Structure of schist in the vicinity of the Klondike goldfield, Yukon

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ABSTRACT

This study describes the structural evolution of the Klondike Schist and the structural setting of mineralized mesothermal veins from which over 500 tonnes of placer gold has been derived. The Klondike Schist was emplaced as a series of thrust slices on top of a structural stack that includes at least three additional thrust slices. A distinctive set of mesoscopic structures, particularly a set of recumbent folds, formed during thrust emplacement. These folds have a general southeast trend, and deform thrust-emplaced ultramafic rocks. Underlying thrust panels contain folds that resemble these thrust-related structures, but have a consistent northeast trend. The Klondike Schist may have been rotated about a vertical axis during the latter stages of thrusting along phacoidal cleavage zones. Extensional sites in post-thrust kink folds and faults host mesothermal gold veins. Hence, gold mineralization postdated thrust stacking. Normal faults offset mesothermal veins, and host late-stage hydrothermal alteration zones.

RÉSUMÉ

Dans cette étude on décrit l’évolution structurale du schiste de Klondike et le cadre structural des veines mésothermales minéralisées dont on a tiré plus de 500 tonnes d’or placérien. Le schiste de Klondike a été mis en place sous forme d’une succession d'écailles de chevauchement au sommet d'un empilement structural comprenant au moins trois autres écailles de chevauchement. Un ensemble distinctif de structures mésoscopiques, en particulier un ensemble de plis couchés, se sont formées pendant le chevauchement. Ces plis ont une orientation générale sud-est et déforment des roches ultramafiques mises en place par chevauchement. Les lames de chevauchement sous-jacentes présentent des plis ressemblant à ces structures associées au chevauchement, mais qui ont une orientation nord-est uniforme. Le schiste de Klondike peut avoir subi une rotation autour d’un axe vertical pendant les derniers stades du chevauchement le long de zones clivées lenticulaires. Des sites d’extension dans les plis et failles en chevrons post-chevauchement renferment les veines d’or mésothermales. La minéralisation en or est ainsi postérieure à l’empilement par chevauchement. Des failles normales décalent les veines mésothermales et renferment des zones d’altération hydrothermale de phase tardive.

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INTRODUCTION

The Klondike goldfield (Fig. 1) has produced over 500 tonnes of alluvial gold from a remarkably small area (<2500 km^2; Knight *et al.*, 1999; Lowey, 2005). The sources for this gold are presumed to have been in the underlying bedrock, as the compositions of placer gold and compositions of gold in nearby gold-bearing quartz veins are closely related (Knight *et al.*, 1999; Mortensen *et al.*, 2005). These veins have mesothermal characteristics, fill fractures in the underlying schist (Rushton *et al.*, 1993), and have been the target of numerous exploration programs over the past 20 years, including a major effort over the past 3 years by Klondike Star Mineral Corporation.

Despite the potential economic significance of the Klondike gold-bearing veins, neither the structure of the host schist nor the structural setting of the veins are known in detail. Although the overall regional geology has been elucidated at the 1: 50 000 scale, and the tectonic setting is reasonably well understood (e.g., Mortensen, 1990, 1996; Gordey and Ryan, 2005), little is known about the structural evolution of the schists that host the auriferous veins. Likewise, the relative timing of gold-bearing vein emplacement, in relation to other structural events affecting the host schists, has not been examined in detail.

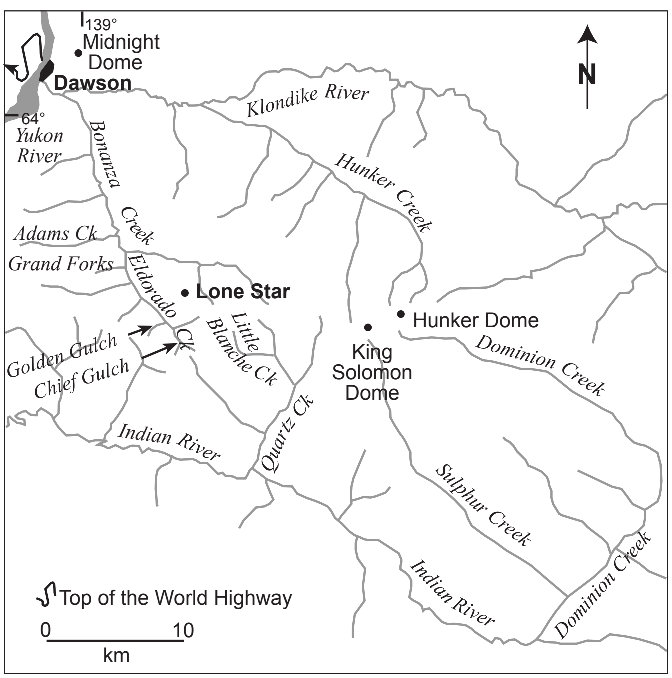


Figure 1. *Location map showing the main study area in the Klondike District and specific localities discussed in the text.*

This report outlines results of detailed structural observations in the Klondike area during the 2006 field season. Due to limited outcrop exposure, observations were obtained mainly from the best-exposed parts of the central and northern Klondike, in areas of recent or current mineral exploration or placer mining activity, as well as in road and stream cuts. We have determined a readily recognizable sequence of structural events that occurred during the evolution of the Klondike Schist, and we have placed the gold mineralization stage within this structural framework. This report provides extensive illustration of the key structural features, with the intention of facilitating further structural mapping and event correlation throughout the Klondike District.

This work has been carried out as part of a regional study of the entire Klondike District and adjacent Indian River area (J. Mortensen, D. MacKenzie and D. Craw, work in progress) that is being funded by the Klondike Star Mineral Corporation.

REGIONAL STRUCTURE

The Klondike Schist in the vicinity of the Klondike goldfield is part of the Yukon-Tanana Terrane, and consists of medium-grade metamorphic rocks of Late Permian age (Fig. 2; Mortensen, 1996). The schist includes a wide range of metasedimentary and meta-igneous rock types, now represented as quartzofeldspathic, micaceous and chloritic schists. These rocks are interlayered on the 1-100 m scale and are pervasively foliated and recrystallized, with few primary features recognizable.

The Klondike Schist forms the upper part of a stacked pile of thrust slabs that includes lithologically distinct Nasina Assemblage (Mortensen, 1990, 1996; Table 1) and a composite slice of little-metamorphosed greenstone and ultramafic rocks of probable Slide Mountain Terrane origin (Mortensen, 1996). The thrust slices of metamorphic rocks are locally separated by additional ultramafic slices (Mortensen, 1996; Mortensen, unpublished mapping), but exposure of the bounding faults is poor. The structure of the Klondike Schist in the Klondike goldfield is, in part, directly linked to the structure of this thrust pile (Table 1, 2). Detailed mapping of rocks within the lower thrust slabs is beyond the scope of this study, but we provide general descriptions of these underlying rocks to facilitate comparison and contrast with the Klondike Schist.

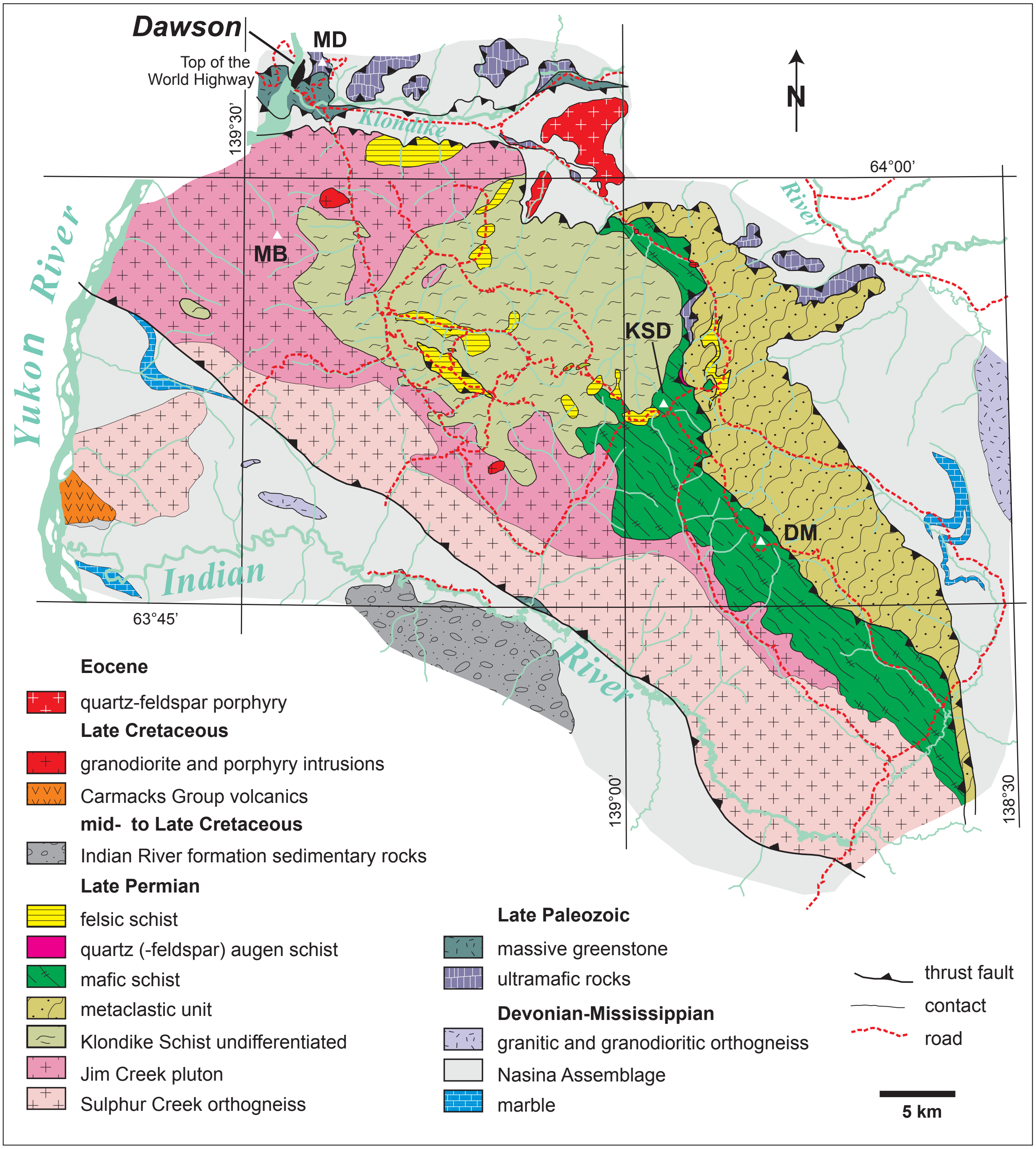


Figure 2. *Geological map of the Klondike District. KSD = King Solomon Dome; MD = Midnight Dome; DM = Dominion Mountain; MB = Mount Bronson.*

The thrust slices in the central and northern parts of the Klondike District, which have been the main focus of our work thus far, have generally increasing metamorphic grade and degree of textural reconstitution up the pile, although the two slices of Nasina Assemblage near the base of the structural stack are separated by greenstone, with little foliation development (Table 1). The Klondike Schist shows the highest metamorphic grade, most pervasive metamorphic reconstitution, and coarsest metamorphic grain size. The syn-metamorphic structures

***Table 1.** Summary comparison of thrust slices (in relative structural order) in the Klondike district (after Mortensen, 1996).*

Thrust slice	Rocks	Metamorphic grade	Textural reconstitution	Metamorphic structures
Klondike Schist (may include 2-3 slices)	micaceous schist, quartzofeldspathic schist, chloritic schist	upper greenschist facies (biotite zone)	pervasive recrystallization, coarse (0.1-1 mm) metamorphic grain size	pervasive coarse mica foliation, strong metamorphic segregation
Nasina Assemblage	dark grey micaceous schist	middle greenschist facies	pervasive recrystallization, fine (0.01-0.1 mm) metamorphic grain size	pervasive slaty foliation, weak metamorphic segregation
greenstone and ultramafic rocks	massive metabasalt and metadiabase, chlorite schist zones; serpentinite	lower greenschist facies	variable recrystallization, fine (0.01-0.1 mm) metamorphic grain size	minor local foliation development
Nasina Assemblage	dark grey micaceous schist	lower greenschist facies	pervasive recrystallization, fine (0.01-0.1 mm) metamorphic grain size	pervasive slaty foliation, weak metamorphic segregation

***Table 2.** Summary of principal structural events relevant to the structure of hydrothermal gold deposit rocks (shown from oldest at bottom, to youngest at top) that affect the Klondike Schist, as compiled in this study.*

Deformation stage	Klondike Schist event	Main feature	Orientation	Mineralization	Deformation	Age*
normal faults	normal faults	gouge zones	NW to N	pyrite in silicified schist and porphyry dykes	regional extension	Late Cretaceous?
mesothermal veins	Au veins	massive discordant quartz veins	variable, commonly NW	Au, pyrite, other sulphide minerals	local extensional sites	Early or Middle Jurassic?
kink folds and faults	D_4	angular folds, faults, shears, gouge zones	two orthogonal, N to NE; E to SE	?	compression	Early or Middle Jurassic?
thrust stacking	D_3	phacoidal cleavage	shallow dip	nil	compression	Early Jurassic?
		recumbent folds, spaced cleavage (S_3)	variable, mainly shallow dip, NW trend	nil		
		serpentine emplacement	shallow dip	nil		
pervasive foliation	S_2	foliation, isoclinal folds	variable	nil	compression	Late Permian?
first foliation	S_1	foliation, segregations	variable	nil	compression	Late Permian?
deposition	S_0	bedding etc.	not seen	sulphide minerals in some rocks		mid-Permian

*Age of events is deduced from regional considerations, after Mortensen (1996)

in the Klondike Schist were imposed on the rocks before thrust stacking, and there are some distinct differences in structural elements between thrust slices (Table 1).

STRUCTURES IN THE NASINA ASSEMBLAGE

Both slices of Nasina Assemblage (Table 1; Fig. 2) have similar structural features, although earlier structures are more readily seen in the lower slice. The Nasina units are typically finely laminated (commonly cm-scale), predominantly micaceous and at least weakly carbonaceous. The schist structure is dominated by a pervasive slaty foliation (S_1) that is defined by oriented fine-grained (<100 micron) metamorphic muscovite and chlorite. Only minor metamorphic segregation has occurred, locally accentuating primary lamination. The foliation is folded by tight to isoclinal folds (F_2) that have some mica recrystallization along fold-axial surfaces (S_2), generally subparallel to S_1 (Fig. 3). The composite S_1 and

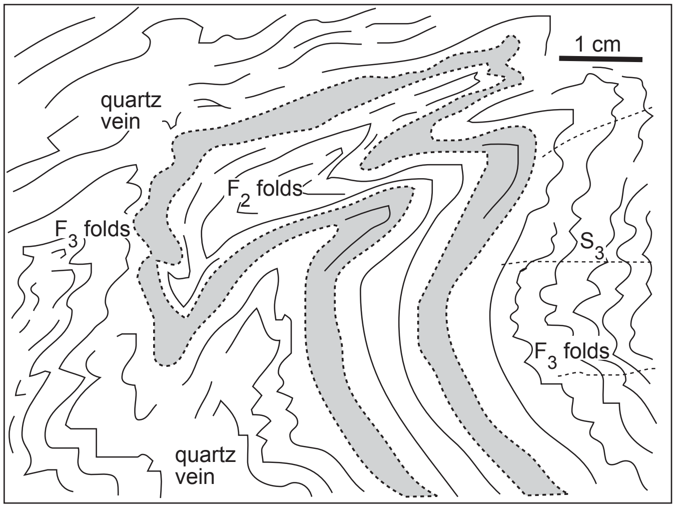


Figure 3. *Field sketch (from photograph) of a complex fold zone in the Nasina Assemblage structurally below the greenstone thrust slice, near Dawson City. The prominent foliation (S_1; grey layer) has been folded by F_2 folds with variable development of S_2 fold-axial surface foliation. These folds have been folded in turn by F_3 crenulations with a spaced cleavage (S_3; dashed). A distinctive chloritic lamina (grey) is traceable through the fold zone.*

S_2 fabric is generally shallow-dipping, except where modified by later structures.

Both earlier fabrics are folded by crenulations (F_3; cm-scale) that are only weakly developed in the lower Nasina thrust slice (Fig. 3). The crenulations have a shallow-dipping spaced cleavage (S_3) with little or no recrystallization of micas (Fig. 3). The crenulations are related to mesoscopic and macroscopic folding of metamorphic fabrics that are visible in some outcrops, both above and below the greenstone slice. A well exposed macroscopic example in the upper Nasina thrust slice on lower Bonanza Creek has recumbent folds with >10-m wavelength (Fig. 4a). The angular relationships between metamorphic foliation and S_3 spaced cleavage vary around both macroscopic and mesoscopic folds (Fig. 4b, c, d). A prominent crenulation lineation (L_3) on the metamorphic foliation has a consistent northeast trend in both the upper and lower Nasina thrust slices (Fig. 5a, b).

The above-described structures are cut or modified by a prominent phacoidal cleavage that has locally reactivated the shallow-dipping foliation. This cleavage is best exposed near the top of the lower Nasina thrust slice, where cleavage surfaces are spaced from 0.1 to 10 m apart and become progressively more closely spaced towards the overlying serpentinite. The cleavage anastomoses around relatively competent lensoidal blocks of schist. Cleavage surfaces are polished, marked by slickensides, and locally coated in recrystallized chlorite. Minor cataclasis has occurred on many surfaces, yielding sub-millimetre zones of grey-black cataclasite.

The pervasive foliation is deformed by small-scale (1-10 cm) angular kink folds in many areas. These kink folds typically have a northwest trend and steeply dipping fold-axial surfaces. Two sets of intersecting kinks are commonly observed, with the second (subordinate) set oriented perpendicular to the dominant set.

STRUCTURES IN THE COMPOSITE GREENSTONE-ULTRAMAFIC THRUST SLICE

The greenstone-ultramafic thrust slice comprises an upper sheet of massive greenstone (mainly massive metabasalt and metadiabase), which is structurally underlain by a laterally less-extensive lens-shaped body of partially to wholly serpentinized harzburgite. The greenstone unit is well exposed in road cuts on the Midnight Dome road, in natural outcrops on both sides of the Klondike River near Dawson and on the bluffs immediately across the Yukon River from Dawson, and in road cuts along the Top of the World Highway (Figs. 1 and 2).

The underlying ultramafic rocks comprise the top of the Midnight Dome and, together with the greenstone unit, form a south-dipping composite slab that is both underlain and overlain by Nasina Assemblage metasedimentary rocks. The greenstone has been extensively chloritized, but foliation is only developed in localized zones, 1-5 m across. Within these zones, the foliation (S_1) is defined by oriented chlorite, and anastomoses around pods of massive greenstone. The foliation has been deformed by synmetamorphic similar folds that are generally intrafolial and have a variably developed fold-axial-surface cleavage (S_2) that is subparallel to the earlier foliation. This relationship is displayed more clearly in a localized zone of deformation around a massive metadiabase clast in a greenstone agglomerate (Fig. 6a). Both these fabrics are folded in places by shallow-plunging crenulations (cm-scale; Fig. 6b) that have a weak fold-axial-surface fabric defined by the sub-parallel orientation of recrystallized chlorite.

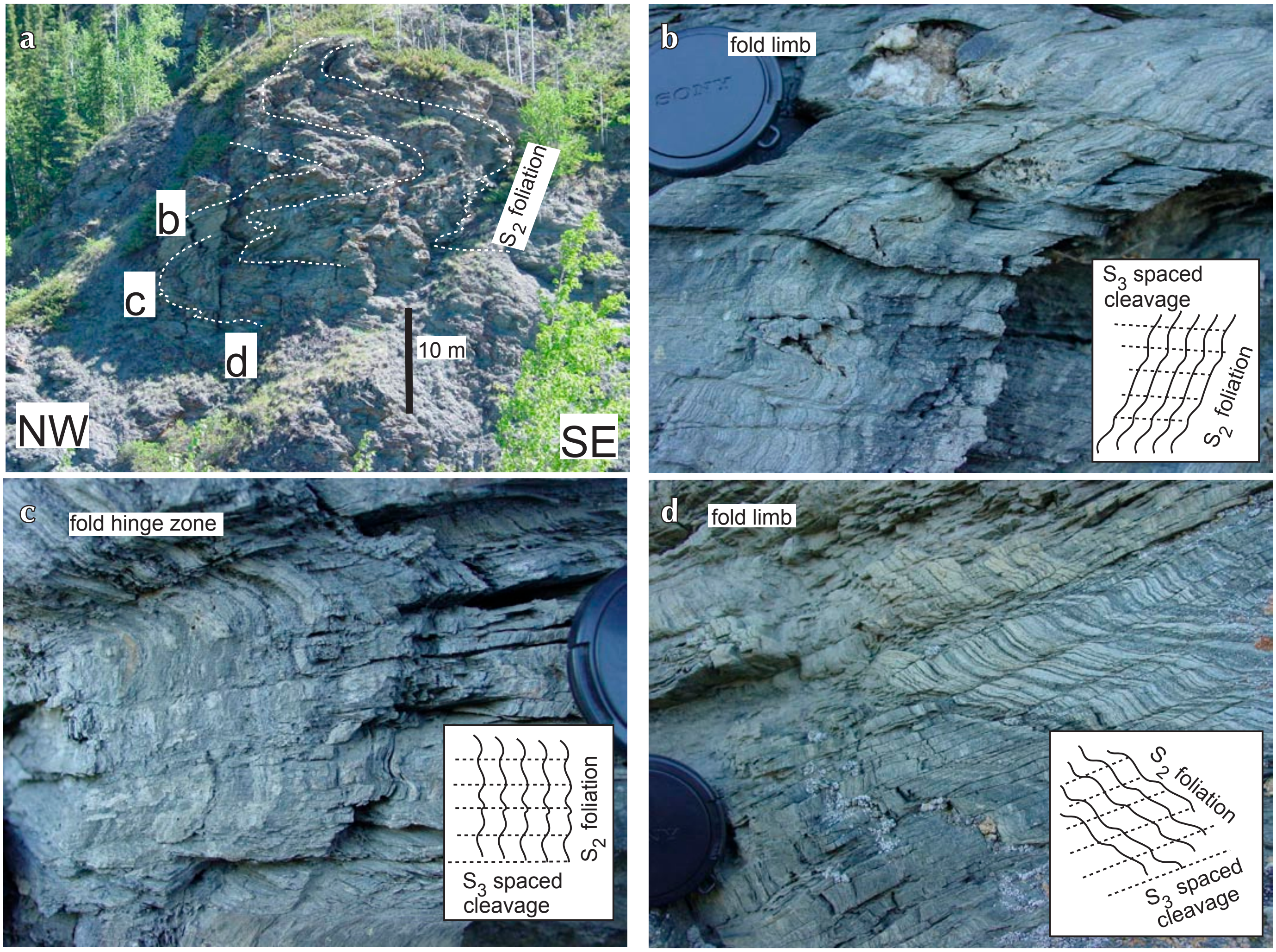


Figure 4. *A set of recumbent F_3 folds in the Nasina Assemblage on a right-limit bluff, 2 km above the mouth of Bonanza Creek. The outcrop in* ***(a)*** *shows the scale of the folds; the whole outcrop is similar to the portions at the top that have the S_2 foliation outlined. Photographs* ***(b)*** *to* ***(d)*** *show the relative dips of S_2 foliation and the S_3 spaced cleavage in different parts of the fold. Simplified sketches on each photo show the interpreted relationships. Note the almost brittle nature of the spaced cleavage, with negligible recrystallization of new micas characterizing the low metamorphic grade of the Nasina Assemblage (Table 1).*

The hinges of F_3 crenulations in S_2 foliation planes define a prominent lineation (L_3; Fig. 6b), and a spaced fold-axial-surface cleavage that cuts across the early fabrics at moderate to high angles. The lineation has a consistent northeast trend (Fig. 5c). All fabrics in the greenstones are cut by spaced (1-10 m) brittle fractures with surfaces marked by slickensides (Fig. 6b). Fabrics and structures within the ultramafic rocks are similar to those described above in the greenstone, except that an early (S_1) foliation is generally not developed.

STRUCTURES IN THE KLONDIKE SCHIST

The Klondike Schist is structurally more complex than rocks in the underlying thrust slices (Table 1). Structural features of the Klondike Schist are summarized in Table 2 (oldest at the bottom, youngest at the top), and these are described in the following sections. No single outcrop contains evidence of all of these structural features.

Within the Klondike District, the Klondike Schist comprises at least three separate thrust slices, with

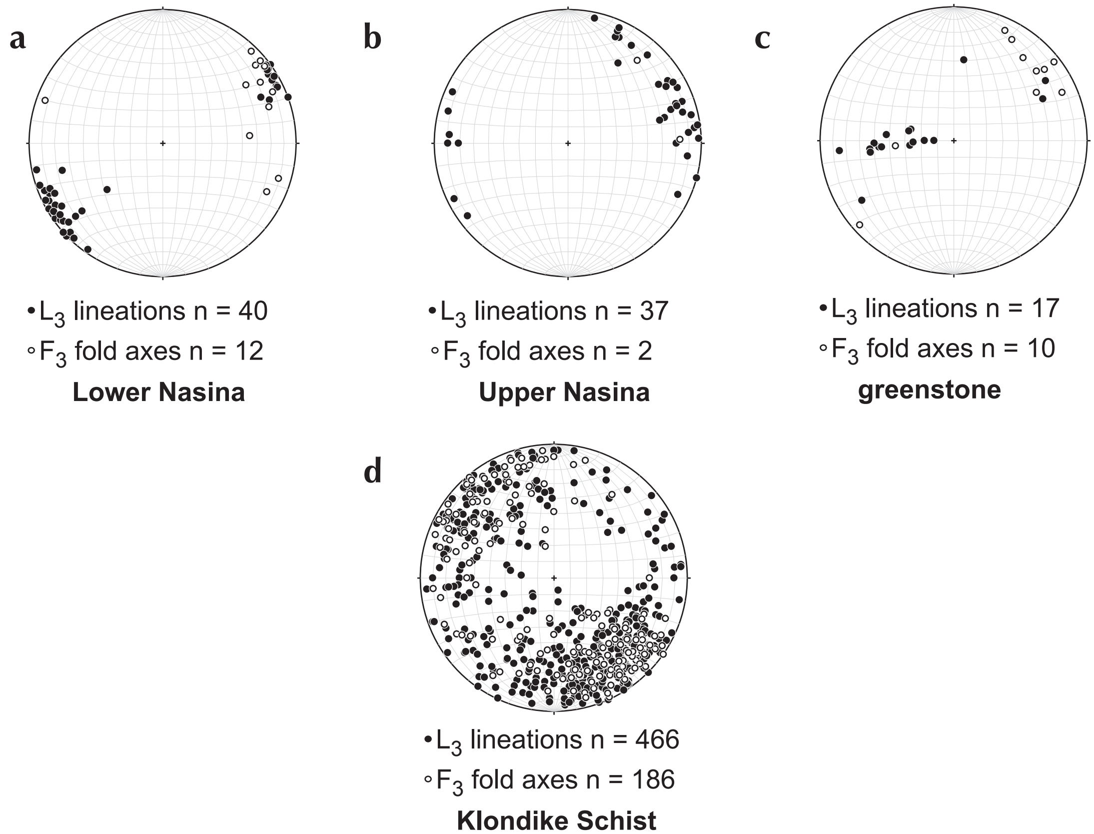


Figure 5. *Lower hemisphere equal-area stereonets for F_3 fold axes and L_3 intersection lineations on the S_2 foliation surfaces.* ***(a)*** *Lower Nasina Assemblage,* ***(b)*** *Upper Nasina Assemblage,* ***(c)*** *Greenstone-ultramafic thrust slice,* ***(d)*** *Klondike Schist.*

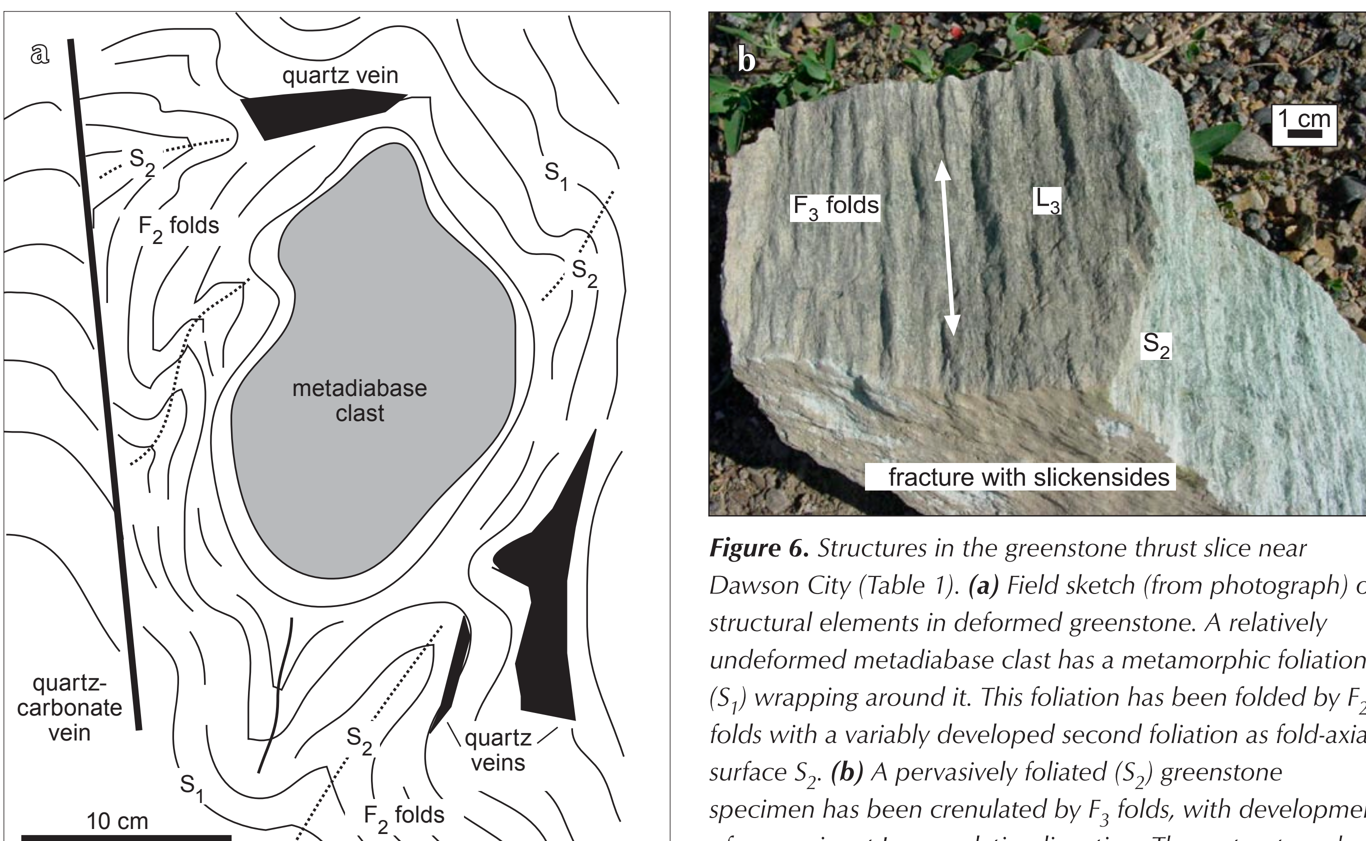


Figure 6. *Structures in the greenstone thrust slice near Dawson City (Table 1).* ***(a)*** *Field sketch (from photograph) of structural elements in deformed greenstone. A relatively undeformed metadiabase clast has a metamorphic foliation (S_1) wrapping around it. This foliation has been folded by F_2 folds with a variably developed second foliation as fold-axial-surface S_2.* ***(b)*** *A pervasively foliated (S_2) greenstone specimen has been crenulated by F_3 folds, with development of a prominent L_3 crenulation lineation. These structures have been cut by a fracture marked by slickensides (bottom).*

distinctly different types of schist occurring above and below thrust boundaries (Fig. 2; Mortensen, 1996). The bounding faults are irregular surfaces deformed by folding and a later phacoidal cleavage (described below). Discontinuous ultramafic horizons of serpentinite and/or talc-carbonate schist mark these thrust faults (Mortensen, 1996; Fig. 7).

A pervasive foliation is the most prominent structural feature in the Klondike Schist. This is a composite feature, being made up of an early metamorphic foliation (S_1) that was folded and reactivated by a second phase of ductile deformation (F_2) during peak metamorphism. F_2 folds, where observed, are generally intrafolial and isoclinal, with a well developed fold-axial-surface foliation (S_2) defined by the parallel orientation of metamorphic micas. The composite foliation development was accompanied by metamorphic segregation (mm- to cm-scale), so that rocks are generally finely laminated (Fig. 8a, b). In addition, numerous foliation-parallel quartz veins occur throughout all host-rock types. These concordant veins locally contain pyrite, especially along their margins, but are apparently barren of gold. The composite foliation is generally shallowly to moderately dipping over most of the Klondike Schist, but later deformation has locally caused steepening near specific structures.

The most prominent folds (F_3) seen in many parts of the Klondike Schist deform the foliation, and overprint and largely obscure the F_1 and F_2 structures. The F_3 folds seen at outcrop scale are minor structures on larger scale recumbent folds similar to those in the Nasina Assemblage (Fig. 4a) that are difficult to recognize in the Klondike area. A prominent spaced cleavage (S_3) has developed parallel to F_3 fold-axial surfaces, and this has been accentuated by recrystallization of micas (Fig. 9). The spaced cleavage in the Klondike Schist (Figs. 8a and 9) has had more extensive mineral recrystallization than in

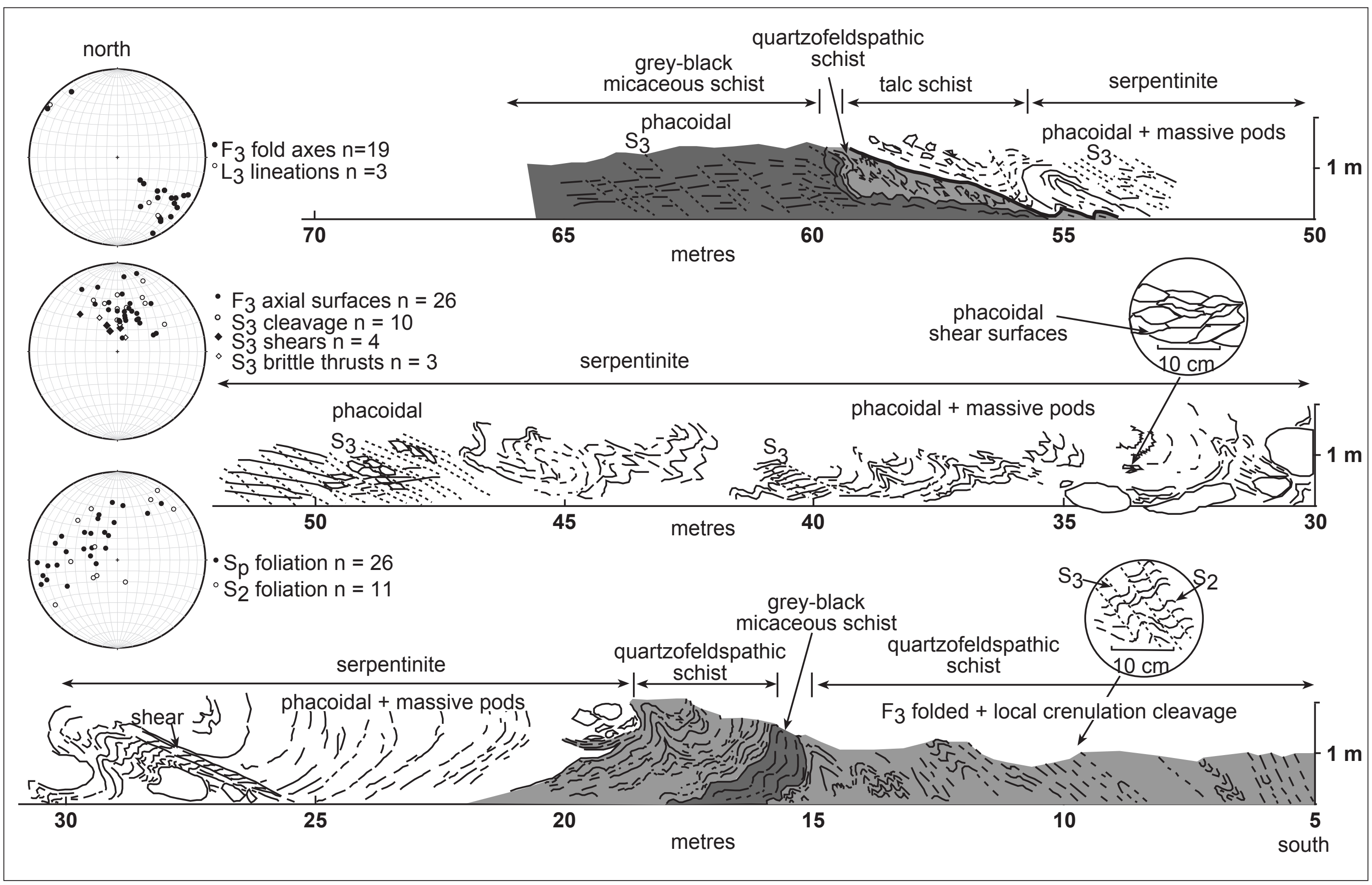


Figure 7. *Sketch of a trench wall through a thrust boundary between two slices of Klondike Schist immediately east of the historic Lone Star mine (see Fig. 1). Sketch covers ca. 60 m from north (upper left) to south (lower right) in three composite sections. Serpentinite (no colour) deformed by F_3 and later phacoidal cleavage separates schist of the lower slice (top left) from schist of the upper slice (lower right). Lower hemisphere equal-area stereonets show orientations of structural elements in the three composite sections. S_p is the prominent undifferentiated foliation.*

the Nasina Assemblage, and many Klondike Schist outcrops are dominated by the S_3 fabric. Small-scale F_3 folds form a prominent crenulation lineation on composite foliation surfaces, and this is accentuated by a lineation defined by intersection of S_3 with the foliation. This prominent lineation (L_3) has widely varying orientations, but it generally plunges southeast (east to south; Figs. 5d and 7).

At least locally, F_3 folds deform and overprint the thrust faults bounding individual thrust slices in the Klondike Schist. At one locality near the historic Lone Star mine (Fig. 1) that was examined in detail in this study, F_3 folds deform one of the thrust faults and the serpentinite marking it (Fig. 7). The locally intense F_3 folds and associated S_3 fabric are traceable both up-section and down-section into the Klondike Schist (Fig. 7).

F_3 folded zones near serpentinite-bearing thrusts in the Klondike Schist are locally overprinted by a phacoidal cleavage (Figs. 7 and 10). Cleavage surfaces are spaced between 0.1 and 10 m apart, and spacing becomes closer towards the thrusts, especially in micaceous schist (Fig. 7). Cleavage surfaces are polished, marked by slickensides, and locally cataclastic, with minor recrystallization of chlorite in chloritic schists (Fig. 10). Cleavage surfaces are partially defined by reactivated foliation, and partially defined by reactivated S_3, although truncation of S_3 is common also (Fig. 10).

The Klondike Schist and thrusts imbricating it are cut by D_4 reverse faults and related kink folds (F_4; Table 2). These structures are variably developed throughout the Klondike District, with locally intense zones separated by large areas that display little or no evidence of this deformation. The structures have developed in two mutually perpendicular directions (Table 2), and some outcrops have structures of both orientations. The folds and faults deform F_3 structures (Figs. 8b and 11), and form broad (km-scale) warps of the pervasive foliation (Fig. 12a). The most prominent features are zones of fault gouge (metre-scale) bordered by zones of steeply dipping sheared foliation (Figs. 13a,b). These zones are commonly accompanied by zones of F_4 folds in adjacent schist (Fig. 12b). The intensity of this F_4 folding decreases over 100 m from the main deformation zone. However, scattered F_4 kinks and associated fractures occur over most of the Klondike Schist.

The youngest deformation event recognizable in the Klondike Schist is a set of normal faults that cut across all earlier structural features (Table 2). These are defined by wide (metre-scale) gouge zones, with locally developed silicification and pyritization of adjacent schist. Some of these normal faults appear to have been controlled by pre-existing D_4 deformation zones (Fig. 12c). The normal-fault zones commonly host dykes of mafic to intermediate composition, and these dykes are variably altered (Fig. 14).

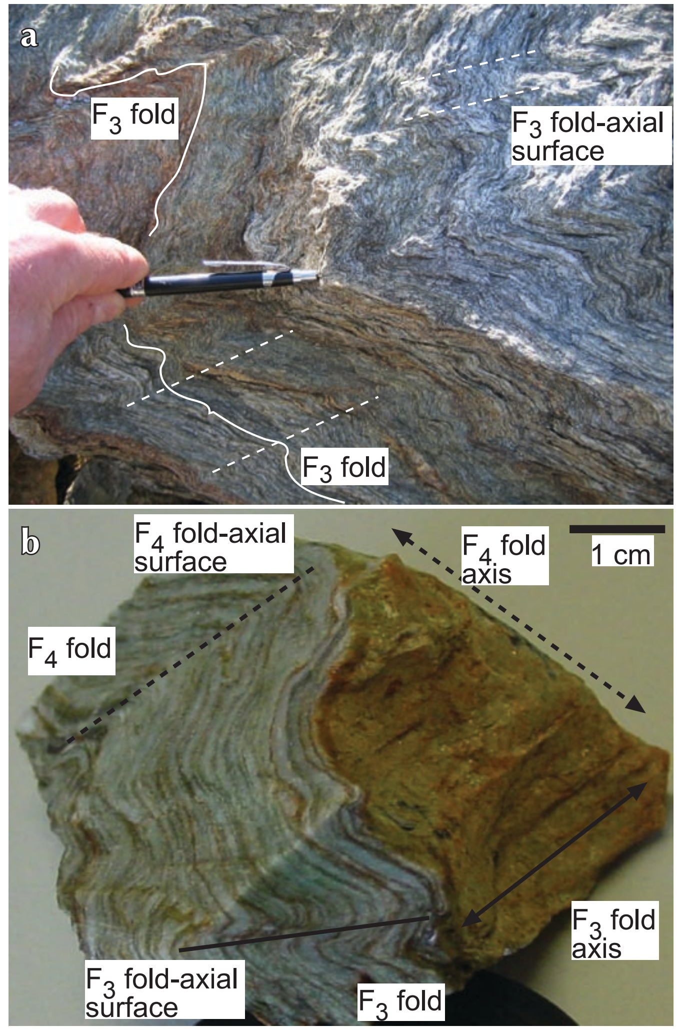


Figure 8. *Photographs of F_3 folds in Klondike Schist, east of Eldorado Creek. Note the finely laminated and segregated host schist, alignment of micas in the spaced cleavage, and local development of a recrystallized mica fabric.*
(a) *Moderately developed F_3 folds of segregated foliation (solid line), with a spaced cleavage parallel to the fold axial surface (dashed lines);* ***(b)*** *specimen showing interference between F_3 folds and F_4 folds (as labelled).*

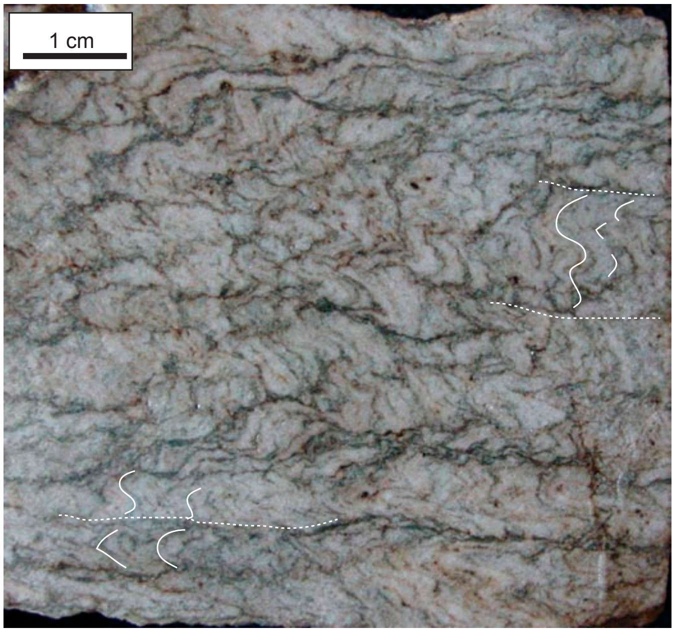


__Figure 9.__ A slab of quartzofeldspathic Klondike Schist, showing remnants of metamorphic foliation (S_1+S_2; solid white lines) that have been folded by F_3 crenulations. Well developed S_3 spaced cleavage (parallel to dashed white lines) locally dominates the rock fabric.

STRUCTURAL CONTROLS ON VEIN FORMATION

Discordant quartz veins (distinct from metamorphic segregations) form in a wide variety of structural settings in the Klondike Schist. Many, but not all, of these veins contain gold, and these are typically mesothermal in style as described by Rushton *et al.* (1993). Detailed examination of gold-bearing vein structures is beyond the scope of this regional structural study, but will be addressed in future work. The following is a summary of observations on these discordant veins in relation to the structures described previously.

Individual veins can follow several different structural features along their strikes and/or dips. The main criterion for structural hosting of veins appears to be whether any pre-existing structural weaknesses in the rock are suitably oriented to open in superimposed extension. Additional mineralized rock has been created by hydrothermal alteration of wall rocks adjacent to extensional zones, whether those extensional zones host quartz veins or not.

D_4 structures are the most common hosts of quartz veins, particularly in fractures parallel to F_4 fold-axial surfaces (Figs. 11, 13b and 15). The geometric relationship between veins, F_4 'axial surface' fractures and F_4 folds is consistent, regardless of orientation of the foliation. Where F_4 folds have upright fold-axial-surface fractures, and foliation is flat-lying, veins have a steep dip (Figs. 11 and 16). Where foliation is steeply dipping and F_4

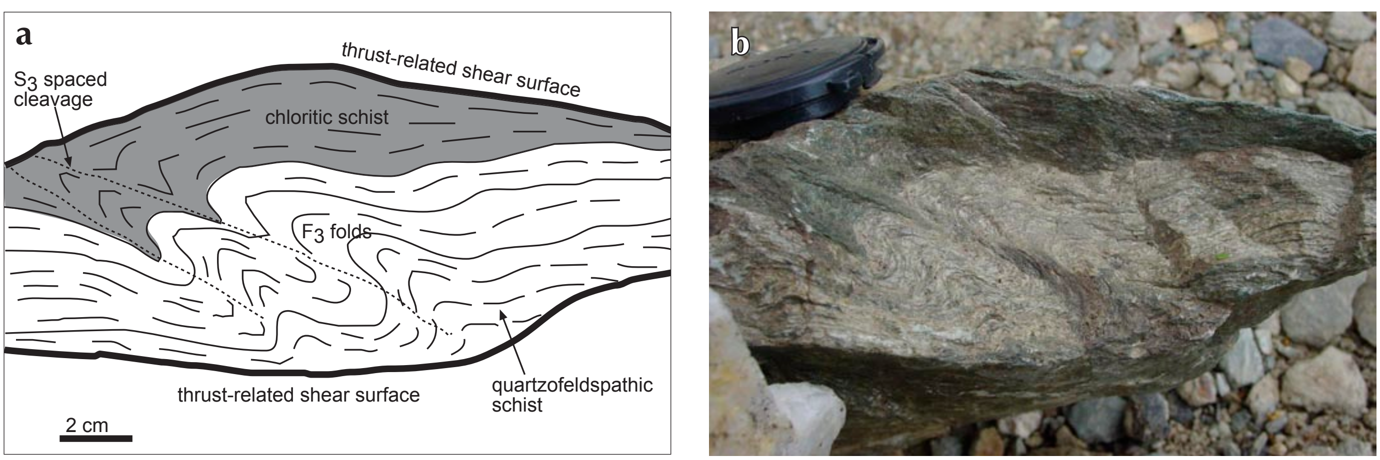


***Figure 10.** Sketch **(a)** and photograph **(b)** of a block from a thrust zone between slabs of Klondike Schist near Hunker Dome (see Fig. 1). F_3 folds and S_3 spaced cleavage are visible in the core of the block, especially in the quartzofeldspathic layer. These features are truncated on the margin of the block by thrust-related shears (thick lines in **a**) that form a phacoidal cleavage around more resistant lenses of rock.*

Figure 11. *Large F_4 fold exposed in the northeast bank of Bonanza Creek at Grand Forks (see Fig. 1). The rocks are strongly affected by F_3 structures, and the prominent layering (white lines) is a combination of S_2 and S_3. The F_3 fold axes plunge steeply down this composite surface. These structural features are folded by the F_4 structure. A prominent set of fractures has developed subparallel to the F_4 fold-axial surface. One of these has been filled by a discordant quartz vein (left).*

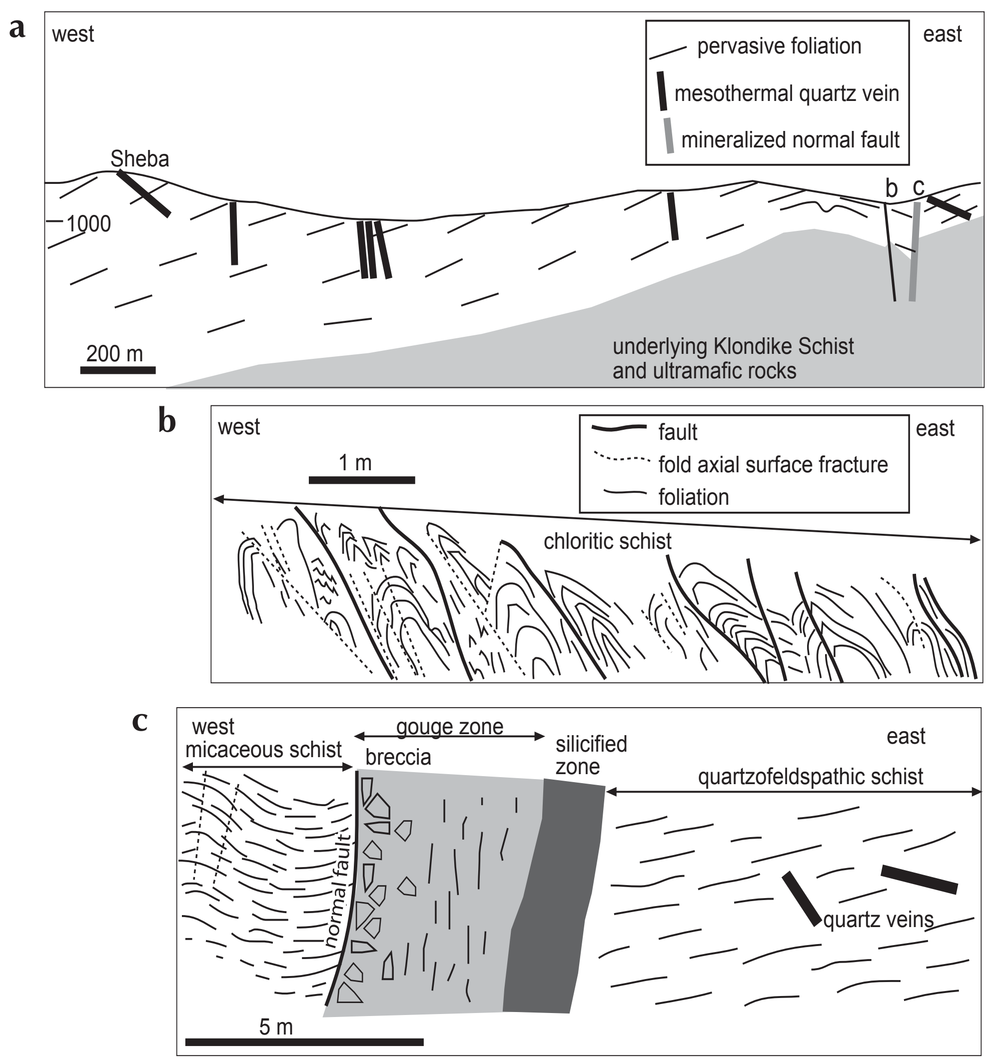
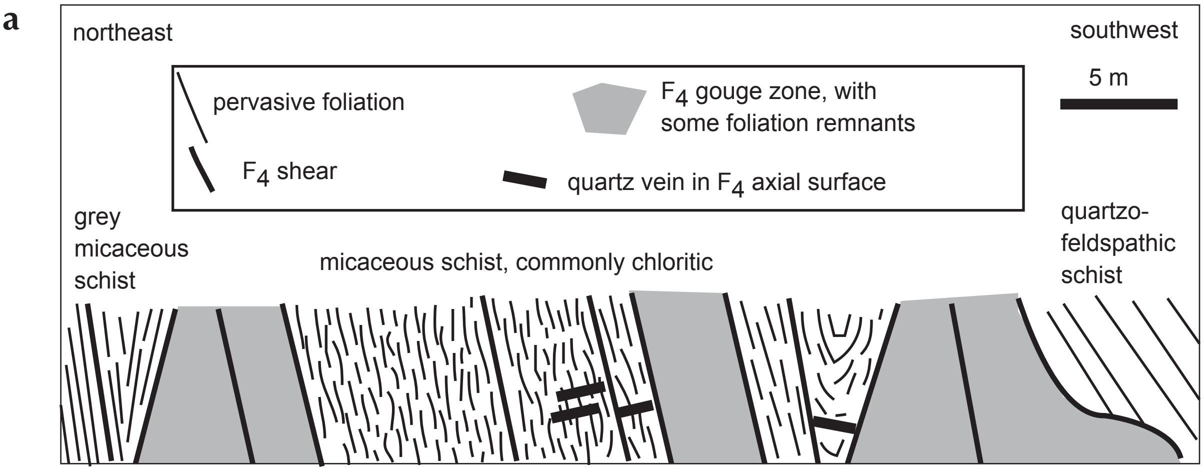


Figure 12. *Sketch sections through some portions of the King Solomon Dome-Hunker Dome area (see Fig. 1), showing structural elements relevant to vein formation in the Klondike Schist.*
(a) *Regional cross-section, east from the Sheba vein system, based on trench mapping, with locations of sections b and c. A broad F_4 antiformal fold of metamorphic foliation is on the east (right) side.*
(b) *F_4 deformation zone adjacent to a steeply dipping F_4 fault on the limb of the large antiform (see **a**).*
(c) *Eastern margin of the F_4 deformation zone, with a combination of normal-fault structures superimposed on F_4 structures. Mesothermal quartz veins fill F_4-related structures and the later normal fault has been hydrothermally altered.*



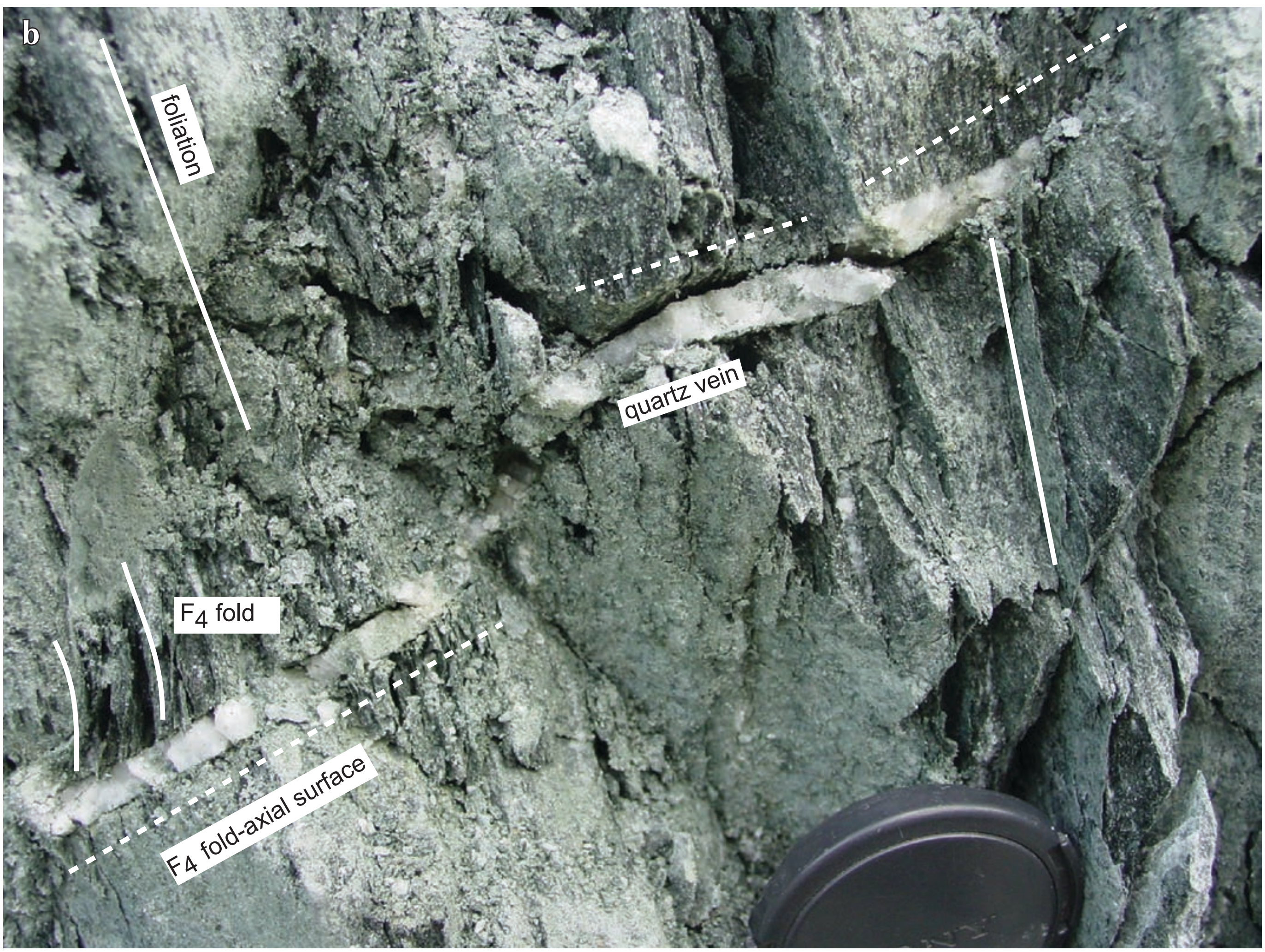


Figure 13. (a) *Section through a trench in the bed of Eldorado Creek near the mouth of Golden Gulch (see Fig. 1), showing an* F_4 *reverse fault and wide deformation zone cutting across Klondike Schist. Zones of gouge separate zones of more intact rock.* F_4 *folds have developed on a steep foliation, and their axial surface fractures are shallow-dipping to the northeast and southwest (northeast in* ***b****). Some of these fractures (dashed lines in* ***b****) are filled with quartz veins, as shown in* ***b****.*

folds have shallowly dipping axial surfaces, fractures and veins are also shallowly dipping (Fig. 13b). Weak F_4 deformation in the King Solomon Dome-Hunker Dome area (Fig. 12a) has resulted in spaced fractures parallel to fold-axial surfaces of two perpendicular F_4 fold sets. Both sets host quartz veins.

In addition, opening of the S_2 pervasive foliation during F_4 deformation, assisted by strong differences in rock types, has produced some near-concordant mineralized veins. Likewise, opening of the S_3 spaced cleavage associated with tight F_3 folding hosts some mineralized veins, especially near F_3 fold hinges.

Further hydrothermal alteration and vein formation occurred along the late-stage normal faults. This hydrothermal activity mainly resulted in alteration, silicification and pyritization of adjacent host rocks

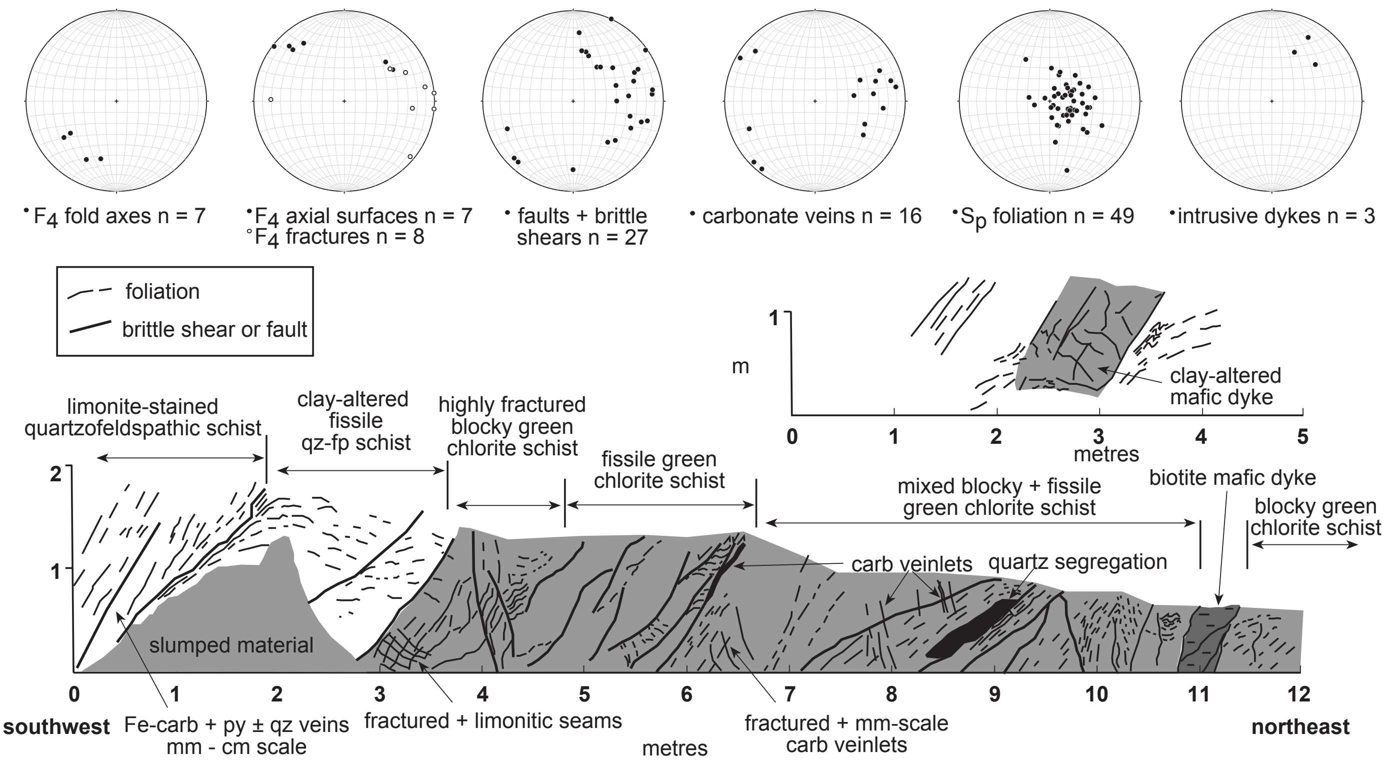


Figure 14. *Section through two parallel trenches cut across a variably mineralized northwest-striking normal fault zone on the ridge crest between the heads of Chief Gulch and Little Blanche Creek (see Fig. 1). In the lower section, chlorite schist (light-grey shading) has been juxtaposed against quartzofeldspathic schist (white, left). The upper section shows an altered, biotite-phyric mafic dyke intruded into quartzofeldspathic schist. Lower hemisphere equal-area stereonets are shown for structures, veins and dykes. S_p is the prominent undifferentiated foliation.*

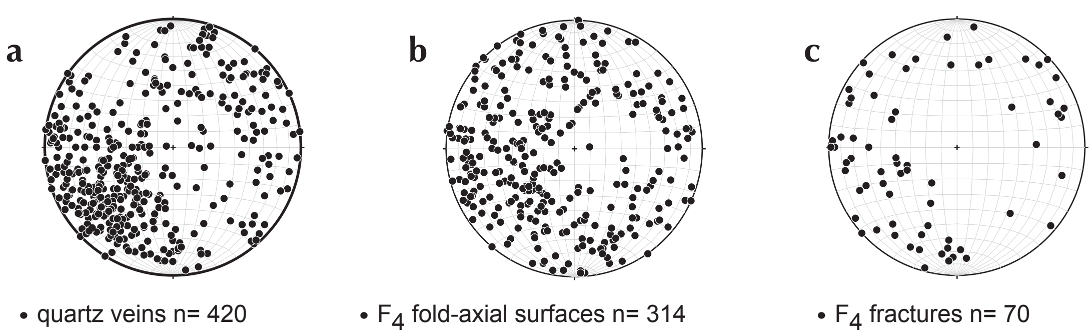


Figure 15. *Lower hemisphere equal-area stereonets from the Klondike Schist.* ***(a)*** *Poles to quartz veins. Main populations are northeast- and east-dipping.* ***(b)*** *Poles to F_4 axial surfaces.* ***(c)*** *Poles to F_4 axial surface-parallel fractures.*

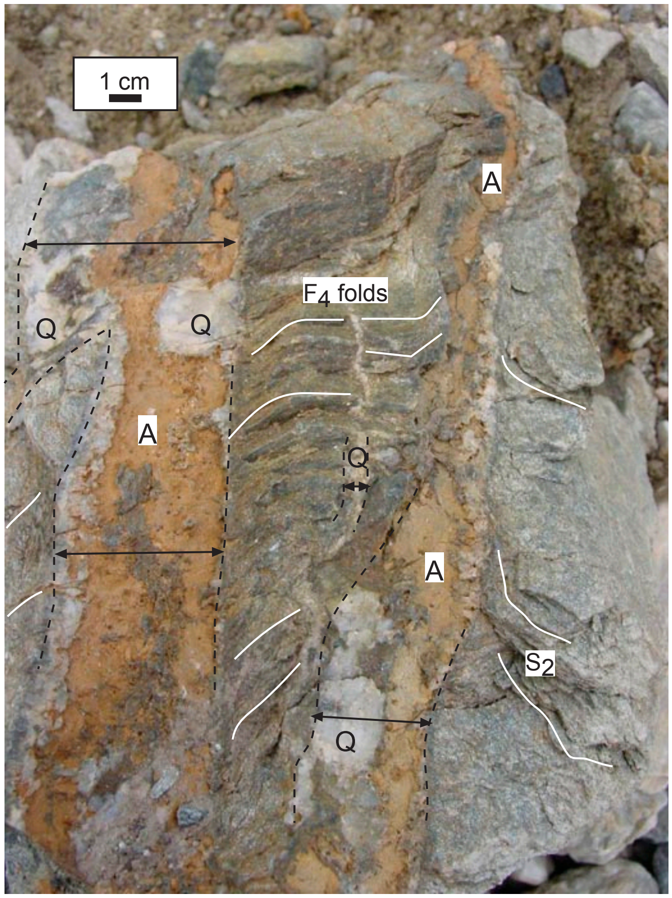


Figure 16. *Quartz (Q) and ankeritic carbonate (A) veins fill steeply dipping extensional fractures (dashed black lines) that have developed parallel to the fold-axial surfaces of F_4 kink folds of metamorphic foliation in Klondike Schist (white lines).*

(Fig. 12c). This style of alteration is structurally later than the mesothermal veins described previously, and normal fault offsets (metre-scale) of mesothermal veins have occurred. The co-existence of the two styles of mineralization in close proximity (e.g., Fig. 12c) results from reactivation of F_4 zones by normal faults that subsequently control later fluid flow.

CORRELATION OF STRUCTURAL EVENTS THROUGH THE THRUST SLICES

All the thrust slices (Table 1) have similar sets of structures: composite foliation (S_1 and S_2), later folds with a spaced cleavage (F_3), and post-F_3 cataclastic phacoidal cleavage or shears. However, correlation of structural features is hindered by lack of appropriate age data and outcrop. Similarly, comparison of bounding faults is hindered by poor exposure. Hence, the correlations outlined below are tentative and subject to revision, but provide useful starting points for further work.

The most plausible structural link between thrust slices is the widespread set of folds and spaced cleavage that is designated F_3 in each slice. The F_3 folds have similar style and northeast trend through the two Nasina Assemblage slices and the intervening greenstone-ultramafic slice (Fig. 5a, b, c). Since the Nasina Assemblage and greenstone have disparate tectonic origins (Mortensen, 1996), having these F_3 structures in common suggests that ductile fold structures formed during, or just after, juxtaposition of the slices. The phacoidal cleavage that is strongly developed near the thrusts postdates the folding and may have involved reactivation of thrust surfaces.

Despite the apparent correlation of F_3 and phacoidal cleavage in the lower three thrust slices, correlation of these structures into the overlying Klondike Schist is more problematic. Regional and local observations support the close relationship between thrust stacking and serpentinite emplacement (Mortensen, 1996). Serpentinite between two Klondike Schist slices has been folded by F_3 (Fig. 7), further supporting the contention that F_3 deformation accompanied or postdated thrust stacking. However, L_3 in the Klondike Schist, while highly variable, has orientations at a high angle to L_3 in the lower thrust stacks (Fig. 5d). One plausible explanation for this discrepancy is that the Klondike Schist slices were rotated about a vertical axis during final emplacement on the well developed phacoidal cleavage zones (Fig. 10) that occur at the thrust zones. If this is correct, thrust-stacking structures in the Klondike Schist include three stages: serpentine emplacement, F_3 deformation, and phacoidal cleavage development. We include all three of these Klondike Schist structural stages in the D_3 thrust-stacking generation in Table 2.

The D_4 faults that are widespread in the Klondike Schist of the Eldorado and Bonanza creek catchments clearly post-date thrust emplacement according to the above structural correlations. These D_4 faults have not yet been traced beyond the Klondike Schist into the underlying thrust slices, but kink folds with similar orientations to D_4 in the Klondike Schist occur throughout the Nasina Assemblage. D_4 structures are steeply dipping, so their extension into the underlying slices should be detectable.

Since mesothermal gold-bearing vein emplacement was partially controlled by F_4 structures, regional mapping of F_4 structures is of potential economic interest.

CONSTRAINTS ON ABSOLUTE AGES OF DEFORMATION EVENTS

The absolute ages of specific deformation and/or mineralization events in the Klondike District are still not well known, although some progress has been made on this front. The early deformation events (D_1 and D_2) that affected both the structurally lower Nasina Assemblage units and the Klondike Schist itself are constrained to be pre-latest Permian on the basis of crosscutting undeformed intrusive rocks. Field relationships described in this paper demonstrate that the regional-scale thrust faulting and F_3 deformation event are broadly synchronous, and, from regional considerations, the thrust faulting appears to be mainly Early Jurassic in age (Dusel-Bacon *et al.*, 2002). We have no direct age constraints on the timing of the D_4 event. The age of formation of gold-bearing quartz veins is still problematical. K-Ar ages of ~140-145 Ma for muscovite within the Sheba vein were reported by Rushton *et al.* (1993), and subsequent re-analysis of material from this same location using Ar-Ar methods yielded data that could be interpreted to indicate either a Late or Early Jurassic age for the veins (M. Villeneuve, pers. comm., 2003). Ar-Ar and K-Ar ages for the host schists in the general area of the Sheba vein (Mortensen, unpublished data), however, suggest that these are all cooling ages and thus provide only a minimum age for the veining. Muscovite from a gold-bearing vein and surrounding schists in the Adams Creek area west of Bonanza Creek (Fig. 1) yield Ar-Ar ages in the range of 178-184 Ma (Mortensen, unpublished data), suggesting a minimum age of 178 Ma for the veining, at least in that area. Since veining was late- or post-D_4, it therefore appears that the D_4 event was Early or early-Middle Jurassic in age and may have immediately followed the D_3 folding and thrust faulting.

The D_5 folding and high-angle reverse fault zones locally contain biotite- and/or feldspar-phyric porphyry dykes that, although not yet directly dated, are most reasonably correlated with the Late Cretaceous Carmacks Group magmatism. These dykes were strongly fractured and faulted within the D_5 deformation zones and locally display strong hydrothermal alteration and pyritization, all suggesting that they were emplaced prior to, or during, the D_5 deformation. High-angle normal faults and hydrothermal alteration (locally including epithermal vein and other forms of epigenetic mineralization) are known to be widely associated with Carmacks Group magmatism elsewhere in western Yukon. Additional work is underway to attempt to better constrain the ages of the various deformation and mineralizing events in the Klondike District.

CONCLUSIONS

This preliminary study presents an internally consistent structural evolutionary framework for the Klondike Schist (Table 2). The structural events and associated features described in Table 2 are readily distinguishable in outcrop, hand specimen and drill core, and provide an additional useful set of observations that help to understand the nature of the rocks of the area.

The Klondike Schist occurs as at least two thrust slices on top of at least three other thrust slices. A distinctive set of crenulation folds (F_3), that are locally parasitic on larger scale (>10 m) recumbent folds of foliation, accompanied thrust stacking and the emplacement of serpentinite in the thrust stack. These folds have a distinctive spaced axial-planar cleavage in all thrust slices. This cleavage has developed locally into a new rock fabric with recrystallized micas in the Klondike Schist. The crenulations associated with this set of folds trend northeast through the otherwise-disparate thrust slices beneath the Klondike Schist, but trend southeast in the Klondike Schist. Syn-emplacement rotation of the Klondike Schist thrust slices along phacoidal cleavage zones is suspected.

The Klondike Schist has been further deformed by a set of orthogonal faults and related kink folds (F_4) and fractures. These structures post-date thrust stacking, and have not yet been traced into underlying thrust slices. Mesothermal vein formation and gold mineralization occurred during or after fault and kink-fold formation, and were partly controlled by local extensional sites developed in the faults and kink folds. Fractures parallel to kink-fold axial surfaces are particularly common hosts for mesothermal veins. Late-stage normal faults have been partially localized by pre-existing F_4 structures, and these late faults offset some mesothermal veins. Hydrothermal alteration and silicification of host rocks accompanied normal fault movement, with a different style of mineralization from the mesothermal veins.

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REFERENCES

Dusel-Bacon, C., Lanphere, M.A., Sharp, W.D., Layer, P.W. and Hansen, V.L., 2002. Mesozoic thermal history and timing of structural events for the Yukon-Tanana Upland, east-central Alaska: $^{40}Ar/^{39}Ar$ data from metamorphic and plutonic rocks. Canadian Journal of Earth Sciences, vol. 39, p. 1013-1051.

Gordey, S.P. and Ryan, J.J., 2005. Geology, Stewart River area (115N, 115O and part of 115J), Yukon Territory. Geological Survey of Canada, Open File 4970, 1:250 000 scale.

Knight, J.B., Mortensen, J.K. and Morison, S.R., 1999. Lode and placer gold compositions from the Klondike District, Yukon Territory, Canada: Its implications for the nature and genesis of Klondike placer and lode gold deposits. Economic Geology, vol. 94, p. 649-664.

Lowey, G.W., 2005. The origin and evolution of the Klondike goldfields, Yukon, Canada. Ore Geology Reviews, vol. 28, p. 431-450.

Mortensen, J.K., 1990. Geology and U-Pb chronology of the Klondike District, west-central Yukon. Canadian Journal of Earth Sciences, vol. 27, p. 903-914.

Mortensen, J.K., 1996. Geological compilation maps of the northern Stewart River map area, Klondike and Sixtymile Districts (115N/15, 16; 115O/13, 14; and parts of 115O/15, 16). Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, Open File 1996-1(G), 43 p.

Mortensen, J.K., Chapman, R., LeBarge, W. and Jackson, L., 2005. Application of placer and lode gold geochemistry to gold exploration in western Yukon. *In:* Yukon Exploration and Geology 2004, D.S. Emond, L.L. Lewis and G.D. Bradshaw (eds.), Yukon Geological Survey, p. 205-212.

Rushton, R.W., Nesbitt, B.E., Muehlenbachs, K. and Mortensen, J.K., 1993. A fluid inclusion and stable isotope study of Au quartz veins in the Klondike district, Yukon Territory, Canada: a section through a mesothermal vein system. Economic Geology, vol. 38, p. 647-678.