Sedimentology, stratigraphy and source rock potential of the Richthofen formation (Jurassic), northern Whitehorse Trough, Yukon

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ABSTRACT

Whitehorse Trough is a frontier basin in south-central Yukon that is thought to contain gas and possibly oil. It formed in the early Triassic as an arc-marginal basin between the ancient North American margin to the east and the volcano-plutonic Stikine Terrane to the west. Three stratigraphic units, termed the Lewes River Group (Upper Triassic), the Laberge Group (Lower-Middle Jurassic) and the Tantalus Formation (Upper Jurassic-Lower Cretaceous), are recognized in the Whitehorse Trough. The Laberge Group is informally subdivided into four units, which, from the base upwards includes the Richthofen, Conglomerate, Nordenskiold and Tanglefoot formations. The Richthofen formation in the Laberge map area (NTS 105E) is characterized by thin- to medium-bedded turbidites, massive sandstone, matrix- and clast-supported conglomerate, scarce ammonites and belemnites, and abundant trace fossils, particularly *Chondrites*. No comprehensive stratigraphic section exists for the Richthofen formation, but it is estimated to be at least 500 m thick and appears to consist of a lower clast-supported conglomerate unit, a middle unit dominated by thin- to-medium bedded turbidites with minor amounts of massive sandstone and clast- and matrix-supported conglomerate, and an upper clast-supported conglomerate unit. The Richthofen formation unconformably overlies the Lewes River Group and was deposited by a southeast-prograding submarine fan (or fans) during the Early Jurassic. It is correlative with the Inklin Formation in northwestern British Columbia. Programmed pyrolysis using Rock-Eval 6 analysis of 63 samples from the Richthofen formation indicates that it is a poor to fair source rock and is gas-prone.

RÉSUMÉ

La cuvette de Whitehorse est un bassin sous-exploré du centre-sud du Yukon qui pourrait renfermer du gaz et probablement du pétrole. Il s'est formée au cours du Trias précoce sous forme de bassin marginal d'arc entre l'ancienne marge nord-américaine à l'est et le terrane volcano-plutonique de Stikine à l'ouest. On a identifié trois unités stratigraphiques dans le bassin de Whitehorse, désignées comme le Groupe de Lewes River (Trias supérieur), le Groupe de Laberge (Jurassique inférieur à moyen) et la Formation de Tantalus (Jurassique supérieur à Crétacé inférieur). Le Groupe de Laberge se subdivise en quatre unités informelles qui, de la base vers le haut, comprennent les formations de Richthofen, de Conglomerate, de Nordenskiold et de Tanglefoot. La formation de Richthofen, située dans la région de la carte Laberge (105E), est caractérisée par des turbidites en lits variant de minces à moyens, du grès massif, des conglomérats à texture non jointive et jointive, de rares ammonites et bélemnites, ainsi que d'abondantes empreintes fossiles, particulièrement des chondrites. Bien qu'aucune coupe stratigraphique détaillée n'existe pour la formation de Richthofen, son épaisseur est estimée à au moins 500 m et elle semble se composer d'une unité inférieure de conglomérat à texture jointive, d'une unité médiane dominée par des turbidites en lits minces à moyens avec de petites quantités de grès massif et de conglomérats à texture jointive et non jointive, ainsi que d'une unité supérieure de conglomérat à texture jointive. La formation de Richthofen repose en discordance sur le Groupe de Lewes River et a été déposée sous forme d'un cône (ou de plusieurs cônes) sous-marin progradant vers le sud-est, au Jurassique précoce. Cette formation est en corrélation avec la Formation d'Inklin, au nord-ouest de la Colombie-Britannique. Une pyrolyse programmée, réalisée par analyse Rock-Eval 6 de 63 échantillons de la formation de Richthofen, indique qu'il s'agit d'une roche mère de faible à bonne qualité, susceptible de renfermer du gaz.

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INTRODUCTION

The Whitehorse Trough is the northernmost of four 'Interior Cordilleran' basins in northwestern Canada (i.e., from south to north: Quesnel, Nechako, Bowser and Whitehorse) that exhibit similar patterns of sedimentary history and tectonic evolution, and have corresponding oil and gas potential (Teitz and Young, 1982). It forms a northward-tapering belt (approximately 70 km wide and 650 km long) of Mesozoic volcanic and sedimentary rocks that extends from northern British Columbia to Carmacks in south-central Yukon (Fig. 1). No petroleum shows have been documented in this 'frontier' basin and no wells have been drilled, but 170 km of deep sounding multi-channel seismic reflection data was acquired in 2004 (White et al., 2004). The National Energy Board (2001) describes the Whitehorse Trough as an 'immature, mainly gas-prone' basin and identified potential source rocks (i.e., Triassic carbonates and Jurassic 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 pinchouts). It is estimated that the expected mean oil content of the basin is ~15x10^6 m^3, and the expected mean gas volume is ~136x10^6 m^3 (K. Osadetz, pers. comm., 2004).

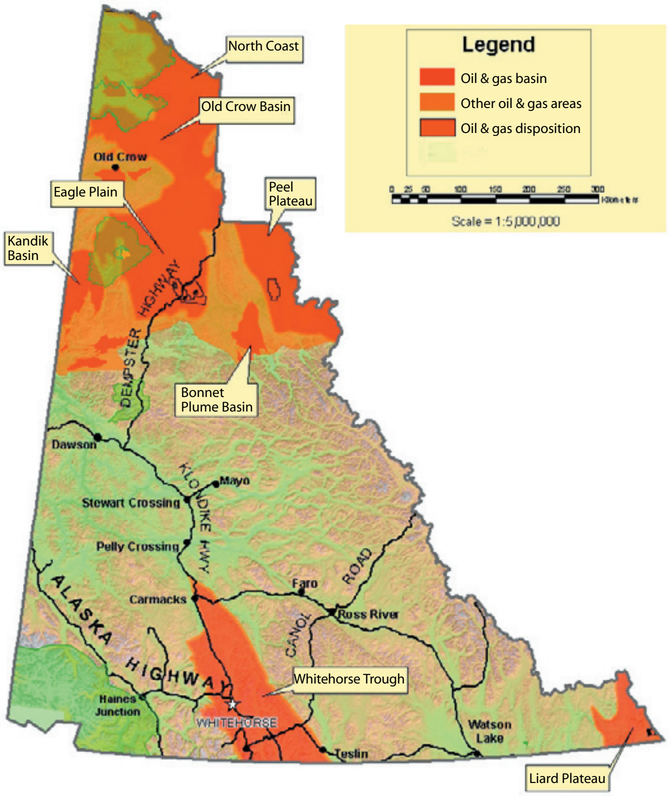

Figure 1. *Oil and gas basins in the Yukon showing the location of the Whitehorse Trough (Energy, Mines and Resources).*

Wheeler (1961) introduced the term 'Whitehorse Trough' and recognized three stratigraphic units (i.e., the Lewes River and Laberge groups and the Tantalus Formation). The Lewes River Group (Upper Triassic) is informally subdivided into the lowermost Povoas formation, consisting of basalt, tuff and agglomerate, and interpreted as subaqueous lava flows; and the uppermost Aksala formation, consisting of sandstone, shale, conglomerate and limestone, and interpreted as deep-marine, reef, beach and tidal flat deposits (Tempelman-Kluit, 1978, 1980, 1984). The Laberge Group (Lower-Middle Jurassic) was informally subdivided by Tempelman-Kluit (1984) into four units, which, from the base upwards includes the Richthofen (i.e., thin- to medium-bedded turbidites), Conglomerate (i.e., framework-supported conglomerate), Nordenskiold (i.e., dacite tuff) and Tanglefoot (i.e., coal-bearing sandstone, shale and conglomerate) formations, which are interpreted as submarine fan, fan delta, subaqueous pyroclastic and delta deposits, respectively (Cairnes, 1910; Lees, 1934; Bostock and Lees, 1938; Lowey, 2004). The Tantalus Formation (Upper Jurassic-Lower Cretaceous) consists of fluvial and paralic sandstone, conglomerate and coal (Lowey and Hills, 1988).

The Whitehorse Trough is interpreted to have originated in Middle to Late Triassic time as either a back-arc or fore-arc basin undergoing oblique convergence, with the ancient North American margin on the east and the volcano-plutonic Stikine Terrane on the west (Tempelman-Kluit, 1978, 1979; Bultman, 1979). Lowey and Hills (1988) demonstrated that sandstone compositions from the Lewes River and Laberge groups and the Tantalus formation indicate sedimentation in two discrete basins: sandstones from the Lewes River and Laberge groups reflect an undissected through to dissected magmatic arc provenance, compatible with a back-arc or fore-arc basin, whereas sandstones from the Tantalus Formation reflect a lithic and transitional orogenic provenance, compatible with an intra-suture embayment basin.

The purpose of this paper is to document the sedimentology and stratigraphy (i.e., lithology, fossils, contacts, distribution, environment of deposition, age and correlation) of the Richthofen formation, primarily in the

Lake Laberge map area (NTS 105E). It is based on examination of outcrops mapped as the Richthofen formation, during which data was recorded on the thickness, type of contact(s), texture, sorting, grading, sedimentary structures, paleoflow direction, colour, clast composition, shape and roundness, and type of lithofacies observed. In addition, samples were collected for thin section microscopy, microfossils, major and trace element whole-rock geochemistry, source rock potential and x-ray diffraction analysis. This report is a preliminary step towards properly formalizing the stratigraphy of the Laberge Group, which is required because of confusion regarding the stratigraphy of the Whitehorse Trough and incorrect descriptions of the strata as 'time-rock' units (see discussion in Lowey, 2004). The paper also presents the results of programmed pyrolysis of samples from the Richthofen formation (mostly from the Lake Laberge map area) that was used to evaluate the source rock potential of this unit.

The Lake Laberge map area was previously mapped by Cairnes (1910), Lees (1934), Bostock and Lees (1938) and Tempelman-Kluit (1978, 1980, 1984). Dickie (1989) and Dickie and Hein (1988, 1992, 1995) provide initial descriptions of the sedimentology and stratigraphy of the Richthofen formation, and Lowey (2004) summarizes the lithostratigraphy of the unit.

SEDIMENTOLOGY AND STRATIGRAPHY

Tempelman-Kluit (1984) proposed the name 'Richthofen formation' for 'recessive, dark brown weathering, thin-bedded, dark brown to greenish, silty shale' with minor conglomerate exposed in the Lake Laberge (NTS 105E) and Carmacks (NTS 115I) map areas. No formal definition of the Richthofen formation has been published and no type section was identified for this unit, although the west shore of Lake Laberge opposite Richthofen Island was designated as the type area (see Lowey, 2004).

LITHOLOGY

Eleven stratigraphically repetitive lithofacies types are recognized in the Richthofen formation (Table 1). The most common lithofacies, based on the total thickness of lithofacies in all measured sections, includes thin-bedded sandstone-mudstone couplets (i.e., facies C2.3, using the code for deep-water sediments of Pickering et al., 1989) and disorganized conglomerate (i.e., facies A1.1). Medium-bedded turbidites (i.e., facies C2.2), disorganized muddy conglomerate (i.e., facies A1.2), and coherently folded and contorted strata (i.e., facies F2.1) are common; whereas disorganized pebbly sandstone (i.e., facies A1.4), graded-stratified pebbly sandstone (i.e., facies A2.8), medium- to thick-bedded sandstone (i.e., facies B1.1), parallel-stratified

Table 1. *Lithofacies types observed in the Richthofen formation, Lake Laberge area (lithofacies classification after Pickering et al., 1989).*

Code	Description	Other characteristics
A1.1	disorganized conglomerate	clasts up to 120 cm long
A1.2	disorganized muddy conglomerate	clasts up to 15 m long
A1.4	disorganized pebbly sandstone	clasts up to 2 cm long
A2.8	graded stratified pebbly sandstone	clasts up to 1 cm long, tuffaceous
B1.1	thick/medium-bedded, disorganized sandstone	–
B2.1	parallel-stratified sandstone	locally tuffaceous
B2.2	cross-stratified sandstone	coarse- to very coarse-grained sand
C2.2	medium-bedded sandstone-mudstone couplets	very fine- to medium-grained sand
C2.3	thin-bedded sandstone-mudstone couplets	very fine- to fine-grained sand, calcareous
C2.3/ D2.1	mixed thin-bedded sandstone-mudstone couplets and muddy siltstone	–
D2.1	graded stratified siltstone	–
F2.1	coherent folded and contorted strata	–

Figure 2. *Thin-bedded sandstone-mudstone couplets (facies C2.3).*

sandstone (i.e., facies B2.1), cross-stratified sandstone (i.e., facies B2.2) and graded-stratified siltstone (i.e., facies D2.1) are rare.

Thin-bedded sandstone-mudstone couplets (C2.3) are less than 10 cm thick, characterized by graded bedding with Bouma Tcde subdivisions (Bouma, 1962), and form sequences at least 40 m thick (Fig. 2). The sandstone is very fine- to fine-grained, and ripple foresets are commonly preserved. These represent 'classical' turbidites and were deposited by turbidity currents (Pickering et al., 1989).

Disorganized conglomerate (A1.1) is clast-supported and characterized by subrounded and spherical plutonic, volcanic and limestone clasts in a sandy to muddy matrix (Fig. 3). Bedding is not apparent and the conglomerate forms sequences at least 85 m thick. It was deposited by confined, noncohesive debris flows (Pickering et al., 1989).

Medium-bedded sandstone-mudstone couplets are 10-30 cm thick (Fig. 4), display graded bedding, contain Bouma Ta(c)de and Tb(c)de subdivisions, and form sequences at least 40 m thick. They were also deposited by turbidity currents (Pickering et al., 1989).

Figure 3. *Clast-supported, disorganized conglomerate (facies A1.1), consisting of subrounded volcanic, plutonic and limestone clasts (Jacob's staff is 1.5 m long).*

Figure 4. *Medium-bedded sandstone-mudstone couplets (facies C2.2).*

Disorganized muddy conglomerate (A1.2) is matrix-supported and characterized by subangular to subrounded, spherical limestone and volcanic clasts in a muddy matrix (Fig. 5). Limestone clasts are up to 15 m long in exposed outcrop dimension (Fig. 6). The disorganized muddy conglomerate was deposited by unconfined, cohesive debris flows (Pickering et al., 1989), and is commonly associated with coherently folded and contorted strata (F2.1). This lithofacies is composed of folded and contorted thin-bedded sandstone-mudstone

Figure 5. *Matrix-supported, disorganized conglomerate (facies A1.2), consisting of subangular limestone clasts.*

Figure 7. *Folded and contorted thin-bedded sandstone-mudstone couplets (facies F2.1; card 8 cm long).*

Figure 6. *Limestone megaclast from matrix-supported, disorganized conglomerate.*

Figure 8. *Massive, medium- to thick-bedded sandstone (facies B1.1; Jacob's staff 1.5 m long).*

couplets (Fig. 7) that represent underwater slides and slumps (Pickering et al., 1989).

Disorganized pebbly sandstone (A1.4) and graded-stratified pebbly sandstone (A2.8) form beds ranging from 0.4 to 1.4 m thick and represent deposition by high concentration turbidity currents (Pickering et al., 1989) or hyperconcentrated density flows (Mulder and Alexander, 2001).

Medium- to thick-bedded sandstone (B1.1) is massive, fine-to medium-grained, and forms sequences at least 38 m thick (Fig. 8). It was deposited by hyperconcentrated density flows (Mulder and Alexander, 2001). Parallel-stratified sandstone (B2.1) and cross-stratified sandstone (B2.2) form beds ranging from 0.5-1.0 m thick, are fine- to medium-grained and represent deposition by high-concentration tubidity currents (Pickering et al., 1989) or hyperconcentrated density flows (Mulder and Alexander, 2001). Graded-stratified siltstone (D2.1) forms sequences at least 10 m thick and was deposited by low concentration turbidity currents (Pickering et al., 1989).

FOSSILS

The Richthofen formation is characterized by a variety of fossils, particularly in the sandstone-mudstone couplets. Pelagic fauna like ammonites are scarce and are preserved as impressions or thin carbonaceous films on bedding planes; belemnites are also scarce, with the guards occurring as longitudinal or transverse sections in outcrop. Trace fossils are common, and in order of decreasing abundance include *Chondrites, Thalassinoides, Zoophycos* and *Planolites*. This ichnocoenose (association of trace fossils) shares characteristics of both the Cruziana ichnofacies (i.e., lower shoreface to lower offshore environments) and the *Zoophycos* ichnofacies (i.e., shelf to slope environments; Pemberton et al., 2001).

THICKNESS

The total thickness of the Richthofen formation is uncertain because no comprehensive stratigraphic section exists. Bostock and Lees (1938) thought that the sandstone-mudstone couplets along the west shore of Lake Laberge formed a sequence at least 300 m thick and possibly more than 1200 m thick. However, examination of the strata reveals that it alternates from right-side-up to overturned and is interbedded with massive sandstone and clast- and matrix-supported conglomerate. Relatively short (~200 m), continuous sedimentologic sections have been measured in the Lake Laberge area, which indicate that the Richthofen formation consists of a lower, clast-supported conglomerate unit at least 200 m thick, a middle unit dominated by thin- to medium-bedded sandstone-mudstone couplets with minor amounts of massive sandstone and clast- and matrix-supported conglomerate at least 100 m thick, and an upper clast-supported conglomerate unit at least 200 m thick.

CONTACTS

Cairnes (1910) determined that the basal unit of the Laberge Group was conglomerate and that it unconformably overlies limestone of the Lewes River Group. Bostock and Lees (1938) suggested that the Laberge Group appears to overlie the Lewes River Group conformably, but were unable to establish with certainty the relations of the two units. However, they (Bostock and Lees, 1938) 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. Tempelman-Kluit (1978) proposed that the Lewes River and Laberge groups represent a single, continuous depositional sequence with perhaps many “local, but minor hiatuses”, leading Hills and Tozer (1981) to conclude that it was impractical to separate the Lewes River and Laberge groups. Tempelman-Kluit (1984) later identified two localities where the Lewes River Group-Laberge Group contact is exposed in outcrop: along the east shore of Lake Laberge opposite Ptarmigan Point (61°16'N, 135°12'W) and on Mount Laurier (61°02'N, 134°02'W). At both of these localities, Tempelman-Kluit (1984) indicates that the Richthofen formation conformably overlies limestone of the Hancock member of the Lewes River Group.

Examination of strata exposed along the east shore of Lake Laberge, opposite Ptarmigan Point, indicates that thin-bedded sandstone-mudstone couplets of the Richthofen formation are overturned and terminate abruptly against massive to thick-bedded limestone belonging to the Hancock member (Fig. 9). This contact is reinterpreted as a steep fault that developed along the south limb of an east-west-trending syncline that is overturned towards the north.

A section measured on the southeast spur of Mount Laurier (Fig. 10) reveals that at least 50 m of fine- to medium-grained, horizontally laminated sandstone and

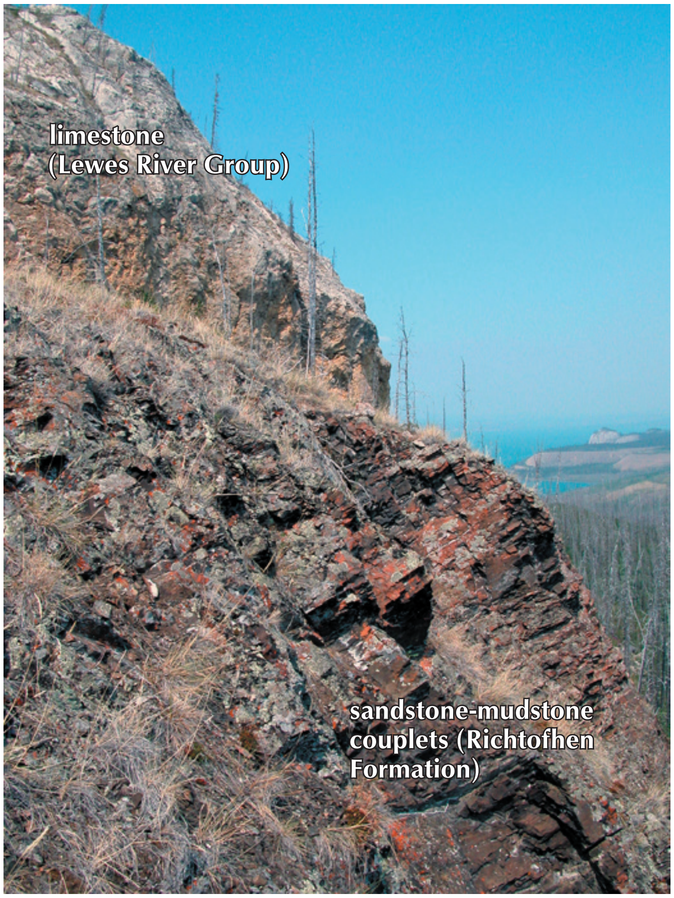

Figure 9. *Overturned sandstone-mudstone couplets of the Richthofen formation juxtaposed against massive limestone of the Hancock Member (Lewes River Group).*

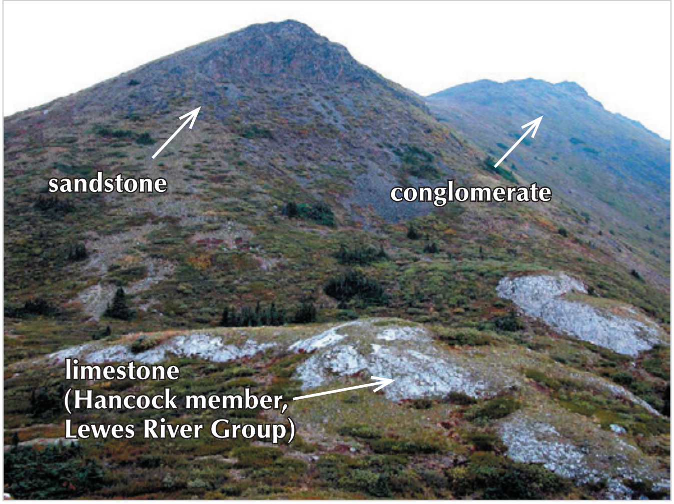

Figure 10. *Mount Laurier, looking north.*

minor amounts of horizontally laminated tuff (Fig. 11), with locally herringbone cross-stratified sandstone, interlaminated mudstone, and rare *Skolithos*, overlies massive to thick-bedded limestone of the Hancock member. Herringbone cross-stratification is commonly associated with tidal deposits (Klein, 1977) and *Skolithos* is commonly associated with shoreline and tidal deposits (Pemberton et al., 2001). This sandstone sequence was mapped by Tempelman-Kluit (1984) as the Richthofen formation, and it is overlain by clast-supported conglomerate with minor amounts of interbedded sandstone that Tempelman-Kluit (1984) mapped as the Conglomerate formation. However, the sandstone sequence is unlike any lithology present in the Richthofen formation and more closely resembles the Mandanna member of the Lewes River Group.

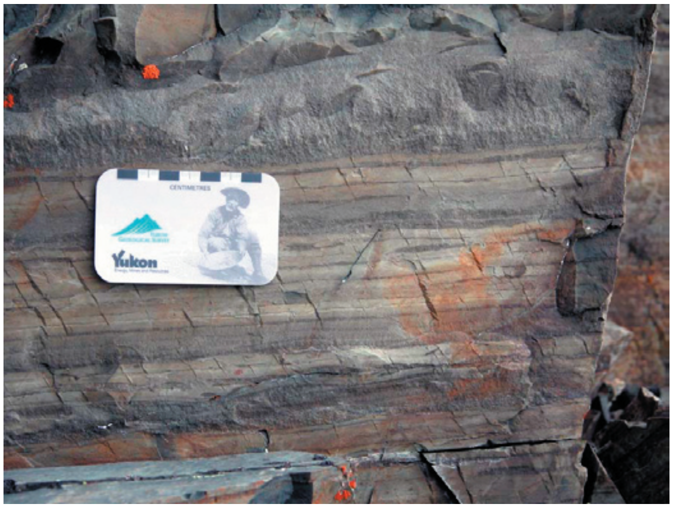

Figure 11. *Horizontally laminated sandstone and tuff, Mount Laurier.*

The Mandanna member, the uppermost unit of the Lewes River Group, is described by Tempelman-Kluit (1984), and Dickie and Hein (1995) as a sequence of siltstone, sandstone and tuff, with locally abundant *Skolithos,* that was deposited in a tidal environment. In addition, Tempelman-Kluit (1978) describes "cross-bedded, quartzose sandstone" (mapped as the Lewes River Group) that grades into bioclastic limestone of the Hancock member in the vicinity of Lime Peak (i.e., directly north of Mount Laurier). Therefore, the sandstone sequence exposed on Mount Laurier is also interpreted as the Mandanna member.

Although Dickie and Hein (1995) state that the Mandanna member is of questionable affinity and could belong to either the uppermost Lewes River Group or the basal Laberge Group, the overlying conglomerate contains, in addition to rounded volcanic and limestone clasts, rounded siltstone and fine-grained sandstone clasts that resemble the underlying sandstone sequence. According to Lahee (1961) and Compton (1985), one of the criteria used in recognizing an unconformity is the presence of clasts from an underlying unit in the overlying unit. Hence, the contact between the sandstone sequence and the conglomerate is interpreted as an unconformity and the conglomerate is assigned to the Richthofen formation.

This conglomerate is interpreted as a submarine fan channel deposit (see the section on Environment of Deposition), and although most 'good' outcrops are ~10 to 100 m wide, submarine fan channels can be ~1 km wide or more (Bouma et al., 1985). Hence, the contact between the Lewes River Group and the overlying Laberge Group may be a disconformity, or even an angular unconformity, and does not support the conclusion of Hills and Tozer (1981) that it is impractical to separate the Lewes River and Laberge groups.

The upper contact of the Richthofen formation is not exposed, but Tempelman-Kluit (1984) indicates that this unit overlaps in age with the Nordenskiold and Conglomerate formations. He (Tempelman-Kluit, 1984) also shows the Richthofen and Tanglefoot formations juxtaposed in an apparent conformable contact along Fox Lake, whereas Dickie and Hein (1995) present a stratigraphic column showing the Richthofen formation interfingering with both the Conglomerate and Tanglefoot formations. The upper contact of the Richthofen formation is the focus of future research.

Figure 12. *Lenticular and wavy bedding in very fine-grained sandstone and mudstone in drill core from the Division Mountain area. The core was incorrectly mapped as Richthofen formation and has now been assigned to the Tanglefoot formation.*

DISTRIBUTION

Division Mountain area

Lowey (2004) demonstrated that the Richthofen formation does not occur at Five Finger Rapids north of Carmacks in the Carmacks map area (NTS 115I) as mapped by Tempelman-Kluit (1984); nor does it occur along Joe or Fossil creeks east of the Division Mountain coal deposit in the Laberge map area (NTS 105E) as mapped by Tempelman-Kluit (1984) and Allen (2000). However, Carnes and Gish (1996, p. 38) reported the Richthofen formation in the Division Mountain area, describing it as “brown weathering black mudstone, with wispy siltstone to fine sandstone laminae in the form of low amplitude cross-stratification, (that) alternates with thick (>10 m) intervals of massive brown weathering calcareous sandstone”. In addition, Cash Resources Ltd. (1998) present several cross-sections showing that the Richthofen formation was intersected in drill core beneath the Tanglefoot formation [Note: in both of these reports and in Dickie (1989), the Richthofen formation is misspelled]. Examination of the drill core at Division Mountain (Fig. 12) reveals that the “black mudstone, with wispy siltstone to fine sandstone laminae”, has lenticular to wavy bedding, and not the graded bedded, sandstone-mudstone couplets characteristic of the Richthofen formation. According to Reineck and Singh (1975), lenticular and wavy bedding is common in tidal and delta-front deposits. Hence, the Richthofen formation does not occur in the Division Mountain area, and strata previously interpreted as this unit is herein assigned to the Tanglefoot formation. This interpretation has important implications regarding the coal reserves in the area, because Cash Resources Ltd. stopped drilling when they intersected what they thought was the Richthofen formation; deeper drilling may reveal additional coal deposits.

Lake Laberge area

Tempelman-Kluit (1984) apparently included all mappable occurrences of conglomerate, including clast- and matrix-supported varieties, in the ‘Conglomerate formation’. However, the matrix-supported conglomerate exposed along Lake Laberge is intrinsically associated with folded and contorted thin-bedded sandstone-mudstone couplets and sandstone-mudstone couplets that are characteristic of the Richthofen formation. In addition, both the matrix-supported and clast-supported conglomerate occurs as stratigraphically repetitive lithofacies which are part of the same depositional system as the sandstone-mudstone couplets. Hence, they should be assigned to the Richthofen formation (perhaps as members), or they should be designated as a new formation(s), because they are not correlative with the Conglomerate formation in the type area at Conglomerate Mountain. The conglomerate at Conglomerate Mountain occurs at a different stratigraphic level and represents a spatially separate deposit than the conglomerate in the Lake Laberge area. In addition, Dickie and Hein (1992) pointed out that the so-called Richthofen and Conglomerate formations in the Whitehorse map area (NTS 105D) are “strongly intercalated” and occur as “laterally equivalent lithozones”. Note that both the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983) and the International Stratigraphic Guide (Salvador, 1994) state that lithocorrelation requires the demonstration of similar lithologic properties and stratigraphic position, which according to Schoch (1989) generally implies that a lithostratigraphic unit was deposited as a continuous body of rock without breaks.

AGE

According to Tempelman-Kluit (1984), the Richthofen formation ranges from Hettangian to Pliensbachian in age (i.e., earliest to middle Early Jurassic). However, Lowey (2004) proposed that the unit ranges from Hettangian to Toarcian in age (i.e., earliest to latest Early Jurassic), based on re-assigning misidentified strata to other formations. Mihalynuk (1999) concluded that Richthofen formation correlative strata across the Yukon border in northwestern British Columbia ranges from Sinemurian to Toarcian in age.

ENVIRONMENT OF DEPOSITION

Paleoflow indicators are sparse in the Richthofen formation, but ripple foresets from thin- and medium-bedded turbidites (i.e., the Bouma Tc division) dip southeast and northwest; groove marks from the base of massive sandstone beds reveal an approximately southeast-northwest to east-west paleoflow direction; and flute marks and current crescent marks from the base of clast-supported conglomerate beds indicate scouring by a southeast-directed paleocurrent (Fig. 13). Flutes and crescents are considered the most reliable paleoflow indicators (i.e., they were deposited by sustained, high-energy flows), and together with the southeast and east direction recorded by the grooves, indicate an overall southeast paleoflow direction. The dip directions of ripple foresets are considered less reliable for recording paleoflow directions because they are difficult to measure (i.e., three-dimensional exposures are generally required) and measured paleocurrent directions may differ by 90° or more from other paleoflow indicators (i.e., thin-bedded turbidites are commonly deposited as overflow sediments on levees adjacent to major channels and in interchannel areas). Dickie (1989) also reports a southeast paleoflow for Richthofen strata from the Lake Laberge area.

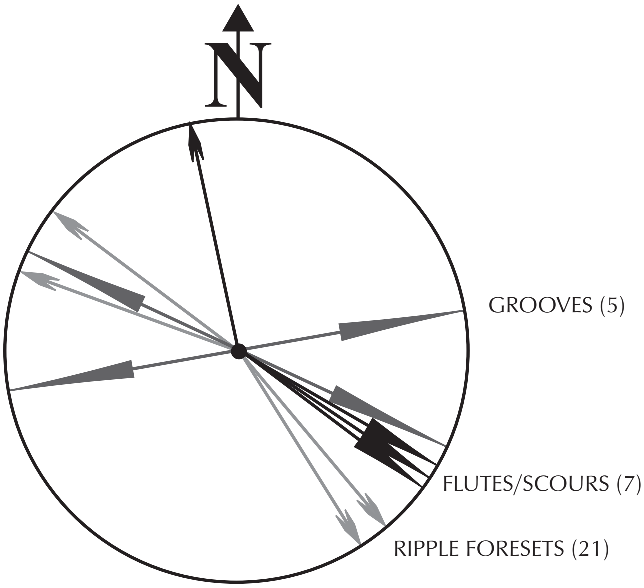

Figure 13. *Summary of paleocurrent data, Richthofen formation (arrows represent mean paleocuurrent directions for the number of measurements indicated).*

The various lithofacies observed in the Richthofen formation and their mode of transport (i.e., primarily sediment gravity flows) are compatible with deposition on a submarine fan (or fans), such as the model proposed by Pickering et al. (1989). Hence, clast-supported conglomerate (i.e., lithofacies A) represents inner-fan channel deposits, massive sandstone (i.e., lithofacies B) represents middle-fan lobe deposits, and thin- to medium-bedded sandstone-mudstone couplets (i.e., lithofacies C) represent outer-fan levee and interchannel/interlobe deposits. The Richthofen formation and correlative strata (see the section on Correlation) crop out for a distance of approximately 400 km along the Whitehorse Trough, which is comparable to some modern days fans, such as the Laurentian Fan and the Mississippi Fan (i.e., 500-1500 km long). However, these are passive-margin fans, and active-margin fans are generally smaller (i.e., 40-400 km long). Reading and Richards (1994) present a classification for turbidite systems based on grain size and feeder system, but not enough paleocurrent data has been obtained from the Richthofen formation to determine if it originated as 'point-source' (i.e., submarine fan), 'multiple-source' (i.e., submarine ramp), or 'linear-source' (i.e., submarine slope apron) sedimentation.

CORRELATION

Souther (1971), working in the Tulsequah map area in northwestern British Columbia, assigned the Inklin and Takwahoni formations of Kerr (1948) to the Laberge Group. The Inklin formation (Lower-Middle Jurassic) consists of approximately 3000 m of interbedded sandstone, sandstone-mudstone couplets, clast- and matrix-supported conglomerate, and minor amounts of limestone interpreted as deep-water marine deposits. The Takwahoni Formation (Lower-Middle Jurassic) consists of approximately 3300 m of clast-supported conglomerate, sandstone and mudstone interpreted as shallow-water marine and fluvial deposits (Souther, 1971). Dickie and Hein (1995) and The National Energy Board (2001) suggested that the Richthofen formation is also correlative, in part, with the Inklin Formation.

SOURCE ROCK POTENTIAL

The petroleum source-rock potential of the Richthofen formation was evaluated by programmed pyrolysis using Rock-Eval 6 analysis (Peters, 1986). Essentially, this method takes approximately 70 mg of pulverized rock and heats it in a nitrogen atmosphere in a special oven, measuring, among other things, the amount of free hydrocarbons in the sample (S1), the amount of potential hydrocarbons in the sample (S2, or kerogen that can be pyrolyzed into hydrocarbons), and the total amount of carbon present in the sample (basically a sum of S1, S2 and other parameters; Tissot and Welte, 1984; Waples, 1985). Sixty-three samples were collected from outcrop of the sandstone-mudstone couplets, and the analyses were performed by the Geological Survey of Canada at Calgary, Alberta (Appendix 1). The guidelines published by Peters (1986) were used for evaluating the source rock potential based on the results of programmed pyrolysis (Table 2). Note that Behar et al. (2001), Lafargue et al. (1998) and Peters (1986) all advise that results of programmed pyrolysis from outcrop samples be interpreted with caution (i.e., organic matter may have been oxidized, resulting in low S1 and S2 values) and supported by other analyses (i.e., vitrinite reflectance). In addition, Waples (1985) notes that results of Rock-Eval analyses provide information only on the present-day hydrocarbon generative capacity of kerogen in the rock.

Three main factors are considered in determining the source rock potential: 1) the generative potential, based on the percent of total organic carbon (TOC), the amount of free hydrocarbons (S1) and the amount of pyrolyzed hydrocarbons (S2); 2) the level of thermal maturation, based on the production index [PI=S1/(S1+S2)] and the temperature of maximum production of pyrolyzed hydrocarbons (T_{max}); and 3) the type of hydrocarbon generated, based on the hydrogen index [HI=(S2x100)/TOC] and the ratio of S2/S3 (S3=CO_2 from organic matter; Peters, 1986).

The thermal maturation of the Richthofen strata is quite favourable, with several samples having a PI within the oil window, or the correct maturation (Fig. 14); similarly, a plot of T_{max} (Fig. 15) shows several samples within the oil window (i.e., some samples are mature, but some are under-mature and over-mature). Note that Peters (1986) considers T_{max} obtained from small S2 values (i.e., <0.2 mg HC/g TOC) unreliable. The generative potential of the rocks is less favourable. A plot of TOC (Fig. 16) shows that most of the samples have only a poor to fair source rock potential due to low amounts of organic carbon. A plot of S1 is even less favourable (Fig. 17), with all samples containing very minor amounts of free hydrocarbons. Similarly, for S2, all samples contain very little organic matter that can be converted to petroleum (Fig. 18). Due to the small values obtained for S2, determining the type of hydrocarbons present is not

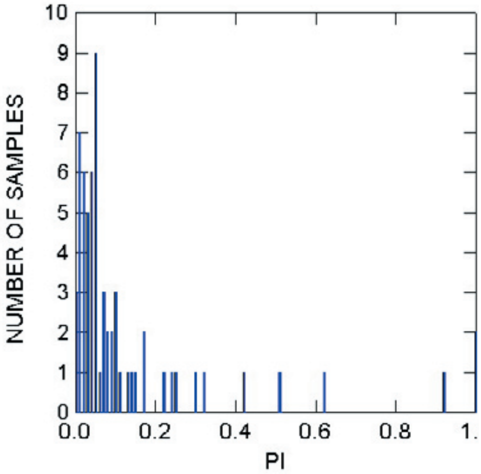

Figure 14. *Plot of PI, Richthofen formation.*

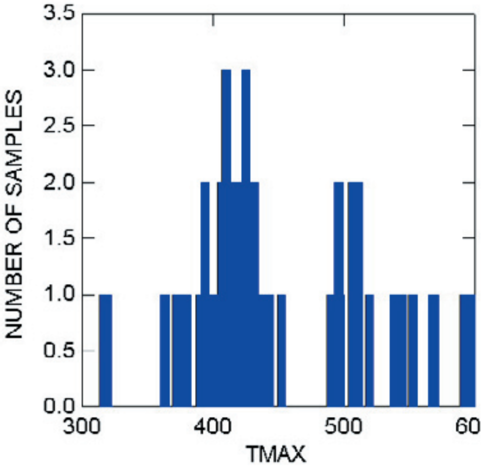

Figure 15. *Plot of* T_{max} *(0°), Richthofen formation.*

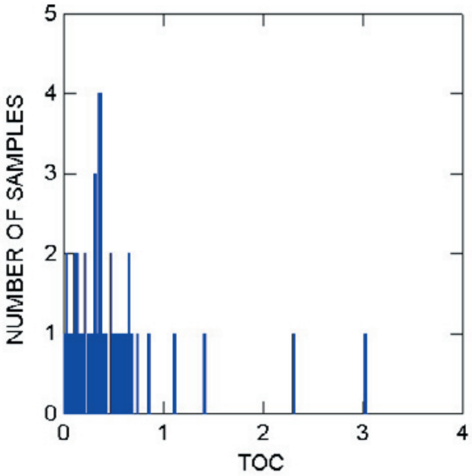

Figure 16. *Plot of TOC, Richthofen formation.*

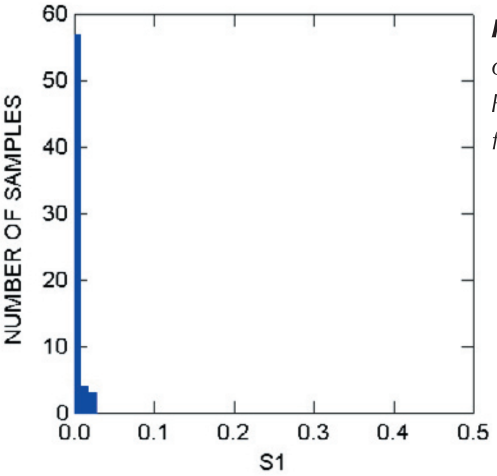

Figure 17. *Plot of S1, Richthofen formation.*

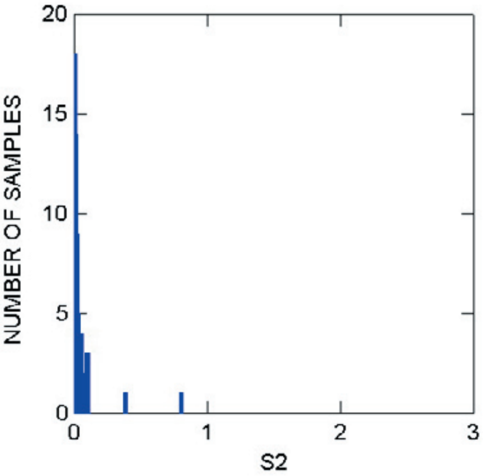

Figure 18. *Plot of S2, Richthofen formation.*

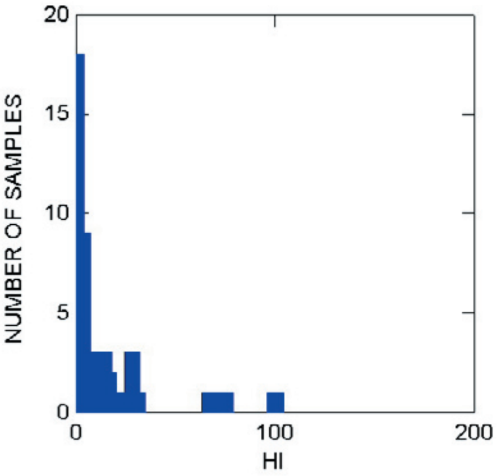

Figure 19. *Plot of HI, Richthofen formation.*

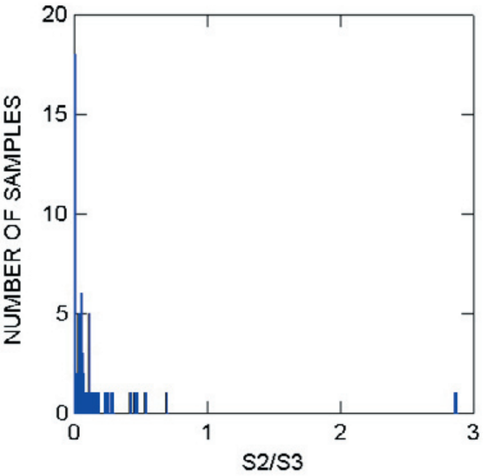

Figure 20. *Plot of S2/S3 ratio, Richthofen formation.*

Table 2. *Programmed pyrolysis guidelines describing level of thermal maturation, generative potential, and type of hydrocarbon generated (from Peters, 1986).*

Level of thermal maturation			
Maturation	**PI [S1/(S1+S2)]**	**T_{max} (°C)**	
top of oil window (birthline)	~0.1	~435 to 445*	
bottom of oil window (deadline)	~0.4	~470	
**depends on the type of organic matter*			
Generative potential			
Quantity	**TOC (wt. %)**	**S1 (mg HC/g C_{org})**	**S2 (mg HC/g C_{org})**
poor	<0.5	0 to 0.5	0 to 2.5
fair	0.5 to 1	0.5 to 1	2.5 to 5
good	1 to 2	1 to 2	5 to 10
very good	>2	>2	>10
Type of hydrocarbon generated			
Type	**HI (mg HC/g C_{org})**	**S2/S3**	
gas	0 to 150	0 to 3	
gas and oil	150 to 300	3 to 5	
oil	>300	>5	

very accurate, but a plot of HI (Fig. 19) and S2/S3 (Fig. 20) indicates that only gas would have been generated. Similarly, the OI-HI diagram is not considered very reliable because most of the carbon is inert, but again only gas would be expected.

DISCUSSION

A study in 1985 by Petro-Canada (Gilmore, 1985; Gunther, 1985) found the Richthofen formation to be the most prospective unit within the Whitehorse Trough, with a strong probability of gas, and possibly some oil, being present. A review of their results, however, indicates that it is actually the Tanglefoot formation (i.e., the uppermost unit of the Laberge Group), and not the Richthofen formation, that has the best source rock potential. Gilmore (1985) makes reference to a “coal-bearing” bed in the Richthofen formation and Gunther (1985) reports vitrinite reflectance values of 0.75 and 0.93 (i.e., within the oil window). However, coal occurs in the Tanglefoot formation, but not in the Richthofen formation.

The fact that the Richthofen formation is not a very good source rock for oil or gas is supported by English (2004) who examined the source rock potential of the correlative Inklin Formation in the Whitehorse Trough in northern British Columbia. Although several samples from his study plot within the oil window, most contain very small amounts of free- and potential-hydrocarbons, indicating that the Inklin Formation has only a poor to fair source rock potential and is gas-prone, similar to the Richthofen formation.

CONCLUSIONS

In conclusion, the Richthofen formation in the Lake Laberge (NTS 105E) map area:

1) is characterized by thin-bedded sandstone-mudstone couplets (i.e., turbidites) and clast-supported conglomerate, and to a lesser extent, medium-bedded sandstone-mudstone couplets, massive sandstone and matrix-supported conglomerate;

2) unconformably overlies the Lewes River Group;

3) does not extend far north or west of Lake Laberge;

4) was deposited as a southeast-prograding submarine fan (or fans); and

5) is a poor to fair source rock and is gas-prone.

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APPENDIX 1

RESULTS OF ROCK-EVAL 6 ANALYSIS

Sample	Easting	Northing	Qty	S1	S2	PI	T_{max}	TOC	HI
GL03-90A	489245	6772712	69.9	0.00	0.00	1.00	-40	0.85	0
GL03-90B	489245	6772712	70.1	0.00	0.00	0.00	-40	0.37	0
GL104-01A	482978	6802442	70.1	0.00	0.09	0.01	494	0.32	28
GL104-02A	482393	6803720	70.7	0.02	0.38	0.04	497	1.41	28
GL104-03A	482168	6804552	70.5	0.01	0.10	0.06	491	0.37	27
GL104-05A	482623	6799519	70.7	0.00	0.03	0.05	508	0.21	14
GL104-08A	480760	6799644	70.6	0.00	0.10	0.03	496	0.48	21
GL104-08B	480760	6799644	70.4	0.02	0.80	0.02	506	3.02	28
GL104-10A	482916	6796053	70.2	0.00	0.09	0.03	506	0.58	16
GL104-16A	485588	6792821	70.5	0.00	0.04	0.02	511	0.39	10
GL104-16B	485588	6792821	70.7	0.00	0.00	0.09	490	0.09	0
GL104-16C	485588	6792821	70.3	0.00	0.10	0.01	519	1.11	9
GL104-17A	487670	6784498	70.5	0.00	0.04	0.01	414	0.52	8
GL104-18A	487314	6784785	70.0	0.00	0.04	0.04	406	0.74	5
GL104-19A	487296	6785151	70.0	0.00	0.02	0.08	395	0.33	6
GL104-20A	487103	6785663	70.6	0.00	0.01	0.11	419	0.14	7
GL104-22A	486673	6786747	70.7	0.00	0.00	0.10	417	0.16	0
GL104-23A	486360	6788169	70.6	0.00	0.00	0.09	404	0.17	0
GL104-24A	489553	6778917	70.7	0.00	0.00	0.15	427	0.32	0
GL104-26A	489406	6778202	70.6	0.00	0.01	0.08	415	0.35	3
GL104-27A	489383	6779415	70.8	0.01	0.01	0.51	372	0.30	3
GL104-28A	489268	6780112	70.3	0.00	0.00	0.00	390	0.11	0
GL104-29A	489175	6780655	70.1	0.00	0.00	0.01	363	0.03	0
GL104-30A	489037	6781689	70.5	0.00	0.04	0.05	427	0.13	31
GL104-31A	488848	6782553	70.2	0.00	0.01	0.07	425	0.36	3
GL104-32A	488094	6783424	70.3	0.00	0.01	0.01	400	0.15	7
GL104-33A	491444	6771562	70.4	0.00	0.01	0.02	443	0.11	9
GL104-34A	491725	6771506	70.0	0.00	0.01	0.04	412	0.01	100
GL104-36A	492078	6772503	70.9	0.00	0.00	0.32	394	0.51	0
GL104-38A	491169	6775360	70.2	0.00	0.01	0.03	380	0.31	3
GL104-41A	489115	6773985	70.4	0.00	0.00	0.14	410	0.61	0
GL104-42A	489883	6775821	70.2	0.00	0.02	0.10	418	0.03	67
GL104-43A	490070	6775227	70.5	0.00	0.03	0.02	379	0.04	75
GL104-44A	490421	6773773	70.5	0.00	0.01	0.10	406	0.05	20
GL104-45A	490594	6768588	70.5	0.00	0.05	0.05	425	0.36	14
GL104-47A	488682	6795733	70.7	0.00	0.01	0.02	591	0.67	1
GL104-48A	488298	6794223	70.6	0.00	0.01	0.25	568	0.32	3
GL104-48B	488298	6794223	70.5	0.00	0.02	0.17	538	0.65	3
GL104-48C	488298	6794223	70.1	0.00	0.00	0.42	418	0.37	0
GL104-49A	489163	6793656	70.4	0.00	0.08	0.05	439	0.31	26
GL104-50A	488339	6791663	70.1	0.00	0.00	0.05	544	0.13	0
GL104-52A	489026	6789126	70.2	0.00	0.02	0.04	569	0.37	5
GL104-53A	489319	6788320	70.0	0.00	0.02	0.01	552	0.65	3
GL104-55A	494422	6776779	70.8	0.02	0.05	0.24	493	0.21	24
GL104-56A	495108	6775504	70.9	0.01	0.03	0.13	496	0.19	16
GL104-57A	495525	6774105	70.8	0.01	0.05	0.17	511	0.35	14
GL104-59A	493297	6763660	70.0	0.00	0.09	0.05	417	0.49	18
GL104-59B	493297	6763660	70.6	0.00	0.02	0.05	410	0.31	6
GL104-60A	491993	6766061	70.9	0.00	0.00	0.22	394	0.18	0
GL104-60B	491993	6766061	70.1	0.00	0.03	0.00	425	0.25	12
GL104-61A	491415	6766150	70.3	0.00	0.02	0.04	402	0.26	8
GL104-63A	492320	6765079	70.8	0.00	0.08	0.03	419	2.30	3
GL104-64B	463503	6802692	70.9	0.00	0.00	0.01	407	0.07	0
GL104-65A	474962	6788368	70.9	0.00	0.01	0.07	452	0.40	3
GL104-74A	490495	6760518	70.6	0.00	0.00	0.92	598	0.55	0
GL104-83A	491538	6763490	70.9	0.00	0.02	0.02	431	0.35	6
GL104-85B	491119	6763203	71.2	0.00	0.01	0.03	438	0.28	4
GL104-86A	491441	6763165	71.1	0.00	0.01	0.05	431	0.68	1
GL104-92A	489819	6759345	70.3	0.00	0.02	0.07	416	0.42	5
GL104-92C	489819	6759345	70.0	0.00	0.03	0.05	410	0.35	9
GL104-93A	490232	6759119	70.1	0.00	0.00	0.30	319	0.47	0
GL104-93C	492711	6760581	70.8	0.00	0.00	0.62	316	0.63	0
GL104-94B	492711	6760581	70.4	0.00	0.00	1.00	-40	0.47	0
GL104-95A	492000	6761523	70.0	0.00	0.05	0.04	433	0.29	17