The Ordovician Transition Zone of Tranny Ridge, Howard's Pass, Yukon: an Examination of Primary Structures, Mineralogy, and Structural History

By

Shawn Bruce Hood

A thesis submitted to the Faculty of Science

in partial fulfilment of the requirements for the degree of

Bachelor of Science

Department of Earth Sciences

Carleton University

Ottawa, Ontario

March, 2008

The undersigned hereby recommend to the Faculty of Science acceptance of this thesis, submitted by Shawn Bruce Hood, in partial fulfillment of the requirements for the degree of Bachelor of Science.

Dr. Sharon Carr, Thesis Supervisor

Dr. John Blenkinsop, Chairman

Department of Earth Science

Abstract

The Transition Zone is a 10 to 80 m thick succession of interlaminated mudstone and limestone that occurs between the Ordovician Rabbitkettle and Duo Lake formations in the vicinity of the Howard's Pass lead-zinc deposit, Yukon. It represents a depositional transition from basinal carbonates of the Rabbitkettle Formation to the basinal black shales of the Duo Lake Formation in the Selwyn Basin. Rocks exhibit bedding of detrital clastics and carbonates, and the presence of robust accessory minerals such as zircon and monazite; these features have been interpreted as indicative of a primary depositional environment. Mountain building commenced during the Jurassic as the Yukon-Tanana terrane overrode the north-western continental margin of North America and rocks of the Selwyn Basin were incorporated into the Selwyn fold and thrust belt. Large-scale open-to-closed folds related to these tectonics trend and plunge shallowly to the northwest. Penetrative slaty cleavage exists at outcrop scale and is the dominant foliation. Rocks have been metamorphosed to lower greenschist facies.

Thesis research focused on the Tranny Ridge locality of the Howard's Pass area and furthers understanding of the lithology, primary environments and structures of the Transition Zone, as well as the regional structural setting of the area based on synthesis of field observations with mapped structures. There is an upwards gradation in the Transition Zone from interlaminated mudstones and carbonate with occasional nodular limestone at the base to laminated black- and tan-weathering mudstone at the top. This is interpreted to represent a gradual cessation in carbonate sedimentation.

Primary stratigraphy within the thesis area has been folded, indicated by stereonet plots of poles to bedding. Calculations from stereonets give an average cleavage of about 308°/70° NE, consistent with published axial planar measurements for folds on the same thrust sheet. In thin section, samples show an anastomosing pervasive cleavage clearly defined by opaque mineral(s). This cleavage is generally at a high angle to bedding and shows refraction between laminations of varying composition. Metamorphic minerals such as chlorite and muscovite are also present, defining metamorphic grade as sub-greenschist.

The Transition Zone should be reclassified as a lithostratigraphic formation. There is little consistency in nomenclature regarding this stratigraphic unit within published literature. Designation as a formation using the lithostratigraphic characterizations required by the International Commission on Stratigraphy would be appropriate, as this unit possesses a distinct appearance, regional presence and important role as a marker unit for the Howard's Pass Pb-Zn deposit.

Acknowledgements

I would like to thank Dr. Sharon Carr for guiding this project and covering research costs. Sharon's valuable assistance, tireless patience and kind encouragement were a constant boon.

Thanks to Dr. Carr and Dr. George Dix for post-defense corrections which greatly improved the clarity and focus of my writing.

Many thanks to Dr. Robert Hodder for suggested this topic and who, along with Duncan Bain, took time during the summer field season to acquaint me with the geology of Tranny Ridge. Much gratitude to Pete Jones, for allowing me to use the SEM and for all his help identifying those pesky fine-grained clastics.

Thanks to Selwyn Resources for kindly funding a portion of this thesis and allowing me to spend a few days in the map area. The opportunity to combine research and academia is greatly appreciated. Many thanks also to my helpful friends PC and CLM who assisted in the field; good times and good BSG.

Last, but certainly not least, I would like to send a great big 'O' to the Fantastic Geobabies. May the set of {Leezy, Trux, Ben, Ahjee, Kate, ROSS!, Scottie Z, Tolik, and Colleen Mecke} never be forgotten in the mighty halls of Carleton.

IN SAXIS VERITAS

Table of Contents

List of Figures

List of Plates

Chapter One: Introduction

Overview

The Transition Zone is a stratigraphic entity within the Howard's Pass lead-zinc deposit and was first described by Morganti (1979). The Howard's Pass is located within the Selwyn Fold Belt and straddles the Yukon – Northwest Territories border in eastern Yukon (Gordey and Anderson, 1993). The Transition Zone is a 10 to 80 m thick sequence of interlaminated mudstone and calcareous mudstone that occurs between the Upper Ordovician Rabbitkettle and Duo Lake formations. It represents a depositional transition from the basinal carbonates of the Rabbitkettle Formation to the basinal, carbonaceous, and graptolitic black shales of the Duo Lake Formation within the Paleozoic Selwyn Basin. This transition from carbonate to siliciclastic deposition is attributed to increased water depth due to rifting associated with the opening of the Panthalassic Ocean (Mair et. Al, 2006). Folds, thrust faults and penetrative cleavage formed during development of the Selwyn Fold and Thrust Belt during the Jurassic-Cretaceous Cordilleran orogeny (Mair et. Al, 2006). Post-orogenic extension has created local tension structures such as outcrop-scale en echelon, quartz filled tension gashes and variously trending, steeply-dipping normal faults (Gordey and Anderson, 1993).

The Transition Zone locally separates the Upper Rabbitkettle Formation and Duo Lake Formation. This stratigraphic entity has experienced various treatments in literature pertaining to the Howard's Pass and Little Nahanni area. In early mapping of these areas, Gabrielse (1973) describe the lower contact of the Road River Group (then a Formation) as the top of the Rabbitkettle Formation, with the Road River Group comprised of all graptolitic calcareous shales of Cambrian to Ordovician age and little mention of a gradational contact. Morganti (1979) introduced the "Transition Formation" as an informal lithostratigraphic unit separating the Rabbitkettle Formation and Road River Group in his synthesis of the Howard's Pass Pb-Zn deposit. Later work by Goodfellow (e.g., 1983, 2007) has used the term "Transition Zone".

A major component of this thesis is to assess the lithological characteristics of the Transition Zone. If this interval represents a change in depositional facies, as described in existing literature, what is the composition of its "end members"? That is, what is the lithological makeup of the lower calcareous and upper clastic portions of the Transition Zone? What sort of lithological gradient exists between them? Does this unit possess identifiable lithologic characteristics, clearly marked and conformable vertical chronological boundaries, and sufficient regional extent to qualify is as a lithostratigraphic entity using the guidelines set forth by the International Commission on Stratigraphy?

A second question regards the nature and genesis of structures within the Transition Zone; specifically, is the origin of the observed layering lithological, tectonic or a combination of both? If the layering is lithological, then what are the processes that caused these primary variations, and what is the geologic significance from a paleoenvironment point of view? If the rock has been deformed, then what are the structures and microstructures, how did they form, and what larger scale structures could they be related to?

Finally, what is the state of deformation of the Transition Zone? Are there any zones of localized deformation in the study area? Can structures within this formation be related to those mapped at the regional scale; for example, is the cleavage related to a regional folding event, and is there evidence for an assessment of metamorphic grade?

Regional Geologic Setting

The term "Selwyn Basin" is used in this thesis following the definition of Gordey and Anderson (1993), and refers to a region of deep-water, offshelf sedimentation that persisted between the late Proterozoic to Middle Devonian. Spatially, the Selwyn Basin is currently bounded by the Cassiar platform, Tintina fault, and Mackenzie platform and is 700 x 200 km in size (Figure 1; Mair et al., 2006). The epicratonic Selwyn Basin developed in a divergent-margin setting circa 760 Ma and persisted from Late Proterozoic until the Mississippian (Mair et al., 2006). The oldest rocks are sedimentary synrift siliciclastics of the Upper Proterozoic to Lower Cambrian Hyland Group, equivalent to upper Windermere strata preserved in the adjacent Mackenzie platform (Ross, 1991; Gordey and Anderson, 1993). Deposition of Gull Lake Formation shales began during the Early Cambrian, followed by finely laminated siliceous limestone and dolomitic mudstone of the Upper Cambrian to Lower Ordovician Rabbitkettle Formation (Gordey and Anderson, 1993). Continued rifting and subsidence of the continental margin between the Early Ordovician and Early Devonian led to deposition of carbonaceous shale, chert and dolomitic mudstone of the Duo Lake and Steel Formations (Road River Group). Several stratiform sedimentary exhalative (SEDEX) base metal deposits are hosted within the basin; these deposits are interpreted to have formed via hydrothermal discharge during Middle to Late Devonian extensional events (Goodfellow, 1995).

Deformation of the Selwyn Basin and development of the Selwyn Fold and Thrust Belt began in the Early Jurassic as exotic elements of the composite Yukon-Tanana terrane overrode the North American continental margin (Mair et al., 2006). Folding and North-directed, thin-skinned thrust sheets developed in the eastern portion of the Selwyn Basin (Mair et al., 2006). Slope-to-basin facies strata were variably deformed, and in some areas weakly metamorphosed during orogenesis (Dusel-Bacon et al., 2002; Mair et al., 2006). The fold belt is characterized by large-scale thrust faulting, open to tight similar folds, imbricate fault zones, and the development of axial planar slaty cleavage (Gordey and Anderson, 1993; Mair et al., 2006). Tranny Ridge is carried by the Appler thrust sheet, located within the Little Nahanni map area (NTS 105I), mapped by Gordey and Anderson (1993)

Methodology

Field mapping was undertaken during August of 2007 while working for Selwyn Resources. Bedrock geology of the study area, Tranny Ridge, was mapped at a scale of 1 : 10 000 (Figure 2). Several objectives of the field study component included: (i) collecting structural information such as attitude of bedding and cleavage, (ii) positioning geologic formation and fault contacts, (iii) field checking of geology maps by previous workers (Gordey and Anderson, 1993; Gordey et al., 1981), and (iv) documenting lithological characteristics of the Transition Zone. About 50 structural measurements were taken and 30 samples were collected for petrographic analysis.

Laboratory work was undertaken between September 2007 and March 2008. Petrography was conducted using transmitted and reflected light microscopes. scanning electron microprobe (SEM) analysis was used to identify minerals that could not be identified by eye or conventional light microscopy. Structural analyses were carried out by evaluating structural measurements at Tranny Ridge and comparing them with those adjacent to the south, located on the Appler thrust sheet and mapped by Gordey and Anderson (NTS mapsheet 105I-6; 1993).

Chapter Two: Primary Geologic Setting

Depositional Setting

Deposition of Selwyn Basin stratigraphy occurred in an offshelf environment between the Late Cambrian and mid-Devonian (Mair et al., 2006). Orientation of the basin was southeast-northwest, with depositional facies distributed parallel to the basin's long axis and symmetrical about it (Goodfellow et al., 1983). Morphology remained similar between early Cambrian and Early Devonian with depth-related facies responding to eustatic sealevel changes, although the passive continental margin sequence on the northeast edge of the basin persisted (Gordey and Anderson, 1993). The Ordovician Transition Zone, ocurring between Rabbitkettle Formation basinal limestones and Duo Lake basinal shales, is commonly accepted as having formed due to sea level transgression with an associated depletion of calcareous sediment (Goodfellow, 1995; Gordey and Anderson, 1993; Morganti, 1979). Based on mapping by Gordey and Anderson (1993) and deformation history by Mair (2006), deposition of Rabbitkettle Formation occurred in a quiet-water, sub-wave base, offshelf setting. Shales and cherts of the Duo Lake Formation dominated sedimentary deposition within the Selwyn Basin during Late Ordovician time. These strata represent a starved basin environment (Goodfellow et al., 1983). Shale-filled troughs of Duo Lake Formation occupy marginal zones parallel to the basins' long axis. Thin, carbonaceous basinal strata of the Duo Lake Formation identify quiet, episodically anoxic, conditions isolated from open ocean (Mair et al., 2006). This isolation may have been due to the development of shallow water platforms over marginal plateaus (Mair et al., 2006).

Regional Stratigraphy of Howard's Pass

Gordey and Anderson (1993, p.139) describe the Rabbitkettle Formation as 494 m thick, containing three varieties of limestone. Lowermost, an orange weathering, argillaceous to silty limestone overlies the upper Proterozoic and Lower Cambrian Vampire Formation. This is overlain by a blue-grey weathering, fine crystalline limestone. The upper 119 m, which is locally exposed in domain A of the study area, consists of grey, grey-weathering, finely crystalline nodular limestone interbedded with argillaceous to silty limestone in beds less than 10 cm thick.

The Transition Zone overlies the Rabbitkettle Formation and is 10 to 80 m thick within the Howard's Pass. This unit represents a Late Ordovician transition from basinal carbonates of the Rabbitkettle Formation to basinal, carbonaceous, and graptolitic shales of the Duo Lake Formation (Figure 3). The upper contact of the Transition Zone with the Duo Lake Formation is based on Total Organic Carbon (TOC) content, as defined by Morganti (1985), although he does not state within his descriptions what value of TOC is used.

Shales of the Duo Lake Formation and overlying Steel Lake Formation belong to the Road River Group (Gordey and Anderson, 1993), which is estimated to be 300 m thick (Gordey and Anderson, 1993). Regionally, biostratigraphic controls show that the Duo Lake Formation conformably overlies the Rabbitkettle Formation (Gordey and Anderson, 1993). The Duo Lake Formation is subdivided locally within the Howard's Pass into six subunits for exploration purposes (see Morganti, 1979 for detailed description of subunit lithofacies).

Local Stratigraphy

Rabbitkettle Formation strata appear in domain A of Tranny Ridge (Figure 2) as a resistant hill (Figure 4). Nodules of limestone within this unit are its most distinguishing field characteristic (Figure 5, i), and are dark grey weathering, up to 2 cm in diameter and abundant within the light-grey weathering, argillaceous to silty limestone matrix. Gordey and Anderson (1993), who do not include the Transition Zone in their stratigraphy, describe the Rabbitkettle Formation as an excellent marker unit beneath the dark weathering shale and chert of the Duo Lake Formation. The Rabbitkettle Formation is said to be "conformably and abruptly" overlain by the Duo Lake Formation (Gordey and Anderson, 1993) description, with the contact between the two sharply delineated in scree. Such is not the case at Tranny Ridge, where the upper contact of the Rabbitkettle Formation is overlain by the Transition Zone and is recessive. The lower boundary of the Road River group was defined as the top of the Rabbitkettle Formation, but this conformable contact is only rarely exposed and often disturbed by thrust faults (Gabrielse, 1973).

The Transition Zone is locally 30 m thick in domain A of Tranny Ridge and 75 m thick in domain B (Figure 2; Figure 4). The upper and lower contacts of the Transition Zone are recessive in both domains A and B. Outcrop exposure on the ridge is poor and extensive frost-heaving has reoriented the rocks and disturbed bedding, cleavage, and contact orientations. Mapping of Tranny Ridge has therefore consisted of careful integration of outcrop measurements, talus composition, marmot-hole-tailing analysis and interpretation of geologic contacts and topography. Based on carbonate content, weathering appearance and mineralogy, I have divided the formation into two subunits: Basal Transition and Upper Transition (Figure 5). Carbonate content is reduced upsection, and rocks grade from laminated mudstone and silty carbonate with minor nodular dolomite at the base to interlaminated black- and orange-weathering mudstone. Exposed sections of Transition Zone are insufficient to show thicknesses of subunits or the contacts between them.

Rocks within the Basal Transition are composed of two basic laminae types: (i) orange- to buff-weathering pale grey laminae of carbonates (dolomite +/- calcite +/- apatite) containing very fine grained quartz and K-feldspar, and (ii) brown clay-rich laminae which contain fine grained quartz and K-feldspar. At the base of the Basal Transition pale grey laminae are composed mainly of carbonate minerals, with carbonate content diminishing upsection towards the Upper Transition. Light grey concretions of limestone are intercalated and occur proximal to the underlying Rabbitkettle Formation; these are similar in appearance to those seen in the Rabbitkettle, although much less common. Dolomite laminae weather orange and mudstone laminae weather black, giving the rock a characteristic “black and tan” colouring (Figure 5, i). Calcareous laminae are up to 5 mm in thickness, and mudstone laminae are up to 2 mm in thickness. Limestone concretions, generally concordant to bedding, are elongate and up to 30 cm long and 5 cm in diameter and overprint the laminae which are continuous from exterior to interior and throughout concretions. Moving upsection towards the Basal Transition-Upper Transition contact, limestone nodules disappear. Finely laminated grey limestone interbedded with black coloured shale with <50% carbonate, are similar to those of the basal Transition Zone, but with increasing percentage of mudstone laminae. The combination of progressive increase in mudstone and decrease in carbonate defines a transitional contact with the overlying Duo Lake (Morganti, 1979). The contact between Rabbitkettle Formation and Transition Zone is gradational over 1 to 10 m and based on calcite content (Morganti, 1979); however, no such contact is visible at Tranny Ridge.

Rocks of the Upper Transition proximal to the Lower Transition-Upper Transition stratigraphic division show characteristic black and tan weathering. This unit is poorly exposed in the study area, although a large knob is located in domain B (Figure 4). Cohesive outcrops are located on steep faces in domains A and B. Black, black weathering laminated shale is predominate and contains some light grey laminae of limestone. Mudstone laminae are up to 5 mm thick. Calcareous laminae are up to 2 mm thick. Moving upsection towards the Duo Lake Formation contact, carbonate laminae decrease in compositional percentage until they disappear entirely. The portion of Upper Transition Formation that is entirely free of carbonate at hand-specimen scale is small, about 5 metres in thickness. In hand specimen or drill core, the lack of calcite, slight shaley appearance and presence of distinct laminae is useful to identify rocks of the Upper Transition Zone.

The upper contact of Transition Zone strata with the Duo Lake Formation is described by Morganti (1979) as gradational over 0.5 to 5 m; however, this contact is not exposed at Tranny Ridge. Rocks of the Duo Lake Formation are recessive and poorly exposed within the study area, and all field identification of this unit was performed using potato chip sized pieces of talus. Duo Lake shales are black and black to bluish dark-grey weathering and occasionally show mild laminations. Laminations are composed of chert and less than 1 mm.

Mineralogy

Thin section petrography was used to analyze the mineralogy of Transition Zone samples. Mineralogy of the Transition Zone is gradational upsection from carbonate to shale, with overall carbonate content decreasing and siliciclastic content increasing upsection. Transmitted and reflected light microscopy was used to identify major minerals, with a scanning electron microprobe (SEM) used to identify very fine grained minerals which could not be resolved using standard light microscopy.

In the Basal Transition Zone, dark grey laminae are composed of silt sized detrital quartz and K-feldspar (Plate 1, a,b,c). These grains are sub-angular, well sorted and up to 25 µm in size. Light grey laminae are composed of between 40-95% silt-sized carbonates, and 5-60% detrital quartz and K-feldspar (Plate 3). Clastic grains are sub-angular, well sorted and up to 25 µm. Recrystallized calcium carbonate and dolomite are up to 25 µm (Plate 3). The modal percentage of carbonate minerals, including detrital carbonates and limestone nodules, is <50%.

Light grey laminae of the Upper Transition Zone contain detrital quartz, feldspar and minor recrystallized carbonates (Plate 4). Dark grey laminae of the upper Transition Zone are composed of detrital K-feldspar and quartz. Detrital zircon (Plate 5) and monazite (Plate 6, ii) and are present as silt-sized accessories.

Primary Features

Primary structures in the Basal Transition subunit are sedimentary in nature and comprise parallel laminae of mudstone, silty limestone and dolostone, with <50% of total composition being carbonate laminae. These laminae are 0.3 mm to 5 mm in thickness (Plate 1). Laminae do not exhibit energy related features such as cross beds or ripples, and are very fine grained.

Primary structures in the Upper Transition subunit are sedimentary in nature and comprise parallel laminae of mudstone and silty carbonate, with all carbonate laminae less than 1 mm. These laminae are 0.3 mm to 5 mm in thickness (Plate 2). Laminae do not exhibit energy related features such as cross beds or ripples, and are very fine grained, indicating suspension load deposition.

Conclusions and Discussion

Summary of Lithology

The Transition Zone at Tranny Ridge is composed of sedimentary rocks that grade upsection from laminated mudstone and silty carbonate with minor nodular dolomite to interlaminated black- and orange-weathering mudstone. Primary features are restricted to rhythmic parallel laminae. The bottom informal member, Basal Transition, is separated from the underlying Rabbitkettle Formation by a total carbonate content less than 50%. Basal Transition is predominately composed of two types of mudstone laminae. Type (i) mudstone laminae are white when fresh and weather orange. These are composed of recrystallized detrital carbonates and detrital clastics of very fine grain size. Type (ii) mudstone laminae are black and composed of mud sized clastics. Minor elongate nodules of limestone are grey and up to 30 cm long. Upper Transition overlies Basal Transition and is separated due to a lack of “significant” carbonate, i.e., it does not effervesce with dilute HCl. This member contains type (i) laminations, although grains of carbonates are rare. Type (ii) laminations are black, mud-sized clastics. The upper contact with the overlying Duo Lake Formation is recessive within the Tranny Ridge area.

Interpretation of Primary Structures

Laminae within both Upper and Lower Transition Zone are interpreted to have been deposited by suspension load deposition, based on the very fine grain size of constituent detrital minerals and lack of energy-related depositional features. This is consistent with Gordey and Anderson’s (1993) conclusion that deposition occurred below storm wave base. The Transition Zone represents a shift from primarily carbonate to primarily clastic sedimentation in a basinal environment due to riftrelated basin subsidence (Mair et al., 2006). Petrographic examination of the Transition Zone at Tranny Ridge reveals evidence of primary sedimentary deposition, primary bedding and detrital grains. Mineralogically, the unit contains diagenetic carbonates and clastic detrital grains of feldspar, monzanite, and zircon. Clastic sediments are also seen in the silty limestones of the upper Rabbitkettle Formation, and shales of the lower Duo Lake Formation (Gordey and Anderson, 1993; Morganti, 1979). Sources of Ordovician sedimentation in the Selwyn Basin are not well documented; clastics may have been derived from terranes to the north or west of the basin or from the margin of North America (Mair et al., 2006).

Stratigraphic Definition

The Transition Zone lies conformably between the Cambrian-Ordovician Rabbitkettle Formation and Ordovician-Silurian Duo Lake Formation. Carbonate content is used to define the contact between the Rabbitkettle and Transition Zone. Near the basal contact of the Transition Zone there is abundant calcite, both as a constituent of limestone and dolomite laminae, and as fracture infill. Rocks at the Basal Transition-Rabbitkettle contact contain less than 50% carbonate, with less than 10% of whole rock composition being carbonate concretions. This is consistent with Morganti's (1979, page 28) definintion of the Rabbitkettle-Transition contact being "...based on calcite content. Rocks having less than 50% calcite are placed within the Transition Zone". Application of dilute hydrochloric acid is sufficient for approximate separation of Basal Transition and Rabbitkettle Formation in the field, coupled with visual inspection: Basal Transition is much darker due to mudstone laminations, and exposed surfaces showing the characteristic “black and tan” weathering.

The contact between Upper Transition and the Duo Lake Formationis distinguishable from overlying Duo Lake

Regional recognition of the Duo Lake Formation, and its Pb-Zn hosting shales, is difficult due to the recessive nature of the formation. Stratigraphic context is therefore important for identification of the Duo Lake Formation; it is overlain by the orange-weathering mudstones of the Steel Formation (see description by Gordey and Anderson, 1993 p.54) and underlain by the Rabbitkettle and Transition Zones. The upper-Rabbitkettle and Transition Zones, although not part of the economic stratigraphy of Howard’s Pass, serve as an easily recognizable footwall to the ore-hosting Duo Lake Formation.

Definition as a Lithostratigraphic Unit

The Transition Zone is not officially recognized as a lithostratigraphic unit. As well, there is a confusion of nomenclature regarding this unit within published literature relating to the Howard’s Pass and Little Nahanni map areas (see Overview). However, the so-called Transition Zone does possess qualities which would allow for proper stratigraphic naming. This unit is regionally mappable throughout the Howard’s Pass Pb-Zn district and useful in core-logging or regional exploration for deducing the lower boundary of the deposit-hosting Duo Lake Formation. Additionally, the Transition Zone possesses easily recognizable field characteristics: it is resistant to weathering, contrasting with the recessive nature of the overlying

Duo Lake Formation (see description in Stratigraphic Definition), and has a typical "black and tan" weathered appearance. Finally, although upper and lower contacts are not exposed at the Tranny Ridge study locality, biostratigraphic work by Gordey and Anderson (1993) indicate that these contacts are conformable; thus the Rabbitkettle and Duo Lake Formations are suitable as boundary units.

The Transition Zone should be reclassified as a lithostratigraphic formation. I suggest that further work be undertaken to establish a type locality for the Transition Zone, and that it be properly named using lithostratigraphic nomenclature set forth by the International Commission on Stratigraphy.

Chapter Three: Structural History

Overview

The Howard's Pass Deposit lies in the Selwyn Fold and Thrust Belt adjacent to the Northwest Territories-Yukon Territory border. Proterozoic and Paleozoic strata strike northwest and underwent folding and thrusting beginning in the Jurassic and lasting about 100 Ma. Intrusion of quartz monzonite and granitic stocks occurred during the Cretaceous. Shortening of the originally 117 km long Selwyn Basin is estimated at about 30%, accommodated by folding, thrusting and pervasive slaty cleavage (Gordey and Anderson, 1993). Tranny Ridge is located on the south-western exposed edge of the Appler thrust sheet, which carries a 4 km thick sequence of Proterozoic to Devonian strata. Large-scale folds have amplitudes of about 5 km and northwesterly trending axes with south-south east striking axial planes. These are cut by thrust faults which dip to the southwest and are in turn dissected by steeply dipping systems of normal faults.

Tectonic History

The geology of the Howard's Pass area has been shaped by a series of tectonic processes that controlled the growth and form of the Proterozoic-Paleozoic continental margin of North America (see Regional Geology). During the late Mesoproterozoic to Neoproterozoic the tectonic setting of North America changed from amalgamation as part of Rodinia to rifting of cratonic blocks and formation of the Pacific margin of North America was established as it separated from Antarctica-Australia-North China-Siberia (Gabrielse and Yorath, 1992; Sears and Price, 2000). The Canadian Cordillera formed during the Mesozoic-Cenozoic and incorporated rocks of the Selwyn Basin, thus forming the Selwyn Fold and Thrust Belt.

Description of Structure

Deformation structures at map scale within the Selwyn Fold Belt include regional-scale thrust faults, imbricate fault zones, large-scale folds, axial-planar slaty cleavage, and zones of closely spaced imbricate thrusts are common (Gordey and Anderson, 1993; Cecile, 2000). There at least three generations of structures and one of very low metamorphism:

- S_0: primary bedding
- S_1: parallel to S_0
- S_2: Synkinematic development of folds and axial planar cleavage
- M_1: Recrystallization of quartz and calcite and growth of pyrite porphyroblasts with synkinematic pressure fringes

Foliation

S_0

There are at least three generations of foliation within the Tranny Ridge Area. S_0 represents primary sedimentary bedding (see primary structures; Figure 6). At the outcrop scale, there are varying bedding-cleavage angles within the Rabbitkettle

Formation and Transition Zone at Tranny Ridge (Figure 6). Within the Transition Zone, S_0 is represented by two types of primary laminae: (i) pale grey, orange weathering calcareous laminae containing silt-sized dolomite +/- minor calcite, apatite, or detrital quartz and feldspar grading upsection to pale grey clastic laminae that are predominately composed of silt-sized detrital quartz and K-spar +/- minor carbonates, and (ii) brown clay-rich laminae. Observed S_0 within the Duo Lake Formation are rare minor chert laminae.

$\underline{S_1}$

This foliation has been folded, along with S_0, and is defined in thin section by an opaque material. Earlier petrographic work by Morganti (1979) on the upper Rabbitkettle Formation - Transition Zone contact area suggests that opacity is due in part to concentrations of organic matter within the cleavage. S_1 is interpreted as a diagenetic foliation parallel to S_0 (Figure 6, Plate 6 in ppl) and is likely due to compaction and expulsion of pore fluid (based on geometric development of foliations by Passchier and Trouw, 1996).

$\underline{S_2}$

S_2 is a pervasive, axial planar slaty cleavage ubiquitous within the Tranny Ridge area. This cleavage is present throughout the Howard’s Pass region and often referred to in area-specific literature as the “regional cleavage” (Figure 6) (Morganti, 1979; Gordey and Anderson, 1993; Hodder and Bain, 2005). At Tranny Ridge, S_2 cleavage is distributed within a cluster with an average orientation of 85/039 SE (Figure 7).

In thin section, S_2 is an anatomizing spaced cleavage (Plate 1, Plate 2) seen within all samples. Cleavage seams are defined by an opaque and appears as accentuated dark seams. These seams are interpreted as accumulations of insoluble material along dissolution surfaces (Passchier and Trouw, 1996, section 4.9) and contain minor amounts of organic material (Morganti, 1979, p. 24-25). Cleavage domains are occasionally associated with very fine grained biotite seams containing a minor component of very fine grained fragments of quartz and K-spar, although these minerals are too fine grained to be identified using optical microscopy, generally less than 5 μm. Morphology of cleavage domains and microlithons is selectively developed within each lamination type and generally consistent from basal to upper Transition Zone. Within the Transition Zone, cleavage domains are anastomosing (Plate 1, Plate 2) but show a large variation in volume percentage of cleavage domains between lamination types. When non-parallel to bedding, S_2 cleavage shows refraction between carbonate and clastic laminations, with higher bedding-to-cleavage angles in quartz-carbonate laminations (Plate 7). Secondary foliations within type (i) laminations are uncommon (i.e., have high spacing), and tend to die out. Secondary foliation within type (ii) laminations are anastomosing and continuous, with a higher volume percentage of cleavage domains. S_2 cleavage domains within limestone concretions of Basal Transition are stylolytic and spaced. Microlithons within type (i) and (ii) are composed of weakly oriented quartz and K-spar. Quartz subgrains are common within detrital grains in Basal and Upper Transition.

F_2 Folds

Folds were not mapped at Tranny Ridge within the Transition and Duo Lake formations due to poor exposure. Outcrops of Rabbitkettle Formation do show kink banding, and parallel folded (class 1B of Ramsay, 1967) quartz veins were seen as float in domain B of the study area (Figure 9). In thin section, shortening via flattened parallel folding (class 1C of Ramsay, 1967) of type (i) quartz-carbonate laminae is ubiquitous (Plate 7). Pi diagrams of bedding (Figure 8) show patterns indicative of folding. The pi axis was calculated at 12°/106°. The axial trace of folds in the Tranny Ridge area, as measured from NTS mapsheet 105I/11 (Gordey and Anderson, 1993), trend 302° NW. Stereonet calculation using this axial trace and the pi axis (above) gives an axial plane of 302°/38° NE (Figure 8).

D_2 Thrust Fault

The boundary between map domains A and B is marked by a repeated panel of stratigraphy and a low “saddle” of topography (Figure 4). Domain A contains Rabbitkettle through to Duo Lake Formation; Domain B contains from Transition Zone through to Duo Lake Formation at southern-most extent of the thesis area (Figure 2). This boundary is interpreted to be a D_2 thrust fault. This fault dips south at a low angle, about 30 degrees. Geographic Information System (GIS) data from the Yukon Geological Survey (Gordey and Makepeace, 1999) shows a 5 km fault projected towards this saddle, located to the west of the study at UTM 487878 E 6930000 N, and with strike and dip of about 115°/40° SW. This fault does not have known a displacement or type (Gordey and Makepeace, 1999). If the strike of the fault is extended 500 m along strike to the SW, coinciding with the boundary between domains, it would account for the southern repetition of stratigraphy.

M_2 Metamorphism

Detrital grains of quartz display undulose extinction indicative of subgrains. Pyrite crystals surrounded by synkinematic fibrous strain fringes of fine grained chlorite (Figure 8) or polycrystalline quartz Figure 9) appear with mild frequency in samples of Upper Transition Zone taken from Tranny Ridge and are slightly more common in Upper Transition than Basal Transition. These pyrite "eyes" are larger and more common in the Southern Knob than the North Hill. Pyrite eyes are up to 4 mm and completely oxidized in outcrop to the North, and up to up to 5 cm in diameter and very rusty when weathered in the south. In some cases, some original pyrite remains. Pressure fringes have sharp boundaries and non-coaxial to one-another, indicating shear during formation.

D_3 Normal Fault

Two faults are inferred within the Tranny Ridge map area (Figure 2). The northern limit of mapping is defined by a fault dipping about 70 degrees south and separating Rabbitkettle Formation from a buff weathering limestone unit to the north. This buff limestone may represent the middle Cambrian Avalanche Formation (Charlie Jefferson, 2008, personal communication).

Summary and Discussion

Bedding within Tranny Ridge is steeply dipping with generally northward strike (although strikes vary dependent on location within folds) and unit contacts cut across topography with little deflection. An inferred D_2 fault, marked topographically by a saddle at the contact between domains A and B, marks the beginning of a stratigraphic panel repeat beginning with Transition Zone and continuing upsection into the younger Duo Lake Formation.

F_2 folds within the Transition Zone at Tranny Ridge have an associated pervasive axial planar cleavage, commonly referred to as the "regional cleavage" in literature specific to the Howard's Pass. Regionally, large-scale folds (i.e., folds with half wavelengths about 5 to 9 km and amplitudes 1 to 2 km) are upright and closed with limb dips not usually exceeding 60 degrees (Gordey and Anderson, 1993). Fold axes of medium scale folds on Tranny Ridge (i.e., with half wavelengths about folds with amplitudes about 1 or 2 km) trend between 196°/78° NE and 211°/85° NE, as calculated using stereonets of plotted bedding.

Outcrop-scale folds are not obvious within exposed sections of Transition Zone, although hand-sized pieces of parallel folded (class 1B of Ramsay, 1967) quartz veins were found in float (Figure 9) proximal to Transition Zone outcrops. Folded silty limestone laminae at thin section-scale are flattened parallel folds (class 1C of Ramsay, 1967). This variance is somewhat consistent Gordey's (1993) description of small-scale folds, that they vary dependent on competence with competent layers (e.g., chert) being of class 1B or 1C (Ramsay, 1967) and incompetent layers (e.g, cleaved pelite) being of class 2 and 3 (Ramsay, 1967).

Axial planar cleavage was averaged at 308°/70° NE or 126°/75° SW using stereonet plots of measured cleavage from the Tranny Ridge area. The scatter of poles between clusters seen in Figure 6 may be due to the inclusion of measurements between map domains A and B and hence between two offset fault blocks.

Orientations of axial planar cleavage at Tranny Ridge were derived from cleavages measured in the field and from stereonet plots of bedding. These sources give 308°/70° SW or 126°/75° NE, and 302°/38° NE, respectively. Published sources (i.e., Gordey and Anderson, 1993, p. 99) give an axial planar cleavage value about 295°/75° NE.

Structural analyses has been conducted using stereonet plots of axial planar cleavage and bedding; this in turn has been compared with regional map patterns on NTS mapsheet 105I (Gordey and Anderson ,1993). For these analyses, medium-scale folds in Tranny Ridge were compared with large-scale folds within the Appler thrust sheet. Resulting stereonets show that both sets of folds have roughly parallel axial surfaces and are therefore likely of the same generation.

M_2 metamorphism is evidenced by the presence of minor chlorite and polycrystalline quartz.

Chapter Four: Summary and Discussion

Summary of Conclusions

The purpose of this thesis is to describe the lithological nature and tectonic structures of the Transition Zone at Tranny Ridge. Although the formation underlies the mineralized strata of the Duo Lake Formation, examination of primary lithology provides clues about the primary depositional environment during subsidence of the Selwyn Basin prior to sedimentary exhalative mineralization. From a depositional facies standpoint, the Transition Zone is one piece in a body of evidence supporting basin subsidence and a corresponding gradation from primarily carbonate to primarily clastic sedimentation.

Fold and thrust style deformation during the Jurassic, characterized by thin-skinned tectonics (Mair, 2006), are associated with pervasive axial planar cleavage, folded type (i) calcareous laminae, realignment of clay minerals (e.g., biotite) within type (ii) brown clay laminae, development of subgrains in detrital quartz grains, the recrystallization of carbonate minerals, and synkinematic pressure shadows of quartz and chlorite. These features, along with the preservation of primary bedding, suggest low grade metamorphism within the Transition Zone.

The Tranny Ridge area is dissected by steeply dipping normal faults to the North, East and South. Examinations of tectonic structures within the Transition Zone of

Tranny Ridge provide a useful method of determining whether the area is structurally comparable to the rest of the thrust sheet; i.e., the area has not experienced oblique faulting. Stereonet calculations of an axial plane within Tranny Ridge suggest that it is structurally conformable with other folds on the Appler thrust sheet to the South.

Stratigraphic Placement

Conceptually, the Transition Zone should be diachronous. Time-stratigraphic diagrams by Gordey and Anderson (1993, figure 12) based on their mapping of NTS mapsheet 105I show a conformable contact between the basinal shales of the Duo Lake Formation and underlying basinal silty carbonates of the Rabbitkettle Formation. Once deposition of the Duo Lake Formation shales began, a landward lateral facies change developed between they and the Rabbitkettle Formation. The Rabbitkettle Formation in turn shares a landward lateral facies boundary with the dolomites and sandy carbonates of the syndepositional Haywire Formation, part of the subsiding shelf Mackenzie Platform. Sequence stratigraphic mapping of the lateral eastern boundary between the Transition and Rabbitkettle formations should reveal an interdigitate relationship with eustatic sealevel-associated sequence boundaries. Furthermore, correlation of stratigraphic sections using a “hinging” stratigraphic section, e.g., the green volcanic tuff layer of the lower Rabbitkettle, would allow for more accurate mapping of facies boundaries.

Conformable Transition

Petrographic evidence of sedimentary features from the Transition Zone of Tranny Ridge supports interpretation as a facies transition between the Rabbitkettle and Duo Lake Formations. This transition is illustrated in my samples by a reduction of carbonate minerals up-section and a corresponding increase of detrital clastics.

The contact between upper Rabbitkettle and Lower Duo Lake is traditionally described within the literature as being conformable based on fossil control and exposed contacts in fold hinges (originally by Gordey and Anderson, 1993, Gordey, 2007, personal communication). However, Fossil control is based on fragmentary graptolites and conodonts collected by Gordey and Anderson (1993, p. 182-183, analyzed by M.J. Orchard and B.S. Norford)

Formation Thickness

The thickness of the Transition Zone varies between the two sections observed: within domain A the formation is roughly 30 meters thick, whereas it is nearly 75 m thick in the domain B, as calculated using observed dips of bedding (Figure 2). This change in thickness could be due to either depositional or tectonic factors. I have inferred a fault boundary as the northern border of domain B; such a structure could accommodate stratigraphic thickening. However, lateral variation in depositional facies might also have influenced unit thickness. From a sedimentary perspective, lateral facies changes such as decreased carbonate production due to lower temperature or reduced clastic input due to sealevel transgression would influence stratigraphic thickness of the Transition Zone by controlling sediment influx. Further stratigraphic mapping in Howard's Pass, such as isopach mapping of clastic vs. carbonate content, might allow for further definition of the Transition Zone in terms of facies distribution.

Zone versus Formation

Morganti (1979) originally gave informal formation status to the Transition Zone because of its distinct, laminated appearance between the carbonates of the Rabbitkettle Formation and shales of the Road River Group. Subsequent work has referred to Morganti's (1979) Transition Formation as the Transition Zone (e.g., Goodfellow et al., 1983 and subsequent publications on Howard's Pass) or not at all, preferring to encapsulate it as a gradational contact (Gordey and Anderson, 1993).

Transitional formations are not uncommon within the Selwyn Basin. Several formations in the vicinity of Howard's Pass, and within the paleo-inner margin of the Selwyn Basin, represent transitional facies between basin and platform deposition: e.g., the upper Proterozoic to Cambrian Vampire Formation, Cambrian Rockslide Formation and Ordovician Sapper Formation (Gordey and Anderson, 1993). These formations represent deep-water facies interstratified with platformal carbonates, a pattern resulting from a migrating carbonate shelf edge (Gordey and Anderson, 1993). The Transition Zone should likewise be elevated to formation status. Results of this thesis have shown that the Transition Zone locally has a substantial thickness, about 30 m in domain A and 75 m in Domain B, and is lithologically identifiable from formations above and below. Mapping and drill-core logging by Morganti (1979), mapping by Hodder and Bain (2005), and regional drill-core logging by Selwyn

Resources provide evidence of the regional extent and stratigraphic placement of the Transition Zone. These qualities will allow for the application of proper lithostratigraphic nomenclature.

Nature of the Transition Zone Laminae

In hand-specimen, laminations within the Transition Zone appear to be primarily sedimentary. However, petrographic examination reveals that primary bedding has been partially transposed into cleavage. This transposition results from tectonically-derived shortening, and has both deformed beds and led to the development of a pervasive, S_0 cutting S_2 foliation. Calcareous Type (i) laminae have been shortened and thickened with S_2 spaced cleavage. Type (ii) laminae contain tightly spaced anatomizing cleavage defined by insoluble minerals, causing these laminae to appear darker than their primary constituent minerals.

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, v. 39 no.6, p. 1013-1051.

Folk, R. L., 1959, Practical petrographic classification of limestones: American Association of Petroleum Geologists Bulletin, v. 43, p. 1-38.

Gabrielse, H., Blusson, S.L., and Roddick, J.A. , 1973, Geology of Flat River, Glacier Lake and Wrigley Lake map-areas, District of Mackenzie and Yukon Territory; Geological Survey of Canada: Memoir 366 (Parts I and II), p. 421.

Goodfellow, W. D., Cecile, M.P., and Leybourne, M.I., 1995, Geochemistry, petrogenesis, and tectonic setting of lower Paleozoic alkalic and potassic volcanic rocks, Northern Canadian Cordilleran miogeocline: Canadian Journal of Earth Sciences, v. 32, p. 1236-1254.

Goodfellow, W. D., Jonasson, I. R., and Morganti, J. M., 1983, Zonation of chalcophile elements about the Howard's Pass (XY) Zn-Pb deposit, Selwyn Basin, Yukon: Journal of Geochemical Exploration, v. 19 no.1-3, p. 503-542.

Goodfellow, W. D., and Rhodes, D., 1991, Geological setting, geochemistry and origin of the Tom stratiform Zn-Pb-Ag-barite deposits (in Mineral deposits of the northern Canadian Cordillera, Yukon, northeastern British Columbia (field trip 14)): Open-File Report - Geological Survey of Canada, p. 177-241.

Gordey, S. P., and Anderson, R. G., 1993, Evolution of the northern Cordilleran miogeocline, Nahanni map area (1051), Yukon and Northwest Territories, Memoir 428, Geological Survey of Canada, p. 214.

Gordey, S. P., and Makepeace, A. J., 1999, Yukon bedrock geology in Yukon digital geology, Geological Survey of Canada Open File D3826 and Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, Open File 1999-1.

Gordey, S. P., Wood, D., and Anderson, R. G., 1981, Stratigraphic framework of southeastern Selwyn Basin, Nahanni map area, Yukon Territory and District of Mackenzie; Current research, Part A: Paper - Geological Survey of Canadano.81-1A, p. 395-398.

Hodder, B., and Bain, D., 2005, Internal Report. Howard's Pass 2005: A Reconnaissance of Geology and an Hypothesis, A Report for Pacifica Resources, Pacifica Resources.

Mair, J. L., Hart, C. J. R., and Stephens, J. R., 2006, Deformation history of the northwestern Selwyn Basin, Yukon, Canada; implications for orogen evolution and Mid-Cretaceous magmatism: Geological Society of America Bulletin, v. 118 no.3-4, p. 304-323.

Morganti, J. M., 1979, The Geology and Ore Deposits of the Howards Pass Area, Yukon and Northwest Territories: the Origin of Basinal Sedimentary Straiform Sulphide Deposits: Unpub. Ph.D. thesis, University of British Columbia.

Passchier, C. W., and Trouw, R. A. J., 1996, Microtectonics: Springer-Verlag, Berlin, Federal Republic of Germany, 289 p.

Ragan, D. M., 1985, Structural geology; an introduction to geometrical techniques, John Wiley & Sons, New York, NY, United States, 393 p.

Ramsay, J. G., 1967, Folding and Fracturing of Rocks: New York, McGraw-Hill Book Company, 568 p.

Ross, G. M., 1991, Tectonic setting of the Windermere Supergroup revisited: Geology, v. 19, p. 1125-1128.

Tucker, M.E., 1993, Sedimentary rocks in the field John Wiley and Sons, Chichester, United Kingdom (1996) 153 p.

Appendices

1) Location and access
2) Sample locations and descriptions
3) Summary of Upper Rabbitkettle Formation mineralogy from Morganti, 1979

1) Location and Access

Howard's Pass is located within the Cordilleran craton margin in eastern Yukon and straddles the Yukon Territory-Northwest Territories border, about 260 km north of Watson Lake and 160 km east-northeast of Ross River. Access to the Howard's Pass property is by fixed wing aircraft or helicopter via Whitehorse (370 km), Ross River (180 km) or Watson Lake (300 km).

The research area is located in a rectangular area roughly defined by UTM coordinates 487675E 6930800N and 488400E 6929400N. The area is about three kilometres northwest of Selwyn Resources' XY Camp (488826E 6926188N)

2) Field Data

Table of field Specimens: sample #, UTM coordinates, sample descriptions, bedding, axial planar cleavages

SAMPLE #	**UTM E**	**UTM N**	**ELV**	**UNIT**	**DESCRIPTION**
SBH001	**488096**	**6930444**		**Road River**	**Frost heaved and very foliated outcrop. Weathered orange-grey, fresh grey-black. Slight sheen on regional cleavage plane almost looks like phyllite.**
SBH002	**488262**	**6929826**		**Transition**	**Taken from talus slope. Boudin shows some shearing? Little fractures filled with quartz**
SBH003	**488183**	**6929732**		**Trans. R.K.**	**Transition Rabitkettle**
SBH004	**488098**	**6930492**	**1829**	**Transition**	**Slightly slumped outcrop, although probably in place. Weathered: Black and tan lamellae. Fresh: Dark grey (as per usual for Transition Fm. Outcrop is about 1m around. Regional cleavage @ 100/88. Kinematic indicator: lazy little 'S' between cleavages.**
SBH005	**488120**	**6930474**	**1838**	**Trans. R.K.**	**Light grey 'boudins' / dark grey matrix. Appears to be a combination of Morganti's wavy banded limestone and transition, with boudins longer and more closely spaced than in true Rabbit Kettle. Black: 50%, tan: 50%. Boudins show some internal foliation.. Relict bedding or S, beyond S into planar fracture? Boudins look planar in section and the 'tan' has been pulled into the regional shear. This sample represents intermediate strain.**
SBH006	**488182**	**6930136**	**1841**	**Upper Transition (?)**	**Funny little grey, calcareous guy with some banding taken from talus.**

SAMPLE #	UTM E	UTM N	ELV	UNIT	DESCRIPTION
SBH007	**488096**	**6930395**		**Trans / R.R**	**Variety of samples taken from probable contact between Transition Fm. And Road River Group. Dark coloured samples from South, brown samples from North of contact.**
SBH008	**488122**	**6930421**	**1845**	**Transition**	**Weathered: Black and tan, but more tan than usual. Fresh: med-grey. Outcrop is quite foliated, with possible slickensides on shear plane. Up to 1cm spacing between foliated 'leaves' of outcrop. Regional cleavage: 074/47 NE. Angle of bedding to cleavage: 0**
SBH009	**488126**	**6930481**	**1838**	**Trans. R.K.**	**Wavy banded limestone showing intermediate strain. Strong reaction with dilute HCl, both on black nodules and tan matrix. Black: 65%, tan: 35%. Regional cleavage: 306/56. Fracture surface on top of outcrop: 114/30 SE**
SBH010	**488151**	**6930485**	**1824**	**Trans. R.K. or R.K.**	**Not too deformed (e.g., boudins parallel but not too strung out). Black: 30%, tan: 70%. Reacts to HCl. Regional cleavage: 288/46. fracture surfaces: 228/02, 136/30, 050/04. Angle of boudins to regional cleavage: 0-30. Fracture cleavage: 310/70 NW.**
SBH011	**488161**	**6930480**	**1824**	**R.K.**	**Tan weathering rabbitkettle with crystalline calcite. Outcrop trends 286 deg NW. Regional cleavage: 298/68 NW. Fractures: 074/44 NE, 150/66 SE (some kinematic indicators of this surface, I think), 302/50 NW, 356/48 NW.**
SBH012	**488149**	**6930442**	**1817**	**Trans. R.K.**	**Looks like a fault bounding Rabbit Kettle and Transition Fm. Rocks in this area show qz+Ca infilling fractures with both R.K. And Transition. Area located on saddle between**

					hills, sudden lithology change with up-section repeat to South suggest fault.
SAMPLE #	**UTM E**	**UTM N**	**ELV**	**UNIT**	**DESCRIPTION**
SBH013	**488151**	**6930420**	**1828**	**Trans. R.K.**	**Talus contact betwen black Transition Fm and tan Transition Fm? Sample is of tan unit.**
SBH014	**488151**	**6930420**	**1828**	**Trans.**	**Talus contact betwen black Transition Fm and tan Transition Fm? Sample is of black unit.**
SBH015	**488148**	**6930422**	**1823**	**Transition**	**That black, scaly looking transition, reminds me of ancient swamp-treebark. Float.**
SBH016	**488150**	**6930396**	**1811**	**Trans. R.R or R.R**	**Black rocks pieces taken from talus - ask Bob and Duncan**
SBH017	**488077**	**6930448**	**1850**	**Transition**	**Slumped over outcrop. Weathered: black and tan. Appears phyllitic. Regional cleavage: 042/24**
SBH018	**488087**	**6930397**	**1844**	**Trans./R.K contact**	**Contact between brown transition formation (North) and Rabbit Kettle (South)**
SBH019	**488058**	**6930445**	**1846**	**check map**	**Frost heaved outcrop, regional shear at 122/28 SE. Weathered: brown-grey, fresh: black. Siliceous**
SBH020	**488068**	**6930429**	**1845**	**Transition**	**Scrappy outcrop of transition. Weathered dark orange**
SBH021	**488270**	**6929763**	**1825**	**Transition**	**Broken mound of transition**
SBH022	**488266**	**6929760**	**1818**	**Transition**	**Transition**
SBH023	**488250**	**6929762**	**1810**	**Transition**	**Rusty stain on surface. Py nodules in transition, calcitic rims. Nodules, up to 5cm, do not appear to have been rotated**
SBH024	**488275**	**6929744**	**1830**	**Transition**	**Py nodules in transition, calcitic rims. Nodules, up to 5cm, do not appear to have been rotated**
SBH025	**488227**	**6929696**	**1852**	**Transition**	**Nice kink banding**

SAMPLE #	**UTM E**	**UTM N**	**ELV**	**UNIT**	**DESCRIPTION**
SBH026	**488270**	**6929650**	**1847**	**Trans./R.R**	**Pencil shaped Transition / road river (?)**
SBH027	**488257**	**6929711**	**1836**	**Transition/RR**	**Black and Tan.**
SBH028	**488062**	**6929739**	**1815**	**Transition**	**Taken from saddle south of southern TRANS knob**
SBH029	**488012**	**6929863**	**1783**	**Transition R.K.**	**Float**
SBH030	**488050**	**6930440**	**1847**	**Trans. / R.K.**	**Scrappy little outcrop, sheared up Lower Transition. Frost heaved. Boudin banding at 20 deg to regional cleavage.**
SBH031	**488020**	**6930484**		**RK**	**Orange dolomite with grey nodular limestone**
SBH032	**487862**	**6930335**		**RK**	**Grey crystalline limestone w calcite veining**

a. Attitude Measurements

		Cleavage		Bedding	
UTM E	UTM N	Strike	Dip	Strike	Dip
487963	6930438	300	58		
487995	6930463	310	70		
488019	6930473	276	80		
488023	6930478	288	62		
488030	6930690	308	72		
488058	6930445	122	28		
488059	6929748	130	80		
488062	6929739	100	70	100	70
488068	6930429	246	60		
488077	6930448	042	24		
488122	6930421	074	47		
488126	6930481	306	56		
488140	6930415	038	54		
488151	6930485	310	70		
488161	6930480	298	68		
488165	6929711	110	86	315	48
488190	6929720	280	85	280	85
488216	6929704	122	68	052	20
488227	6929696	130	70	100	60
488230	6929717	130	80		
488250	6929701	116	70	120	24
488252	6929692	118	78	114	52
488256	6929760	130	44		
488260	6929681	310	80	110	90
488263	6929688	124	78	298	50
488264	6929680	140	64	280	40
488266	6929679	134	64	038	45
488266	6929760	115	75		
488267	6929780	240	90		
488270	6929763	320	72		
488277	6929752	320	90		
488279	6929663	290	39	6929663	290
488300	6929783	320	90		

3) Brief summary of Upper Rabbitkettle Formation mineralogy from Morganti, 1979

The upper Rabbitkettle Formation is referred to by Morganti (1979) as the “Wavy Banded Limestone” and described using the classification schema of Folk (1959) as intercalated siliceous microsparite and argillaceous micrite. Thin section petrography by Morganti (1979) shows that calcareous mudstone contains 20-30% calcite, 15-25% quartz and 45-65% clay. X-ray diffraction analysis from samples of upper Rabbitkettle, analyzed by Morganti (1979), indicate clay composition of 1Md and 2M muscovite. Some laminae are darkened by minor amounts of organic matter, and are described as being concentrated in the cleavage. Quartz increases within micrite laminae upsection from 10% to 30%. Calcareous mudstone also shows a progressive decrease in carbonate content at the top of the Rabbitkettle

Figures

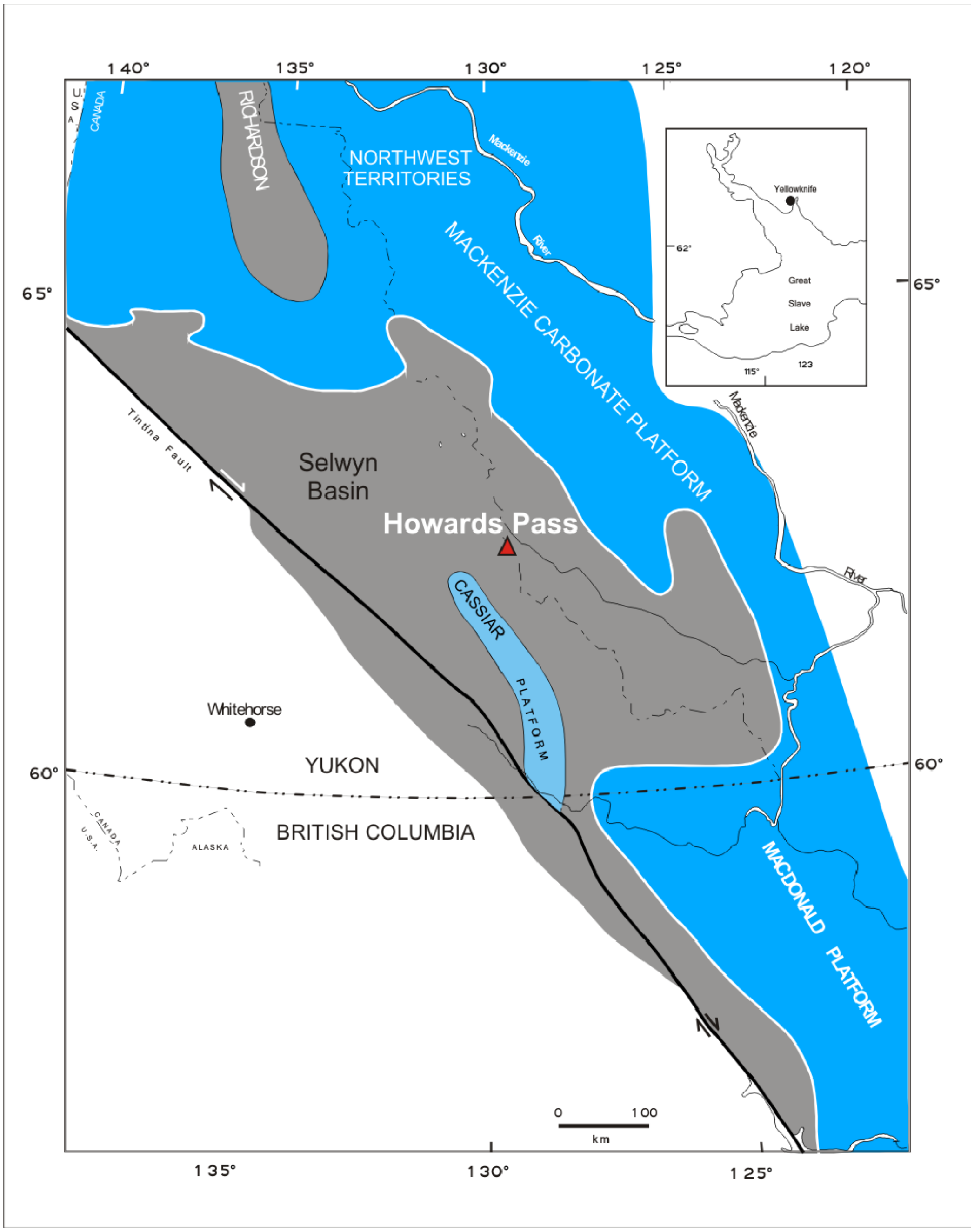

Figure 1: Location of Howard's Pass

Location of Howard's Pass within the Selwyn Fold and Thrust belt (i.e., modern locations of Selwyn Basin strata). See Appendix A for access and geographic coordinates. Modifed from Goodfellow (2007)

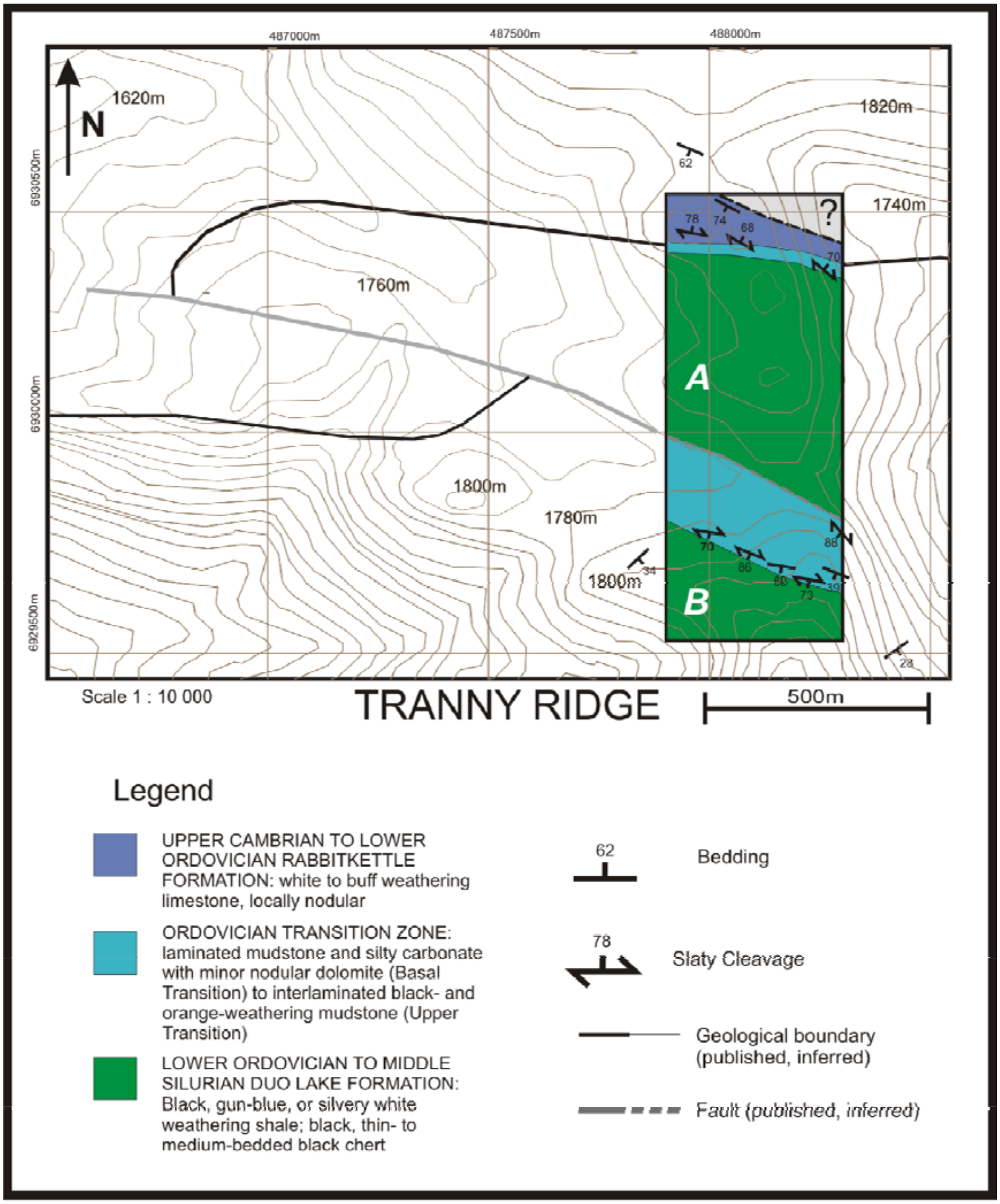

Figure 2: Geologic sketch map of Tranny Ridge

Topographic map of Tranny Ridge showing structural measurements and geological contacts. Published geological contacts and faults are taken from NTS mapsheet 105I (Gordey and Anderson, 1993). Mean magnetic declination is 27° 31.5’ decreasing 12.9’ annually (Gordey and Anderson, 1993).

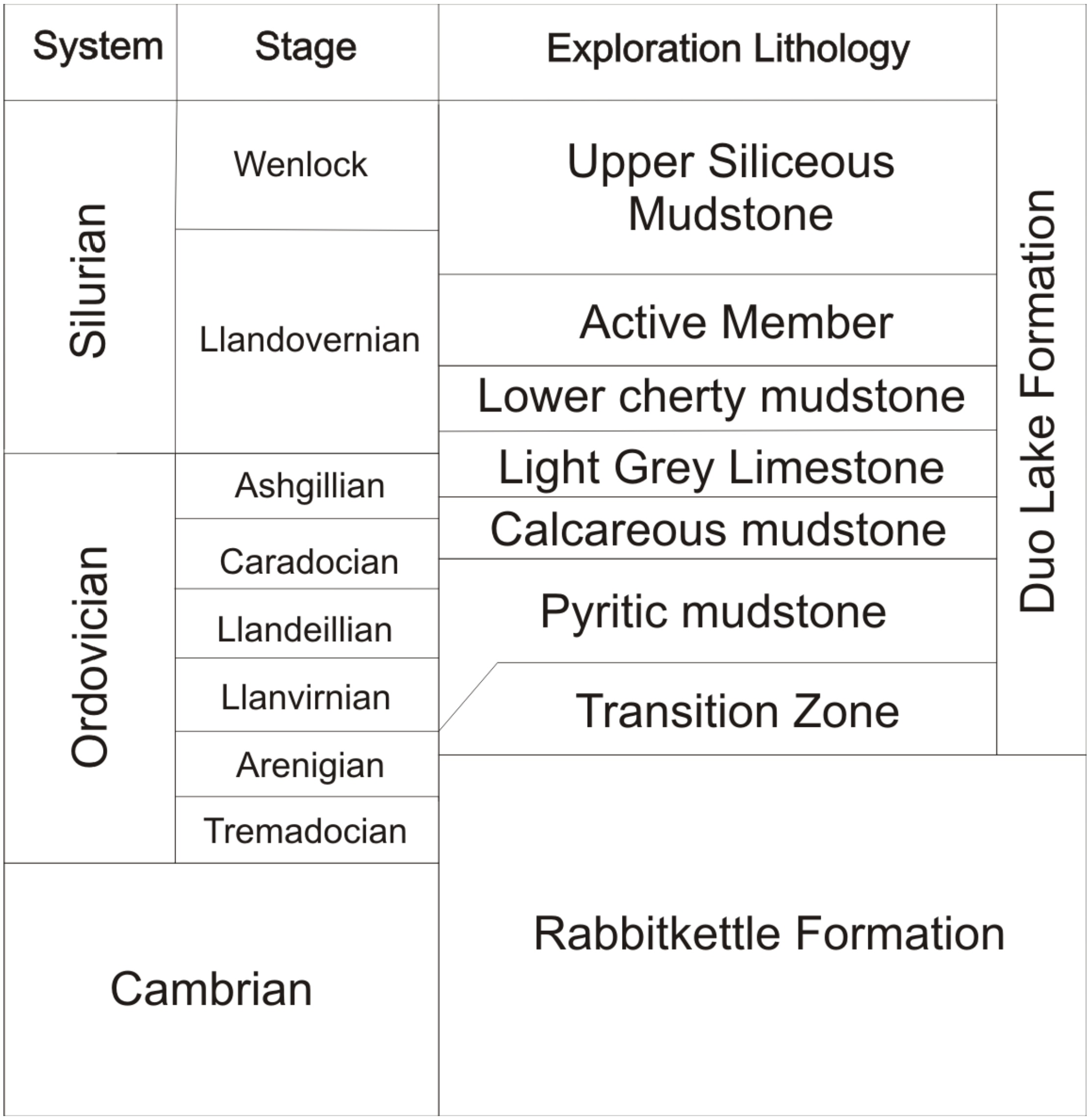

Figure 3: Stratigraphic Setting

Stratigraphic setting of Transition Zone (modified from Goodfellow and Jonasson, 1990; Hodder and Bain, 2006).

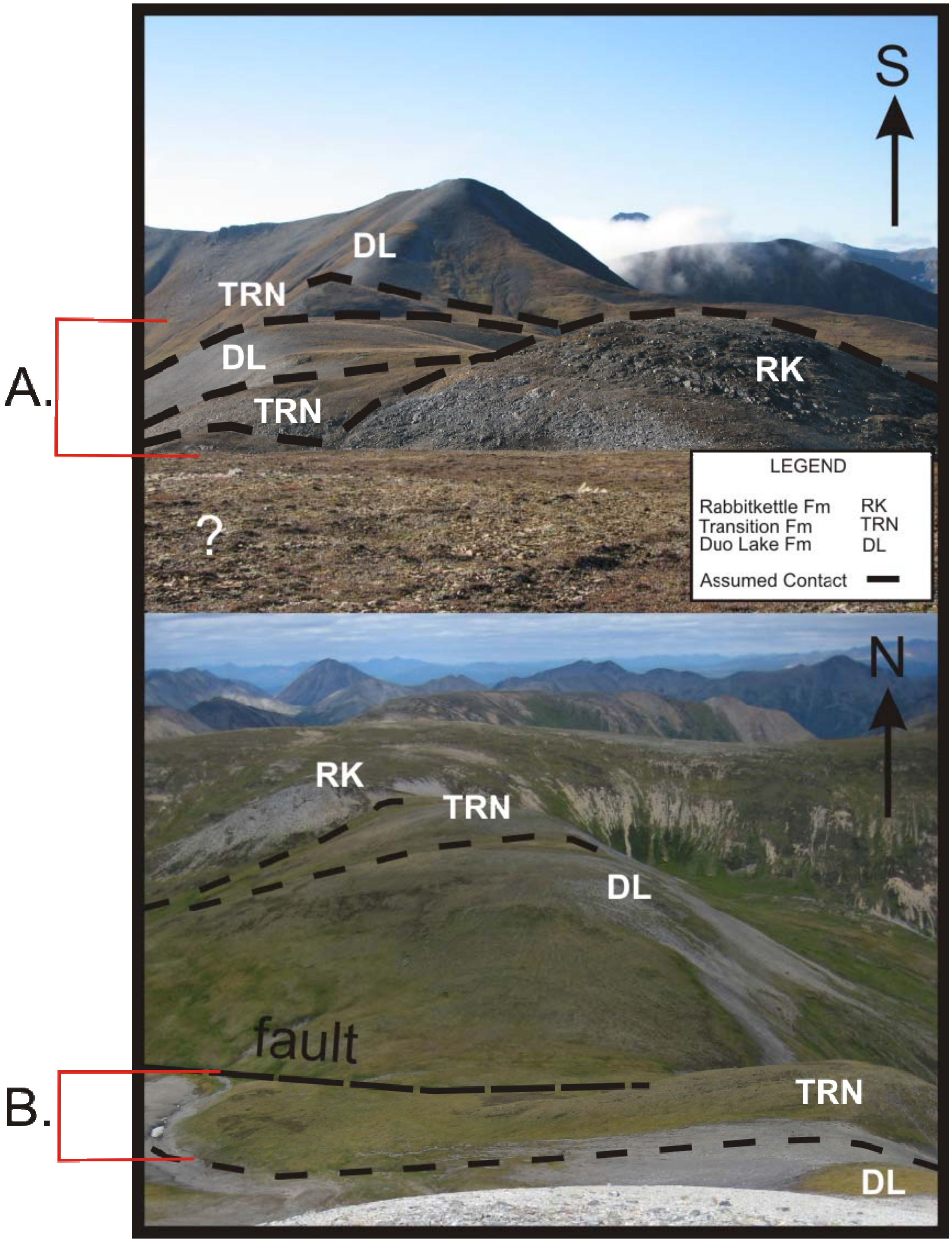

Figure 4 Northward and Southward views of Tranny Ridge

View along Tranny Ridge with geologic contacts. Top: northward view. Bottom: southward view. Domains A and B of Tranny Ridge shown to left of image

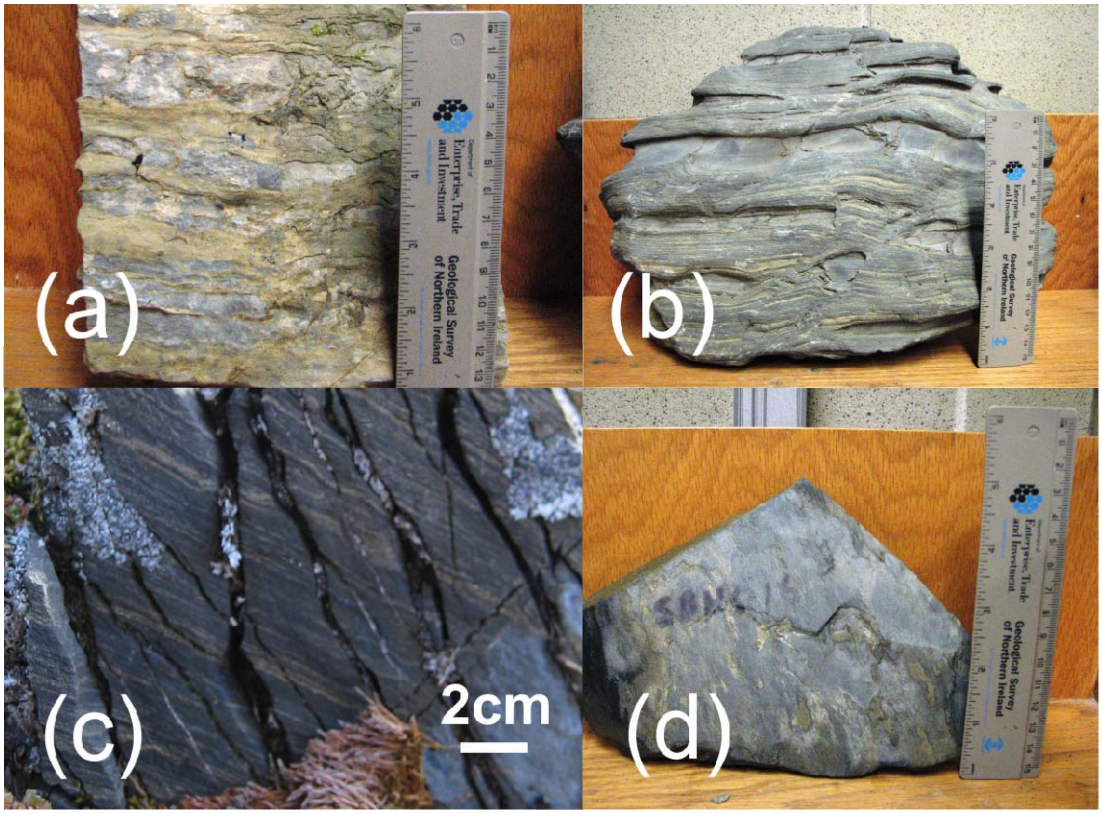

Figure 5: Representative hand specimens

Sample transition through Transition Zone of Tranny Ridge in hand sample. (a) Rabbitkettle Formation (b) Basal Transition Zone (c) Upper Transition Zone (d) Basal Duo Lake Formation

Figure 6: Structural surfaces in outcrop

S_0, S_1, and S_2 foliations in outcrop of Transition Zone located in domain B of Tranny Ridge. Bedding dips to the southwest. S0 = bedding, S1 = diagenetic foliation, S2 = axial planar cleavage.

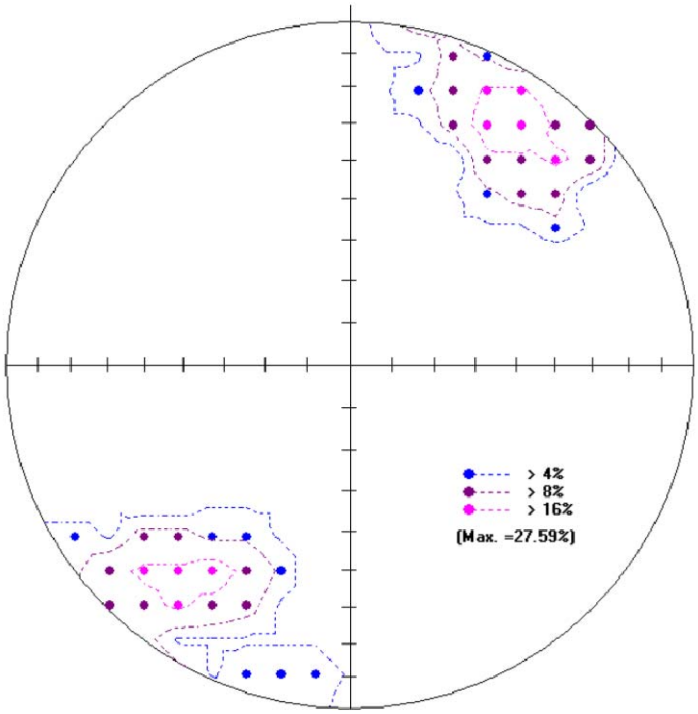

Figure 7: Stereogram of poles to cleavage

Lower hemisphere equal area plot of S_2 poles contoured by density, with distribution of poles to cleavage falling within a cluster. Average orientation of foliations is 85/039 SE. n = 29

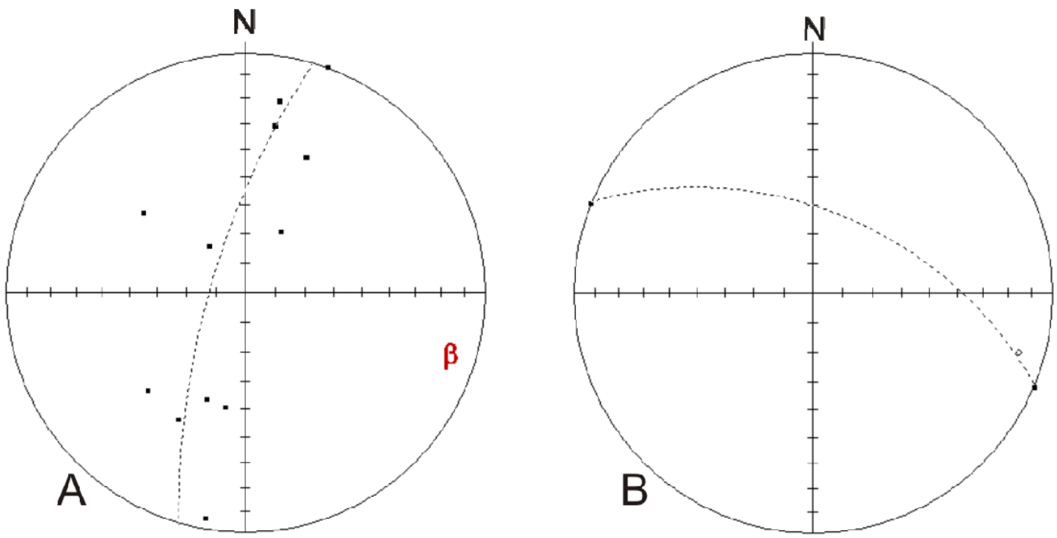

Figure 8: Stereogram of poles to bedding

The pi axis was calculated at 12°/106°. Using an axial trace trend of 302° NW from folds in the Tranny Ridge area (NTS mapsheet 105I/11, Gordey and Anderson, 1993), the axial plane of S_2 is calculated at 302°/38° NE for Tranny Ridge. n= 12.

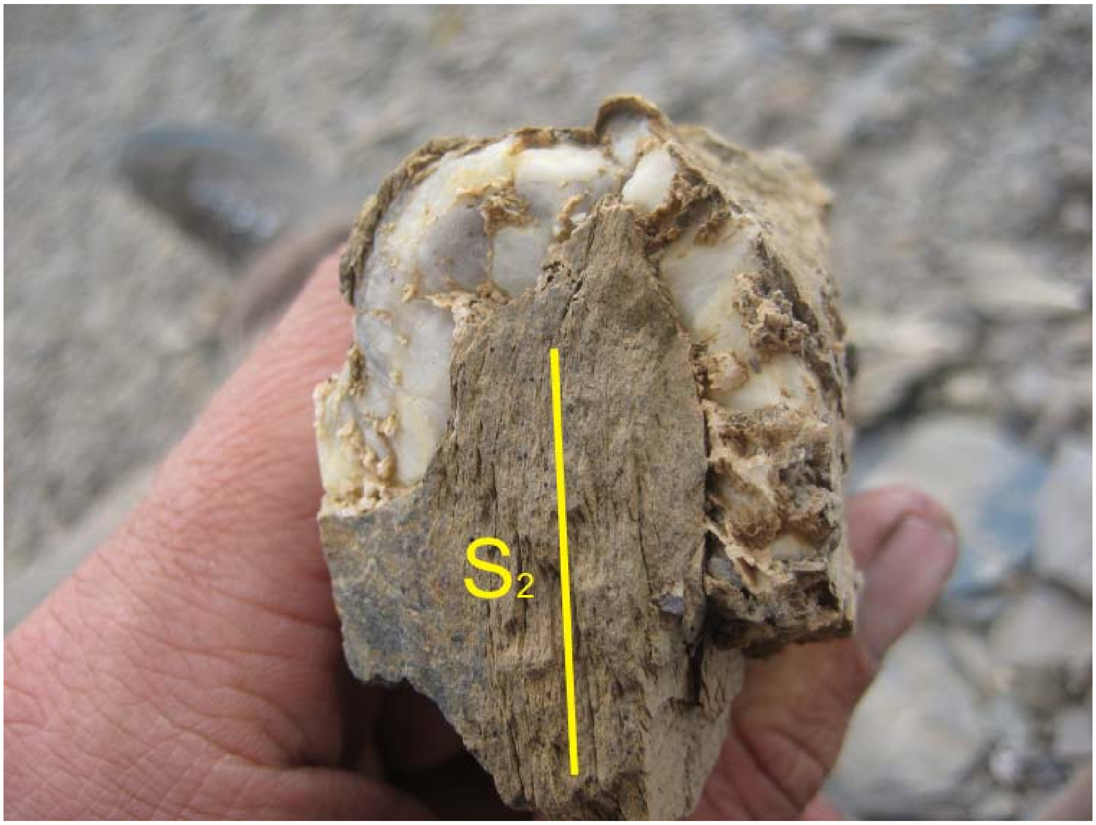

Figure 9: Folded quartz vein with axial planar cleavage

Folded quartz vein from float in domain B showing relationship of axial planar cleavage to fold. Note boudinage in quartz vein.

Plates

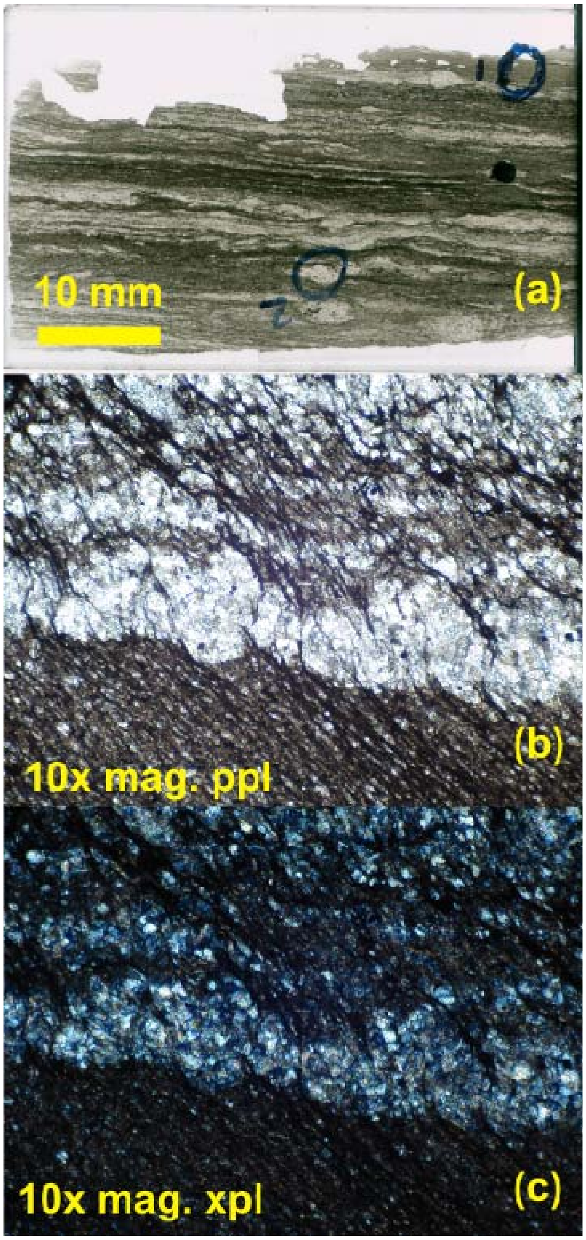

Plate 1: Photomicrograph of rocks from Basal Transition

(a) Photograph of representative thin section (b) Plain polarized light (ppl) (c) Crossed polarized light (xpl). Note folding of type (i) and pervasive cleavage in type (i) laminae. Sample SBH-024.

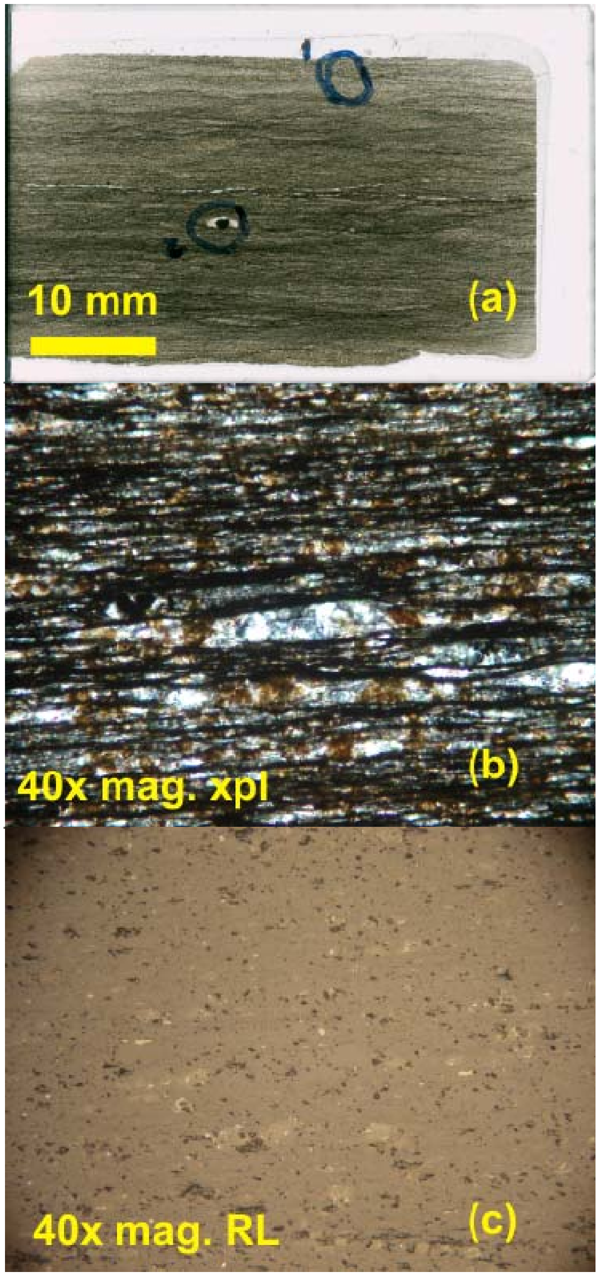

Plate 2: Photomicrograph of rocks from Upper Transition

Upper Transition Zone. (d) Photograph of representative thin section (b) Cross Polarized Light (c) Reflected Light. Note recrystallizat ion of quartz in (b) and presence of oxides in (c). Sample SBH-030.

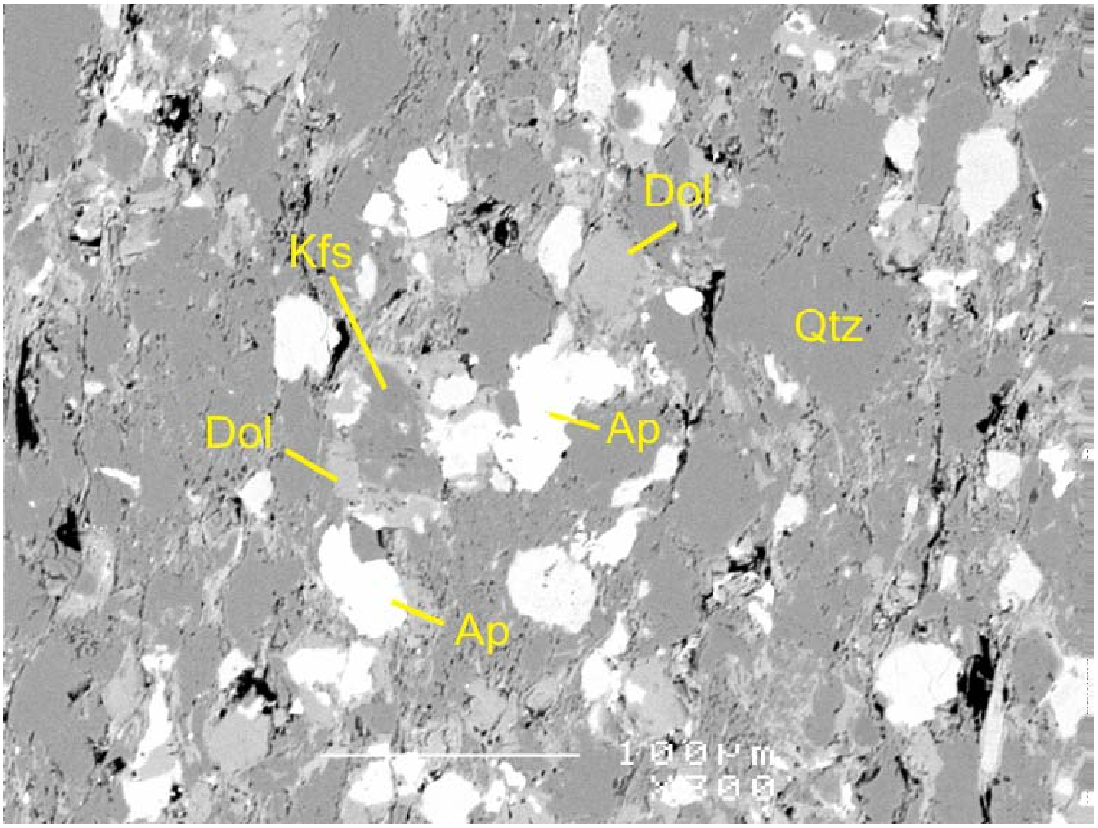

Plate 3: SEM micrograph of Basal Transition

Thin section micrograph showing grain mineralogy of a grey lamination in Basal Transition Zone. Taken using SEM. AP = apatite, Ksp = potassium-feldspar, Qtz = quartz. Thin section SBH-030.

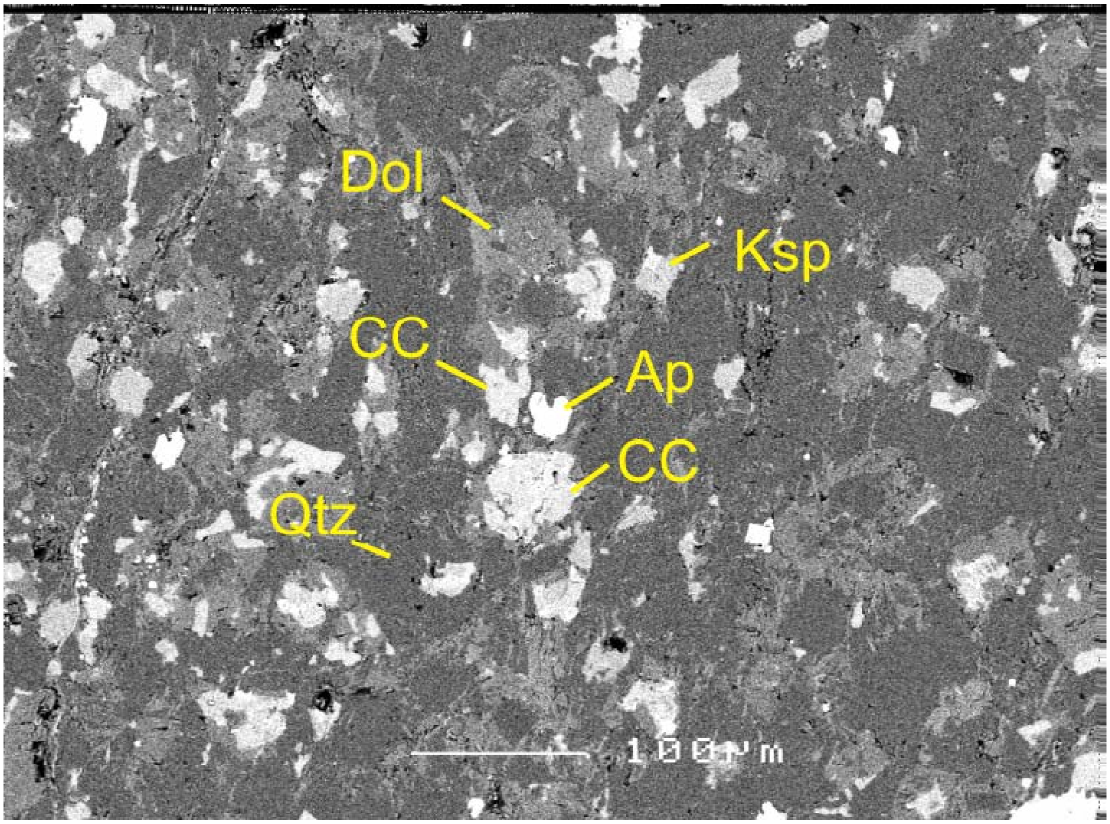

Plate 4: SEM micrograph of Upper Transition

Thin section micrograph showing grain mineralogy of a grey lamination in Upper Transition Zone. Taken using SEM. AP = apatite, CC = calcite, Dol = dolomite, Ksp = potassium-feldspar, Qtz = quartz. Thin Section

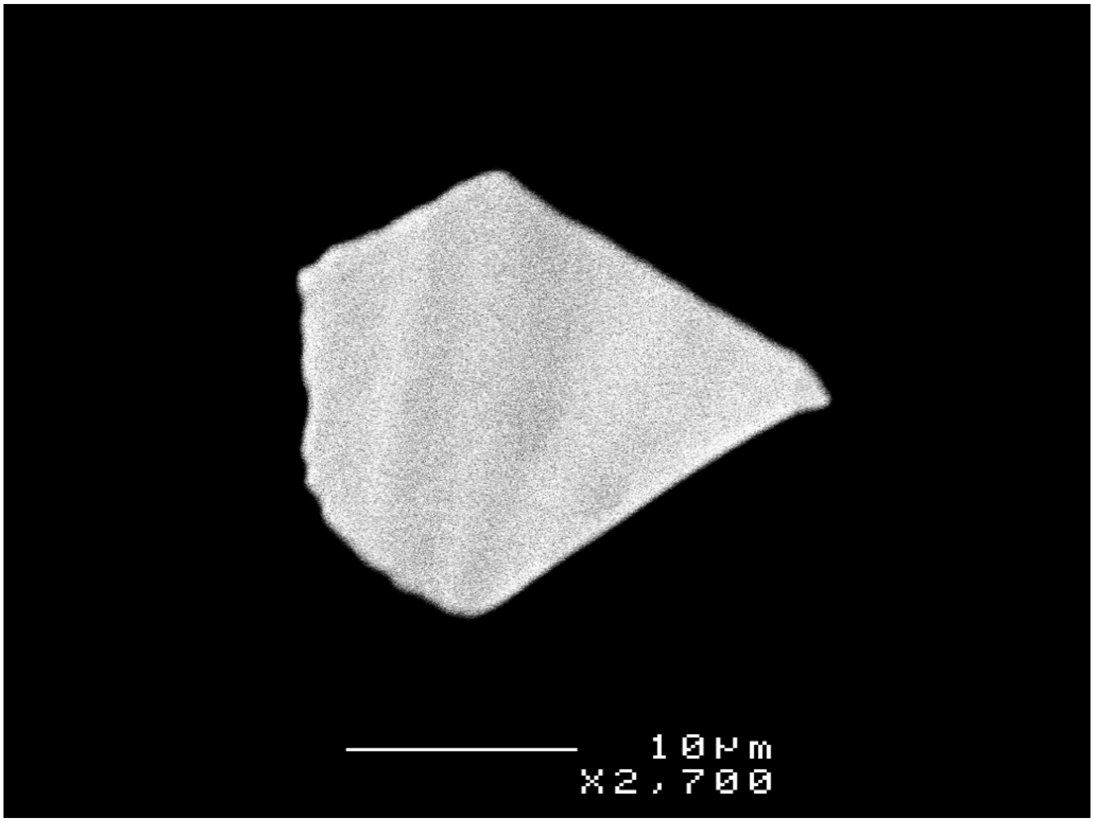

Plate 5: SEM micrograph of detrital zircon

SEM micrograph of detrital zircon from Upper Transition Zone, sample SBH-030.

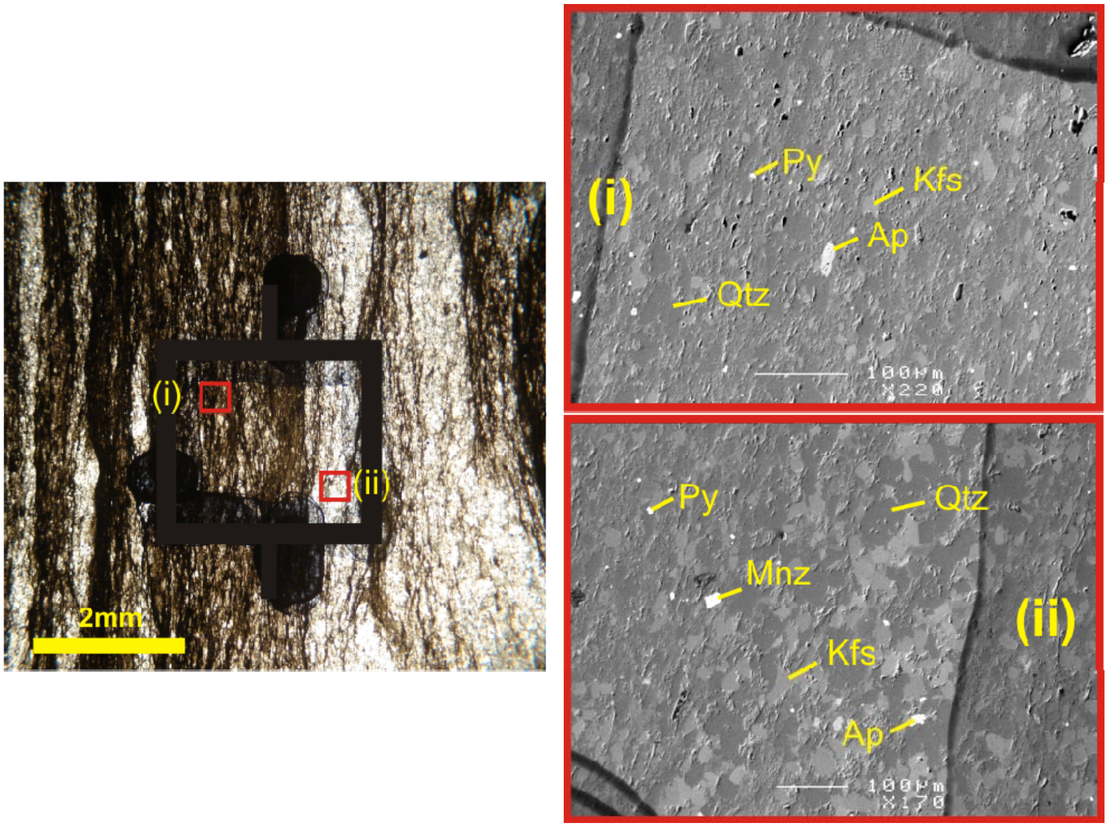

Plate 6: Comparison of brown-clay and light-grey clastic laminations

SEM micrographs of brown-clay (i) and grey-white (ii) laminations in Upper Transition. Note the similarity of grain mineralogy between domains (i) and (ii); difference in hand specimen coloration is a function of grain size.

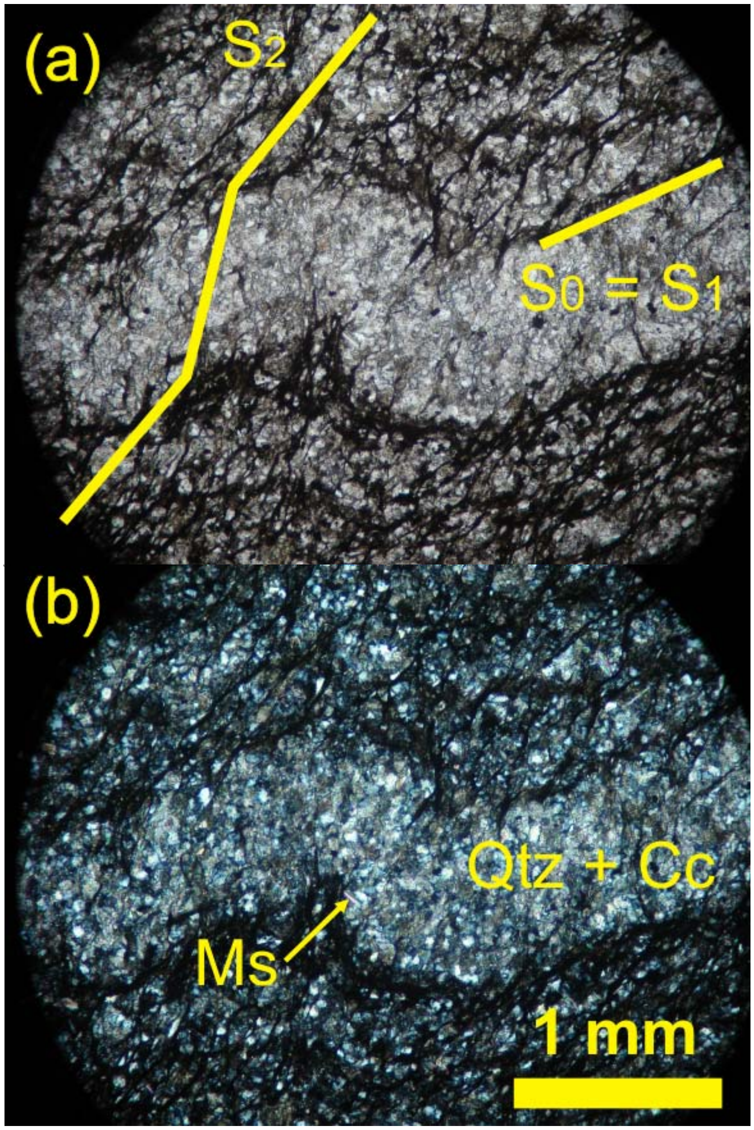

Plate 7: Light-grey type lamination

Parallel fold in light-grey lamination. Note refraction of axial planar cleavage between layers of different composition. Qtz = quartz, Cc = carbonate, and Ms = muscovite. Top micrograph in ppl, bottom in xpl.

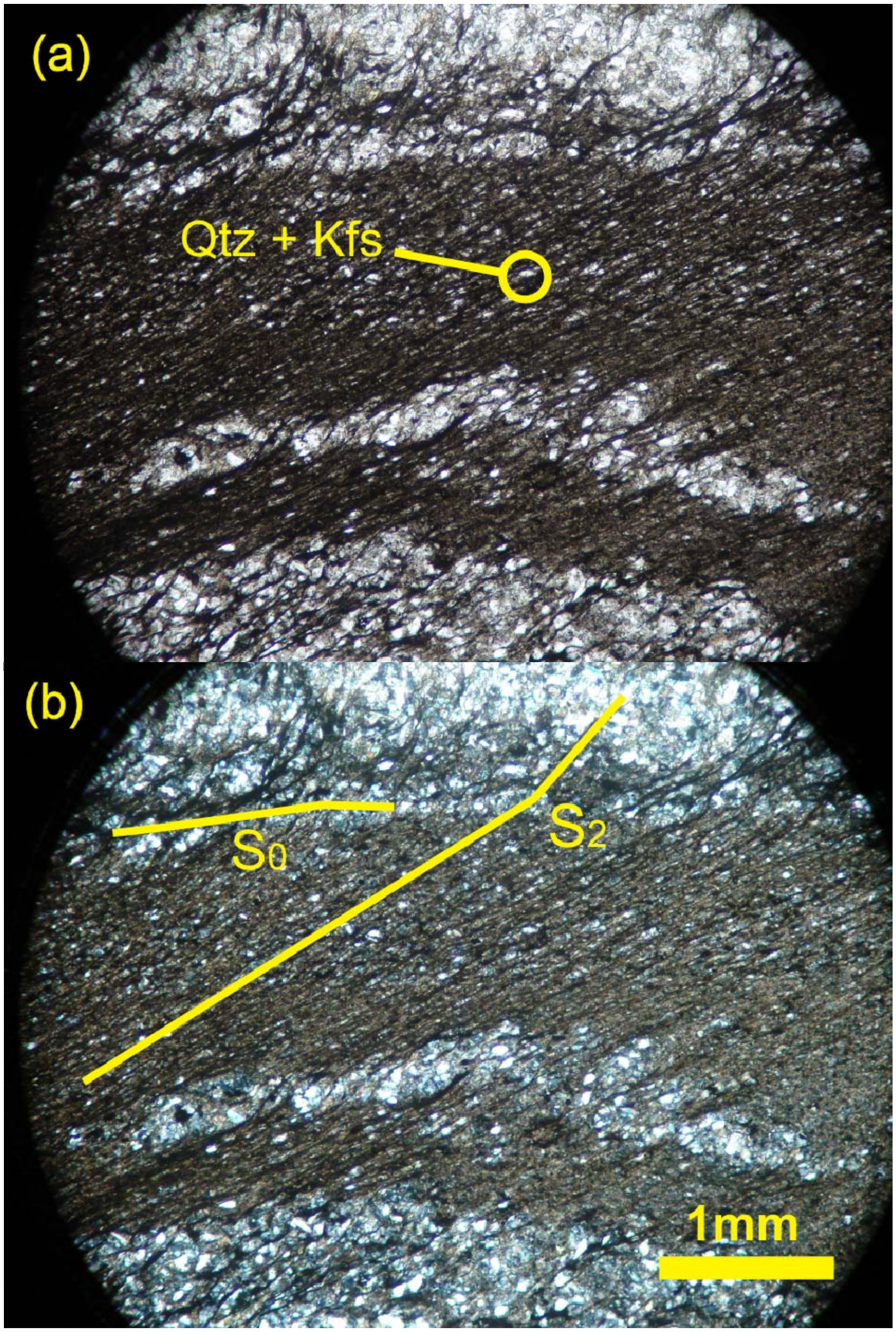

Plate 8: Brown-clay type lamination within Basal Transition

Micrographs of brown-clay lamination. Note denser spacing of cleavage domains in clay lamination compared to light-grey lamination. Qtz = quartz, Kfs = K-feldspar. Top micrograph in ppl, bottom in xpl.

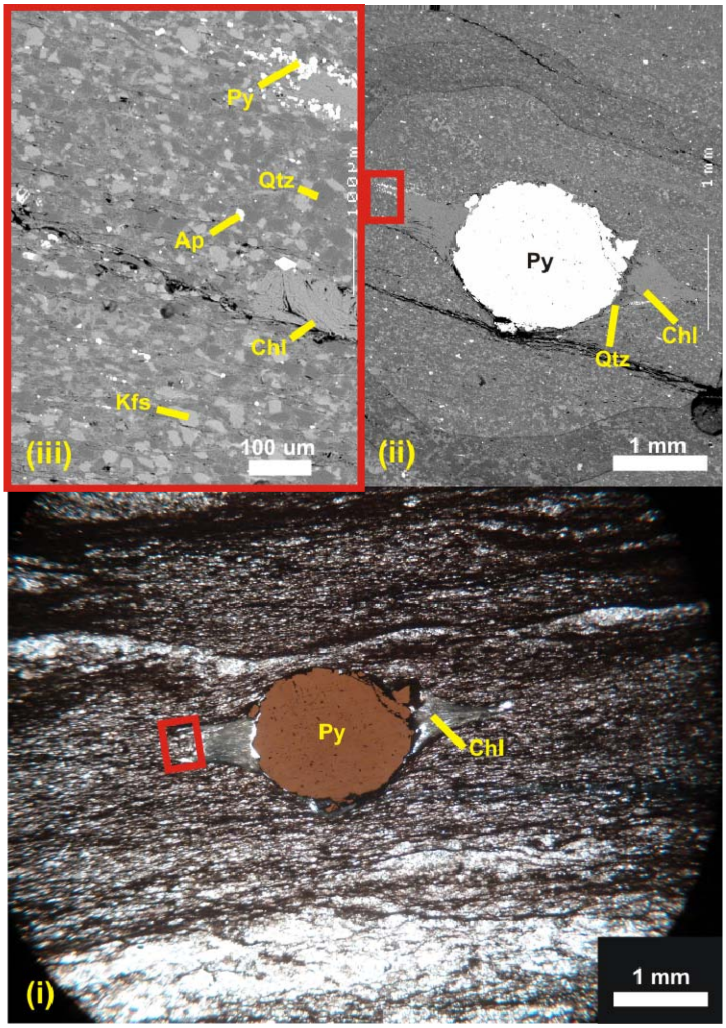

Plate 9: SEM photomicrograph of mineralogy of Upper Transition

Upper Transition (SBH-030) showing: (i) pyrite with synkinematic a pressure fringe and long axis aligned parallel to pervasive slaty cleavage. Taken using ppl and reflected light combination. (ii) photomicrograph of same pyrite eye using SEM. (iii) Expanded view showing mineralogy of left portion of pressure fringe, surrounded by red box in (ii). Py = pyrite, Chl = chlorite, Qtz = quartz, Kfs = K-feldspar, and Ap = apatite.

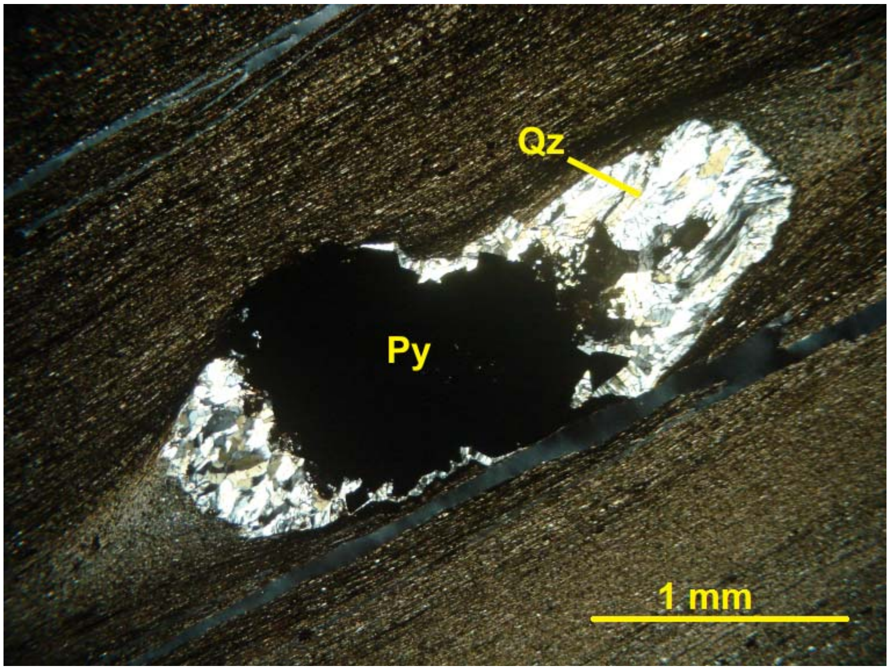

Plate 10: Pyrite with pressure fringe

Micrograph in xpl of pyrite eye in Upper Transition with polycrystalline quartz pressure fringe. Thin section SBH-001.