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GEOLOGY OF THE GREENWOOD - GRAND FORKS AREA, BRITISH COLUMBIA

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INTRODUCTION

The Greenwood - Grand Forks area, about 350 kilometres east of Vancouver, contains the Boundary mining camp, and has been mapped and studied geologically since major deposits of copper and gold were first mined and smelted in the area about the turn of the century. Maps and reports from this work defined the rock units, described the mineral deposits in detail and identified some elements of the structure, particularly the Tertiary faults. Major structural patterns which could be integrated within the area and beyond it, however, were not recognized. The present map (Figure 1, in pocket) outlines these structural patterns and these notes describe the geology in relation to the map.

The history of mining in the area and of geological work has been summarized in recent reports by Church (1986) and by Little (1983) and the significant references are given at the end of these notes. The data on which this study is based are derived from detailed mapping (scales of 1:12 000 and greater) carried out between 1981 and 1987 by the writer and associates for Kettle River Resources Ltd. and Noranda Exploration Ltd. in the search for gold, and for the Geological Survey Branch in 1988 and 1989. All of the area shown in Figure 1, with the exception of the larger blocks of Tertiary, has been remapped. All available published and unpublished data have been referred to throughout the study. Unpublished, detailed and accurate outcrop maps (scale 1:12 000) which were prepared between 1969 and 1971 for the Granby Mining Company by James Paxton, H. Kim and others have been particularly useful because they allowed the fieldwork to focus on problem solving and interpretation.

SUMMARY

The Greenwood - Grand Forks area, referred to in these notes as the map area, contains Late Paleozoic and Mesozoic volcanic and sedimentary rocks, mainly in the greenschist facies of regional metamorphism, which are intruded by Mesozoic plutons and unconformably overlain by Tertiary volcaniclastic and flow rocks. The rock units are described in the legend to Figure 1 and the relationships are summarized in Table 1.

The preTertiary stratiform rocks are contained in a series of five, north-dipping thrust slices (*see* Figure 2, in pocket) with bounding faults which at many places are marked by layers and lenses of deformed serpentinite. These thrust slices lie above high-grade metamorphic complexes exposed to the south in northern Washington and to the east beyond the Granby River fault (Preto, 1970). These metamorphic rocks are not mapped or described in the present work.

The Late Paleozoic rocks in the Greenwood area are the Knob Hill Group of chert, greenstone and related diorite and serpentinite, and the Attwood Group of dark grey argillite, limestone and minor volcanic rocks. Although direct evidence is scarce, all these rocks probably represent the disrupted parts of an extensive ophiolitic suite. They are unconformably overlain by the Brooklyn Formation of clastic sedimentary rocks, limestone and largely submarine pyroclastic breccias and related dioritic intrusions. These rocks probably formed in an environment of growth faulting and explosive vulcanism.

The distribution of the Tertiary rocks is controlled by a complicated array of extension faults. Three sets are recognized. The oldest are gently east-dipping, at or near the base of the Tertiary. Later, dominantly west-dipping listric normal faults have caused rotation so that the Tertiary strata dip to the east at moderate angles. The apparent offset on each of five of these faults is measured in kilometres. The third and latest faults are north to northeast trending, steeply dipping, strongly hinged and influenced by the earlier faults.

This structural framework controls the distribution of the rock units and hence the interpretation of the stratigraphic succession and the understanding of the mineral deposits.

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TABLE 1. TABLE OF FORMATIONS

AGE	NAME	MAP SYMBOL	LITHOLOGY
Eocene	Penticton	Epi	Dikes, sills & irregular plutons of pulaskite syenite, monzonite & diorite. (Coryell intrusions).
		Eps	Stratiform units, arkosic, volcaniclastic sediments (Kettle River Formation), flows of andesite, trachyte & phonolite (Marron Formation).
			Unconformity
Cretaceous	Nelson	qd	Mainly granodiorite & quartz diorite, minor diorite (d) & gabbro (g).
Jurassic	Lexington	qfp	Quartz feldspar porphyry.
Triassic	Brooklyn	TRb	
		TRBv	Fragmental greenstone & related microdiorite.
		TRb1	Limestone, calcareous sandstone & conglomerate & skarn.
		TRbs	Green & maroon tuffaceous sandstone, siltstone & hornfels.
		TRba	Dark grey to black siltstone & argillite.
		TRbbx	Chert breccia or sharpstone conglomerate & minor tuff, tuffaceous siltstone, sandstone & breccia & maroon & green limestone-cobble conglomerate.
			Unconformity
Carboniferous or Permian	Attwood Group	Pa	
		Paa	Black cherty siltstone, phyllite & argillite.
		Pal	Grey to white limestone, cherty limestone & minor dolomite.
		Pav	Andesitic volcanics.
			Fault contacts
	Knob Hill	Pkc	Chert, grey argillite, siliceous greenstone &minor limestone.
		Pkv	Greenstone, pillow lava & breccia, amphibolite & minor limestone.
		Pkx	Fine chert breccia & conglomerate.
		Pkm	Grey & green schist and phyllite, buff to white quartzite, minor crystalline limestone, white dolomite, fine-grained calcsilicate gneiss, quartz biotite gneiss & amphibolite.
	Serpentinite	sp	Serpentinite & listwanite.
	Old Diorite	od	Coarse & fine-grained hornblende diorite.

GEOLOGY

KNOB HILL GROUP

The Knob Hill Group occurs throughout the map area in two distinct facies of deformation and metamorphism; a relatively undeformed part in the greenschist facies of regional metamorphism (Units Pkv, Pkc and Pkbbx), and a sheared and deformed part (Unit Pkm) in a higher grade of metamorphism.

MAP UNITS PKV, PKC AND PKBX

These map units comprise most of the Knob Hill Group occurring across the central and northern parts of the map area. Although strongly folded, they are blocky rocks with only restricted lenses showing penetrative fabrics. They are composed mainly of greenstone and chert, with minor amounts of black siltstone, chert-pebble conglomerate, greenstone conglomerate, chert breccia and small lenses of limestone. Most of these rock types are present at or near the type locality on Knob Hill, 4 kilometres east of Greenwood.

The greenstones (Pkv) are mostly pillow lavas and breccias and agglomerates derived from them. Good pillow structures are rare, but crusts of pillows outlined by curving dark bands or epidote layers, interpillow lenses of chert, epidote, limestone or jasper, or vaguely mottled or banded dark and light green masses within the greenstone are taken to be remnants of pillow structures. The rocks are aphanitic, commonly calcareous basalts and andesites which grade into massive fine-grained diorites and are criss-crossed by narrow irregular, white-weathering feldspathic veinlets and lenses. Some of the diorites are dikes whereas others cover large areas and apparently grade into greenstones derived from lavas. Others become coarse grained and are mapped as part of the Old Diorite (od).

The fine-grained sediments of the Knob Hill Group (Pkc) are mainly grey, buff or creamy white cherts, which are highly fractured and only locally show ribbon structure or bedding. Grey chert grades into dark grey and sooty black argillite, which in a few places contains small lenses of blue-grey finely crystalline limestone. Large areas contain massive chert without greenstone which in some places forms bluffs and bold outcrops such as those near the head of Nicholson Creek or west of Eholt. Mostly the chert is mixed with greenstone and in some areas, where neither rock type predominates, the rocks are shown as such (Pkv+c). Small lenses of chert, and locally of red jasper, are found in most of the greenstones, and at places siliceous greenstones are difficult to distinguish from greenish chert. The argillites are grey to black and rarely show any bedding. They form small to very large lenses mainly associated with chert. The chert-argillite contacts are both gradational and sharp. Commonly deformation has caused the argillite to flow between chert lenses.

The limestones are not shown on Figure 1 because of their small size. Some are stubby lenses of white crystalline limestone a few metres across in greenstone, others are lenticular beds, mainly at chert-greenstone contacts which can be traced for several metres to more than a kilometre. One of the most continuous is along the westerly trending chert-greenstone contact 4.5 kilometres south and a kilometre west of Eholt. Another forms prominent outcrops on the west side of the east branch of upper Nicholson Creek. Blue-grey limestone mixed with grey cherty argillite occurs above the railway grade on the west slope of July Creek and contains corals and bryozoa (Little, 1983, p. 12 and fossil locality F7). Other occurrences of grey cherty limestone are on the west slope of Boundary Creek near the crest of the ridge 3 km southwest of Greenwood, and on the south-facing upper part of the ridge 1.5 kilometres northeast of the Kettle River Park.

Buff to cream-coloured and grey chert breccia and pebble conglomerate (Pkbx) occur locally in the Knob Hill Group. A prominent bed 100 to 200 metres thick trends northwest and dips to the northeast on the southwest slope of Knob Hill and is exposed again on Montezuma Ridge to the northwest. Extensive areas of buff chert breccia occur west of the Greyhound Creek fault 2 to 3 km southwest of Greenwood. They contain small lenses of black siltstone and buff chert sandstones which dip to the north, and grade into massive white to buff chert. These rocks are shown as part of the Brooklyn Formation by Little (1983) and as part of the Attwood Group by Church (1986), and the present correlation is based on their close association with the Knob Hill chert.

The stratigraphy and structure of the Knob Hill Group are poorly understood, but in the east half of the map area where lithologies are more varied than in the west half, an apparent succession has been established. On the southwest slopes of Knob Hill and to the west and north, mappable units of chert, conglomerate, grey and siliceous argillite interfinger with greenstone and trend northwest and west, dipping to the northeast at moderate angles. Minor folds plunge between north and northeast at 20° to 30° and have west-dipping axial planes. Two to three kilometres northeast of Knob Hill, thin-bedded cherty and tuffaceous argillites in the same sequence dip to the north and are right-side-up. To the south the greenstones pass into diorite which grades into or is intruded by coarse-grained diorite mapped as Old Diorite, which is closely associated with serpentinite. To the north on the south slopes of Eholt Creek the sequence is less varied, consisting of fairly thick layers of chert and greenstone which dip to the north at moderate angles, and these units continue northward into the area, at the north edge of the map area, complicated by intrusions of Nelson plutonic rocks. Within this sequence there are no recognizable structural repetitions, although there are Tertiary extension faults, Mesozoic and Tertiary intrusions, complex facies changes and minor folds. The interpretation suggested here is that the lower part of the Knob Hill Group consists of a mixed and highly variable sequence containing chert, argillite, conglomerate and breccia interfingering with mafic pillow lavas and greenstone grading into and intruded by fine-grained diorite which is a phase of the Old Diorite complex. The upper part is mainly chert and greenstone and the group is more than 5 kilometres thick. The lower part is well exposed on the western slopes of Boundary Creek 2 to 4 kilometres south of Greenwood. It is less well exposed west of July Creek and in the valley of Neff Creek where greenstones predominate and the sedimentary part is grey siltstone and minor chert. A good section of the upper part of the Knob Hill Group is exposed in the cliffs on the west side of the Granby River south of Pass Creek.

In the west half of the map area the thickness and internal structure and stratigraphy of the Knob Hill Group are more obscure than in the east half. Attitudes of primary structures consisting of bedding in siliceous argillites and cherts, greenstone-chert contacts, and beds of limestone, are found at relatively few places but consistently strike between 70° and 100° and dip steeply north or south. Although greenstone-diorite and greenstone-chert contacts are too indefinite to be traced on the ground, inferred contacts are shown on Figure 1. Chert with little or no greenstone outcrops on the hills at the head of Nicholson and Wallace creeks whereas greenstone and diorite with only minor chert are found farther to the south and west along the valley of the Kettle River for several kilometres north of Rock Creek. Between are mixed greenstones and cherts which also contain most of the limestone lenses.

No evidence has been found for tight or isoclinal folding of these Knob Hill rocks. Major repetitions of stratigraphy by faults subparallel to the formations have not been recognized, although a possible east-trending fault follows the serpentinite 1 to 2 kilometres north of Rock Creek, which may thicken the section. The width of the outcrop of Knob Hill rocks from the Kettle Valley to the north edge of the map area, where they are cut off by the Nelson intrusions, is about 10 kilometres. Thus, the Knob Hill Group in the western part of the map area appears to be of comparable thickness to that in the east. Relationships between the greenstones and the diorite and serpentinite exposed in the valley of the Kettle River north of Rock Creek and in lower Bubar Creek suggest that the stratigraphic top is to the north.

Map Unit Pkm

The deformed part of the Knob Hill Group is exposed in three areas; one in the southwest corner of the map area south of Rock Creek, the second across the southern part of the east half of the map area between Boundary Falls and Spencer, west of Grand Forks, and the third in a small area 1.5 kilometres southeast of Greenwood. These rocks include schists, quartzites, gneisses, amphibolite, marble, dolomite, calcsilicate gneiss and mylonite which characteristically show a penetrative foliation and one or or more lineations.

In the area 3 to 5 kilometres south of Rock Creek, well exposed in the head of Myers Creek, the lithologies are superficially very similar to those of the Knob Hill Group to the north and the rocks have been mapped as Knob Hill by Little (1983). They are rusty white chert and quartzite, micaceous quartzite and banded siliceous mylonite as well as greenstone, sheared greenstone (locally with elongate pillow structures) and chlorite schist. Minor amounts of grey and white crystalline limestone grading into calcareous greenstone and limy chlorite schist are also present. A lens of white dolomite within this deformed sequence is quarried 4.5 kilometres southeast of Rock Creek by Mighty White Dolomite Ltd. In this deformed part of the Knob Hill Group lenses of relatively blocky rock, tens to hundreds of metres across, occur between zones of schist and mylonite. The schistosity and deformed zones trend 295° and dip 40° to 60° north but weave around the more competent blocks.

The base of the deformed zone is well defined by a sheared zone, taken to be a thrust fault, trending 305° and dipping 60° northeast along the contact of a belt of dark grey siltstones and sandstones lying to the southwest. The deformed zone is more than a kilometre wide. The upper contact of this deformed part of the Knob Hill Group with the relatively undeformed part is not well defined, partly because of the poor outcrops south of the Kettle River and partly because the transition seems to be gradational.

The largest area containing rocks belonging to the deformed part of the Knob Hill Group (Pkm) is in the southeastern part of the map area between Boundary Falls and Grand Forks. These rocks are well exposed along both sides of Boundary Creek for 2.5 kilometres north of Boundary Falls and on the southwestern slopes and western ridge of Mount Attwood. In this belt these rocks are bounded by faults and occur within the second and at the western end of the third thrust slices (*see* Figure 2). Because of their metamorphism and intense deformation, Little (1983) referred to them as a metamorphic assemblage (Pml). Church (1970) originally described them as the "basement complex" but subsequently mapped them as part of the Knob Hill Group. This correlation is continued here without additional evidence, as a "best guess", because of the lithologies and in spite of the difficulty of explaining the contrast in structural style between these rocks and the relatively undeformed Knob Hill rocks.

This part of the Knob Hill Group consists of green chlorite and chlorite-amphibole schists, grey quartz-mica schist and phyllite, grey quartz-mica gneiss, blocky white to buff and grey quartzite and chert and calcareous grey schist grading into grey and locally white crystalline limestone. The layers and foliation trend northwest and dip northeast at moderate angles. The gross structure and stratigraphy are unknown. Most outcrops show lineations and crenulations structural studies of which on the western slopes of Mount Attwood have not revealed dominant trends or structural patterns. White quartzite, which is probably metachert, forms large lenses mainly enclosed in grey phyllite with which it interfingers. These appear to be structural lenses with terminations plunging to the north. Isoclinal folds can be seen in some of the limestones and at one locality near the old lime kiln in upper Potter Creek the fold hinges have a low plunge parallel to a lineation in the adjacent schists. In the eastern part of the belt, in the valley of Stacey Creek and on the ridge to the north, the rocks are less sheared and include blocky greenstones, grey chert and crystalline limestone. In the same belt farther east on Highway 3 near Spencer, rusty buff to grey-chert chip conglomerate and sandstone occur with the more typical highly deformed grey schists.

The third area of deformed Knob Hill rocks southeast of Greenwood is on the southern edge of the Greenwood granodiorite and is surrounded on three sides by serpentinite. It lies west of, and beneath the type section of the undeformed Knob Hill but the contact is covered and is probably a fault. These relationships between the deformed and undeformed parts of the Knob Hill Group are similar to those in the southwestern corner of the map area. The deformed rocks in this area southeast of Greenwood are well-foliated metachert and grey siliceous phyllite with lenses of green amphibolite and chlorite schist.

AGE

A Carboniferous or Permian age of the Knob Hill Group was established by Little (1983, p. 12) from a single fossil locality at an elevation of 1200 metres on the western slope of July Creek above the abandoned railway 1.5 kilometres south of Snowshoe Creek. The locality is included in an area shown on Figure 1 as Unit Pkc and is a lens of chert, grey argillite, limestone and chert-pebble conglomerate dipping gently to the north and interfingering with a thick mass of volcanics and greenstones in a poorly exposed area to the northwest. These rocks are in the lower part of the group and are intruded by Old Diorite from which a potassium-argon date of 258±10 Ma has been obtained by Church (1986, p. 19). Several recent samples of limestone and chert from widely separated places in the group have not yielded microfossils and no new age data can be reported here.

OLD DIORITE

The Old Diorite, named by Church (1986, p. 19), outcrops principally in the eastern part of the map area in a narrow belt at the base of the Knob Hill Group above the Lind Creek fault and in the western part of the area near Rock Creek. It consists of a striking, coarse-grained hornblende diorite with many crisscrossing light-coloured veins of felsic rock. The texture is highly variable and the veins commonly bound blocks of differing texture and composition. Rarely the blocks have a light and dark layering. The coarse-grained phases grade into finer grained diorites and these in turn into greenstones of the Knob Hill Group. Pervasive felsic veinlets usually continue through the transition. Dikes and irregular bodies of Old Diorite also intrude the Knob Hill greenstone.

The Old Diorite forms bluffs and bold outcrops and is well exposed on the east side of the Kettle River just north of Rock Creek, in the cliffs west of Boundary Creek 3 kilometres south of Greenwood, on the bluffs west of July Creek 4 kilometres southeast of Phoenix, and at the head of Neff Creek. In all these localities it is closely associated with serpentinite and with the lower part of the Knob Hill Group. Away from this belt, Old Diorite has been found with serpentinite at the head of Gibbs Creek in the Mount Wright fault zone and as small blocks or lenses in the serpentinite of the Mount Attwood fault about a kilometre west of the summit of Mount Attwood. Small lenses of Old Diorite with a moderately well developed foliation occur in Unit Pkm on the lower west ridge of Mount Attwood and at the head of March Creek.

The age of the Old Diorite is indicated by a potassium-argon wholerock date of 258±10 Ma from drill core from the Winnipeg mine about 3 kilometres south of Phoenix (Church, 1986, p. 19). Church also found fragments of Old Diorite in conglomerates of the Brooklyn Formation. Thus, the Old Diorite is Permian or possibly older.

SERPENTINITE

Serpentinite (sp) occurs in irregular lenticular bodies in the relatively undeformed parts of the Knob Hill Group, and as fairly continuous sheets along faults. It is either blocky or schistose antigorite serpentinite, or brown-weathering altered serpentinite, referred to as listwanite. The antigorite serpentinite is dark green to black with a greasy or rough fracture which weathers blue-grey, dark green or brown. Remnants of pyroxene and of uralitic textures are seen at only a few places, the most prominent being within the thick mass exposed on Highway 3 at the head of July Creek about 1.5 kilometres south of the turnoff to Phoenix. Listwanite is most abundant in the western half of the map area, and is found locally at other places, particularly at the Jackpot-Athelstan mine 5 kilometres southeast of Phoenix, and between Hardy and Goat mountains. It is a yellow-brown-weathering, hard, aphanitic, grey to light grey rock with veinlets of quartz and iron carbonate and flecks of dark minerals and locally of bright green mica. It is commonly cut by irregular fractures which appear to be relicts of foliation found in much of the antigorite serpentinite.

The most continuous layers of serpentinite are along the Lind Creek, Mount Attwood, Mount Wright and No. 7 faults, and along unnamed faults obscured by the Tertiary rocks in the west half of the map area. These layers are sinuous and generally dip northward at low to moderate angles more or less parallel to the foliation and attitudes of the adjacent rocks. They range in size from very small lenses to prominent masses estimated to be as much as 700 metres thick. Internally they are either blocky and massive or foliated. Foliated serpentinites have irregular weaving planes of schistosity commonly surrounding boudins of blocky serpentinite and locally of the wallrocks. At places the foliation outlines local folds, as on the southwest slope of the ridge about 2 kilometres southwest of Mount Attwood, or reflects the complexities of intersecting faults, as in the area between Hardy and Goat mountains and near the Winnipeg and Jackpot-Athelstan mines.

The age of the serpentinites has always been uncertain (Little, 1983, p. 22) and the present work does not provide an unequivical conclusion. Most, if not all, of the serpentinites are tectonically emplaced, and contact relationships seen in the field do not establish the age. In spite of a careful search, no fragments of serpentinite have been found in conglomerates of the Brooklyn Formation, and it must be concluded that the serpentinites were not at or near the surface in Middle Triassic time. The close association between serpentinite, the Old Diorite and the greenstones of the Knob Hill Group, and the pillow lava-chert association within that group suggest that these rocks are parts of a disrupted ophiolite suite, a possibility recognized by Little (1983, p. 4). This interpretation is adopted here, and the serpentinites are considered to be Carboniferous or Permian, and to have been emplaced tectonically along structures as they developed at various times during the Mesozoic and Tertiary.

ATTWOOD GROUP

The Attwood Group is mainly dark grey to black argillite, siliceous argillite, phyllite and slate, light and dark grey limestone, minor chert- and argillite-chip conglomerate and minor greenstone. The age based on several collections of fossils is comparable to that of the Knob Hill Group, but the stratigraphic relationship between the two groups is not known. The rocks occur in five fault-bounded segments across the southern part of the map area. These are: (1) a narrow band of grey siltstone and sandstone in the extreme southwestern corner of the map area, (2) a large area of mainly grey phyllite straddling the International Boundary on the hills east of Midway, (3) a sinuous discontinuous belt in the fourth fault slice (Figure 2) extending from the west side of Boundary Creek north of Boundary Falls to the east side of July Creek on the south slope of Hardy Mountain, (4) a small lens of black argillite in the lower part of Gibbs Creek west of Spencer and (5) a very small block of argillite and dark grey limestone on the east side of the Granby River about 5 kilometres north of Grand Forks. In all of these segments the rocks are tightly folded and in none of them has the internal stratigraphy been worked out. They are correlated with each other on the basis of general lithological similarity.

At the type locality on Mount Attwood the dominant lithology is dark grey siliceous argillite which, on the ridge to the east, contains a prominent lens of dark and light grey, locally cherty limestone dipping to the north at low to moderate angles. Farther to the east, the Mount Attwood rocks are offset by the July Creek fault and occur again only as a narrow lens dipping to the north between the Eagle Mountain fault and the base of the Brooklyn Formation, exposed along Highway 3 and to the east on Hardy Mountain. This lens of the Attwood Group contains grey, locally cherty limestone, siliceous argillite and grey to buff limy phyllite. To the west along the ridges and northwestern slopes of Mount Attwood the argillites are less siliceous and a lenticular bed of grey limestone and locally of argillite and chert-chip conglomerate and breccia is present along the southern edge of the group above the Mount Wright and Mount Attwood faults. Farther west near the Skomac mine (Church, 1986, p. 51) 4.5 kilometres south of Greenwood, black slate and argillite with minor conglomerate form a syncline with axis plunging at a low angle to the west, and axial plane dipping at a moderate angle to the north. The Attwood rocks form a sliver between the serpentinite and Old Diorite on the Lind Creek fault to the north and serpentinite along the Mount Wright fault to the south.

Volcanic rocks within this belt occur only at the head of Lind Creek and along the upper valley of Skeff Creek immediately south of and under the Lind Creek fault.

AGE

Fossils have been collected at several localities in the Attwood Group from the grey limestones. The localities include the syncline near the Skomac mine (Church, 1986, p. 10) the ridge east of Mount Attwood, the east side of July Creek, the lens west of Spencer and the block north of Grand Forks, (Little, 1983, p. 9 and Tempelman-Kluit, 1989 Sheet 4). The fossils, which include macrofossils and conodonts, are Carboniferous or Permian.

BROOKLYN FORMATION

The Brooklyn Formation unconformably overlies the Knob Hill and Attwood groups. It is exposed in erosional and faulted segments throughout the map area. The formation, named for the Brooklyn mine at Phoenix, 4 kilometres east of Greenwood, has three main lithological components (*see* Figure 3 and 4). These are: (1) chert breccia (Trbbx) commonly referred to as sharpstone conglomerate (Seraphim, 1956), (2) limestone (Trbl), and (3) volcanic rocks (Trbv) including greenstone and green pyroclastic breccia and subvolcanic microdiorite. All the components are highly lenticular and change rapidly through lateral and vertical transition zones containing sandstones, siltstones, calcareous sandstones and siltstones (Trbs), and conglomerate and various volcaniclastic rocks. Disconformities occur throughout the section. The main components are referred to as members, some of which have been named in the past, for example Brooklyn, Stemwinder, B.C. and Mother Lode limestones (Seraphim, 1956), Rawhide member (Little, 1983, p. 17), Providence Lake microdiorite and Eholt formation (Church, 1986). The main components, beginning with the sharpstone conglomerate and grading upward and laterally through finer grained clastic sediments into limestone and/or volcanic rocks, are repeated one or more times resulting in members such as the upper sharpstone and Stemwinder limestone at Phoenix and the repeated sharpstone-limestone-greenstone sequences in the Summit Camp southeast of Eholt.

Diagrammatic stratigraphic columns, based on mapping of the Brooklyn rocks on scales of 1:12 000 and greater and representing the rock types and their relationships within a relatively small area, are given in the following illustrations: Columns 1-4 at and near the type locality at Phoenix, which have been compiled from detailed maps of the area (scales 1:2500) show the rapidity with which the facies change over a relatively small area; Columns 5 and 6 are to the north and east and separated from the Phoenix sections by Tertiary faults; Column 7 is in a third fault block along the western slopes of the Granby River; Columns 8 and 9 are to the west of Greenwood in separate fault blocks, 8 near the Deadwood Camp and 9 north of the Copper Camp. All these sections are in the uppermost or fifth thrust slice (Figure 2) whereas Column 10 is in the third and Column 11 is in the fourth slice.

Integration of the geology between these areas leads to the following conclusions.

(a) The sharpstone conglomerate is a locally derived fanglomerate, widespread in some areas and more restricted in others. It is repeated at intervals throughout the section and in places the higher fans coalesce with the basal fan. Minor rhyolitic tuff and green tuffaceous sandstone lenses suggest that the sharpstones may have originated through explosive vulcanism, or they may be related to growth faults, though none have been identified. At times and in places where these high-energy sediments were not deposited, siltstones and sandstones were, and these interfinger with limestones and volcanic rocks.

(b) Recent conodont collections (M.J. Orchard, Geological Survey of Canada conodont file) give a Middle Triassic (Ladinian) age for limestone members at various levels in the Brooklyn succession. Many of the best collections of conodonts as well as other fossils (Little, 1983, p. 15) have been made along Highway 3 from Spencer, west of Grand Forks, north to the head of Fisherman Creek. The limestones vary in lithology and include dark grey flaggy argillaceous limestone, massive grey and white limestone and heterogeneous limestone breccias, and they are interbedded with different rock types at each locality. The present map (Figure 1) shows that these localities are in different fault slices which may have been together or at widely separated places at the time of deposition. The stratigraphic position of the fossil localities shown on the columns is based on replotting the localities from the data contained in GSC paper 79-29 (Little, 1983) and the GSC conodont file (M.J. Orchard, personal communication) and by determining the structure and sequence of rock units at each locality.

(c) In the Phoenix area dikes and irregular small intrusions of microdiorite cut the Brooklyn Formation and appear to form feeders for greenstone and pyroclastic breccia at the top of the exposed section. Similar relationships of microdiorite, massive and fragmental greenstone and pyroclastic breccia are found in the Summit Camp 2 to 4 kilometres southeast of Eholt. Farther south the greenstones contain lenses of limestone with Ladinian conodonts. It is for these reasons that the microdiorite and greenstones are considered to be components of the Brooklyn Formation and are shown as such on Figure 1. However, a potassium-argon date of 206±8 Ma on amphibole from the Providence Lake microdiorite at Phoenix is reported by Church (1986, p. 20), suggesting a younger age for the microdiorite and some of the greenstones as concluded by Little (1983, p. 19) who referred to the fragmental greenstones as Jurassic (Unit Jv).

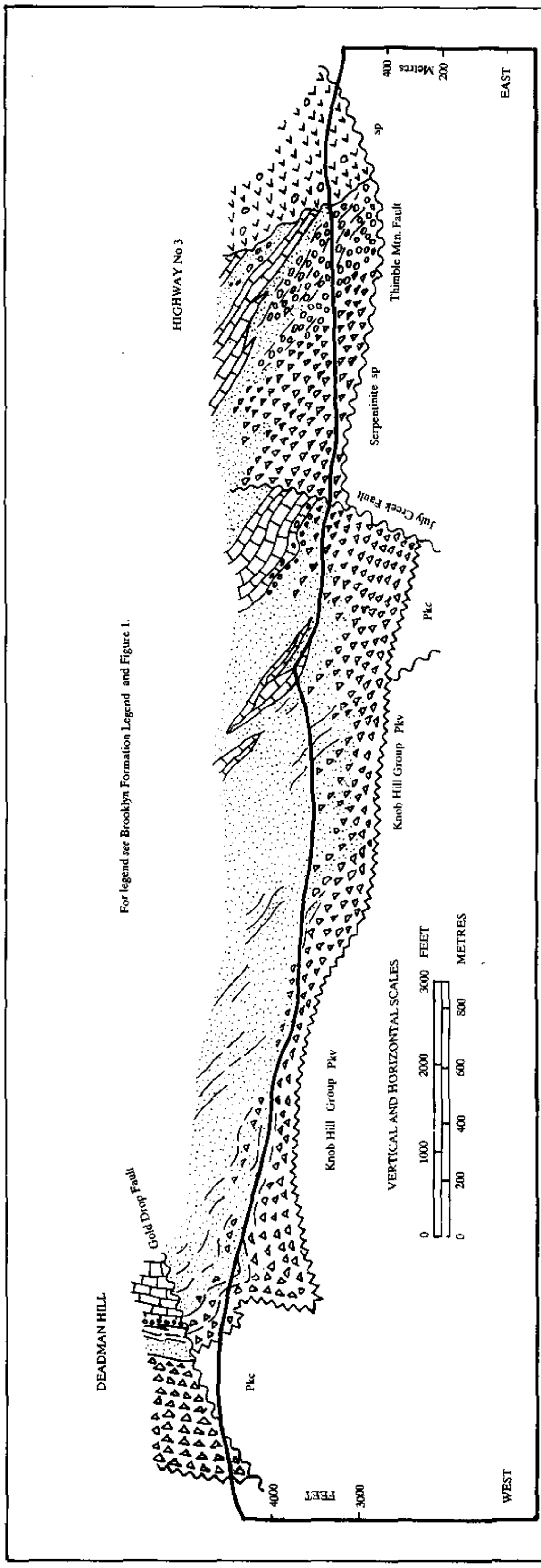
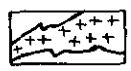


Figure 3. East-West Section Showing Structure of the Brooklyn Formation Northeast of Phoenix.

BROOKLYN FORMATION LEGEND

Greenstone and fragmental greenstone: blocky aphanitic rocks with vague, matrix-supported, subrounded felspathic and epidote-rich fragments 2 to 10 centimetres across, probably pyroclastic breccia grading into volcanic conglomerates and sandstones.



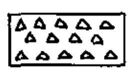
Microdiorite: dark green aphanitic to fine-grained subvolcanic intrusives, commonly fractured and pyritic or vaguely brecciated.

Limestone: mainly massive, buff to white crystalline with silicate lenses or white and dark grey color bands. Some dark grey limestone with beds 5 to 10 centimetres thick, limestone breccia and limestone cobble conglomerate.

Chert pebble conglomerate: rounded, white, buff to grey chert pebbles up to 3 centimetres across in a limestone matrix.

Fine-grained clastic sediments: green to brown sandstone, thin-bedded or massive grey, green or maroon siltstone, locally hornfelsic with disseminated pyrite and pyrrhotite. Minor calcareous sandstone and siltstone and limestone.

Limestone cobble and boulder conglomerate: rounded and angular blocks of limestone, sedimentary and volcanic rocks supported by a matrix of maroon or green tuffaceous siltstone and sandstone.



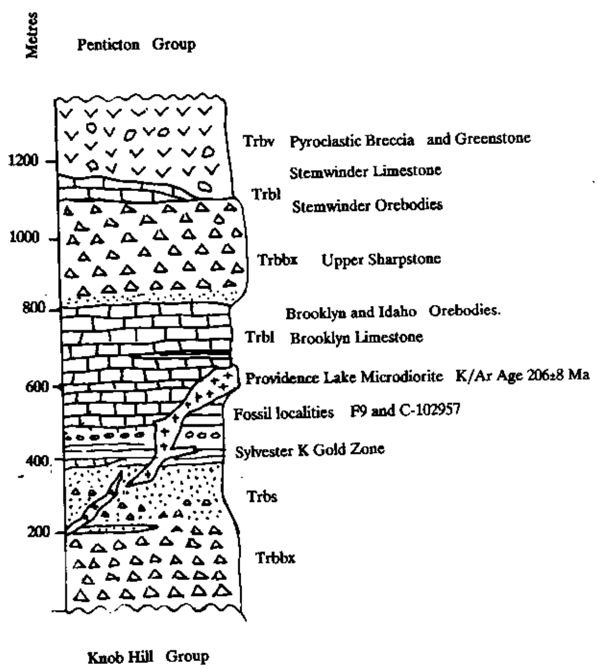
Sharpstone conglomerate: brown-weathering, grey, buff, or greenish chert breccia with angular to subangular fragments of buff, white and maroon chert, white and purple quartz, greenstone, limestone, chlorite schist, quartz-biotite gneiss and other locally derived rocks.

Unconformity **Fault**

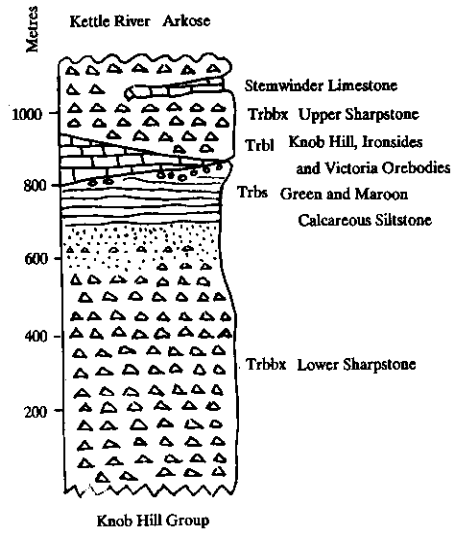
F15 Fossil collection number of Little (1983).

C-117754. Fossil collection number M.J.Orchard (personal communication) GSC Conodont Data file (82E)

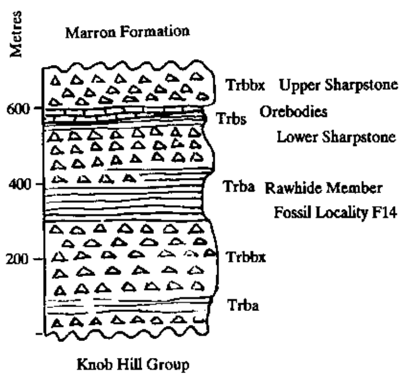
Figure 4. Brooklyn Formation Legend.



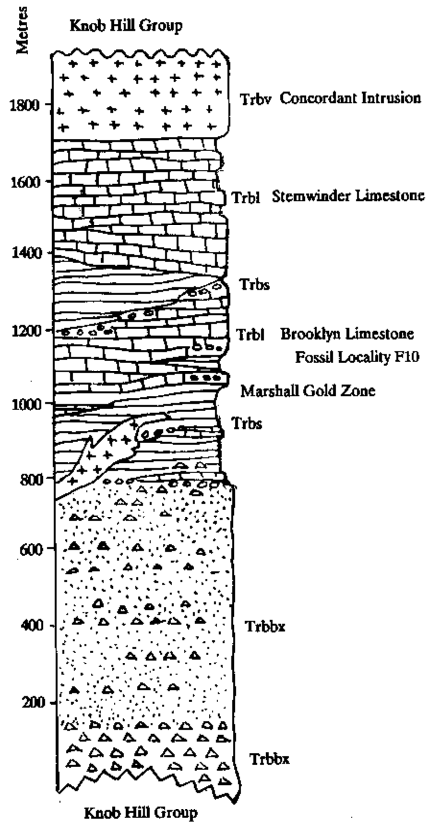
Column 1. Brooklyn Formation Type Section - Montezuma Ridge North of Phoenix.



Column 2. Brooklyn Formation Phoenix Pit Area.



Column 3. Brooklyn Formation 1 km East of Phoenix, Snowshoe, Rawhide and Monarch Mine Area.



Column 4. Brooklyn Formation North of Providence Lake.

(d) A spectacular maroon limestone-cobble conglomerate, exposed in rock cuts along Highway 3 a kilometre south of the turn off to Phoenix at the head of Fisherman Creek, lies disconformably above the basal sharpstone. The cobbles of limestone up to 25 centimetres across, some of which have yielded Carboniferous or Permian conodonts (M.J. Orchard, 1986 conodont file), are supported by a matrix of tuffaceous maroon siltstone and sandstone. The conglomerate changes facies rapidly into finer grained locally calcareous volcaniclastic rocks which interfinger with lenses of grey and white limestone exposed near the Phoenix road turnoff. This wedge of maroon-coloured rocks and the overlying Brooklyn limestones and clastic rocks to the north are disconformably overlain east of Highway 3 by a thick member of fragmental greenstone (Trbv), which outcrops widely to the east and in lower thrust slices to the south. These relationships are shown in Column 6 and the cross-section of Figure 3. The limestones overlying the maroon volcaniclastic rocks were shown by Little (1983, p. 18) to be Upper Triassic from a collection (F15) containing the coral *Thecosmillia suttonensis*, and on this basis he defined another formation, Unit uTrsv. Recent collections containing conodonts from the same area, however, are Middle Triassic (M.J. Orchard, 1986, Geological Survey of Canada conodont File). In spite of this conflicting fossil evidence and the radiometric date referred to above, the best interpretation of the relationships seen in the field and shown on Figure 1, is that all these units, many of them separated by disconformities, are parts of the Brooklyn Formation, the age of which is Middle and possibly Upper Triassic.

(e) Black siltstones (Trba) have been mapped as members of the Brooklyn Formation at three places in the map area, two about a kilometre southeast of Phoenix, and the other west of the Granby River at Fisherman Creek.

Southeast of Phoenix the Rawhide member of black siltstone is exposed along a former railway grade, now the haul road from Phoenix to the Lone Star mine and on the power line above it. The siltstone is overlain and grades upward and laterally into the lower sharpstone conglomerate of the Phoenix mine area (Column 3; Little, 1983, p. 17; Seraphim, 1956, p. 385). It is about 100 metres thick and underlain by massive, buff-weathering chert breccia about 250 metres thick. This chert breccia in turn is underlain by about 30 metres of black siltstone which is also underlain by more chert breccia, in an area with only scattered outcrops along an old railway grade and in an old trench. These members dip at low angles to the northwest, graded bedding and channeling show they are right-side-up, and there is no indication of tight folding.

The black siltstone member of the Brooklyn Formation exposed in Fisherman Creek above the Canadian Pacific Railway track and in the hills to the south, dips to the north and west and is underlain and grades into conglomerate and breccia. In the transition zones, massive black siltstone contains lenses of fine-grained dark grey chert-chip breccia with coarse fragments of black siltstone which in turn grades into and is underlain by coarse conglomerate locally containing cobbles of limestone. Gradded bedding and chanelling indicate that the section is right-side-up.

(f) Rocks mapped as the Brooklyn Formation 3 to 4 kilometres west of Midway are altered and intruded by many Tertiary dikes and older irregular bodies of quartz feldspar porphyry and granodiorite. They consist of two members, a thick grey and white, massive or thick-bedded crystalline limestone and a fine to coarse-grained, generally massive chert breccia which dip to the north at moderate angles. The chert breccia lies above and grades into the limestone, but the stratigraphic top is not known.

(g) The faulted blocks of Brooklyn Formation at the head of Wallace Creek display a sequence of members which is typical of the formation, and the very small faulted remnant 3 kilometres to the west, north of Lee Creek, contains the basal sharpstone and an overlying green tuffaceous sandstone. Lenses of sharpstone along Bubar and Davis creeks are mapped as Brooklyn with less certainty than the others. They appear to form the fillings of shallow basins or channels unconformably above the Knob Hill cherts and greenstones. The fragments are less angular than in typical Brooklyn sharpstone, and in places less well cemented. None of the other Brooklyn members are exposed. Finally, dark grey chert breccia and conglomerate, with a few lenses of grey to black slatey argillite, exposed near the entrance to the Kettle River Provincial Park, 4 kilometres north of Rock Creek and on the lower slopes to the west, have been mapped as possibly Brooklyn Formation. These rocks dip to the north at moderate angles, are truncated on the north and west by faults and overlie Knob Hill greenstones to the south. They appear to die out to the east occurring in only a few scattered outcrops east of the Kettle River.

LEXINGTON QUARTZ FELDSPAR PORPHYRY

This group of small felsic plutons (qfp) was named by Church (1970, p. 417) from the Lexington mineral claim near the head of Goosmus Creek just north of the International Border in the southeastern part of the map area. The largest pluton, well exposed in the valley of Gidon Creek, is a light-coloured, medium-grained porphyry with medium to coarse phenocrysts of quartz and feldspar. The pluton tapers eastward and becomes finer grained and highly sheared in the No. 7 fault zone and sheared serpentinites in Goosmus Creek. These sheared porphyries which host pyritic gold deposits on the Lexington, City of Paris and nearby mineral claims, are at the type locality and are described in detail by Church (1970, p. 416; 1986, p. 20).

Similar felsic plutons occur across the southern part of the map area to the west and are referred to as Unit KTi by Little and described in considerable detail by him Little (1983, p. 25, Map 1500A). These bodies to the west of the type locality, though mainly fine to medium-grained quartz feldspar porphyries, are quite variable, generally grey, equigranular or pophyritic and range in composition from diorite to quartz monzonite.

The age of the Lexington porphyry has been determined from samples taken in the City of Paris mine area submitted by Church (1986) which gave a uranium-lead zircon age interpreted as an "Early Jurassic zircon, probably Sinemurian, with inherited lead of early Proterozoic or Archean age" (The University of British Columbia Geochronology Laboratory report).

NELSON INTRUSIONS

Parts of the southern edge of the Wallace Creek quartz diorite batholith and the northern edge of a similar pluton in the southwest corner of the map area are shown on Figure 1 but only the margins have been studied. Smaller plutons of granodiorite occur across the northeastern part of the map area which are satellitic to the Wallace Creek batholith. The largest of these is the Greenwood stock centreed on the city of Greenwood. Irregular dike-like tongues of granodiorite and quartz diorite occur along the southern fringe of the Wallace Creek batholith south and east of Eholt Creek, and a group of small irregular bodies occurs on Mount Attwood extending into Skeff Creek. These plutons outcrop within a broad, poorly defined zone of hornfels and skarn which continues eastward on to Hardy Mountain.

The Nelson plutonic rocks are mainly granodiorite but include quartz diorite (qd) and diorite (d). A small body of gabbro (g) 4 kilometres south of Eholt, known as the Cyclops gabbro, is shown as part of the Nelson suite, but the age is not known. Similarly, diorite along the southwest edge of the Greenwood stock may be part of the Triassic Providence Lake suite (Trbv) as suggested by Church (1986, Figure 1).

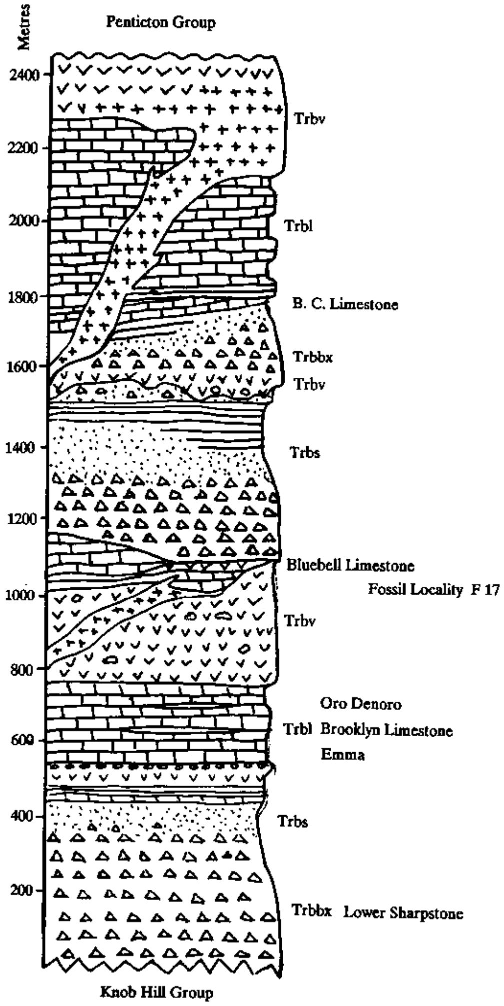
Zones of hornfels and skarn of various widths occur adjacent to the Nelson plutons. In the southwestern corner of the map area grey siltstones become rusty weathering blocky hornfels within about 300 metres of the granodiorite contact. In the northern and northeastern part of the map area, hornfels and skarn occur in all the preTertiary rocks of appropriate composition within 3 or 4 kilometres of the Wallace Creek batholith, and a poorly defined zone surrounds the satellitic plutons on Mount Attwood, in Skeff Creek and to the east on Hardy Mountain. Within these zones the grey siltstones and cherts become very rusty through the development of pyrrhotite, or show a purplish color from the presence of biotite. The greenstones are altered to amphibolite and at lower grades contain abundant epidote. Rocks of the Brooklyn Formation, particularly the calcareous transitional members, are strongly affected by thermal metamorphism. Siltstones become epidote and biotite hornfels locally containing andalusite, zoisite and pyroxene. Calcareous rocks become skarns of various types, the most abundant being rich in epidote, quartz (both white and jasperoidal) calcite, garnet, pyroxene and amphibole. Skarn containing pyrite, pyrrhotite, hematite, magnetite and chalcopyrite and locally bornite, chalcocite and native copper constitutes the ore which has been produced from the Copper Camp, the Mother Lode - Deadwood Camp, Phoenix, the Summit Camp and in the area west of Midway, and is present at the prospects in Skeff Creek and on Hardy Mountain.

A porphyry copper deposit in Nelson granodiorite and diorite occurs on Buckhorn Creek 3.5 to 4 kilometres west of Greenwood. Molybdenite associated with a siliceous pyrrhotite-rich skarn and a small body of quartz diorite has been explored at the head of the west branch of Ingram Creek, 3 kilometres west of the Copper Camp.

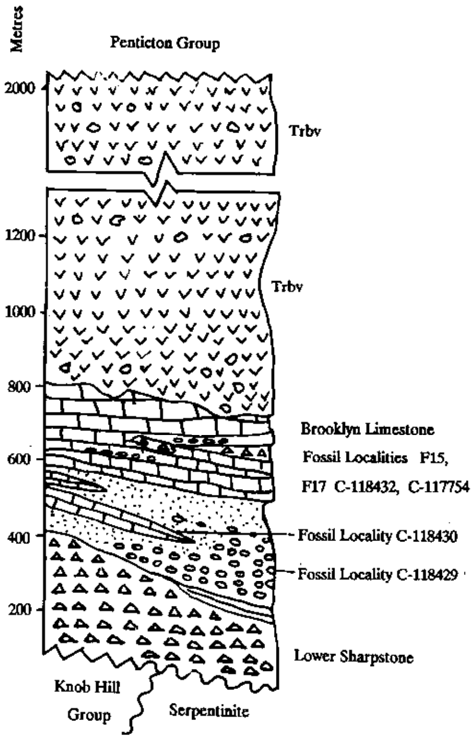
PENTICTON GROUP

The Tertiary Penticton Group consisting of sedimentary and volcaniclastic rocks in the lower part and mainly lava flows in the upper part, unconformably overlies the older rocks. Dikes, sills and irregular small plutons of alkalic rock form an integral part of the group. The emphasis in this study has been on the structural and stratigraphic relationships between the Penticton Group and the older rocks and consequently on Figure 1 the only map units distinguished are the stratiform rocks (Eps), the intrusive rocks (Epi) and an extensive breccia (Epbx) at one locality in the centre of the area just north of the International Border. The lithologies and stratigraphic succession within the group and the petrography and chemistry of the flows and intrusive rocks are described in detail by Church (1986, p. 18), (Little, 1983, p. 25), and Monger (1968). In the present study the base and contacts of the Group with the older rocks have been mapped, but the internal parts have not, and the geology of the large block of the Penticton Group in the western part of the area is modified from the map of Little (1983, Map 1500A).

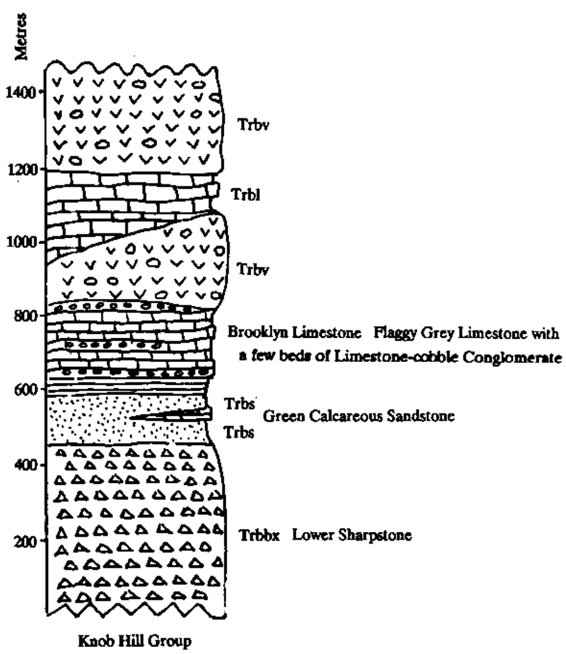
The Kettle River Formation is characteristically whitish grey to buff, coarse-grained arkosic and tuffaceous sandstone. Bedding is scarce and well developed only in the finer sandstones. The sandstones grade into buff and grey siltstone with local coaly beds. At most places these rocks lie directly above the older formations or are separated from them by a Tertiary dike. A basal conglomerate consisting of rounded cobbles of the underlying crystalline rocks is present at only a few places, such as on the south slope of Baker Ridge in the eastern part



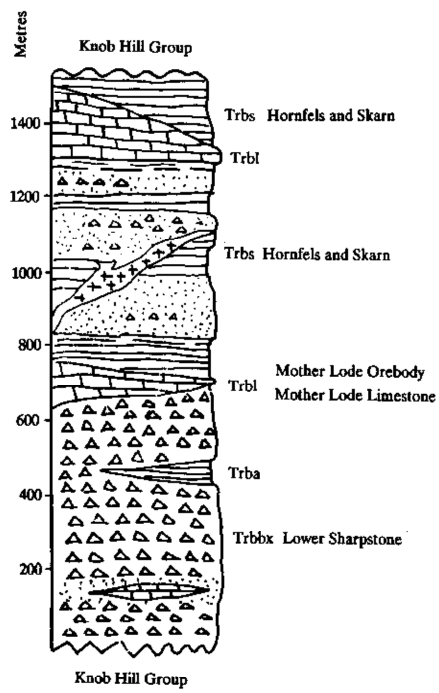
Column 5. Brooklyn Formation - Summit Camp, Hills Southwest of Wilgress Lake to Rathmullen Creek.



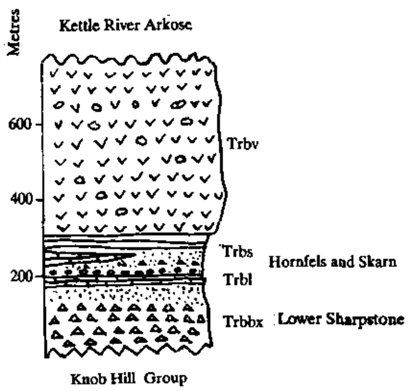
Column 6. Brooklyn Formation - Section Along Highway No. 3 Near Road Turnoff to Phoenix.



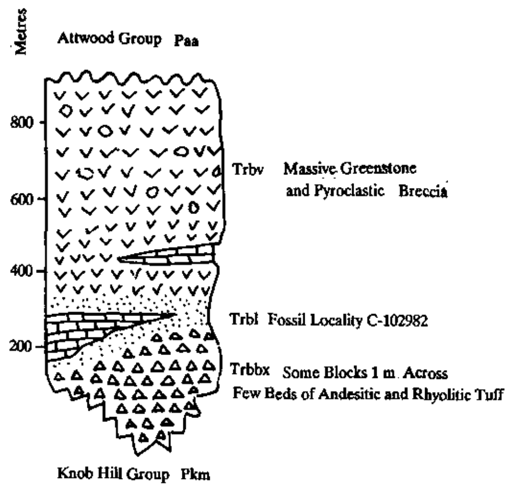
Column 7. Brooklyn Formation Above and Below Canadian Pacific Railway Right-of-way South of Lower Brown Creek.



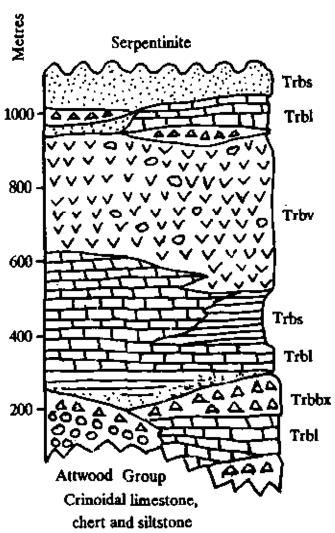
Column 8. Brooklyn Formation, Mother Lode Mine to Deadwood Ridge Section.



Column 9. Brooklyn Formation, Deadwood Ridge on B.C. Hydro Power Line Right-of-way.



Column 10. Brooklyn Formation, West Summit of Mt. Attwood.



Column 11. Brooklyn Formation, Hardy Mountain on the Western Slope to East of Crook Lake.

of the area, and in the area 4 to 5 kilometres west of Midway. In the western part of the area, local lenses of a coarse boulder conglomerate are present which are referred to by Church (1980) as the Springbrook Formation.

The base of the Penticton Group at many places is a fault dipping less steeply to the east than the dip of the bedding and formational boundaries. Fault features such as gouge and breccia are rarely exposed and the decision as to whether or not the contact is a fault depends in part on the presence or absence of the basal conglomerate. This criterion, however, is not foolproof, as conglomerates similar to the basal conglomerate occur at various horizons in the Kettle River Formation.

Above the Kettle River and Springbrook sedimentary formations is the Marron Formation consisting of thick andesite, trachyte and phonolitic lava flows, and these rocks are shown together with the sedimentary formations as Uuit Eps. The stratiform units are distinguished from the intrusive Tertiary rocks, Unit Epi, for structural reasons. The intrusive rocks include dikes, sills and irregular bodies of buff to light grey feldspar porphyry and pulaskite, grey diorite, syenodiorite and monzonite. They are particularly abundant near the base of the Tertiary and along faults. Mainly they are not shown on Figure 1 even though at many places gently dipping dikes and sills lying parallel to hillsides, though relatively thin, form significant areas of outcrop. Small plutons of pink syenite, light grey monzonite and, in the northeastern part of the area, large bodies of pink syenite and quartz monzonite are very irregular in form and only the general outlines are shown on Figure 1.

A large breccia pile (Epbx) is exposed 4 to 5 kilometres east of Midway along the western side of the Bodie Mountain fault. It consists of jumbled blocks of chert, black cherty phyllite, greenstone and rarely of pulaskite. These rocks are described by Little (1983, p. 29) as part of the Klondike Mountain Formation which overlies the Penticton Group in northern Washington. At this locality, however, the breccia interfingers with and is overlain by flows and tuffaceous rocks of the Marron Formation on the slopes south of Norwegian Creek. Similar breccia, covering an area too small to be shown on Figure 1, occurs along the Thimble Mountain fault on the southeastern slopes of Baker Ridge near the eastern margin of the map area, where it also includes also blocks of arkose of the Kettle River Formation. These breccias appear to be fanglomerates which developed along fault scarps during the deposition of the Marron Formation.

STRUCTURAL FRAMEWORK

The regional distribution of the rock units in the Greenwood area is controlled by faults. The preTertiary rocks are on the northern flank of a Precambrian gneiss complex exposed in Washington and in the Grand Forks area east of the Granby River fault. In the eastern part of the map area they are contained in a series of five northward-dipping thrust sheets which, for descriptive purposes, have been numbered (Figure 2, in pocket). The bounding faults are preTertiary and are highly modified by and form an integral part of the Tertiary extensional fault regime. In the western part of the map area, similar preTertiary thrust faults are recognized, but because of the Tertiary cover they cannot be correlated certainly with those in the eastern part.

Tertiary extension faults bound the blocks of Tertiary strata, which dominate the geology of the western part of the map area and form isolated remnants at Phoenix, on Thimble Mountain and to the north, (Carr and Parkinson, 1989). The western part of the map area is the northern extension of the Toroda Creek graben (Pearson, 1967), and the eastern part is north of the Republic graben and the horst between the two, both of which die out north of the International Boundary, with only the eastern bounding fault of the graben continuing as the Granby River fault. The pattern of Tertiary faults is complex, but in its simplest form consists of three sets, one dipping at low angles to the east less steeply than the Tertiary stratiform rocks, a second dipping at low angles to the west but curving and complex in detail, and a third set dipping steeply and trending between north and northeast. The Tertiary faults are obscured and complicated by the Tertiary intrusions (Epi) which from field observations are both syn and post-faulting.

Identification of both the Tertiary and preTertiary faults and the recognition of the thrust slices has been one of the main components of this project. Faults have been identified on the ground by tracing contacts, identifying fault features, mapping layers of serpentinite, searching for pods of serpentinite along suspected fault contacts, and by mapping the geology on both sides of contacts to determine transgression and continuity of the units. Some of the faults have already been named by Little (1983) and Church (1986). Faults shown on previous maps have been evaluated on the ground, and although it is difficult to prove that a feature is not a fault, some have been dropped from the present map. The faults shown are well documented but it is certain that many exist which have not been identified. Mapping of faults with a low dip and a curving trace is particularly challenging.

PRETERTIARY STRUCTURES

The main elements of the preTertiary structure are:

- Thrust faults commonly marked by layers and lenses of serpentinite,
- Fold and fault structures within each of the fault slices, which differ from one slice to another,
- Large and small-scale folds with axes plunging to the north and steeply dipping axial planes which are present in all the fault slices and therefore are probably Mesozoic and preNelson,
- A regional northward dip of the strata and the thrust faults probably caused by the development of the gneiss domes before the deposition of the Penticton Group and after the emplacement of the Nelson plutons.

The thrust faults and the structural characteristics of the thrust slices in the eastern part of the map area are described in the following paragraphs.

FIRST THRUST SHEET

The first and lowest thrust sheet straddles the International Boundary and is exposed east of Midway in an arcuate belt between the head of Goosmus Creek and the Bodie Mountain fault. The hangingwall is the No. 7 fault and associated layer of sheared serpentinite which dips at low to moderate angles to the north and northeast. Church (1970) describes in detail the rocks in this highly deformed zone which contains the quartz-sulphide vein at the No. 7 mine and the pyritic gold mineralization farther east on the Lexington and City of Paris properties as well as the Lone Star copper deposit on Goosmus Creek just south of the border. To the southeast the No. 7 fault curves southward and is offset by the Tertiary Bacon Creek fault on the western side of the Republic graben (Parker and Calkins, 1964) as it crosses the International Border. Judging from the map pattern shown by Parker and Calkins, it continues southeastward across the graben 5 to 7 kilometres south of the border. To the west the No. 7 fault curves southward and is joined and offset by the west-dipping Tertiary Bodie Mountain fault. Thus, this remnant of the first thrust sheet is exposed in the horst between the two Tertiary grabens and forms a north-plunging nose beneath the more regular thrust sheets above and to the north. The footwall of the thrust sheet, well exposed 1 to 2 kilometres south of the border, is a north-dipping fault described by Orr (1985, p. 25) and Orr and Cheney (1987, p. 65) as a zone of mylonitization which transgresses quartzite and schist of the underlying metamorphic sequence and is interpreted as a Mesozoic thrust.

The rocks in the first thrust sheet are mainly dark grey to black phyllite with minor deformed greywacke and fine conglomerate probably belonging to the Attwood Group, lying south of a well-defined belt of massive amphibolitic greenstone correlated tentatively with the volcanic member of the Brooklyn Formation. They are isoclinally folded on axes which have a low plunge either to the east or the west and with axial planes which themselves have been deformed on roughly coaxial broad upright folds. Minor, essentially recumbent, isoclinal folds with axes parallel to a pervasive lineation are well displayed in the basin southeast of Rusty Mountain. Large isoclinal folds are indicated by digitations of greenstone and green phyllite along the southern contact of the Brooklyn Formation on the northwestern ridge of Rusty Mountain.

The Lexington quartz feldspar porphyry intrudes the Brooklyn greenstone on the north forming a wide body tapering to the east and becoming progressively more schistose as it enters the No. 7 fault zone and sheared serpentinite.

SECOND THRUST SHEET

The second thrust sheet contains mainly the highly deformed parts of the Knob Hill Group (Pkm). The No. 7 fault forms the footwall and the Mount Wright fault (MWF), and associated serpentinite, the hangingwall. It is truncated on the west by the Bodie Mountain and Greyhound Creek faults, and on the east by the Granby River fault.

The Mount Wright fault is well defined throughout its length by a layer of serpentinite ranging from a few metres to a few hundred metres thick on Mount Wright. It dips to the north at low to moderate angles and truncates various formations along its hangingwall. The deformed metamorphic rocks in the footwall, which form most of the second thrust sheet, have a strong schistosity and penetrative lineation. In general this dips to the north and northeast at moderate angles, but is highly variable even within one outcrop. Stereoplots of lineations and foliations made at a number of places on the western ridges of Mount Attwood give an average strike of the foliation of 320° to 330° and a dip of 35° to 60° to the northeast, with lineations concentrated at 120/15, 315/20 and 355/55. Terminations of lenses of quartzite tend to have a steep plunge parallel to rodding at quartzite-phyllite contacts. Isoclinal fold hinges which are seen rarely, have a low plunge. Major folds have not been identified within the thrust sheet and faults or shear zones parallel to the shistosity are common. Remnants of the Brooklyn Formation within the thrust sheet north of Boundary Falls appear to be truncated on the north by such a fault.

THIRD THRUST SHEET

The third thrust sheet contains rocks of the Brooklyn Formation unconformably overlying isolated lenses of the deformed Knob Hill Group and the Attwood Group. The thrust sheet pinches out on the west ridge of Mount Attwood where the Mount Attwood fault splits upward from the Mount Wright fault to form the hangingwall of the third thrust sheet.

The Mount Attwood fault (MAF), which dips to the north at low to moderate angles, is well defined throughout its exposed length by sheets and lenses of serpentinite south of Greenwood and on Mount Attwood, and by a thick Tertiary syenodiorite dike to the east on Hardy Mountain where it is described by Little (1983, p. 31) as the Eagle Mountain fault (EMF). South of the summit of Mount Attwood at an elevation of 1525 metres, the Mount Attwood fault appears to be intruded by a quartz diorite body mapped as one of the Nelson plutons. The fault at this locality is marked by a few metres of serpentinite and the intrusion, which is a pyritic felsite follows the fault and is not sheared. These relationships are interpreted to mean that movement on the Mount Attwood fault is preNelson, and probably on Eagle Mountain the fault was reactivated in Tertiary time.

The Brooklyn Formation in the third thrust sheet has the typical lenticular sharpstone conglomerate at the base, overlain and grading into green tuffaceous sandstone and siltstone followed by lenses of limestone overlain by, and interfingering with a thick green pyroclastic breccia which is the dominant lithology.

Mainly, these rocks dip and face to the north and northeast. On the southwest slopes of Mount Attwood, however, the base of the formation and the basal sharpstone, siltstone and limestone members define a large overturned syncline with axes plunging north at 35° and with axial plane striking east and dipping to the north (Figure 2, Section G-G^1). The unconformably underlying rocks of the Knob Hill Group at this locality contain minor folds which reflect the geometry of the fold outlined by the Brooklyn. The fold is truncated by the Mount Attwood fault and no other folds of this nature are found within the third thrust sheet. On Eagle Mountain, however, a basal section of the Brooklyn Formation very similar to that on Mount Attwood, unconformably overlies rocks of the Attwood Group, strikes north, dips steeply and is truncated on the south by the Mount Attwood fault. The close similarity between these two sections and the abrupt steepening of the Brooklyn Formation above the fault suggest that the Eagle Mountain section is the faulted extension of the Mount Attwood section. If this is so the upper plate has an apparent offset to the east of several kilometres which includes any movement in Tertiary time.

Another feature of the third thrust sheet is the folded lens of grey to black cherty argillite of the Attwood Group exposed on the slopes of Gibbs Creek. The rocks have a well-defined slatey cleavage which strikes 310° and dips 20° to the south, and is parallel to the axial plane of an overturned anticline with low plunge to the northwest. The fold is outlined on the ridge north of Gibbs Creek by the bedding and bedding-cleavage relationships. To the north the overturned contact of the Attwood rocks with pyroclastic breccia of the Brooklyn Formation is strongly sheared and has been mapped by Little (1983, p. 30) as the south-dipping May Creek thrust. This, however, is the normal unconformable relationship between these two formations and the contact, though sheared, may or may not be a fault. These relationships on Gibbs Creek are similar to those between the same two units in the first thrust sheet on the northwest ridge of Rusty Mountain.

FOURTH THRUST SHEET

The fourth thrust sheet is broken into four segments by northerly trending Tertiary normal faults. The two western segments are composed of rocks of the Attwood Group; the next one to the east, between the July Creek fault and Hardy Mountain, contains a sliver of the Attwood Group unconformably overlain by the Brooklyn Formation; and the easternmost segment exposed north of Hardy Creek on Goat Mountain is a tilted block of the Brooklyn Formation.

The Lind Creek fault forms the hangingwall of the thrust sheet. It dips to the north at 25° to 50° and has a sinuous map trace partly caused by the low dip, and partly by folds which are well defined on the northern slopes of Hardy Mountain. The fault is lined with schistose serpentinite which occurs mainly as large irregular bodies in its hangingwall, associated with Old Diorite. The footwall of the thrust sheet is the Mount Wright fault in the west followed by the Mount Attwood and Eagle Mountain faults, all of which dip to the north at moderate angles.

The slates, argillites, siltstones and limestones of the Attwood Group within the fourth thrust sheet are tightly folded on axes with low plunge to the northwest and axial planes dipping to the north at moderate angles. West of Boundary Creek at the Skomac mine Church *et al.* (1982, p. 64; 1986, p. 55) has defined a tight syncline of this style and in the area to the east on the western slopes of Mount Attwood minor folds of this type are common in the Attwood Group, but the internal structure of the thrust sheetin this area is not known. The cleavage and most of the bedding dip to the north and northeast and in addition to the tight folds with a low plunge, the rocks contain open folds with axes plunging to the north and axial planes dipping steeply westward.

FIFTH THRUST SHEET

The Lind Creek fault forms the footwall of the fifth thrust sheet. It dips to the north beneath the serpentinite and Old Diorite and the lower parts of the Knob Hill Group. This group together with faulted remnants of the unconformably overlying Brooklyn Formation comprise the stratiform rocks of the thrust sheet. They are intruded by large bodies of Nelson granodiorite which form the upper or northern limit of rocks in the sheet.

The Knob Hill Group generally dips to the northeast and north and in the lower part is complexly folded. Many minor folds in the cherts and the lenticular chert-siltstone-greenstone sequences southwest of Greenwood, on Knob Hill and west of Phoenix, are local contortions with apparently random orientations. In those same areas, however, map-scale folds and related minor structures plunge consistently to the north at 25° to 40° with axial planes dipping steeply west. In areas east, northeast and north of Phoenix as far as Eholt, bedded rocks in the Knob Hill Group do not display minor folds. In general they dip at moderate angles to the north but in several areas the dip is to the west and northwest, possibly reflecting a pattern of north-plunging z-shaped overturned folds.

The Brooklyn Formation lies with marked unconformity above the Knob Hill Group. The members at most places strike 10° to 25° and dip steeply, directly across the trends of the underlying rocks. These steeply dipping panels are exposed in several faulted segments across the northern part of the map area. Only near Phoenix and eastward to Highway 3 and on Volcanic Mountain on the east side of the Granby River are large folds displayed in the Brooklyn Formation. The fold structure of the area east of Phoenix is shown in the cross-section of Figure 3. The form at the west end is of an open syncline west of a small open anticline with axis plunging 20° at 10° to 20°and the axial plane dipping steeply to the west.

Folds are spectacularly outlined by the Brooklyn limestone on Volcanic Mountain in south-facing cliffs above the Granby River. They are recumbent with low west-dipping axial planes and a low north plunge (Preto, 1970, p. 69). They lie above a west-dipping Tertiary listric normal fault on which the folds have been rotated clockwise (down on the east) some 40°. They form the eastern limb of a large east-verging anticline-syncline pair.

In the other segments the members of the Brooklyn Formation dip steeply to the east or are vertical or overturned to the west. The stratigraphic top as indicated by graded beds and known stratigraphy is to the east. These steeply dipping beds become more gently dipping downward and toward the east but rarely dip less than 50°.

Rocks of the Knob Hill Group forming an integral part of the fifth thrust sheet continue westward across the northern part of the map area into the valley of the Kettle River north of Rock Creek.

PRETERTIARY FAULTS IN THE WEST HALF OF THE MAP AREA

In the western part of the map area several faults comparable to the thrust faults in the eastern part of the area have been recognized in the windows between the Tertiary rocks. One such fault in the area of preTertiary rocks 4 to 6 kilometres west of Midway, dips at a low angle to the north beneath sheared serpentinite lying north of sharpstone conglomerate of the Brooklyn Formation. The rocks are intruded by quartz, feldspar porphyry, suggesting a link with the No. 7 fault and the rocks south of it. Similar rocks are exposed in lower Bubar Creek 10 kilometres northwest of Midway, but rocks beneath the serpentinite are not exposed. Farther to the west, along the valley of the Kettle River north of Rock Creek, serpentinite and quartz feldspar porphyry occur with Knob Hill greenstones and Old Diorite in an area complicated by many north-trending Tertiary faults. These three areas may expose parts of one thrust fault beneath a thick section of Knob Hill rocks which is continuous with the fifth and uppermost thrust sheet of the eastern part of the map area. The second and fourth thrust sheets may have pinched out under the Tertiary cover in the Toroda Creek graben in a manner similar to the pinching out of the third thrust sheet on the ridge west of Mount Attwood.

Another significant thrust fault is exposed in the southwestern corner of the map area, which trends 305° and dips 60° to the northeast. It forms the northern contact of dark grey siltstones and sandstone, probably Attwood Group, and lies beneath deformed Knob Hill rocks which themselves are strongly sheared. How this fault and related sheared zone relate to the thrust faults in the eastern part of the map area or to the Chesaw thrust mapped by Cheney (Orr and Cheney, 1987, p. 58) a few kilometres to the south, is not clear.

Tertiary Structures

The structure of the map area is dominated by Tertiary extension faults which control the distribution and attitude of the Tertiary strata as well as the Brooklyn Formation across the northern part of the area. In simplest form the faults belong to three sets, the earliest dipping gently to the east, the second dipping at low angles to the west and curved both in strike and in dip, and the third dipping steeply and trending between north and northeast. The fault zones contain gouge, breccia, and rolled or roundstone breccia, and the walls are commonly polished, grooved and show slickensides. The steeply dipping set often contains vugs lined with crystalline and chalcedonic quartz.

Earliest Fault Set

The earliest fault set, offset, and possibly reactivated by the later faults, lies at or near the base of the Penticton Group. Faults of this set dip eastward less steeply then the overlying strata. Evidence for them is difficult to obtain because they are rarely well exposed, are commonly intruded by a complex array of dikes and sills and are subparallel to the overlying beds. One classic locality is at Phoenix in the east wall of the open pit. The fault is marked by a narrow zone of gouge, intruded by irregular pulaskite dikes some of which show signs of faulting, and transgresses imperceptibly the overlying beds of sandstone and siltstone. Mapping and drilling show that to the east and north, the fault in depth cuts upward through the Kettle River Formation into the Marron lavas.

Significant east-dipping faults of this set are shown on Figure 1 along the eastern side of Ingram Creek and northward across Mother Lode Creek to the powerline on Deadwood Ridge, where it is well defined, but not exposed. Another occurs to the west, running from the head of the west fork of Ingram Creek near Matthew Lake, where it dips to the south, to the upper part of Wallace Creek where it is truncated by the Copper Camp fault.

Second Fault Set

Faults of the second set dip mainly at low angles to the west and are the most complex of the three sets. They are listric normal faults which are arcuate both in plan and section. From east to west they include; the Granby River fault (GRF), the Thimble Mountain fault (TMF), the Snowshoe fault (SNF) and related faults at Phoenix; the Bodie Mountain fault (BMF), the Deadwood Ridge fault (DRF), Windfall Creek fault (WFC) and related faults on the east side of the Toroda Creek graben referred to by Parrish *et al.* (1988, p. 197 and Figure 1) as the Greenwood fault; the Copper Camp fault (CCF) and several unnamed gently west-dipping faults in the western part of the map area. The west dipping faults are marked by spectacular zones of sheared, crushed and brecciated rock and polished and slickensided surfaces. Above the Bodie Mountain and Thimble Mountain faults slide breccias containing large blocks of both preTertiary and Tertiary rocks indicate that they are growth faults on which movement was taking place during deposition of the Penticton Group.

The dip of these faults determined from direct observation, from the form of the surface trace and from drill data is 55° or less, typically flattening downward and at places reversing to dip east. Many of these faults are scoop-shaped with northern segments dipping southward and southern segments dipping northward. Locally, the offset of rock units and orebodies on the north and south segments shows a large component of strike slip.

On a regional scale the apparent offset on these west-dipping faults is clearly defined by several segments of the basal Brooklyn Formation exposed across the northern part of the map area. The basal Brooklyn in each of the segments trends east of north and dips steeply. The most easterly segment near the Granby River fault lies beneath and is truncated by the gently west-dipping Thimble Mountain fault (TMF) on Thimble Mountain. Five kilometres to the west, above the Thimble Mountain fault, the basal Brooklyn appears again south of Eholt. It appears again at Phoenix, apparently offset about 1 kilometre to the west on the Snowshoe fault (SNF). The next segment of the basal Brooklyn is 6 to 7 kilometres farther west, near Deadwood, in a zone of complex faults along the eastern edge of the Toroda Creek graben. More segments of the basal Brooklyn occur to the west, one in the Copper Camp offset 3.5 kilometres on the Deadwood Ridge fault (DRF) and one beyond it offset 2.5 kilometres on the Copper Camp fault (CCF). Two additional faulted segments of the Brooklyn Formation occur farther west above two other west-dipping listric faults which are unnamed.

Probably rotation on these gently west-dipping listric faults is primarily responsible for the 30° to 50° eastward dip of the stratiform rocks of the Penticton Group. Recent work by Marquis and Irving (in press) has shown that rocks beneath the stratiform Tertiary have also been tilted. A rotation of say 40° indicate that the earlier set of faults which now dip to the east would have dipped to the west before tilting. It would also cause the steeply dipping parts of the Brooklyn Formation to have been gently dipping. Probably before the Tertiary faulting the Brooklyn Formation was broadly folded on north-plunging axes with steep axial planes. While it is not possible to determine the overall magnitude of the extension across the map area above the Granby River fault, because the geometry of the fault planes is not known and there are no transgressive markers, it must be in the order of 10 to 20 kilometres, judging from the apparent offsets of the Brooklyn segments.

A number of west-dipping Tertiary faults along the northwest edge of the map area were linked by Little (1983, Map 1500A) as the Wallace Creek fault. Careful mapping along the fault, which at many places is well exposed, has resulted in the map pattern shown on Figure 1. At least four faults which strike north and dip to the west at 30° to 50°, when traced southward, curve in strike to the west and in dip to the north. They are along the southern edge of a thick section of the Kettle River Formation which is terminated on the north beyond the map area by the prominent northwesterly trending Windfall Creek fault. The easternmost of the four faults, for which the name Wallace Creek fault (WCF) has been retained, is joined by the gently west dipping Copper Camp and Deadwood Ridge faults and together the fault curves to the northwest along the Windfall Creek fault (WCF) which dips to the south and continues for several kilometres beyond the map area. These faults form a huge scoop-shaped Tertiary "slump block" opening to the west and containing mainly a thick section of the Kettle River Formation.

The Granby River fault which forms the eastern edge of the map area, has been accurately mapped and described by Preto (1970, p. 68 and Figure 1). Where exposed south of Sand Creek, the fault zone dips 55° west and is marked by a zone of crushed greenstone 50 to 100 metres wide cut by many minor faults dipping west at 40° to 50°. These rocks lie above chloritic, shattered, gneissic granodiorite of the Grand Forks gneiss complex. Lenses of white chert associated with the greenstone are crushed, porcelaneous mylonite in the fault zone, and the greenstones with minor chert lenses for several hundred metres above it are shattered. To the north of Sand Creek the fault can be fairly accurately located and, judging from the trace, it dips at low to moderate angles to the west. The fault is offset by a number of later, north-and north-east-trending steeply dipping faults which to the south dominate the structure and become the eastern edge of the Republic graben in northern Washington.

Third Fault Set

Faults of the youngest set are steeply dipping and trend between north and northeast. These faults dominate the structure in northern Washington (Cheney and Orr, 1987) and in the western half of the map area (Monger, 1968). They are discontinuous structures, with strongly hinged movements which commonly curve in strike and dip. They join and have re-activated older faults. On most of these faults the west side has been dropped down, but on the Bacon Creek fault in northern Washington, which dips to the east on the west side of the Republic graben, the east side is down. Faults of this set with the largest offsets are the Greyhound Creek fault (GCF) and the July Creek faults (JCF) and an unnamed fault along Boundary Creek 2 to 3 kilometres south of Greenwood on which the horizontal displacement of key contacts is 2, 3 and 1.5 kilometres respectively. The vertical component of displacement is unknown. Careful mapping indicates that the fault in Boundary Creek and the July Creek fault splays to follow serpentinites and zones of weakness where the faults cut the Lind Creek, Mount Attwood and Mount Wright thrusts. These older faults control the magnitude and direction of displacement and cause the late faults to be discontinuous. Similarly the Bacon Creek fault joins the No. 7 fault and related serpentinite zone. It has a right-hand horizontal displacement of a kilometre or more, which is taken up by dip slip on the north-dipping No. 7 fault.

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GREENWOOD

SIMILKAMEEN DIVISION OF YALE DISTRICT

BRITISH COLUMBIA

Scale 1:50,000 Échelle

BC Ministry of Energy, Mines and Petroleum Resources

OPEN FILE 1990-25

Figure 2

Geological Cross Sections Greenwood - Grand Forks Area

For Locations of Sections and Legend see Figure 1

Vertical & Horizontal Scales 1:50 000

Base Lines of Sections are at Sea Level