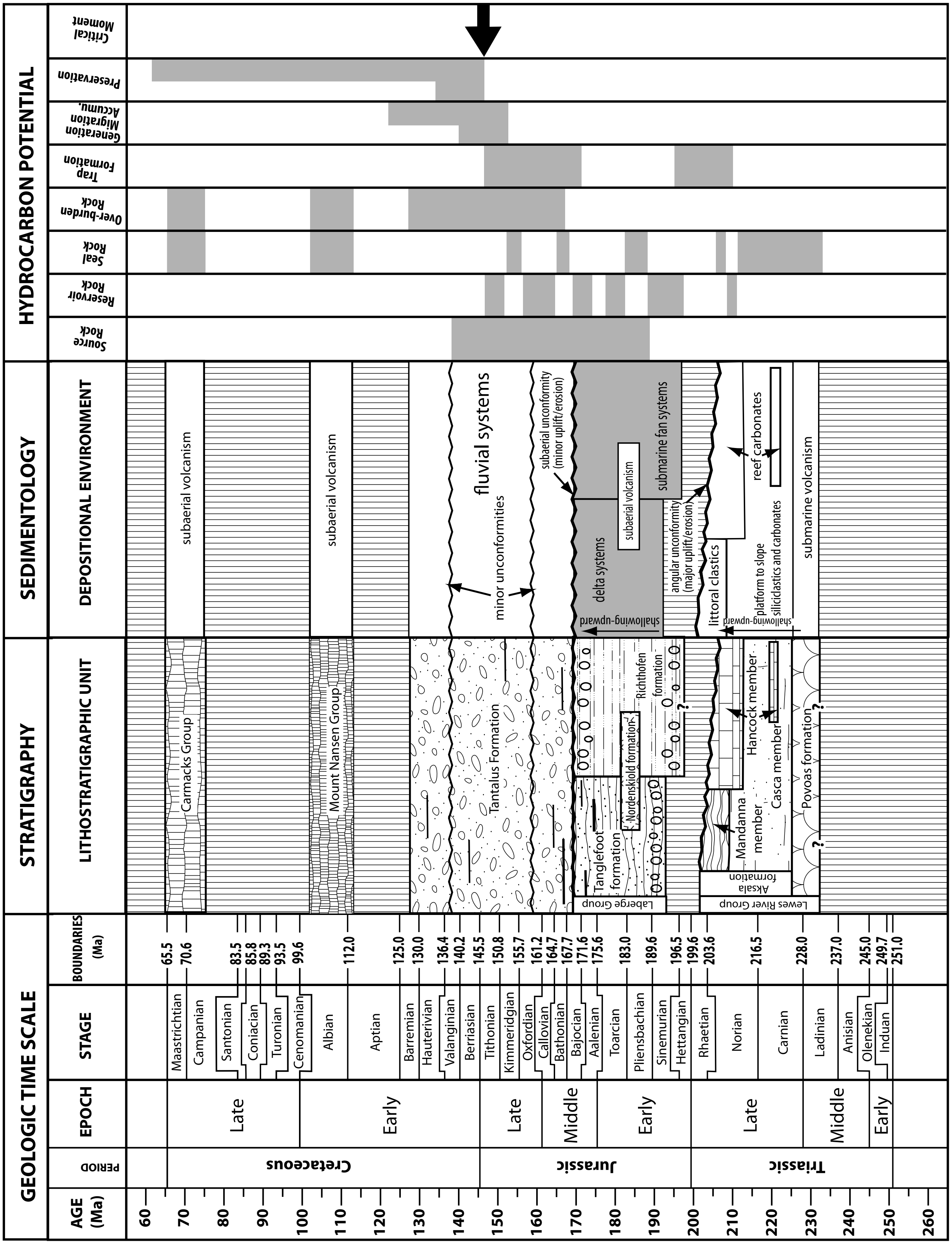


*Figure 3. Summary of the stratigraphy, sedimentology and hydrocarbon potential of the Laberge Group, Whitehorse trough, Yukon.*

lithostratigraphic units, in order of decreasing rank, include supergroup, group, formation, member and bed. Hence it was not appropriate for Hart (1997) to redefine formations (*i.e.*, lithostratigraphic units) as time-rock units (*i.e.*, chronostratigraphic units) based on collections of fossils (*i.e.*, biostratigraphic units). Lowey (2004, 2005) demonstrated that the Conglomerate formation was not a lithostratigraphic unit and reassigned strata in this unit to the Richthofen and Tanglefoot formations. The Laberge Group is herein informally subdivided into the Richthofen, Tanglefoot and Nordenskiold formations.

## TYPE LOCALITY AND TYPE SECTION

No type sections, or stratotypes, have been described for the Richthofen, Tanglefoot and Nordenskiold formations. The type area for the Richthofen formation is the west shore of Lake Laberge, and the type area for the Tanglefoot formation is the Division Mountain area, northwest of Lake Laberge. The type area for the Nordenskiold formation is the Nordenskiold River valley near Montague Mountain and Conglomerate Mountain north of Lake Laberge.

## LITHIC CHARACTERISTICS

The Richthofen formation is characterized by graded siltstone to very fine grained sandstone and mudstone couplets, or thin-bedded turbidites. Also occurring in the Richthofen formation and associated with the couplets are conglomerate, pebbly sandstone, massive sandstone, volcaniclastic rocks and minor amounts of limestone. The Tanglefoot formation is characterized by coal-bearing, interbedded sandstone and mudstone. Also occurring in the Tanglefoot formation and associated with the interbedded sandstone and mudstone are conglomerate, pebbly sandstone, volcaniclastic rocks and minor amounts of limestone. The Nordenskiold formation is characterized by bedded to massive crystal-rich volcaniclastic material. It is dominated by angular to subangular plagioclase feldspar, quartz and potassium feldspar, with minor amounts of lithic and vitric clasts (Fillmore, 2006).

## CONTACT RELATIONS

Cairnes (1910) determined that the basal unit of the Laberge Group was conglomerate and that it unconformably overlies limestone of the Lewes River Group. Cockfield and Bell (1926) thought that the contact appeared to be an angular unconformity. However Bostock and Lees (1938) suggested that the Laberge Group appears to overlie the Lewes River Group conformably, but they were unable to establish with certainty the relations of the two units. Bostock and Lees (1938) also noted that conglomerate assigned to the Laberge Group appears to rest directly on the Lewes River Group, indicating that a period of erosion had preceded deposition of the conglomerate. Wheeler (1961) interpreted the contact between the Lewes River and Laberge groups as a disconformity along the western margin of the Whitehorse trough, and suggested that the contact may be conformable near the centre of the basin and angular along the eastern margin. Tempelman-Kluit (1984) thought that the Lewes River and Laberge groups were a single depositional sequence (*i.e.*, with no major unconformity separating the two units), and suggested that it was impractical to subdivide them. As a result, the Laberge Group is included with the Lewes River Group in the Lexicon of Canadian Stratigraphy (Hills *et al.*, 1981). Most subsequent workers (*e.g.,* Dickie and Hein, 1995; Hart, 1997) followed Tempelman-Kluit's (1984) practise, and interpreted the Lewes River-Laberge contact as a facies boundary.

A key criterion to recognizing unconformities is a basal conglomerate containing clasts from an underlying unit (Shanmugam, 1988). Both the Richthofen and Tanglefoot formations contain limestone clasts lithologically similar to the underlying Hancock member of the Lewes River Group, and several of these clasts reveal Carnian-Rhaetian conodonts identical to the Hancock member (Orchard, 2004, 2006, 2007). The Richthofen formation also contains rare clasts of maroon mudstone that are lithologically similar to the underlying Mandanna member of the Lewes River Group (Fig. 4). Furthermore, Lowey (2005) demonstrated that at two localities where Tempelman-Kluit (1984) mapped the Lewes River-Laberge contact as conformable, one locality was a fault contact and the other was an angular unconformity.

Hart and Pelletier (1989) mapped the Lewes River-Laberge contact exposed on Jackson Hill south of Whitehorse as conformable, and referred to the contact as a "transition" between the two units. At this locality (Fig. 5), conglomerate of the Richthofen formation has eroded the underlying limestone and pyroclastic units of the Mandanna member, and immediately west of the exposed contact, the Hancock member is folded into an anticline. The pyroclastic rocks, referred to by Hart and Pelletier (1989) as siltstone, reveal a zircon U-Pb age of 201.5 ± 0.6 Ma (Mortensen, 2005). This contact is herein reinterpreted as an angular unconformity. Hart (1997) also mapped the contact between the Lewes River Group and Laberge Group in the Pilot Mountain subdivision area north of Whitehorse as a facies boundary (Fig. 6a). Conglomerate, sandstone and mudstone described as the Richthofen formation by Hart (1997), are reassigned to the Casca and Mandanna members in this study, and the contact re-interpreted as an angular unconformity (Fig. 6B). There is no compelling evidence to suggest that the Lewes River Group–Laberge Group contact is either conformable or a facies boundary, but rather it appears to be a major unconformity generally marked by a basal conglomerate in the Richthofen and Tanglefoot formations.


***Figure 4.*** *Clast of the Mandanna member (Aksala formation), Lewes River Group, in conglomerate of the Richthofen formation, Takhini Crossing, Yukon (clast located above and to the left of the scale).*

The Richthofen-Tanglefoot contact is not exposed and it is uncertain if the two units overlap stratigraphically. Although the Nordenskiold formation occurs mainly as isolated outcrops near the centre and western margin of Whitehorse trough, lithologically similar strata are present locally as thin to thick beds in both the Richthofen and Tanglefoot formations (see comments under Distribution and Thickness).

The contact between the Laberge Group and Tantalus Formation is not exposed in outcrop, but both Cockfield and Bell (1926) and Bostock (1936) stated that it was apparently conformable. The contact is present in drill core in the Division Mountain area (*i.e.*, DDH 97-63, UTM E445122 N 6796798, NAD 83). The contact occurs at a depth of 58.8 m and is marked by the first occurrence of chert clasts. At the contact, coarse sand-sized to granule chert occurs in a 1.2-m-thick, rusty-weathering, massive sandstone bed. It is overlain by a 0.4-m rubble zone (consisting of rusty-weathering fragments of quartz- and

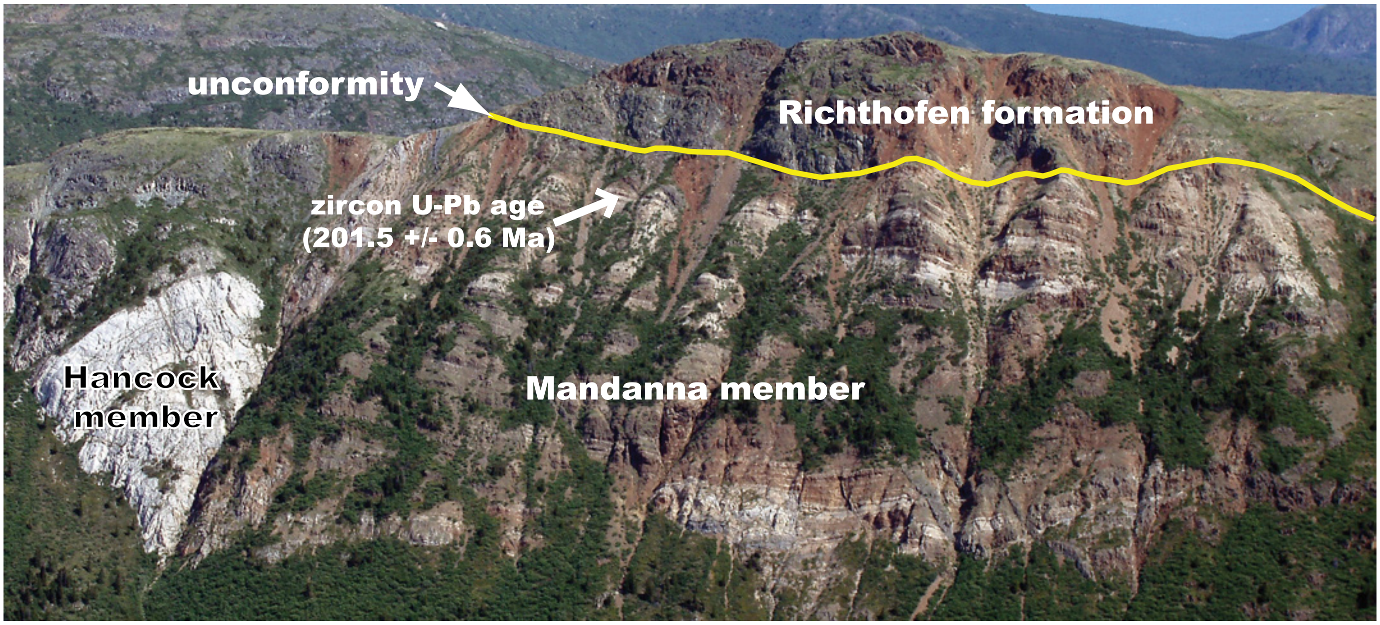


***Figure 5.*** *Angular unconformity between the Hancock and Mandanna members (Aksala formation, Lewes River Group), and the overlying Richthofen formation (Laberge Group), Jackson Hill, Yukon. View looking north. The Hancock member consists of limestone, the Casca member consists of interbedded limestone and volcaniclastics (that reveal a zircon U-Pb age of 201.5 ± 0.6 Ma), and the Richthofen formation consists of conglomerate.*

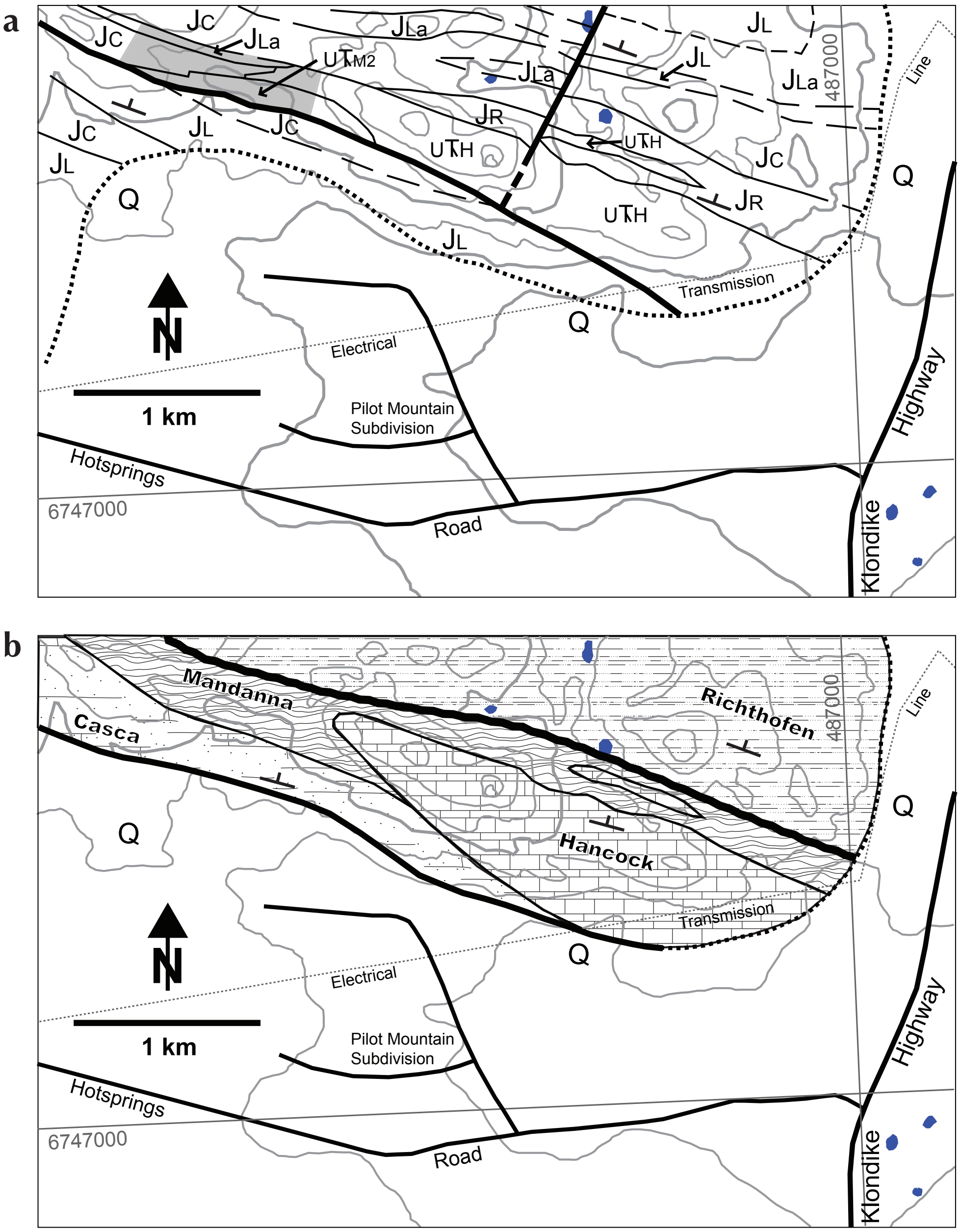


***Figure 6.*** *General geology of the Pilot Mountain Subdivision area, Whitehorse trough, Yukon.* ***(a)*** *Interpretation based on Hart (1997). Shaded area highlights facies contacts between the Lewes River Group (units UŦH and UŦM2) and Richthofen formation (units JA, JC, JL, JLa and JR).* ***(b)*** *Interpretation based on this study. Heavy wavy line indicates an unconformity between the Lewes River Group (i.e., Casca, Hancock and Mandanna members) and the Richthofen formation. Upper Laberge map sheet, NTS 105 D/14, 1:50 000 scale. (Refer to Figure 3 for key.)*

feldspar-rich sandstone and conglomerate), which is overlain by a 0.75-m-thick granule to fine chert–pebble conglomerate bed. The contact is interpreted as a minor unconformity. Hill (1977) similarly placed the Laberge-Tantalus contact at the base of massive chert-pebble conglomerate observed in drill core from the Carmacks 'south' area (*i.e.*, south of Carmacks and the Yukon River). However, in the Carmacks 'north' area (*i.e.*, north of Carmacks and the Yukon River, including Tantalus Butte), the Laberge-Tantalus contact has been assumed to be at some unknown distance below the massive chert-pebble conglomerate exposed at Tantalus Butte (Cairnes, 1910; Bostock, 1936; Hills, 1977; Tempelman-Kluit, 1984). Lithostratigraphically, it would be more practical to place the contact at the base of the chert-pebble conglomerate, as it is in the Carmacks south and Division Mountain area.

## DISTRIBUTION AND THICKNESS

The Richthofen formation is restricted to the southern half of the Whitehorse trough and the Tanglefoot formation occurs in the northern half. The two formations probably overlap in the vicinity north of Lake Laberge and Little Fox Lake (Fig. 7), but the strata have not been observed juxtaposed in outcrop. The Nordenskiold formation was

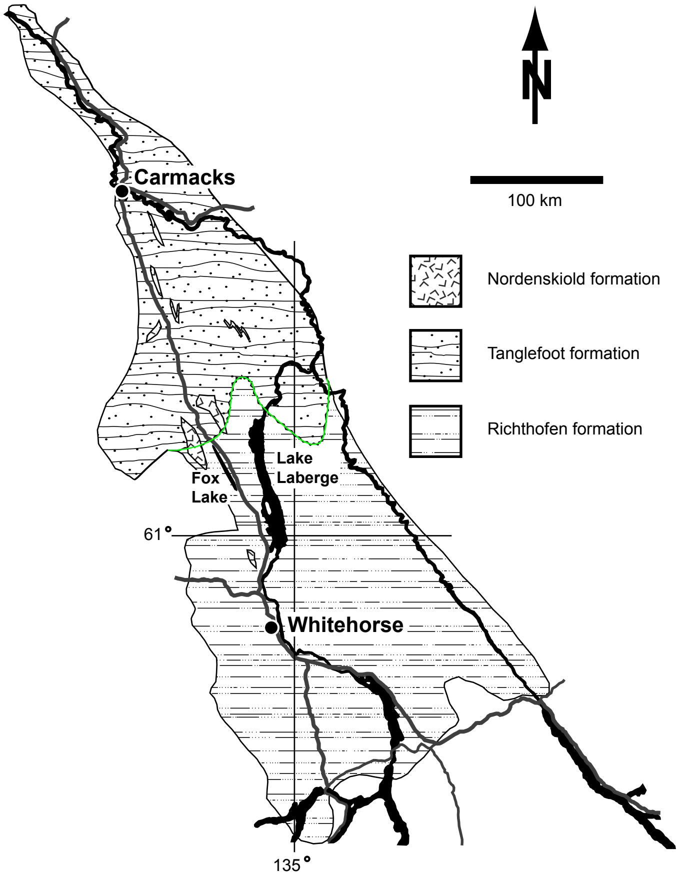


***Figure 7.*** *General distribution of the Richthofen, Tanglefoot, and Nordenskiold formations (Laberge Group), Whitehorse trough, Yukon.*

subdivided by Tempelman-Kluit (1984) into a southern marine unit and a northern subaerial unit. However, at several localities in the south the volcaniclastics occur in sandstone-mudstone couplets belonging to the Richthofen formation; and at several localities in the north the volcaniclastics occur in coal-bearing sandstone and mudstone beds belonging to the Tanglefoot formation. Hence where the volcaniclastics represent a minor component of the strata, these rocks are reassigned either to the Richthofen or Tanglefoot formations. Therefore, the Nordenskiold formation occurs mainly as isolated, massive outcrops near the centre and western margin of Whitehorse trough, but also occurs as thin to thick beds in both the Richthofen and Tanglefoot formations (that are more properly referred to as lithostratigraphic members, lenses, or beds; *c.f.,* North American Commission on Stratigraphic Nomenclature, 2005).

Precise determinations of the thickness of these units are not possible due to the scattered nature of the exposures. Previously reported thicknesses (*e.g.,* Cairnes, 1910; Cockfield and Bell, 1926; Bostock, 1936; Bostock and Lees, 1938; Wheeler, 1961; Hart, 1997) are probably overestimates, because they are based mainly on calculations from a map and not from measured stratigraphic sections. Only relatively short (~200 m), continuous sedimentologic sections have been measured, which indicate that the Richthofen formation is at least 500 m thick in the Lake Laberge area near the central part of the basin (Lowey, 2005), at least 1000 m thick in the Carcross area near the southern part of the basin, and possibly 2000 m thick farther south (Eisbacher, 1974). Based on a deep seismic survey, White *et al.* (2006) interpreted the Tanglefoot formation to be ~3000 m thick in the Carmacks area near the northern part of the basin. However, this too is probably an overestimate, because the Tanglefoot formation is depicted as maintaining a constant thickness in both the east-west (line 1) and north-south (line 2) seismic sections through to the margins of the basin (White *et al.*, 2006). Drill holes at Tantalus Butte near Carmacks penetrated up to 300 m of strata before stopping, and drill holes in the Division Mountain area near the west-central part of the basin penetrated approximately 300 m of continuous Tanglefoot strata before stopping at what was mistakenly thought to be the Tanglefoot-Richthofen contact (Carne and Gish, 1996).

## AGE AND CORRELATION

Lowey (2004) demonstrated that by re-assigning previously misidentified units to other formations (particularly the now obsolete 'Conglomerate formation' to the Richthofen and Tanglefoot formations), the Richthofen and Tanglefoot formations span almost the same age. Additional re-assignment of misidentified strata to these units, together with a review of previous data (*e.g.,* Hart, 1997 and references therein; Clapham *et al.*, 2002), indicates that the Richthofen and Tanglefoot formations are at least Sinemurian to Bajocian in age (Early-Middle Jurassic). The reported occurrence of Hettangian strata in the Richthofen formation is contentious (Frebold and Poulton, 1977; Taylor *et al.*, 1984; Jakobs, 1994; Palfy and Hart, 1995; Clapham *et al.*, 2002). U-Pb zircon ages from the Nordenskiold formation range from 188.5-182.5 Ma (Pliensbachian, or Early Jurassic; Hart, 1997; M. Colpron, pers. comm., 2007).

Souther (1971), working in the Whitehorse trough in northwestern British Columbia, redefined the Inklin and

Takwahoni formations of Kerr (1948) to the Laberge Group. The Inklin Formation (Lower-Middle Jurassic) consists of an estimated 3000 m of interbedded sandstone, sandstone-mudstone couplets, clast- and matrix-supported conglomerate and minor amounts of limestone interpreted as deepwater marine deposits (Souther, 1971). It is correlative with the Richthofen formation. The Takwahoni Formation (Lower-Middle Jurassic) consists of an estimated 3300 m of clast-supported conglomerate, sandstone and mudstone interpreted as shallow-water marine and fluvial deposits (Souther, 1971). It is correlative with the Tanglefoot formation. Johannson and McNicoll (1997) reported a U-Pb age of 186.6 ± 0.1 Ma from a rhyodacitic lithic-crystal tuff from the Whitehorse trough in northwestern British Columbia, which is similar in age to the Nordenskiold formation.

# SEDIMENTOLOGY

A major unconformity (spanning ~5 million years) separates the Laberge Group from the Lewes River Group (Fig. 3): Lewes River Group strata are at an angle to the unconformity and are locally truncated by the unconformity. According to Embry (1997, 2006), uplift and tilting of strata (*i.e.*, his 'tectonic tilt test') is evidence for the influence of tectonism on sedimentation. In addition, the interpretation of the Laberge basin as a collapsing fore-arc basin, in which the Lewes River arc was undergoing uplift and erosion, also suggests that tectonics was a major control of sedimentation of the Laberge Group.

## LITHOFACIES TYPES

Lithological characteristics of the Laberge Group strata are provided by Lowey (2004, 2005). The Richthofen formation is characterized by sediment-gravity-flow deposits, whereas the Tanglefoot formation is characterized by traction deposits (Table 1). The sixteen lithofacies types recognized in the Richthofen formation include conglomerate, sandstone, sandstone-mudstone couplets, siltstone, and siltstone-mudstone couplets (interpreted as debris flows and high- to low-concentration turbidity currents), folded and contorted strata (interpreted as submarine slides), lime mudstone (interpreted as biogenic ooze), and volcaniclastic rocks

***Table 1.*** *Comparison of lithofacies types in the Richthofen and Tanglefoot formations (Laberge Group), Whitehorse trough, Yukon (lithofacies codes modified from Pickering et al., 1989, and Miall, 1996).*

| **Richthofen formation** | |
|---|---|
| A1.1 | Disorganized conglomerate |
| A1.2 | Disorganized muddy conglomerate |
| A1.3 | Disorganized gravelly mudstone |
| A1.4 | Disorganized pebbly sandstone |
| A2.6 | Inversely graded pebbly sandstone |
| A2.8 | Graded-stratified pebbly sandstone |
| B1.1 | Thick/medium-bedded, disorganized sandstone |
| B2.1 | Parallel-stratified sandstone |
| C2.2 | Medium-bedded sandstone-mudstone couplets |
| C2.3 | Thin-bedded sandstone-mudstone couplets |
| D1.1 | Structureless siltstone |
| D2.2 | Thick irregular siltstone-mudstone laminae |
| D2.3 | Thin regular siltstone-mudstone laminae |
| F2.1 | Coherent folded and contorted strata |
| G1.1 | Lime mudstone |
| V | Volcaniclastic sandstone |

| **Tanglefoot formation** | |
|---|---|
| Gcm | Clast-supported massive conglomerate |
| Gh | Clast-supported horizontally stratified conglomerate |
| Sm | Massive fine to coarse-grained sandstone |
| Sh | Horizontally laminated very fine to coarse-grained sandstone |
| Sl | Low-angle, cross-bedded fine-grained sandstone |
| St | Trough cross-bedded fine-grained sandstone |
| Fm | Massive siltstone and mudstone |
| Fl | Interlaminated very fine grained sandstone and mudstone |
| C | Coal |
| L | Coral wackstone to floatstone |
| O | Oyster rudstone |
| V | Volcaniclastic sandstone |

(interpreted as resedimented syn-eruptive pyroclastic material). The twelve lithofacies types recognized in the Tanglefoot formation include conglomerate (interpreted as debris flow and river channel deposits), sandstone (interpreted as river channel and marine shoreface deposits), mudstone (interpreted as overbank, abandoned channel and waning flood deposits), coal (interpreted as vegetated swamp deposits), carbonate wackstone/ floatstone/rudstone (interpreted as marine bar and offshore deposits), and volcaniclastic rocks (interpreted as resedimented syn-eruptive pyroclastic material).

## FOSSILS

The Richthofen formation contains sparse and limited macrofossil, microfossil and trace fossil assemblages (Table 2). Marine macrofossils include only planktonic forms (*i.e.*, ammonites and belemnites). Rare fossilized wood fragments are present locally. Microfossils include degraded and blackened spores and pollen. The trace fossil assemblage (*i.e.*, *Helminthopsis, Phycosiphon, Planolites* and *Zoophycos*, in order of decreasing abundance) is similar to the distal *Cruziana* ichnofacies and proximal *Zoophycos* ichnofacies, typical of lower offshore to shelf marine environments (Pemberton *et al.*, 2001). In contrast, the Tanglefoot formation contains rich and varied macrofossil, microfossil and trace fossil assemblages (Table 2). Macrofossils include planktonic and benthonic forms (*i.e.*, ammonites, belemnites, pelecypods, brachiopods, corals, gastropods and crinoids). Trigonoiid bivalves identified by Poulton (1979) indicate shoreline to shallow marine environments, as do most of the other benthonic fauna. Fossilized wood fragments are locally abundant. Microfossils include spores, pollen and fungi/algae that indicate a well drained (semi-arid) alluvial plain and costal plain environment (Sweet, 2007). The trace fossil assemblage (*i.e.*, *Scolicia, Asterosoma, Thalassinoides, Skolithos* and *Zoophycos*, in order of decreasing abundance) is similar to the distal *Skolithos* and proximal *Cruziana* ichnofacies, typical of middle to lower shoreface and upper offshore marine environments (Pemberton *et al.*, 2001).

***Table 2.*** *Comparison of fossils in the Richthofen and Tanglefoot formations (Laberge Group), Whitehorse trough, Yukon.*

| | Richthofen formation | Tanglefoot formation |
|---|---|---|
| Macrofossils | ammonite | wood |
| | belemnite | ammonite |
| | (wood)[1] | pelecypod |
| | | brachiopod |
| | | coral |
| | | gastropod |
| | | crinoid |
| | | (belemnite) |
| Microfossils | (spore) | spore |
| | (pollen) | pollen |
| | | (fungi/algae) |
| Trace fossils | *Helminthopsis* | Rooting |
| | *Phycosiphon* | *Scolicia* |
| | *Planolites* | *Asterosoma* |
| | *(Zoophycos)* | *Thalassinoides* |
| | | *Skolithos* |
| | | *(Chondrites)* |

[1] *Parentheses indicate a minor component.*

## ENVIRONMENT OF DEPOSITION

Wheeler (1961) suggested that the Laberge Group (*i.e.*, Richthofen formation) in the Whitehorse map-area was deposited partly in a marine environment, but thought that some conglomerate was deposited on an alluvial fan or delta because it was well rounded (implying a transport distance of ~16-32 km), and one bed displayed a channel-shaped cross-section. However, it is now recognized that coarse-grained clastic deposits like gravel can be 'resedimented' into a deepwater environment (Walker, 1975). Eisbacher (1974) recognized the deepwater character of what is now referred to as the Richthofen formation, and concluded that it was deposited in submarine fan systems. The lithofacies types and the fossil assemblages in the Richthofen formation support the interpretation of submarine fan systems. Based on the distribution of the Richthofen formation and the correlative Inklin Formation, these were probably partly coalescing submarine fans systems similar to the multiple-source mud/sand-rich ramp model of Reading and Richards (1994). Limited paleoflow directions indicate an overall southeast transport direction (Lowey, 2005).

Long (1986) interpreted the upper Laberge Group (now referred to as the Tanglefoot formation) as a broad coastal zone characterized by tidal marshes and high constructive river-dominated deltas. The lithofacies types and the fossil assemblages in the Tanglefoot formation support the interpretation of deposition on a coastal plain dominated by delta systems. The presence of coral wackestone to floatstone and oyster rudstone suggest the accumulation of bioclastic bars in a shallow marine environment.

Alternatively, the unique occurrence of the oyster rudstone may be interpreted as a supratidal storm deposit (*c.f.,* Boyajian and Thayer, 1995).

The Nordenskiold formation represents mainly subaerially erupted pyroclastic deposits. The occurrence of volcaniclastic rocks in the Richthofen and Tanglefoot formations (*i.e.*, as Nordenskiold members, lenses, or beds) is interpreted as reworked syn-eruptive pyroclastic material.

As stated previously the Richthofen and Tanglefoot formations probably overlap in the vicinity north of Lake Laberge and Little Fox Lake, and represent, in part a facies change. This 'transition' zone is characterized by very thin to thin-bedded graded siltstone and mudstone couplets, and it is difficult to distinguish pro-delta turbidites of the Tanglefoot formation from thin-bedded turbidites of the Richthofen formation. Some of these graded beds may represent distal storm deposits that accumulated on a shelf environment (*c.f.,* Davis *et al*., 1989; Walker and Plint, 1992). Figure 8 summarizes the paleogeography of the Whitehorse trough during Pliensbachian time (late Early Jurassic, or ~185 Ma).

## TECTONIC PROVENANCE

Lowey and Hills (1988) determined that sandstone compositions from the Laberge Group indicate a dissected arc provenance. Conglomerate compositions are also used to infer tectonic provenance, but due to the preferential weathering of carbonate clasts, the decomposition of igneous clasts into sand-sized mineral grains, and the ambiguous provenance of some chert clasts, they provide only a rough estimate (Cox and Lowe, 1995a,b; Veizer and Mackenzie, 2004). Approximately 3000 clasts from the Laberge Group were identified at 34 stratigraphic sections throughout the Whitehorse trough (Appendix 1). Clast compositions from the Richthofen formation plot entirely within the volcanic arc field, whereas clast compositions from the Tanglefoot formation plot mainly in the volcanic arc field with a few plotting in the basement uplift field (Fig. 9). Cox and Lowe (1995a) note that dissected-arc-derived conglomerates tend to plot between the P+M+Q and V poles. Hence

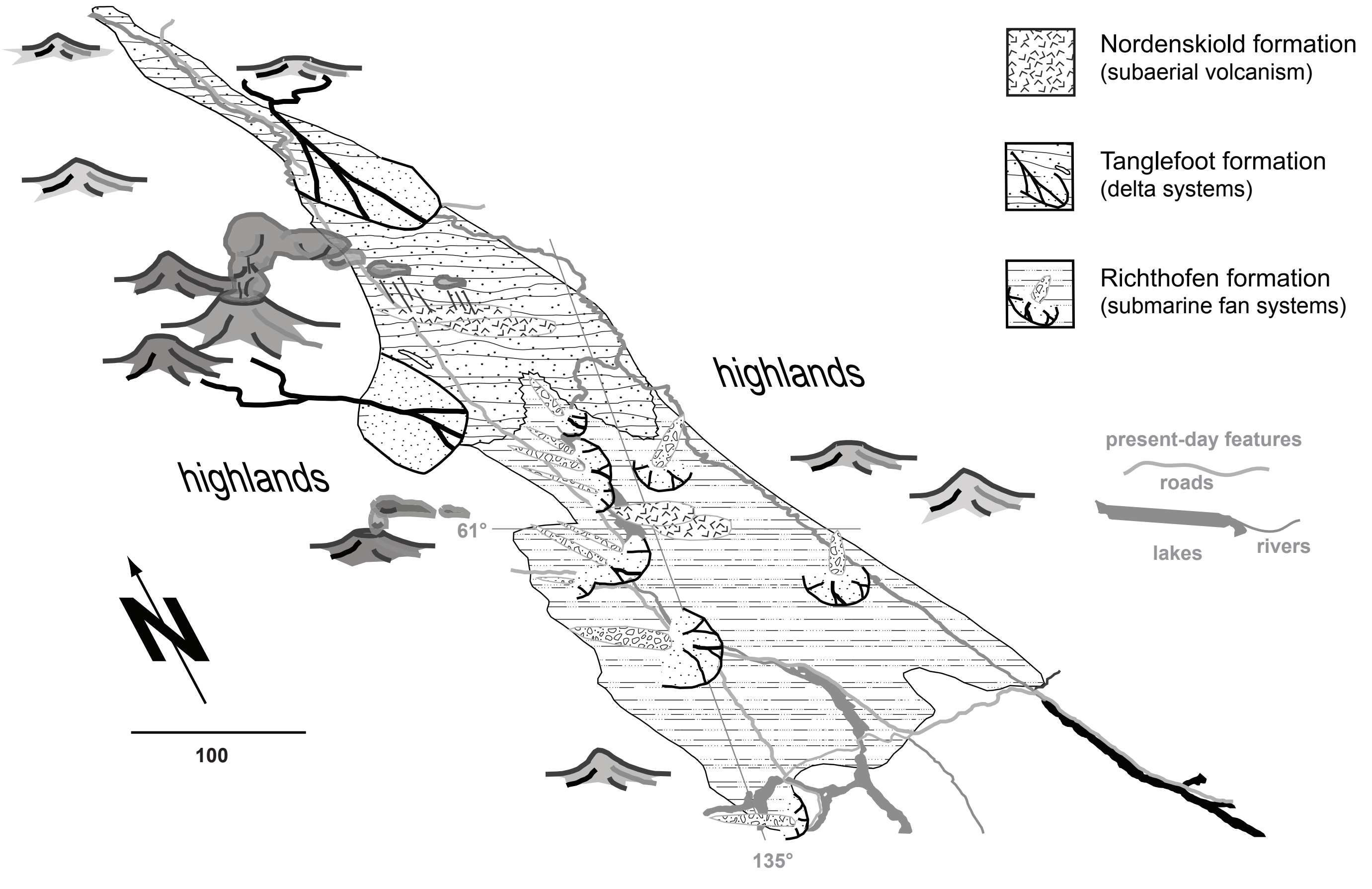


***Figure 8.*** *Paleogeography of the Whitehorse trough during Pliensbachian time (Early Jurassic, or ~ 185 Ma) (oblique view).*

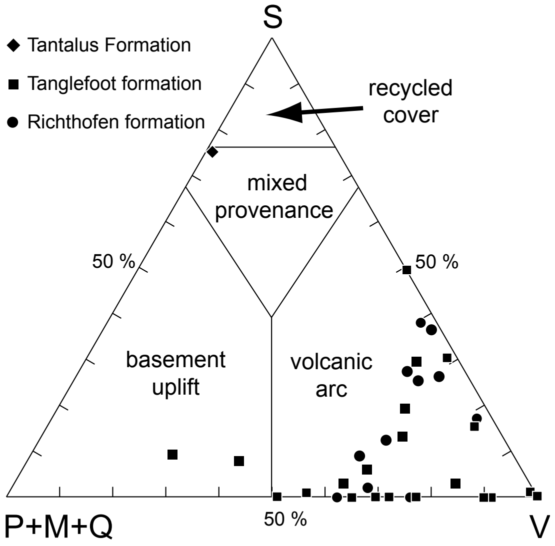


***Figure 9.*** *Conglomerate clast compositions of the Richthofen and Tanglefoot formations (Laberge Group), Whitehorse trough, Yukon. P+M+Q=sum of plutonic, metamorphic and quartz clasts; V=sum of volcanic clasts; and S=sum of sedimentary clasts. Conglomerate composition of the Tantalus Formation is shown for comparison (from Bultman, 1979). Compositional fields for conglomerate clast populations of differing tectonic provenance from Cox and Lowe (1995a, b).*

conglomerate compositions from the Richthofen and Tanglefoot formations also indicate a dissected arc provenance, in agreement with the sandstone compositions from the Laberge Group. Fillmore (2006) determined that the geochemical composition of the Nordenskiold formation is characteristic of high-potassium arc volcanism.

## HYDROCARBON POTENTIAL

The hydrocarbon potential of the Laberge Group is summarized in a petroleum system 'events chart' (Fig. 3). This chart shows the chronology of the four essential elements (*i.e.*, source rock, reservoir rock, seal rock and overburden rock) and two processes (*i.e.*, trap formation and generation-migration-accumulation) of a petroleum system (Magoon and Dow, 1994). A petroleum system is a natural system that encompasses a pod, or potential pod, of source rock, related oil and gas, and the geological elements and processes essential for petroleum accumulation to take place (Magoon and Dow, 1994).

The events chart also shows the major rock units of the petroleum system, and the critical moment, or that point in time best depicting the generation-migration-accumulation of most of the hydrocarbons in a petroleum system (Magoon and Dow, 1994).

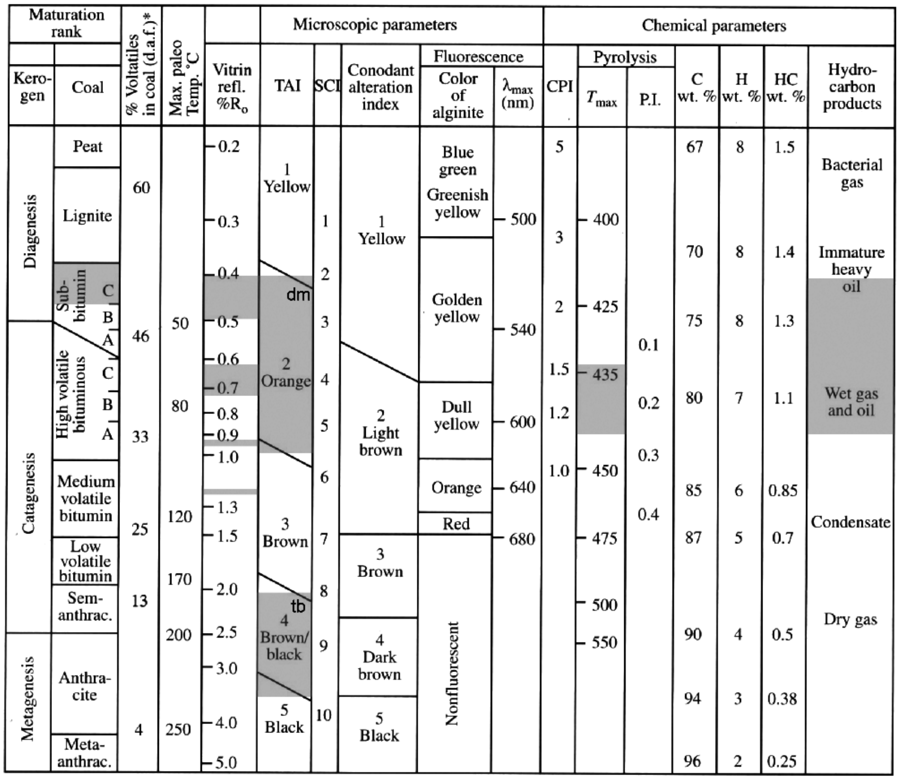
### SOURCE ROCK

Lowey and Long (2006) provide a detailed report on the source rock potential of the Whitehorse trough. Source rock potential is generally based on maturation levels determined by programmed pyrolysis and combustion, coal rank, vitrinite reflectance, and the colour of microfossils (Fig. 10). The Richthofen formation is a poor to fair source rock, gas-prone and postmature, and the Tanglefoot formation is a good to very good source rock, mainly oil-prone with a possibility of gas, and mature. The Nordenskiold formation has no source rock potential. Petroleum fluid inclusions consisting of medium and light oils (*i.e.*, mainly 23°- 32° and 40°- 44° API gravity*) [*API gravity=American Petroleum Institute degrees, which are inversely proportional to density] are present locally in the Tanglefoot formation, and indicate a minimum trapping temperature of 110-115°C (Fluid Inclusions Technologies, Inc., 2007). The Richthofen formation is interpreted as a spent source rock, whereas the Tanglefoot formation is interpreted as a potential source rock and possibly an effective source rock. The northern part of Whitehorse trough is the most prospective area for hydrocarbon exploration (particularly the Division Mountain, Tantalus Butte and Five Finger Rapids areas). The Tantalus is also a potential source rock (Lowey and Long, 2006).

### RESERVOIR ROCK

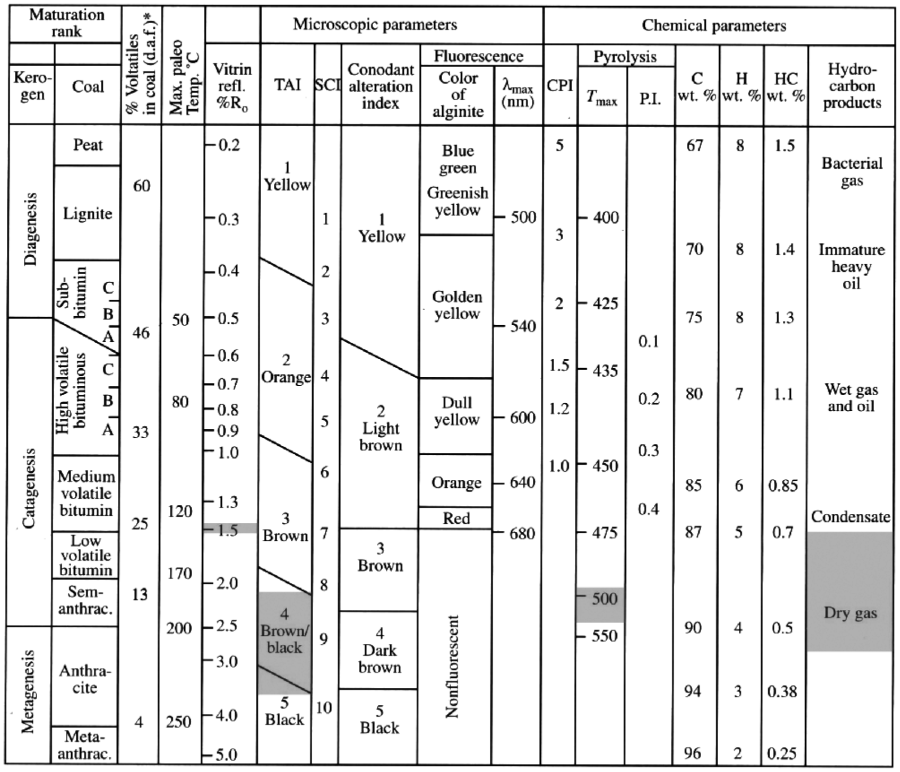
Potential reservoir rocks exposed at the surface were used to estimate subsurface reservoir quality (Tobin, 1997). All lithologies in the Richthofen and Nordenskiold formations exhibit tight depositional facies and are interpreted as a high risk for reservoir quality. Medium- to thick-bedded feldspathic sandstone in the Tanglefoot formation range from porous, with minimal weathering, to exhibiting abundant secondary porosity of uncertain origin, and is interpreted as a low and moderate to high risk for reservoir quality. The Lewes River Group is also interpreted as a high risk for reservoir quality (although limestone in the Mandanna member is locally fractured and may be a potential reservoir), whereas massive to thick-bedded lithic sandstone in the Tantalus Formation is tightly compacted, but porous and weathered, and is

***Figure 10.*** *Summary of thermal maturation levels (shaded areas) in the Richthofen and Tanglefoot formations (Laberge Group), Whitehorse trough, Yukon (dm=samples from Division Mountain area; tb=samples from Tantalus Butte area). Correlation of maturation parameters is from Hunt (1996).*



*Dry ash free

***Tanglefoot formation***



*Dry ash free

***Richthofen formation***

interpreted as a moderate to high risk for reservoir quality.

## SEAL ROCK

Interbedded conglomerate, sandstone and mudstone beds in the Richthofen formation and volcaniclastic beds in the Nordenskiold formation represent potential regional seals. Mudstone beds in the Tanglefoot formation are potential local seals. In addition, rocks lacking porosity and permeability occur throughout the Lewes River Group (and include basalt and volcaniclastics in the Povoas formation and interbedded sandstone and mudstone in the Aksala formation), whereas massive conglomerate in the Tantalus Formation is a potential regional seal and mudstone beds are potential local seals. The overlying volcanic flows of the Carmacks Group and Mount Nansen Formation are also potential regional seals.

## OVERBURDEN ROCK

Overburden rock for the Tanglefoot formation includes the Tantalus Formation (~1500 m thick), Carmacks Group (~1000 m thick) and Mount Nansen Formation (~500 m thick). The Carmacks Group and Mount Nansen Formation are also an overburden rock for the Tantalus Formation.

### TRAP FORMATION

Potential stratigraphic traps in the Laberge Group include unconformities and pinchouts in the Tanglefoot formation. Potential stratigraphic straps in the Lewes River Group include reefs in the Aksala formation (*i.e.*, Hancock member). Unconformities and pinchouts may also be potential stratigraphic traps in the Tantalus Formation. Structural traps include anticlines and high-angle faults that probably formed in Middle Jurassic time (~170 million years ago (mya)) and affected all strata in the Whitehorse trough.

### GENERATION-MIGRATION-ACCUMULATION

The generation-migration-accumulation of potential hydrocarbons is difficult to estimate without adequate subsurface data and a proper burial history chart. However, burial of potential source rocks is thought to have started in Late Jurassic time (~150 mya).

### PRESERVATION

The preservation, modification or destruction of any possible hydrocarbons probably began in Early Cretaceous time (~140 mya) and may be continuing today.

### CRITICAL MOMENT

The critical moment, or point in time that best depicts the generation-migration-accumulation of possible hydrocarbons in the Whitehorse trough, is estimated to be Early Cretaceous time (~145 mya).

## ACKNOWLEDGEMENTS

Expert helicopter flying was provided by Capital Helicopters. Discussions with Darrel Long and Maurice Colpron regarding the Whitehorse trough are greatly appreciated.

## REFERENCES

Allen, T., 2000. An evaluation of coal-bearing strata at Division Mountain (115H/8 east-half, 105E/5 west-half), south-central Yukon. *In:* Yukon Exploration and Geology 1999, D.S. Emond and L.H. Weston (eds.), Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 177-198.

Bates, R.L. and Jackson, J.A., 1987. Glossary of geology. American Geological Institute, Boulder, Colorado.

Beaton, A.P., Cameron, A.R. and Goodarzi, F., 1992. Petrography, geochemistry and utilization potential of the Division Mountain coal occurrences, Yukon Territory. *In:* Current Research, Part E, Geological Survey of Canada, Paper 92-1E, p. 23-32.

Bostock, H.S., 1936. Carmacks district, Yukon. Geological Survey of Canada, Memoir 189.

Bostock, H.S. and Lees, E.J., 1938. Laberge map-area, Yukon. Geological Survey of Canada, Memoir 217.

Boyajian, G.E. and Thayer, C.W., 1995. Clam calamity: A recent supratidal storm-deposit as an analog for fossil shell beds. Palios, 10, p. 484-489.

Bultman, T.R., 1979. Geology and tectonic history of the Whitehorse Trough west of Atlin, British Columbia. Unpublished Ph.D. thesis, Yale University, 284 p.

Cairnes, D.D., 1910. Preliminary memoir on the Lewes and Nordenskiold rivers coal district, Yukon Territory. Geological Survey of Canada, Memoir 5.

Carne, R.C. and Gish, R.E., 1996. Geology of the Division Mountain coal deposit of Cash Resources Ltd. *In:* Yukon Exploration and Geology, 1995, Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 37-42.

Clapham, M.E., Smith, P.L. and Tipper, H.W., 2002. Lower to Middle Jurassic stratigraphy, ammonoid faunas and sedimentary history of the Laberge Group in the Fish Lake syncline, northern Whitehorse Trough, Yukon, Canada. *In:* Yukon Exploration and Geology 2001, D.S. Emond, L.H. Weston and L.L. Lewis (eds.), Yukon Geological Survey, p. 73-85.

Cockfield, W.E. and Bell, A.H., 1926. Whitehorse district, Yukon. Geological Survey of Canada, Memoir 150.

Colpron, M., Nelson, J. and Israel, S., 2007. A transect through the accreted terranes of the northern Canadian Cordillera. Arizona Geological Society, Ores and Orogenesis Symposium Field Trip No. 15, September 19-23, 2007, and Yukon Geological Survey Open File 2007-3.

Cox, R. and Lowe, D.R., 1995a. A conceptual review of regional-scale controls on the composition of clastic sediment and the co-evolution of continental blocks and their sedimentary cover. Journal of Sedimentary Research, A65, p. 1-12.

Cox, R. and Lowe, D.R., 1995b. Compositional evolution of coarse clastic sediments in southwestern United States from 1.8 to 0.2 Ga and implications for relationships between the development of crustal blocks and their sedimentary cover. Journal of Sedimentary Research, A65, p. 477-494.

Davis, H.R., Byers, C. and Pratt, L.M., 1989. Depositional mechanisms and organic matter in Mowry Shale (Cretaceous), Wyoming. The American Association of Petroleum Geologist Bulletin, vol. 73, p. 1103-1116.

Dickie, J.R. and Hein, F.J., 1995. Conglomeratic fan deltas and submarine fans of the Jurassic Laberge Group, Whitehorse Trough, Yukon Territory, Canada: Fore-arc sedimentation and unroofing of a volcanic arc complex. Sedimentary Geology, vol. 98, p. 263-292.

Eisbacher, G.H., 1974. Evolution of successor basins in the Canadian Cordillera. *In:* Modern and ancient geosynclinal sedimentation, R.H. Dott and R.H. Shaver (eds.), Society of Economic Paleontologists and Mineralogists, Special Publication No. 19, p. 274-291.

Embry, A., 1997. Global sequence boundaries of the Triassic and their identification in the Western Canada sedimentary basin. Bulletin of Canadian Petroleum Geology, vol. 45, p. 415-433.

Embry, A., 2006. Practical sequence stratigraphy: Concepts and applications. Canadian Society of Petroleum Geologist, Short Course Notes, May 23-24, 2006.

Fillmore, J.A., 2006. Character and origin of the Lower Jurassic (Pliensbachian) Nordenskiold dacite, Whitehorse Trough, Yukon Territory, Canada. Unpublished Honours B.Sc. thesis, Laurentian University, Sudbury, Ontario, 28 p.

Fluid Inclusion Technologies, Inc., 2007. Fluid inclusion petrography and microthermometry of ten samples. Fluid Inclusion Technologies, Inc. report MT070023.

Freebold, H. and Poulton, T.P., 1977. Hettangian (Lower Jurassic) rocks and faunas, northern Yukon Territory. Canadian Journal of Earth Sciences, vol. 14, p. 89-101.

Gilmore, R.G., 1985. Whitehorse field party. Unpublished Report, Petro-Canada, 16 p. (plus photographs)

Gunther, P.R., 1985. Geochemical evaluation of Whitehorse field party samples. Unpublished Report, Petro-Canada, 19 p. (plus appendices)

Hart, C.J.R., 1997. A transect across northern Stikinia: geology of the northern Whitehorse map area, southern Yukon Territory (105D/13-16). Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, Bulletin 8, 112 p.

Hart, C.J.R. and Pelletier, K.S.,1989. Geology of Whitehorse (105D/11) map area. Open File Report 1989-2, Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs.

Hill, R.P., 1977. Report on preliminary evaluation, Carmacks coal project. Unpublished report prepared for the Cyprus Anvil Mining Corporation. Yukon Mineral Assessment Report 092031.

Hills, L.V., Sangster, E.V. and Suneby, L.B. (eds.), 1981. Lewes River Group. Lexicon of Canadian Stratigraphy, Volume 2, Yukon Territory and District of Mackenzie. Canadian Society of Petroleum Geologists.

Hunt, J.M., 1996. Petroleum geochemistry and geology, Second edition. W.H. Freeman and Company, New York. International Subcommission on Stratigraphic Classification, 1994. International Stratigraphic Guide, Second edition, A. Salvador (ed.), Geological Society of America, Boulder, Colorado.

Jakobs, G.K., 1994. Jurassic stratigraphy in the northwestern Teslin and northeastern Whitehorse map areas, Yukon Territory. *In:* Current Research 1994-E, Geological Survey of Canada, p. 1-6.

Johannson, G.G. and McNicoll, V.J., 1997. New U-Pb data from the Laberge Group, northwest British Columbia: implications for Stikinian arc evolution and Lower Jurassic time scale calibrations. *In:* Radiogenetic Age and Isotopic Studies, Report 10, Geological Survey of Canada, Current Research, 1997-F, p. 121-129.

Kerr, F.A., 1948. Taku River map-area, British Columbia. Geological Survey of Canada, Memoir 248.

Koch, G., 1973. The Central Cordilleran Region. *In:* The Future Petroleum Provinces of Canada, R.G. McCrossan (ed.), Canadian Society of Petroleum Geologists, Memoir 1, p. 37-71.

Lees, E.J., 1934. Geology of the Laberge area, Yukon. Transactions of the Royal Canadian Institute, no. 43, vol. 20, part 1, 48p.

Long, D.G.F., 1986. Coal in Yukon. *In:* Mineral deposits of the northern Cordillera, J.D. Morin (ed.), Canadian Institute of Mining and Metallurgy, Special Volume 37, p. 311-318.

Lowey, G.W., 2004. Preliminary lithostratigraphy of the Laberge Group (Jurassic), south-central Yukon: implications concerning the petroleum potential of the Whitehorse Trough. *In:* Yukon Exploration and Geology 2003, D.S. Emond and L.L. Lewis (eds.), Yukon Geological Survey, p. 129-142.

Lowey, G.W., 2005. Sedimentology, stratigraphy and source rock potential of the Richthofen formation (Jurassic), northern Whitehorse Trough, Yukon. *In:* Yukon Exploration and Geology 2004, D.S. Emond and L.L. Lewis (eds.), Yukon Geological Survey, p. 177-191.

Lowey, G.W. and Hills, L.V., 1988. Lithofacies, petrography and environments of deposition, Tantalus Formation (Lower Cretaceous), Indian River area, west-central Yukon. Bulletin of Canadian Petroleum Geology, vol. 36, p. 296-310.

Lowey, G.W. and Long, D.G.F., 2006. Summary of Rock-Eval data for the Whitehorse trough, Yukon: implications concerning the hydrocarbon potential of a frontier basin. *In:* Yukon Exploration and Geology 2005, D.S. Emond, L.L. Lewis and L.H. Weston (eds.), Yukon Geological Survey, p. 207-230.

Magoon, L.B. and Dow, W.G., 1994. The petroleum system. *In:* The petroleum system- from source to trap, L.B. Magoon and W.G. Dow (eds.), American Association of Petroleum Geologists, Memoir 60, p. 3-24.

Miall, A.D., 1996. The geology of fluvial deposits. Springer, New York, 582 p.

Mihalynuk, M.G., Nelson, J. and Diakkow, L.J., 1994. Cache Creek terrane entrapment: oroclinal paradox within the Canadian Cordillera. Tectonics, vol. 13, p. 575-595.

Mortensen, J.K., 2005. Geochronology report for 2004 YGS samples. Report, Department of Earth and Ocean Sciences, University of British Columbia, May 6, 2005.

National Energy Board, 2001. Petroleum resource assessment of the Whitehorse Trough, Yukon Territory, Canada. Oil and Gas Resource Branch. Department of Economic Development, Government of the Yukon, 59 p.

North American Commission on stratigraphic nomenclature, 2005. North American stratigraphic code. American Association of Petroleum Geologists Bulletin 89, p. 1547-1591.

Orchard, M.J., 2004. Report on conodonts and other microfossils. Geological Survey of Canada Report No. MJO-2005-12.

Orchard, M.J., 2006. Report on conodonts and other microfossils. Geological Survey of Canada Report No. MJO-2007-22.

Orchard, M.J., 2007. Report on conodonts and other microfossils. Geological Survey of Canada Report No. MJO-2007-12.

Palfy, J. and Hart, C.J., 1995. Biostratighraphy of the Lower to Middle Jurassic Laberge Group, Whitehorse map area (105D), southern Yukon. *In:* Yukon Exploration and Geology, 1994, Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 73-86.

Pemberton, S.G., Spila, M., Pulham, A.J., MacEachern, J.A., Robbins, D. and Sinclair, I.K., 2001. Ichnology and sedimentation of shallow to marginal marine systems: Ben Nevis and Avalon reservoirs, Jeanne D'Arc basin. Geological Association of Canada Short Course Volume 15.

Pickering, K.T., 1989. Deep-marine environments: Clastic sedimentary and tectonics. Unwin Hyman, London, 416 p.

Poulton, T.P., 1979. Jurassic trigoniid bivalves from Canada and western United States of America. Geological Survey of Canada, Bulletin 282.

Reading, H.G. and Richards, M., 1994. Turbidite systems in deep-water basin margins classified by grain size and feeder system. The American Association of Petroleum Geologists Bulletin 78, p. 792-822.

Shanmugam, G., 1988. Origin, recognition, and importance of erosional unconformities in sedimentary basins. *In:* New perspectives in basin analysis, K.L. Kleinsphen and C. Paola (eds.), Springer- Veerlag, New York, p. 83-108.

Souther, J.G., 1971. Geology and mineral deposits of Tulsequah map-area, British Columbia (104K). Geological Survey of Canada, Memoir 362.

Souther, J.G., 1991. Volcanic regiems, Chapter 14. *In:* Geology of the Cordilleran Orogen in Canada, H. Gabrielse and C. Yorath (eds.), Geological Survey of Canada, Geology of Canada, vol. 4, p. 457-490.

Sweet, A.R., 2007. Applied Research Report on 100 Samples From the Laberge Group and Laberge Group?, Jurassic and Cretaceous, Whitehorse Trough, Yukon Territory (NTS 115H, I; 105E, I, L). Paleontological Report 06-ARS-2007, Geological Survey of Canada.

Taylor, D.G., Callomon, J.H., Hall, R., Smith, P.L., Tipper, H.W. and Westermann, G.E.G., 1984. Jurassic ammonite biogeography of Western North America: the tectonic implications. *In:* Jurassic-Cretaceous biochronology and paleogeography of North America, G.E.G. Westermann (ed.), Geological Association of Canada Special Paper 27, p. 121-141.

Teitz, H.H. and Young, F.G., 1982. Canadian hydrocarbon resource development up to the year 2000. Journal of Petroleum Geology, vol. 4, 347-375.

Tempelman-Kluit, D.J., 1979. Transported cataclastite, ophiolite and granodiorite in Yukon: evidence of arc-continent collision. Geological Survey of Canada, Paper 79-14, 27 p.

Tempelman-Kluit, D.J., 1984. Geology, Laberge (105E) and Carmacks (115I), Yukon Territory. Geological Survey of Canada, Open File 1101. (1:250,000 scale).

Tobin, R.C., 1997. Porosity prediction in frontier basins: a systematic approach to estimating subsurface reservoir quality from outcrop samples. *In:* Reservoir quality prediction in sandstones and carbonates, J.A. Kupecz, J. Gluyas and S. Bloch (eds.), American Association of Petroleum Geologists, Memoir 69, p. 1-18.

Veizer, J. and Mackenzie, F.T., 2004. Evolution of sedimentary rocks. *In:* Treatise on geochemistry, Volume 7, Sediments, diagenesis, and sedimentary rocks, H.D. Holland and K.K. Turekian (eds.), Elsevier Pergamon, New York, p. 369-407.

Walker, R.G., 1975. Generalized facies models for resedimented conglomerates of turbidite association. Geological Society of America, Bulletin 86, p. 737-748.

Walker, R.G. and Plint, A.G., 1992. Wave- and storm-dominated shallow marine systems. *In:* Facies models, response to sea level change, R.G. Walker and N.P. James (eds.), Geological Association of Canada, p. 219-238.

Wheeler, J.O., 1961. Whitehorse map-area, Yukon Territory. Geological Survey of Canada, Memoir 312, 156 p.

Wheeler, J.O. and McFeely, P., 1991. Tectonic assemblage map of the Canadian Cordillera, Geological Survey of Canada, Map 1712A, 1:1 000 000 scale.

White, D., Colpron, M., Buffett, G. and Roberts, B., 2006. Structural constraints for oil and gas assessment in the Whitehorse Trough: New results from seismic profiling. *In:* Yukon Exploration and Geology 2005, D.S. Emond, G.D. Bradshaw, L.L. Lewis and L.H. Weston (eds.), Yukon Geological Survey, p. 315-323.

# APPENDIX 1: Results of pebble count analysis of the Richthofen and Tanglefoot formations (Laberge Group), Whitehorse Trough, Yukon

| SAMPLE | UNIT | Syenite | Monzonite | Quartz Monzonite | Granite | Granodiorite | Diorite | Gabbro | Gneiss | Schist | Argillite | Quartz | Basalt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GL03-4 | Tanglefoot | 0 | 0 | 0 | 0 | 1 | 2 | 5 | 0 | 0 | 0 | 0 | 55 |
| GL03-7 | Tanglefoot | 0 | 0 | 0 | 43 | 15 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| GL03-11B | Ttanglefoot | 0 | 0 | 0 | 2 | 2 | 3 | 0 | 0 | 0 | 0 | 1 | 25 |
| GL03-21 | Tanglefoot | 0 | 3 | 0 | 4 | 10 | 11 | 1 | 0 | 0 | 0 | 0 | 30 |
| GL03-26A | Tanglefoot | 0 | 0 | 0 | 1 | 12 | 19 | 0 | 2 | 0 | 0 | 0 | 7 |
| GL03-28 | Tanglefoot | 0 | 0 | 0 | 7 | 10 | 19 | 0 | 3 | 0 | 0 | 0 | 26 |
| GL03-34B | Tanglefoot | 0 | 0 | 0 | 2 | 7 | 5 | 0 | 0 | 1 | 1 | 8 | 9 |
| GL03-35A | Tanglefoot | 0 | 0 | 0 | 0 | 4 | 3 | 0 | 0 | 0 | 0 | 0 | 24 |
| GL03-36A | Tanglefoot | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 45 |
| GL03-42 | Tanglefoot | 0 | 15 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 18 | 18 |
| GL03-52A | Tanglefoot | 0 | 0 | 7 | 6 | 26 | 7 | 0 | 0 | 0 | 0 | 5 | 74 |
| GL03-54A | Tanglefoot | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| GL03-55A | Tanglefoot | 1 | 1 | 0 | 0 | 10 | 2 | 0 | 0 | 0 | 0 | 0 | 10 |
| GL03-55B | Tanglefoot | 2 | 0 | 0 | 0 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 19 |
| GL03-56 | Tanglefoot | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 6 |
| GL03-76 | Tanglefoot | 0 | 0 | 0 | 0 | 10 | 14 | 0 | 0 | 0 | 0 | 0 | 27 |
| GL03-76AA | Tanglefoot | 0 | 14 | 0 | 0 | 4 | 2 | 0 | 0 | 0 | 0 | 0 | 31 |
| GL03-76AAA | Tanglefoot | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 57 |
| GL03-76H | Tanglefoot | 0 | 2 | 0 | 1 | 7 | 2 | 0 | 0 | 0 | 0 | 0 | 25 |
| GL03-80 | Richthofen | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 |
| GL03-87 | Richthofen | 0 | 9 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 12 |
| GL04-3A | Richthofen | 0 | 0 | 0 | 0 | 22 | 14 | 2 | 0 | 0 | 0 | 0 | 32 |
| GL04-3B | Richthofen | 0 | 0 | 1 | 0 | 8 | 19 | 0 | 0 | 0 | 0 | 0 | 25 |
| GL04-6 | Richthofen | 0 | 0 | 0 | 0 | 4 | 3 | 0 | 0 | 0 | 0 | 0 | 25 |
| GL04-14 | Richthofen | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 26 |
| GL04-46 | Richthofen | 0 | 0 | 4 | 0 | 5 | 5 | 0 | 0 | 0 | 0 | 0 | 31 |
| GL04-67 | Richthofen | 0 | 9 | 0 | 0 | 14 | 2 | 0 | 0 | 0 | 0 | 7 | 39 |
| GL04-88 | Richthofen | 0 | 0 | 0 | 0 | 23 | 53 | 0 | 0 | 0 | 0 | 0 | 56 |
| GL04-91 | Richthofen | 1 | 0 | 0 | 0 | 35 | 12 | 0 | 0 | 0 | 0 | 1 | 26 |
| GL04-99 | Richthofen | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 12 |
| GL04-103 | Tanglefoot | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| GL04-106 | Richthofen | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 13 |
| GL05-18 | Tanglefoot | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 7 |
| GL07-100 | Tantalus | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## APPENDIX 1 continued

| SAMPLE | UNIT | Andesite | Rhyolite | Dacite | Porphyry | Felsite | Agglomerate | Sandstone | Siltstone | Mudstone | Chert | Limestone | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GL03-4 | Tanglefoot | 0 | 0 | 1 | 3 | 8 | 2 | 0 | 0 | 0 | 0 | 0 | 77 |
| GL03-7 | Tanglefoot | 0 | 0 | 0 | 5 | 23 | 0 | 5 | 0 | 1 | 3 | 0 | 103 |
| GL03-11B | Ttanglefoot | 0 | 0 | 1 | 18 | 4 | 0 | 0 | 1 | 1 | 0 | 0 | 58 |
| GL03-21 | Tanglefoot | 0 | 0 | 0 | 18 | 16 | 0 | 3 | 0 | 3 | 0 | 1 | 99 |
| GL03-26A | Tanglefoot | 0 | 0 | 0 | 18 | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 69 |
| GL03-28 | Tanglefoot | 0 | 0 | 0 | 19 | 5 | 0 | 0 | 0 | 1 | 0 | 0 | 90 |
| GL03-34B | Tanglefoot | 0 | 0 | 0 | 8 | 26 | 0 | 0 | 0 | 2 | 0 | 0 | 69 |
| GL03-35A | Tanglefoot | 0 | 0 | 0 | 40 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 75 |
| GL03-36A | Tanglefoot | 0 | 0 | 0 | 18 | 0 | 0 | 0 | 0 | 0 | 0 | 28 | 93 |
| GL03-42 | Tanglefoot | 0 | 0 | 0 | 6 | 2 | 0 | 0 | 0 | 5 | 0 | 0 | 65 |
| GL03-52A | Tanglefoot | 0 | 0 | 0 | 18 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 145 |
| GL03-54A | Tanglefoot | 0 | 0 | 97 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 100 |
| GL03-55A | Tanglefoot | 0 | 0 | 0 | 41 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 75 |
| GL03-55B | Tanglefoot | 0 | 0 | 0 | 61 | 0 | 0 | 0 | 0 | 0 | 0 | 23 | 122 |
| GL03-56 | Tanglefoot | 0 | 0 | 0 | 29 | 2 | 0 | 0 | 0 | 0 | 0 | 7 | 46 |
| GL03-76 | Tanglefoot | 0 | 0 | 0 | 34 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 86 |
| GL03-76AA | Tanglefoot | 0 | 0 | 0 | 17 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 72 |
| GL03-76AAA | Tanglefoot | 0 | 0 | 0 | 47 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 107 |
| GL03-76H | Tanglefoot | 0 | 0 | 0 | 11 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 50 |
| GL03-80 | Richthofen | 0 | 0 | 0 | 48 | 1 | 1 | 0 | 1 | 0 | 0 | 33 | 97 |
| GL03-87 | Richthofen | 0 | 0 | 0 | 54 | 0 | 0 | 0 | 0 | 7 | 0 | 22 | 107 |
| GL04-3A | Richthofen | 0 | 0 | 0 | 48 | 0 | 0 | 0 | 0 | 3 | 2 | 6 | 129 |
| GL04-3B | Richthofen | 0 | 0 | 0 | 36 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 91 |
| GL04-6 | Richthofen | 0 | 0 | 0 | 23 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 73 |
| GL04-14 | Richthofen | 0 | 0 | 0 | 48 | 0 | 0 | 0 | 0 | 0 | 0 | 16 | 93 |
| GL04-46 | Richthofen | 0 | 8 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 58 |
| GL04-67 | Richthofen | 19 | 5 | 0 | 31 | 0 | 0 | 0 | 18 | 0 | 0 | 0 | 144 |
| GL04-88 | Richthofen | 2 | 0 | 0 | 55 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 198 |
| GL04-91 | Richthofen | 13 | 1 | 0 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 103 |
| GL04-99 | Richthofen | 3 | 2 | 0 | 45 | 0 | 1 | 0 | 16 | 0 | 0 | 8 | 92 |
| GL04-103 | Tanglefoot | 3 | 0 | 0 | 5 | 5 | 0 | 0 | 1 | 0 | 3 | 15 | 39 |
| GL04-106 | Richthofen | 8 | 0 | 0 | 12 | 2 | 0 | 0 | 0 | 0 | 12 | 10 | 59 |
| GL05-18 | Tanglefoot | 0 | 0 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 24 |
| GL07-100 | Tantalus | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 | 100 |
|  |  |  |  |  |  |  |  |  |  |  |  |  | 3008 |