

Contrasting structural settings of mafic and ultramafic rocks in the Yukon-Tanana terrane

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ABSTRACT

Four different suites of mafic and ultramafic rocks occur in the Yukon-Tanana terrane between the Klondike goldfield and Stewart River area. Greenschist facies chloritic schist of mafic to intermediate composition is interlayered with quartzofeldspathic schist in the Klondike Schist. Amphibolite facies mafic gneisses, a major component of basement between Indian River and Stewart River, were emplaced with granitoids during Paleozoic metamorphism as gabbro and pyroxenite intrusions. These greenschist and amphibolite facies gneisses were subsequently sliced into kilometre-thick slabs and stacked by Jurassic thrust faults. This thrust stacking was accompanied by emplacement of discontinuous slices (~100 m thick) of variably serpentinized harzburgites and associated mafic and ultramafic rocks. The thrust stacking occurred under greenschist facies conditions and formed regionally continuous retrogressive shear zones in the amphibolite facies basement. Pyroxenite plutons with little or no deformation or alteration were emplaced in association with Mesozoic granitoids. Recognition of these different mafic/ultramafic rocks facilitates regional mapping.

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INTRODUCTION

The western Yukon region, from the Klondike goldfield to the Stewart River area, is currently the focus of intense exploration activity. This modern day gold rush is the result of recent discoveries of gold-bearing hydrothermal systems hosted in local metamorphic basement lithologies. Despite much of the regional geology having been mapped at 1:50 000 scale (Mortensen, 1996; Ryan and Gordey, 2001, 2004; Gordey and Ryan, 2005), the structural setting and inter-relationships among the different basement lithologies are still being unravelled (e.g., Berman *et al.*, 2007; MacKenzie *et al.*, 2008a,b, 2010; MacKenzie and Craw, 2010); of particular difficulty are the various mafic and ultramafic rocks.

Pyroxenites and gabbros in the White River area were originally mapped as Jurassic intrusive rocks, similar to

those at Pyroxene Mountain that were controlled by Jurassic D_3 structures (MacKenzie and Craw, 2010). However, the White River pyroxenites generally have incipient amphibolite facies foliations on their margins (MacKenzie and Craw, 2010), and are now thought to be part of the Paleozoic basement on the basis of mapping during the 2011 field season in the Black Hills Creek and Barker Creek areas. This incipient foliation is related to the metamorphic D_2 event and is referred to herein as late metamorphic foliation (Table 1). Recognition of relict primary metagabbro and pyroxenite mineralogy and textures in the mafic orthogneisses in the Paleozoic basement distinguishes these from the greenschist facies Jurassic D_3 shear zones. These Jurassic shear zones can also contain tectonically emplaced ultramafic rocks of the Slide Mountain terrane, which further complicates the interpretation of ultramafic rocks in the area.

Table 1. Summary of the principal geological events affecting mafic and ultramafic rocks (in bold type) in the Yukon-Tanana terrane (modified after MacKenzie *et al.*, 2008a; 2010).

Age	Unit or event	Structural elements	Tectonics	Associated intrusions	Metamorphism	Gold
Pliocene-Recent	White Channel and modern gravels		Regional uplift and erosion			Placer
Eocene		Faults	Regional extension	Dykes	Hydrothermal alteration	?
Late Cretaceous	Carmacks Gp/ andesitic volcanism	Faults			Hydrothermal alteration	Epithermal
Middle Cretaceous	Indian River/fluval	Faults		Ignimbrites and feeders	Hydrothermal alteration?	Epithermal, paleoplacer?
Jurassic-Cretaceous?	White River, Klondike Au mineralisation	F_4 folds & fractures; N & W trending faults	Collision	?	Hydrothermal alteration	Orogenic veins; disseminated Au with sulphides
Jurassic	Slide Mountain Terrane/ collision and thrusting	Serpentinite emplacement , D_3 , phacoidal cleavage, local S_3 shear fabric	Thrust stacking	Pyroxenite , granitoid plutons;	Localized greenschist facies	
Permian	Late metamorphic deformation	Local late metamorphic foliation (D_2 continuation)	Assembly, Yukon-Tanana & Slide Mountain terranes	Gabbro & pyroxenite ; granitoids	Greenschist facies (Klondike); amphibolite facies (Indian River-Stewart River)	
Mid-late Paleozoic	Metamorphic deformation	Pervasive S_1 & S_2 foliations		Gabbro & pyroxenite ; granitoids		
Early Paleozoic?	Mafic tuffaceous sediments , quartzofeldspathic sediments, quartzite, marble	Bedding (S_0)		Minor gabbro		

Airborne magnetic maps (e.g., Shives *et al.*, 2002a,b) have proven useful for delineating the mafic and ultramafic lithologies on the ground and our new interpretations are based on the combination of this geophysical data and our on-going structural mapping between the Klondike goldfield and the Stewart River area (Figs. 1 and 2). We recognize four different types of mafic and ultramafic rocks in the area, in different structural settings. Our focus in the 2011 summer field season was on basement structure and the four types of mafic and ultramafic rocks near Stewart River, as part of gold exploration in the vicinity of White River prospects (e.g., MacKenzie *et al.*, 2010; Wainwright *et al.*, 2011). Herein we link the new results from the Stewart River area with our previous work (MacKenzie *et al.*, 2007, 2008a,b) in the White River area and the Klondike goldfield.

REGIONAL GEOLOGY

The metamorphic basement rocks in the Klondike goldfield-Stewart River area form part of the Yukon-Tanana terrane and consist primarily of pervasively foliated and recrystallized schists and gneisses that were deformed and metamorphosed during the Paleozoic, ending with the Klondike Orogeny in the Late Permian (Mortensen, 1992, 1996; Mortensen *et al.*, 2007; Berman *et al.*, 2007; Beranek and Mortensen, 2011). Metamorphic grades of these basement rocks range from greenschist facies in the Klondike area to amphibolite facies in the Stewart and White River areas. Three generations of premetamorphic and synmetamorphic granitoids were intruded into gneisses in the Stewart River area in the Devonian, Mississippian, and Permian (Ruks *et al.*, 2006), and synmetamorphic plutonism occurred in the Klondike area in the Permian (Mortensen, 1990, 1996). Granitoids and host schists and gneisses have seen development of at least two metamorphic foliations, the second of which (S_2 ; Table 1) dominates at most outcrops. The basement rocks were locally reformed during Jurassic thrust stacking, resulting in the development of narrow shear zones (D_3 ; Table 1).

As the metamorphic pile was exhumed in the Jurassic and Cretaceous, regional compression (F_4) gave way to regional extension and the region was cut by a set of north and west trending high angle normal faults (Table 1). Extension continued through the Late Cretaceous to the Eocene, when transcurrent displacement along the Tintina fault was initiated (Fig. 1; Gabrielse *et al.*, 2006). The emplacement of Cretaceous to Paleogene igneous rocks

is controlled by this phase of extension and associated normal faults (Gabrielse *et al.*, 2006; Mortensen, 1996).

MAFIC AND ULTRAMAFIC ROCKS

CHLORITIC KLONDIKE SCHIST

The central and southern portion of the Klondike goldfield is underlain by medium to dark green chloritic schist, which is mineralogically distinct from other, nearby, Klondike Schist lithologies (Figs. 1 and 3). The schist has mafic to intermediate composition with the greenschist facies mineral assemblage quartz-actinolite-chlorite±epidote (Figs. 1 and 3; Mortensen, 1990, 1996). The chloritic schist is pervasively foliated ($S_1 + S_2$) and this foliation, as well as the thrust contact at the base of the unit dip shallowly west to southwest (Fig. 1). There are gradational and interlaminated contacts between chloritic schist and adjacent micaceous and quartzose metasedimentary schists. There is also a close spatial association between chloritic schist and small bodies of well foliated medium-grained metagabbro. The overall composition, volcanic textures and morphology of the chloritic schist suggest derivation from intermediate to mafic igneous rocks (Mortensen, 1990), possibly as tuffaceous or volcanogenic sediments.

METAGABBROS AND METAPYROXENITES

Much of the basement schist and gneiss in the Yukon-Tanana terrane occurs as interlayered quartzite, micaceous schists, and minor marble derived from Paleozoic clastic sedimentary rocks. These metasedimentary gneisses are interlayered with metamorphosed granitoid orthogneisses, especially in the Stewart River area (Figs. 1 and 2). In addition, the metasedimentary and granitoid orthogneiss sequence was intruded by synmetamorphic mafic igneous rocks that are now variably foliated metagabbros and metapyroxenites (Figs. 1 and 2; Mortensen, 1990). All these gneisses are interlayered on the 1 to 1000 m scale. Most of the metagabbros and metapyroxenites have, with their host gneisses, a well developed foliation that is a composite of a first penetrative foliation (S_1) and an overprinting second foliation (S_2). Many of the amphibolite facies metagabbros and metapyroxenites in the Stewart River area have late metamorphic ductile folds of S_2 , with a local, weakly developed, late metamorphic axial planar parallel cleavage (Fig. 4). This phase of late metamorphic ductile folding is an extension of D_2 deformation in these amphibolite facies rocks (Table 1), and is not recognizable in lower grade (greenschist facies) rocks.

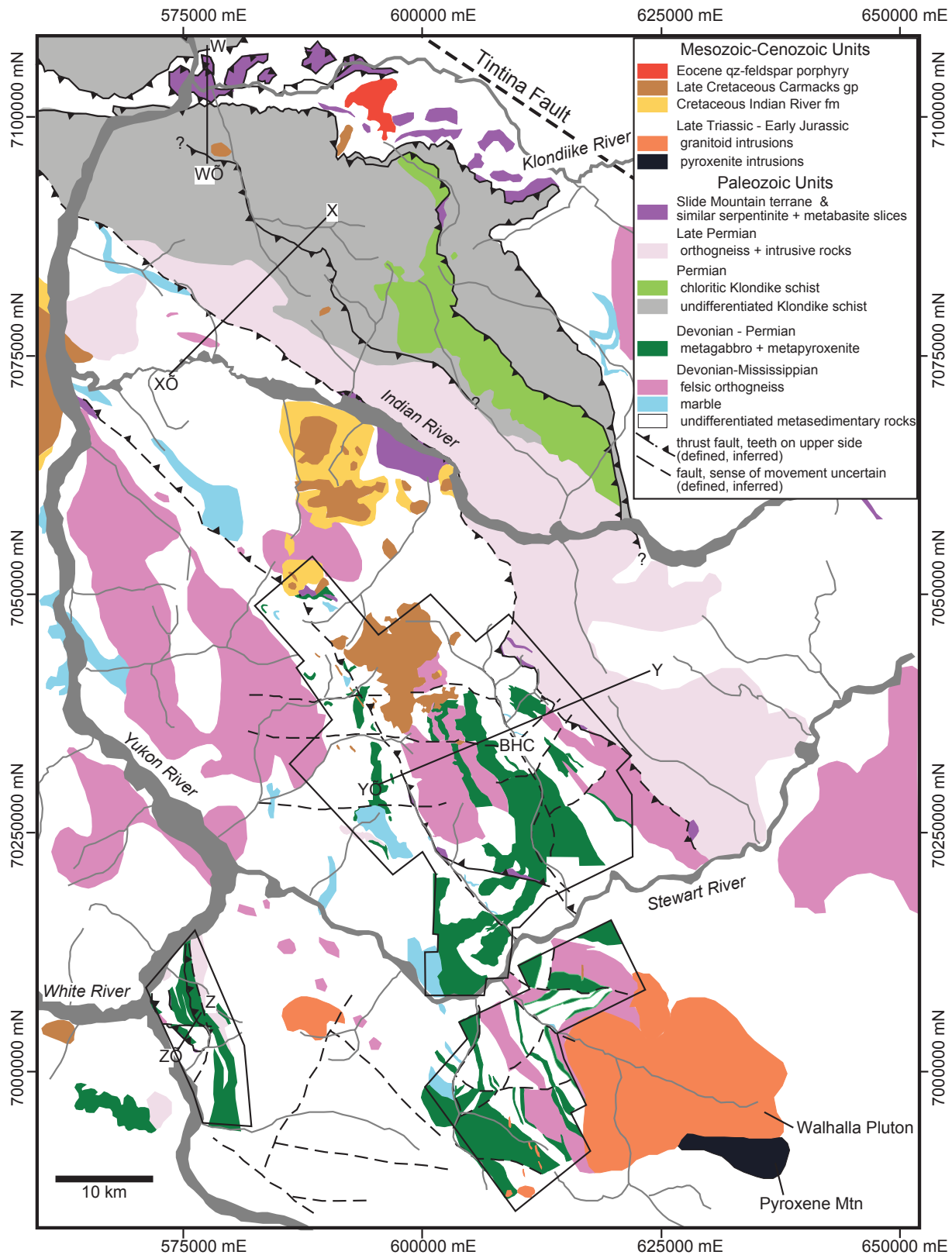


Figure 1. Geological map of the Klondike - Stewart River area, central western Yukon (modified after Ryan and Gordey, 2004; MacKenzie et al., 2008a,b, 2010 and MacKenzie and Craw, 2010). Outlined areas have been mapped in more detail at 1:10 000 and 50 000 scale. Labelled lines mark locations of cross sections in Figure 2. BHC = Black Hills Creek.

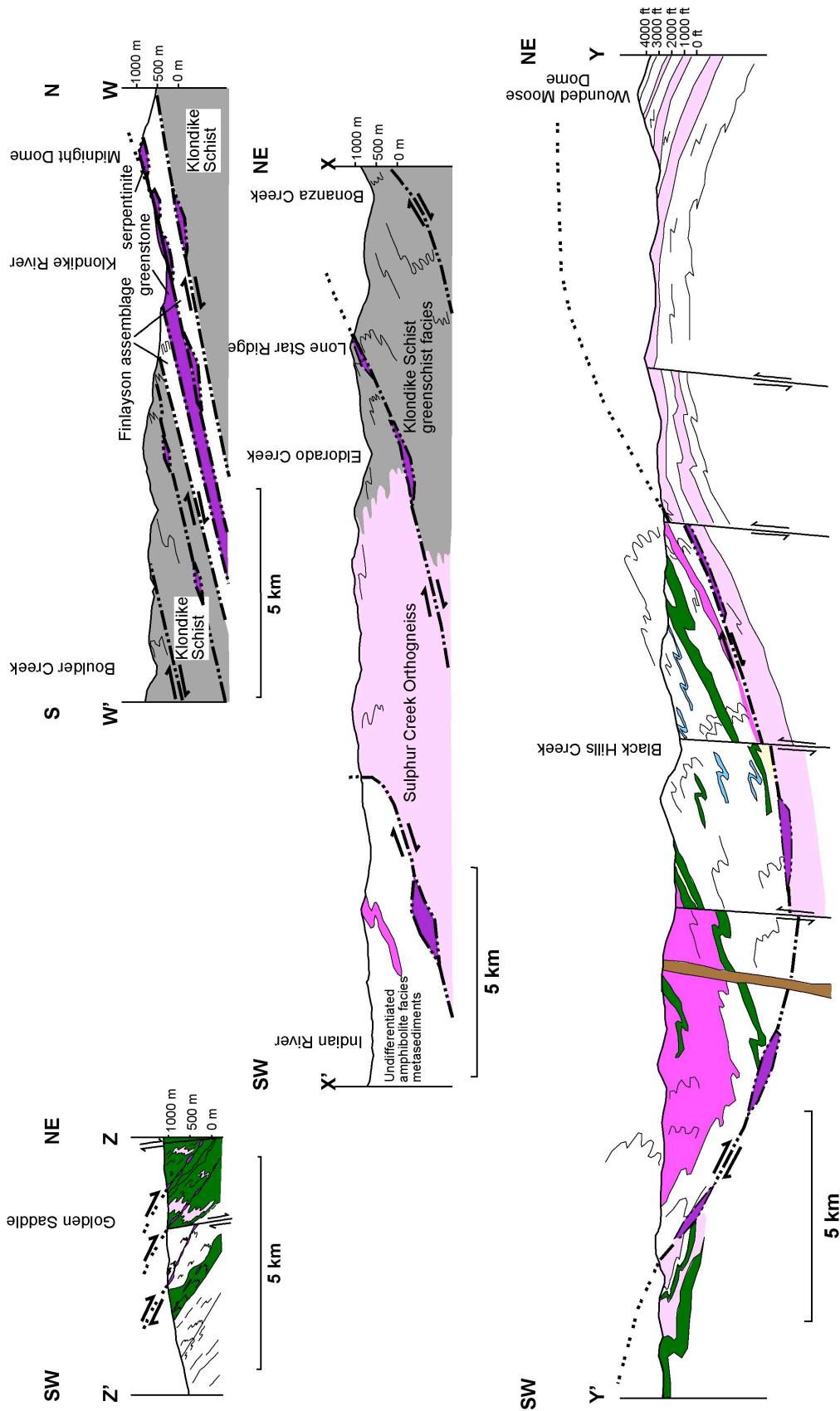


Figure 2. Cross sections through the Klondike-Stewart River area as located by section lines in Figure 1.

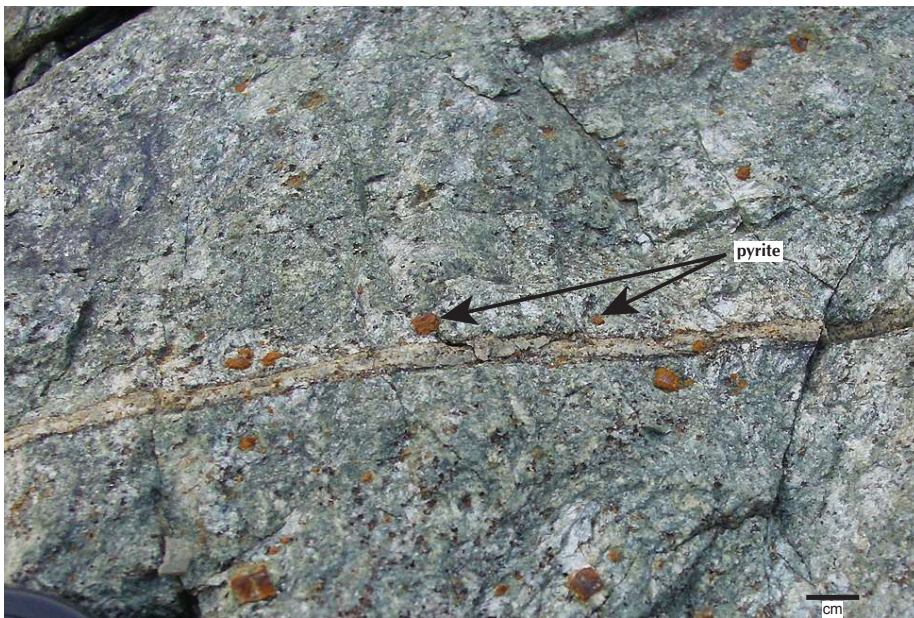


Figure 3. Gold-bearing quartz vein cuts chloritic schist in the Klondike goldfield with an alteration halo of disseminated pyrite cubes up to 1 cm across.

Despite the metamorphic overprint, primary magmatic minerals and textures are locally preserved in less deformed parts of the metagabbros and metapyroxenites (Figs. 5 and 6). For example, intrusion breccias are interpreted on the basis of angular clasts of earlier gabbro and granitoid host rocks within a mafic to intermediate matrix (Fig. 5). We also see xenoliths or rafts of the surrounding metasedimentary rocks (0.1-10 m scale) near margins of metagabbro and metapyroxenite bodies and in some of the mafic rocks a relict coarse-grained texture is discernible. We interpret these rocks as plutonic pyroxenites, probably cumulates (Fig. 6). No primary olivine has been observed in these rocks. The primary mafic minerals have mostly been recrystallized to variably aligned metamorphic hornblende (Fig. 7), and biotite. Most mafic bodies are essentially completely recrystallized to hornblende-rich gneisses with S_2 foliation, but some appear to be controlled by, or cut, the S_2 foliation and have only the incipient late metamorphic foliation imposed on them (Fig. 4). Therefore, at least two generations of mafic intrusions were emplaced during metamorphism.

SERPENTINITE AND METABASITE SLICES

Between Indian River and Stewart River, serpentinite bodies occur sporadically along greenschist facies shear zones that cut the amphibolite facies basement gneisses (Fig. 1). Deformation along the shear zones is primarily ductile (D_3 ; Table 1), but some late-stage brittle shearing has occurred as well, in zones up to 100 m wide. The shear zones are traceable for tens of kilometres with this combination of serpentinites

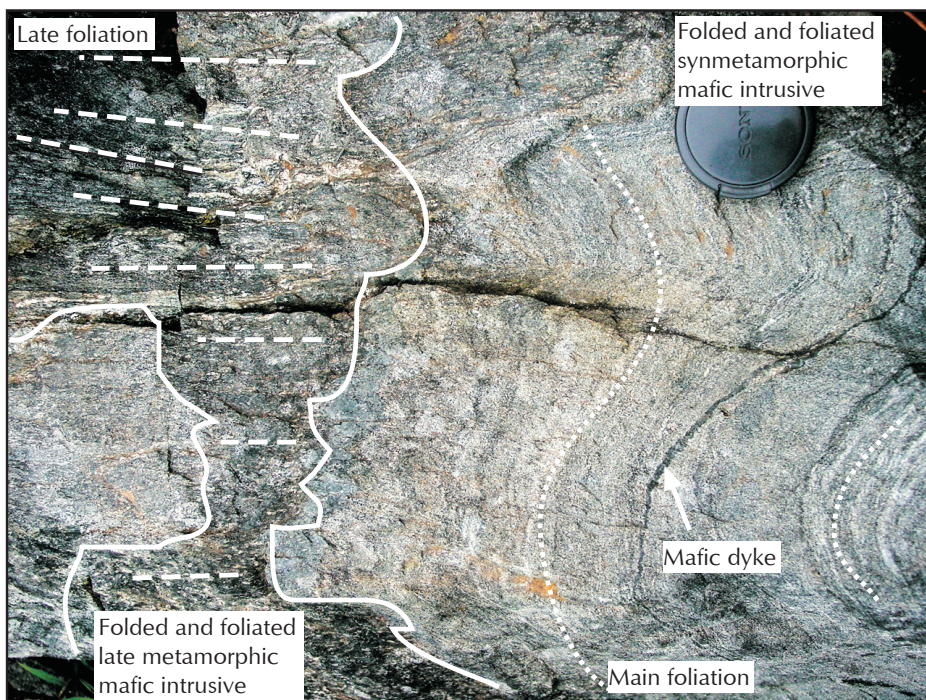


Figure 4. Late metamorphic foliation (thick white dashed lines, left) weakly developed in a late metamorphic mafic dike cutting a well-foliated (light white dotted lines) and metamorphosed mafic orthogneiss (right). Both bodies have been folded by late metamorphic folds, and the late metamorphic foliation has formed parallel to the fold axial surface of these late metamorphic folds.



Figure 5. Intrusion breccia from Black Hills Creek area. Unfoliated leucocratic metagabbro encloses angular xenoliths of more mafic metagabbro.

and localized greenschist facies overprint (Fig. 1). Ultramafic contacts are typically at a low to moderate angle (20-50°) to the adjacent gneiss foliation (Fig. 2). Serpentinites are locally affected by D_3 structures, principally semiductile, tight to angular folds with weak axial planar cleavage. Where D_3 deformation was intense, the ultramafic rocks form lenticular pods or phacoids that are cut by anastomosing semiductile shears (Fig. 8). Locally a new S_3 greenschist facies foliation developed parallel to shears and on the margins of individual phacoids. Serpentine is commonly accompanied by magnetite, talc, chlorite, and actinolite in metasomatic zones. Hence, the ultramafic rocks show up as prominent highs in published aeromagnetic images (e.g., Shives et al., 2002a,b).



Figure 6. Unfoliated coarse pyroxenite south of Stewart River. Coarse (up to 2 cm) pale brown pyroxenes (centre, protruding crystals) have been partially replaced by finer grained hornblende (black, recessive).

POST-METAMORPHIC PYROXENITE INTRUSIONS

Some pyroxenite plutons, including dikes and sills associated with Late Triassic to Early Jurassic granitoid intrusions, intrude the metamorphic sequence (Gordey and Ryan, 2005). The Pyroxene Mountain pyroxenite intrusion associated with the Walhalla granite (Gordey and Ryan, 2005; Mortensen, unpublished data) is the most significant such feature in the Stewart River area (Fig. 1). This pyroxenite is massive and coarse grained, with no metamorphic overprint (Fig. 9), although minor shearing has occurred along pluton margins. The lack of foliation and metamorphic overprint in these rocks is important for distinguishing them in the field from the relict pyroxenites that occur in the Paleozoic metagabbro/metapyroxenite intrusive rocks within the gneiss basement (Figs. 6 and 7). However, both these types of pyroxenites have minor localized epidote-chlorite alteration.

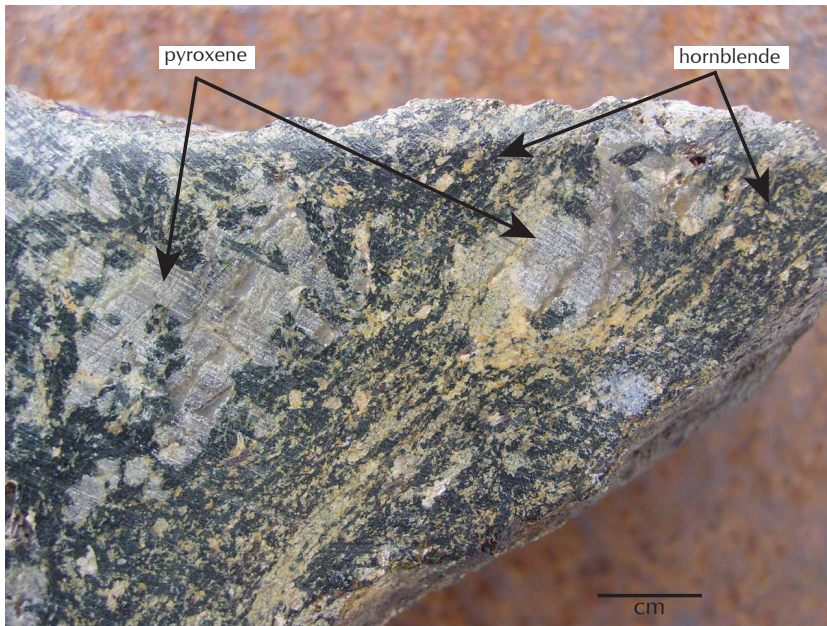


Figure 7. Variably foliated pyroxenite with hornblende, from the Barker Creek area, south of Stewart River (Fig. 1). Coarse (up to 15 mm) pale brown pyroxenes (centre left and centre right) have been cut and partially replaced by finer grained black hornblendes that define a strong foliation on the right margin of the sample.

DISTINCTIONS BETWEEN PALEOZOIC MAFIC AND ULTRAMAFIC GNEISSES AND SLIDE MOUNTAIN TERRANE SLICES

Some synmetamorphic to late metamorphic (Paleozoic) mafic metagabbros and pyroxenites resemble the ultramafic rocks emplaced in Jurassic D₃ shear zones, and distinction in the field can be difficult. The following points of distinction have been used to interpret outcrops and construct the maps and sections in Figures 1 and 2.

- Paleozoic mafic and ultramafic rocks apparently have intrusive contacts with metasedimentary rocks. In contrast, Slide Mountain ultramafic rocks were structurally emplaced along shear zones that are traceable for kilometres or tens of kilometres (Fig. 1)
- Paleozoic mafic and ultramafic rocks are invariably associated with mafic metagabbros and mafic gneisses, some of which are leucocratic. In contrast, Slide Mountain ultramafic rocks are not closely associated with mafic gneisses, although some are in structural contact with felsic orthogneisses.
- No olivine has been seen in the Paleozoic metagabbros or pyroxenites. Slide Mountain ultramafic rocks are generally olivine-rich or at least olivine-bearing

to some degree, which led to the production of abundant serpentine during greenschist facies metamorphism.

d. Paleozoic synmetamorphic to late metamorphic mafic and ultramafic rocks all have some degree of amphibolite facies metamorphic overprint, although this may be subtle in the case of late metamorphic intrusions. Principal features include localized hornblende±biotite foliation; replacement of pyroxene by hornblende; hornblende-rich lineation; and garnet-hornblende assemblages. Greenschist facies retrogression has occurred locally, but relict amphibolite facies assemblages can normally be found in close proximity to these mafic/ultramafic bodies. In contrast, Slide Mountain ultramafic rocks have only greenschist facies overprint and shear foliation development.

e. Paleozoic mafic and ultramafic rocks have some retrograde alteration to greenschist facies assemblage epidote-actinolite-chlorite. No serpentine has been seen in the Paleozoic rocks. Slide Mountain ultramafic rocks are typically serpentinized to varying degrees, commonly with talc and magnesite and only subordinate actinolite and chlorite.

REGIONAL STRUCTURE

Recognition of the above distinctive features of the four different types of mafic/ultramafic rocks over the whole Klondike-Stewart River portion of the Yukon-Tanana terrane has helped us to interpret outcrops and map patterns, and to compile the regional structural map (Fig. 1) coupled with the cross sections (Fig. 2). The key large-scale structural feature is that the metamorphic basement rocks consist of mappable thrust sheets that are stacked one upon another from the Stewart River area to the Klondike goldfield (Figs. 1 and 2). Thrust sheets that are part of this regional structural feature have been previously mapped in detail in the Klondike goldfield (Mortensen, 1990, 1996; MacKenzie *et al.*, 2008a,b), and we have been able to extend this overall structure to the Stewart River as part of the present study (Figs. 1 and 2).

Ultramafic rocks mainly consisting of serpentinized harzburgites and serpentinites occur as fault bounded slices separating distinct lithological units and thrust



Figure 8. (a) Outcrop of deformed serpentinite from Black Hills Creek area (Fig. 1). Metre-scale lenses (phacoids) of less-deformed serpentinite have foliated and altered zones (cm to m scale) anastomosing around them to define a crude shear fabric dipping gently SE to left and away from the camera. (b) Close-up showing anastomosing cleavage surfaces and crosscutting white serpentine-magnetite veins running top to bottom.

slices (Figs. 1 and 2; Mortensen, 1996; MacKenzie *et al.* 2008a,b). These ultramafic rocks are locally accompanied by massive to weakly foliated metabasaltic rocks. In the Klondike goldfield, the serpentinite and associated metabasites are considered to be part of a dismembered Permian Slide Mountain, and were tectonically emplaced in the Yukon-Tanana terrane during Jurassic thrusting (Fig. 1; Mortensen, 1990; MacKenzie *et al.*, 2008a,b). This thrust emplacement was accompanied by localized ductile

and brittle shearing under greenschist facies conditions (D_3 , Table 1). Some of the ultramafic lithologies are variably altered to talc-carbonate±magnesite schist and quartz-carbonate-fuchsite listwaenite (e.g., MacKenzie *et al.*, 2008b).

In the Klondike goldfield, the Klondike Schist is thrust over several slices of Paleozoic (Nasina facies) metasedimentary rocks and mafic and ultramafic rocks of the Slide Mountain terrane (section W-W', Fig. 2). An imbricated package of



Figure 9. (a) Massive outcrop of unfoliated and unsheared pyroxenite intrusive on Pyroxene Mountain (Fig. 1). (b) Close-up showing coarse unaltered euhedral pyroxene crystals (photo is 3 cm across).

at least three different slices of Klondike Schist is stacked on top of two lower grade thrust slices of Finlayson assemblage (Nasina facies) and an intervening slice of relatively undeformed greenstone and discontinuous lenses of serpentinite (section W-W', Fig. 2; MacKenzie *et al.*, 2008b). All these slices overlie another slice of Klondike Schist that crops out north of the Klondike River (Figs. 1 and 2). The chloritic schist unit, described above, sits in the upper Klondike Schist package and its lower contact is a low-angle thrust over-riding another slice of Klondike Schist in the southeastern portion of the Klondike goldfield. The thrust contact is marked by discontinuous fault bounded slices of serpentinite that are considered part of the Slide Mountain terrane (Fig.1; Mortensen, 1990, 1996).

South of Indian River, a package of amphibolite facies metasedimentary rocks is thrust over greenschist facies Sulphur Creek orthogneiss and Klondike Schist (Figs. 1 and 2, section X-X'). The underlying schist package is in turn thrust over another slice of Klondike Schist at Lone Star Ridge (section X-X', Fig. 2). Both the Lone Star Ridge thrust (Fig. 2; MacKenzie *et al.*, 2007, 2008b) and the thrust bounding the Sulphur Creek orthogneiss (Fig. 1) are marked intermittently along strike by deformed lenses of serpentinite and ultramafic rocks.

In the Black Hills Creek area, a slice of amphibolite facies metasedimentary rocks and orthogneiss is thrust over a similar, but possibly younger, package of metasedimentary rocks containing Late Permian orthogneiss (Figs. 1 and 2, section Y-Y'). The thrust fault is gently folded, so that it has an apparent normal displacement along its NE dipping limbs (section Y-Y', Fig. 2). In the White River area, a series of thrust slices are juxtaposed along NE dipping thrusts that may be similarly folded (section Z-Z', Fig. 2; MacKenzie *et al.*, 2010; MacKenzie and Craw, 2010).

Thrust imbrication in all the above examples resulted in semiductile shearing and macroscopic folding on the 10-50 m scale by tight to isoclinal folds (F_3) with an axial planar spaced cleavage (MacKenzie *et al.*, 2008a, b). Tabular bodies of ultramafic rocks and serpentinites that were emplaced along the faults acted as loci for D_3 deformation and greenschist facies retrogression and metasomatism. A new S_3 greenschist facies foliation is locally developed, particularly next to, and within, these ultramafic bodies. These D_3 structures are locally overprinted by semibrittle folds, angular kinks, and fractures associated with a late compressional phase of

regional scale warping and upright folding (F_4 ; Table 1; MacKenzie *et al.*, 2008a,b). This latter deformation also resulted in larger-scale folding and warping of regional S_2 foliation and D_3 thrust faults (Fig. 2).

CONCLUSIONS AND SIGNIFICANCE FOR GOLD MINERALIZATION

Four different types of mafic/ultramafic rocks have been recognized in the Yukon-Tanana terrane. Chloritic schists in the greenschist facies Klondike Schist are interlayered with metasedimentary rocks. Amphibolite facies metagabbros and metapyroxenites were intruded, in at least two stages, during Paleozoic metamorphism of basement metasedimentary rocks. Permian Slide Mountain terrane mafic and ultramafic rocks were dismembered in the Jurassic and emplaced along regionally extensive thrusts and associated shear zones, mainly as serpentinite bodies. These thrusts were formed under greenschist facies conditions with retrograde mineralogy that overprints amphibolite facies gneissic fabrics. Finally, massive, unaltered and unfoliated Jurassic pyroxenite intrusions were emplaced in association with granitoids.

Recognition and distinction of the four types of mafic and ultramafic rocks and their structural settings has enabled these features to be used as mappable units for construction of the regional map and cross sections (Figs. 1 and 2), and this aspect may be useful for gold exploration. Gold-bearing veins in the Klondike goldfield are largely controlled by F_4 structures at the outcrop scale, and perhaps regional-scale as well (MacKenzie *et al.*, 2008a). The broad F_4 folds and warps shown on a regional-scale in Figure 2 may help to define zones and orientations of more localized and more intense F_4 folding that may host orogenic gold south of Indian River (Fig. 1). In contrast, gold mineralization in the White River area is partially controlled by composite late metamorphic and D_3 shear zones, and is partially controlled by crosscutting faults (MacKenzie *et al.*, 2010; MacKenzie and Craw, 2010). Recognition and mapping of these structural features, as done on the regional-scale in Figure 1, is therefore of potential exploration significance for that deposit type.

At the outcrop-scale, the mafic and ultramafic rocks described above have varying significance to gold mineralization, depending on their structural settings as described above. Chloritic schists in the Klondike

goldfield act as hosts for orogenic gold-bearing veins, in a similar manner to adjacent quartzofeldspathic schists. However, chloritic schists were apparently more reactive to hydrothermal fluids than the quartzofeldspathic schists, and there are significant (metre-scale) hydrothermal alteration zones in chloritic schists adjacent to many veins. These alteration zones have variable amounts of disseminated pyrite (Fig. 3) and iron-bearing carbonate, and some disseminated gold (MacKenzie *et al.* 2008c). Some hydrothermal alteration of pyroxenites and associated mafic gneisses accompanied gold mineralization in the White River area, but this alteration was limited in extent (MacKenzie *et al.*, 2010; MacKenzie and Craw, 2010). Foliated margins of mafic gneiss bodies have had minor gold-bearing vein emplacement (MacKenzie *et al.*, 2010; MacKenzie and Craw, 2010). However, the weakly foliated hornblende-rich mafic gneisses and unfoliated pyroxenites appear to have been impermeable barriers to hydrothermal fluid flow (MacKenzie *et al.*, 2010). Ultramafic rocks in D₃ thrust zones have had some hydrothermal alteration but no significant gold mineralization has been detected as yet, in either White River area or the Klondike goldfield (MacKenzie *et al.* 2008a, 2010; MacKenzie and Craw, 2010). Pyroxenite intrusions at Pyroxene Mountain show no evidence for associated hydrothermal alteration or Au mineralization.

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