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Geology of the Riondel Area Central Kootenay Arc Southeastern British Columbia

By Trygve Höy

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MINISTRY OF ENERGY, MINES AND PETROLEUM RESOURCES
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Geology of the Riondel Area

SUMMARY

The Riondel area includes approximately 300 square kilometres of mountainous terrain along the east shore of Kootenay Lake in southeastern British Columbia. It is within the central part of the Kootenay Arc, a north-trending arcuate structural zone that lies east of the Shuswap Metamorphic Complex and merges in the east with the Purcell anticlinorium.

Rocks within the Riondel area have been correlated with a Lower Paleozoic sequence exposed along the trend of the arc to the north and south. This sequence includes dominantly quartzite and schist of the Hamill Group, overlain by interlayered calcareous schist, quartzite, and marble of the Mohican Formation, a persistent and extensive Lower Cambrian marble, the Badshot Formation, and dominantly micaceous schist, calc-silicate gneiss, and amphibolite gneiss of the basal part of the Lardeau Group.

The structure of the area is dominated by a series of west-dipping tight to isoclinal folds (Phase 2) that are superposed on the inverted underlimb of an earlier recumbent anticlinal structure, named the Riondel nappe. In the western part of the area the sequence of rocks is inverted, and older rocks occupy the cores of Phase 2 synforms and younger rocks the cores of antiforms.

Three sets of faults are recognized in the area. The oldest are parallel with axial planes of the north-trending Phase 2 folds and are inferred to be reverse faults. Two strike faults in the southeastern part of the area appear to be normal faults with downthrow to the west, and a number of steep, southwest-trending transverse faults in the western part of the area are late structures displacing the northerly trend of units and the Phase 2 folds.

The grade of regional metamorphism ranges from the upper greenschist facies in the east to the upper amphibolite facies in the west. Metamorphic isograds, which have been defined in both pelitic and calcareous rocks, trend north-south approximately parallel to the dominant structural trends, although locally cut across them.

The Bluebell deposit, a replacement lead-zinc deposit in the Lower Cambrian Badshot Formation, *is the only important producer within the area. It milled* in excess of 5 million tonnes of lead-zinc-silver ore during the periods 1895 to 1927 and from 1952 until its closure in 1971. A number of smaller lead-zinc-silver veins or replacement deposits occur in the Badshot Formation or overlying calcareous schists of the Index Formation.

RÉSUMÉ

La région de Riondel englobe environ 300 km^2 de terrain montagneux en bordure est du lac Kootenay dans le sud-est de la Colombie Britannique. Elle se situe dans la partie centrale de l'arc de Kootenay, une zone structurale N–S qui s'individualise à l'est du complexe métamorphique de Shuswap avant de disparaitre dans l'anticlinorium de Purcell plus à l'est.

Les roches de la région ont été mises en corrélation avec une séquence du Paléozoique inférieur affleurant au nord et au sud de l'arc. La séquence comprend, en ordre ascendant, les quartzites et schistes du groupe de Hamill, l'interstratification de schiste calcaire, de quartzite, et de marbre de la formation de Mohican, le marbre continu et étendu de la formation de Badshot et les schistes micacés, gneiss calcosilicatés, et gneiss amphibolitiques de la partie inférieure du groupe de Lardeau.

La structure dominante de la région est représentée par une série de plis, sérres à isoclinaux, à pendage vers l'ouest (Phase 2); ces plis se superposent au flanc inférieur renversé d 'un anticlinal couché plus ancien (nappe de Riondel). Dans la partie ouest de la région, la séquence lithologique est inversée; les roches les plus vieilles occupent le coeur des synformes de la Phase 2 et les roches les plus jeunes, le coeur des antiformes.

Les failles de la région se répartissent en trois systèmes. Les plus anciennes sont parallèles aux plans axiaux des plis à direction nord de la Phase 2; on suppose qu'il s'agit de failles inverses. Deux failles directionnelles dans la partie sud-est semblent être des failles normales avec rejet à l'ouest; dans la partie ouest, plusieurs failles tranversales, plus récentes, de forte inclinaison et de direction sud-ouest, ont décalé les strates ainsi que les axes des plis de la Phase 2.

Le métamorphisme va du faciès supérieur des schistes verts dans la partie est de la région au faciès supérieur des amphibolites dans la partie ouest. Les isogrades, définis aussi bien dans les roches pélitiques que dans les roches calcaires, sont à peu près parallèles aux orientations dominantes N–S des structures; on compte toutefois quelques orientations recoupantes.

La région n'a connu qu'un seul producteur d'importance. Il s'agit du gisement Bluebell, une minéralisation de substitution en plomb-zinc-argent dans la formation de Badshot. On a traité plus de 5 millions de tonnes de minerai entre 1895 et 1927 et entre 1952 et 1971, année de fermeture. Plusieurs veines ou gîtes de substitution de moindre importance se présentent dans la formation de Badshot ou dans les schistes calcaires sus-jacents de la formation d'Index.

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INTRODUCTION

LOCATION, ACCESS, AND TOPOGRAPHY

The Riondel area includes approximately 300 square kilometres of mountainous terrain along the east shore of Kootenay Lake in southeastern British Columbia (Fig. 1). Access to the area is provided by a road extending north from Highway 3, along the Kootenay

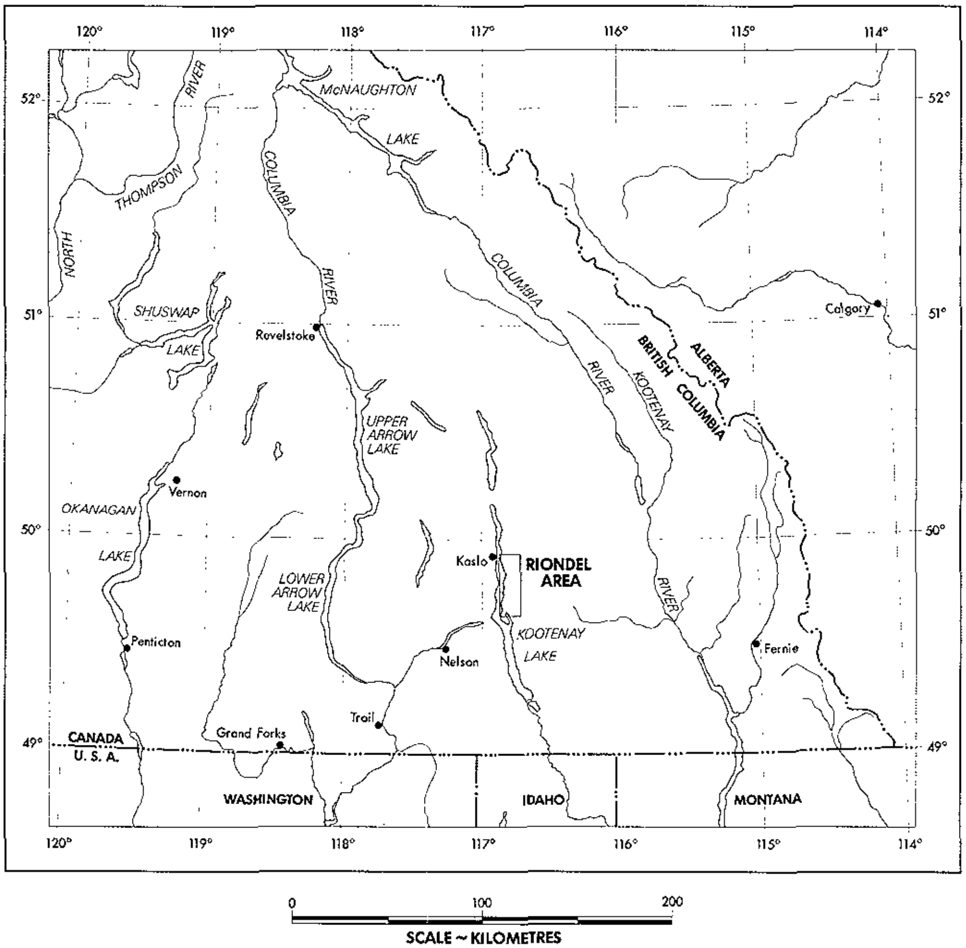

Figure 1. Map showing the location of the Riondel area.

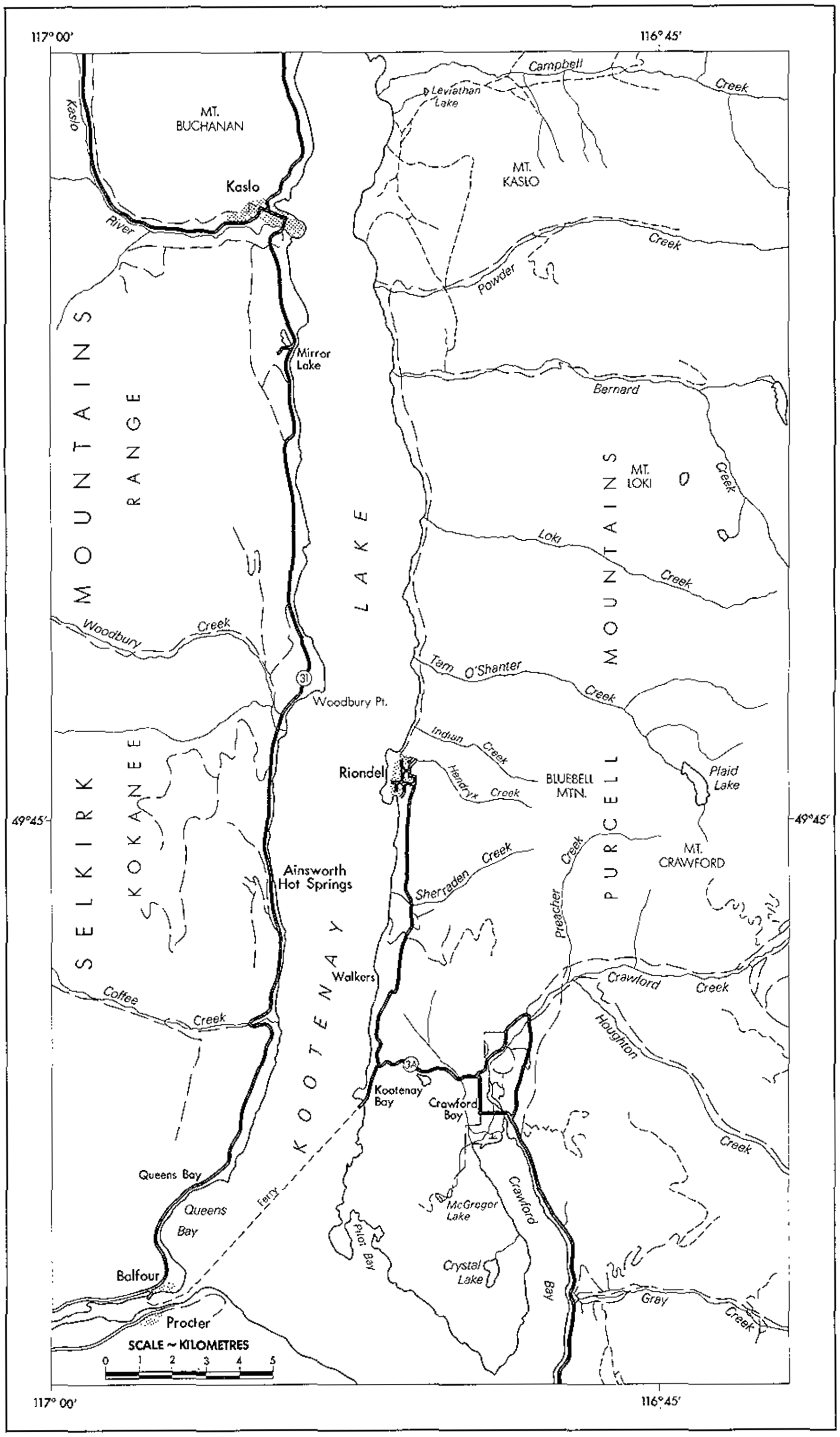

Figure 2. Physiographic features of the Riondel area.

Lake shoreline, to the northern limit of the map-area, 15 kilometres north of Riondel. Gravel logging roads follow both Powder and Bernard Creeks, allowing easy access to the northeastern part of the map-area (Fig. 2).

Deep east/west-trending valleys transect the north/south topographic and structural grain and provide natural cross-sections. Rock exposures are generally good to excellent above 2 000 metres. At lower elevations, however, the slopes are heavily wooded with hemlock, fir, cedar, spruce, and tamarack, and extensive rock exposures are uncommon (Plates I and II).

HISTORY OF EXPLORATION

The Bluebell mine at Riondel is one of the oldest mines in British Columbia. Its early development history is marred by a dispute that led to the murder of one of the original stakers of the property. In 1882, the property was staked by Robert Evan Sproule. He was unable to register the claims with the Gold Commissioner who resided on the Wild Horse River several days journey to the east because of a law which did not allow a man to be absent from his claims for more than 72 hours at any one time. Thomas Hammill, representing George J. Ainsworth, a river-boat captain on the Columbia River, restaked Sproule's claims in the presence of the Gold Commissioner and was thereby able to register them immediately. The following year, a court decision granted the mineral rights to Sproule. This decision was reversed on appeal and Sproule, incensed by the decision, murdered Hammill.

Production from the Bluebell property commenced in 1895 and continued intermittently until 1927 under various owners. Initially, the ore was smelted at Pilot Bay, located on the shore of Kootenay Lake 3.5 kilometres south of Kootenay Bay. Total production during this period amounted to 542,000 tons averaging 6.5 per cent lead, 8.2 per cent zinc, and 2.8 ounces silver per ton (79 grams per tonne). Cominco Ltd. acquired the property in 1942 and from 1952 to closure of the mine in 1971, mined an additional 4.771 million tons averaging 5.1 per cent lead, 6.3 per cent zinc, and 1.7 ounces silver per ton (48 grams per tonne).

There has only been limited exploration and development of the lead-zinc-silver properties in the Riondel area (Table 9). In 1927, the Berengaria Mining Company explored in the vicinity of a large mineralized boulder discovered near the mouth of Sherradin Creek. The source of the boulder was not located. It contained in excess of 350 tons of ore grading approximately 20 per cent combined lead-zinc and 3.6 ounces silver per ton (93 grams per tonne).

The only present mineral production in the Riondel area is dolomite from an underground mine on Crawford Creek north of Crawford Bay. The Crawford Creek Dolomite quarry, owned by International Marble and Stone Company Limited of Calgary, produces approximately 50 000 tonnes of crushed dolomite annually for use in the building trade.

Plate I. View of the southern part of the Riondel area from the Kootenay Bay-Balfour ferry. Bluebell Mountain is in the centre of the picture, Crawford Peak on the right (south) side, and the peak of Mount Loki is visible to the left of Bluebell Mountain.

Plate II. Kootenay Lake viewed toward the south. Crawford Bay and Crawford Peninsula are in the foreground.

GEOLOGICAL WORK

In 1928, J. F. Walker published a report and map of the Kootenay Lake District, an area that included the northern half of Kootenay Lake and all of Duncan Lake. Walker (1928) combined the complexly interfolded metasedimentary rocks of the Lardeau Group, Badshot Formation, and Hamill Group, calling them the Lardeau Series. He restricted the Badshot Formation to the easternmost exposure of thick limestone in the area and the Hamill Series, to rocks exposed east of that limestone.

Rice (1941) in his bulletin on the Nelson east-half map sheet did not substantially revise Walker's geological map of the Riondel area.

A number of recent graduate thesis studies include a part or all of the Riondel area. Crosby (1968) and Livingstone (1968) recognized the existence of complex folds in the western part of the area. The regional metamorphism in the central part of the Kootenay Lake area was studied by Winzer (1973).

The geology of a large part of the Kootenay Arc has been ellucidated in a series of excellent reports by Dr. James T. Fyles of the British Columbia Ministry of Energy, Mines and Petroleum Resources. His description of the complex geology of the Duncan Lake area to the north of the Riondel area (Fyles, 1964), of the Ainsworth-Kaslo area on the west shore of Kootenay Lake (Fyles, 1967), and of the Salmo area at the southern end of the Kootenay Arc (Fyles and Hewlett, 1959) would suggest that the geology of the Riondel area was considerably more complex than previously described.

The Riondel area was mapped by the author during the summers of 1972 and 1973. Additional reconnaissance mapping to the north of the Riondel area in 1975 as a staff member of the Ministry demonstrated that major structures continued northward to the Fry Creek batholith. Mapping was done on Provincial government air photographs and transferred to 1:25 000 topographic base maps and has been published in the form of a preliminary map (Höy, 1974b). The mapping has demonstrated that the isoclinal north-trending folds that dominate the structure of the area developed in an inverted panel of rocks. This panel is the underlimb of a westward-closing nappe.

ACKNOWLEDGMENTS

The structure, stratigraphy, and metamorphism of the Riondel area formed the basis of a Ph.D. thesis submitted to Queen's University, Kingston, Ontario. I wish to thank D. M. Carmichael and R. A. Price for their supervision of the project, and my wife, Lorraine, for her continued encouragement and support.

Discussions with students and faculty at Queen's University, R. L. Brown of Carleton University, Paul Ransom of Cominco Ltd., P. B. Read of Geotex Consultants Limited, and James T. Fyles of the British Columbia Ministry of Energy, Mines and Petroleum

Resources helped clarify many problems in the area. D. A. Archibald, Queen's University, has kindly allowed publication of some of his preliminary age dating results in the Kootenay Arc. Roy Jeffery is thanked for his assistance in the field in 1973.

The thesis study was financed by a National Research Council of Canada scholarship, by NRCC research grants awarded to Drs. Carmichael and Price, and by a field research grant provided by Cominco Ltd. Fieldwork in 1975 while employed by the British Columbia Ministry of Energy, Mines and Petroleum Resources completed mapping of the Riondel area.

D. G. MacIntyre and A. Sutherland Brown of the British Columbia Ministry of Energy, Mines and Petroleum Resources were the critical readers of this manuscript. The map and diagrams were draughted by Pierino Chicorelli.

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2

GENERAL GEOLOGY

INTRODUCTION

The Riondel area is in the central part of the Kootenay Arc, a north-trending arcuate structural zone in the southeastern Canadian Cordillera (Fig. 3). The Kootenay Arc is characterized by north-trending isoclinal to tight folds that developed in a succession of rocks ranging in age from Hadrynian to Early Mesozoic. The arc merges on the east with the Purcell Anticlinorium, a broad north-plunging structure in Helikian and Hadrynian rocks that are cut by steep longitudinal and transverse faults, and on the west with the Omineca Crystalline Belt comprising the Shuswap Complex and the Nelson and Kuskanax batholiths.

Deposition of miogeosynclinal sedimentary rocks in southeastern British Columbia spanned an interval of more than 1 100 million years. The aggregate thickness of these sedimentary rocks exceeds 14 000 metres. They were derived primarily from the North American craton to the northeast and consequently were deposited as a northeasterly tapering sedimentary wedge on the western margin of the continent.

The oldest rocks are exposed in the Purcell Anticlinorium east of the Kootenay Arc (Fig. 3). They include argillites, mudstones, intercalated sandstones, and stromatolitic carbonates of the Purcell Supergroup of Helikian and Early Hadrynian age. Coarse clastics and slates of the Windermere Supergroup of Hadrynian age unconformably overlie the dominantly fine-grained detrital rocks of the Purcell Supergroup. The Windermere Supergroup includes the Toby Formation, a basal conglomeratic mudstone, and the Horsethief Creek Group, a thick accumulation of shale, quartzose and feldspathic sandstone, and quartz pebble conglomerate. A succession of Paleozoic quartzites, carbonates, and fine-grained clastic rocks overlies Windermere rocks. Well-sorted Lower Cambrian quartzite of the Hamill Group overlies the Horsethief Creek Group and is in turn overlain by the Badshot Formation, a thin but widespread carbonate unit. The Badshot is the host of virtually all the replacement and stratiform lead-zinc deposits in the Kootenay Arc. The Badshot is overlain by the Lardeau Group, a succession of argillite, shale, calcareous shale, and minor quartzite of Early Cambrian and later age.

The Kootenay Arc has undergone intense polyphase deformation. In general, the earliest recognized structures are tight to isoclinal, north-trending recumbent folds. In the Lardeau area in the northern Kootenay Arc, evidence indicates that these structures developed during the Cariboonan orogeny in Devono/Mississippian time (Wheeler, 1968, 1972; Read, 1975, 1976).

More open but locally isoclinal, north-trending Phase 2 folds with upright to steeply west-dipping axial surfaces are superposed on the Phase 1 folds. These folds dominate the structure of the Kootenay Arc and account for the pronounced north/south structural grain. In the Lardeau area, radiometric dates restrict the second phase of deformation to an interval between 178 Ma and 164 Ma. The older limit is set by a K/Ar date from the core of the pre to syn-tectonic Kuskanax batholith, the younger by both the post-tectonic northern part of the Nelson batholith and the Mount Carlyle stock (Read and Wheeler, 1975). The latest discernible deformation in the arc caused faulting and gentle folding of the earlier structures.

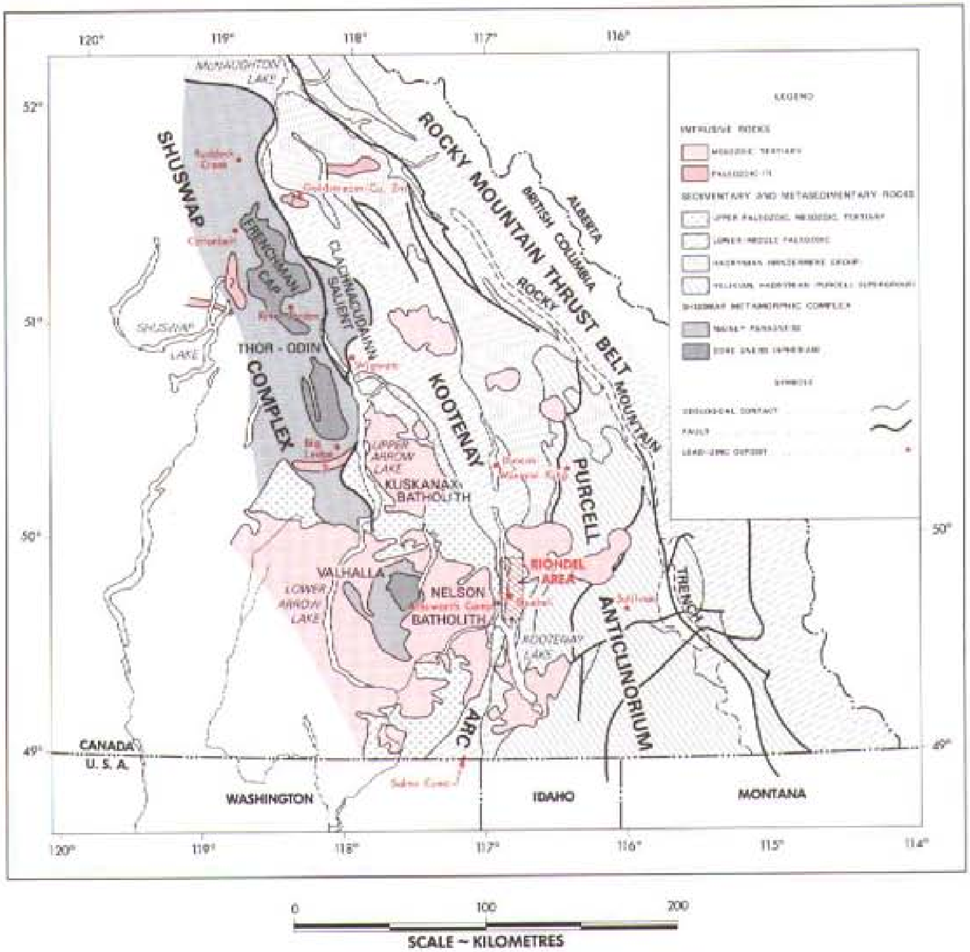


Figure 3. General geological map of southeastern British Columbia.

The Riondel area is in the central part of the Kootenay Arc. It is located within a local metamorphic culmination and near a regional structural culmination. North of the Riondel area, fold axes generally plunge to the north at low angles (Fyles and Eastwood, 1962; Fyles, 1964; Read, 1973) whereas to the south, axes most commonly plunge south (Fyles and Hewlett, 1959). Both syn-tectonic and post-tectonic quartz monzonite stocks are exposed within the northern part of the area.

A lead-zinc metallogenic province extends from northern Idaho and Montana through southeastern British Columbia to north of Revelstoke in the northern Selkirk Mountains. Included in this metallogenic province are a variety of detrital sediment and carbonate-hosted lead-zinc deposits (Fig. 3). The Bluebell deposit at Riondel in the central part of the Kootenay Arc is a replacement deposit in the Lower Cambrian Badshot marble. The H.B. mine at Salmo (Fyles and Hewlett, 1959), the Duncan deposit at Duncan Lake (Fyles, 1964), and the Wigwam south of Revelstoke (Thompson, 1979) are stratiform lead-zinc deposits which also occur in the Badshot marble. Lead-zinc deposits within the Shuswap Complex are highly deformed and metamorphosed sulphide layers that occur in calcareous shales of unknown age. They generally are found peripheral to a series of domal structures cored by Aphebian gneiss which occur along the eastern margin of the complex.

TABLE 1. TABLE OF FORMATIONS

Group	Formation	Map Unit	Estimated Thickness *metres*	Description
Lardeau	Index	L4	top not exposed	micaceous schist and gneiss
		L3	400 – 450	calc-silicate gneiss, amphibolite, schist; impure marble; amphibolite layer and pure white quartzite layer near base
		L2	700	biotite-hornblende gneiss, amphibolite; minor calc-silicate gneiss, marble, and schist
		L1	150	micaceous schist
	Badshot	B	15 – 30	white crystalline calcite marble, dolomite
	Mohican	M	~50	interlayered quartzite, calcareous and micaceous schist, limestone, and dolomite
Hamill		H4	230	dark quartzite, dark fine-grained quartz-rich schist
		H3	60 – 200	massive, white quartzite
		H2	2 000	interbedded micaceous schist, quartzite, and siltstone; minor amphibolite
		H1	1 600	massive, white quartzite; gritty quartzite
Horsethief Creek		HTC	base not exposed	fine-grained, light grey to green chlorite-muscovite schist and phyllite; rare white quartzite and marble near top

Plate III. Plaid Lake, viewed from the south, with vertical to steeply west-dipping schist and quartzite of the Hamill Group on the far shore.

Plate IV. Crossbedding in the basal Hamill unit (H1i), east of Mount Crawford.

STRATIGRAPHY

Rocks within the map-area have been correlated with the Hadrynian/Cambrian sequence established in the Duncan Lake area to the north (Fyles, 1964) and in the Salmo area to the south (Fyles and Hewlett, 1959). The composite stratigraphic sequence established in *the Riondel area is presented in Table 1. The upper part of the sequence, the Lardeau* Group, is most complete in the Bluebell Mountain antiform, the Hamill succession is based on mapping in the Mount Loki area, and Horsethief Creek rocks are exposed only in the southeastern part of the map-area (Fig. 4, in pocket).

Stratigraphic thicknesses of the units are difficult to estimate because they have been modified by deformation; estimated thicknesses are generally from the attenuated limbs of Phase 2 folds and hence are minimum values.

HORSETHIEF CREEK GROUP

The oldest rocks in the area outcrop only in the southeastern part of the map-area along the Crawford Creek road. These rocks have been mapped as Horsethief Creek Group because of their lithologic similarity to Horsethief Creek Group rocks due south and because they are directly below the Hamill Group. The exposure consists of 300 to 400 metres of fine-grained light green to grey chlorite and chlorite-muscovite phyllite and schist, with rare beds of quartz pebble conglomerate. Rare white quartzite layers and one thin marble layer occur within the top 100 metres of the exposed section.

Recognizable primary structures are rare; dark grey laminations within the light green schists may represent original bedding planes. These layers are commonly cut by a pronounced mineral foliation. A crenulation cleavage is common in the schists and phyllites.

The contact with the overlying Hamill Group sedimentary rocks is obscured by at least a 100-metre width of overburden.

HAMILL GROUP

The Hamill Group includes about 3 500 metres of quartzite, schist, and meta-siltstone, with rare amphibolite and calcareous layers. It has been subdivided into four distinct units (Table 1).

UNIT H1

Basal quartzites (unit H1) which overlie the Horsethief Creek Group are exposed only in the southeast corner of the map-area (Plate III). They consist of approximately 1 000 metres of medium to coarse-grained, grey to grey/green feldspathic quartzite (H1i) overlain by 600 metres of massive white quartzite (H1ii).

Very conspicuous crossbedding (Plate IV) and graded bedding in unit H1i indicate that these west-dipping beds are right-side-up. In general the grain size decreases upward through the section. Thin quartz pebble conglomerate layers common near the base of unit H1i are absent near the top. The contact with the overlying white quartzite of unit H1ii is sharp. These quartzites lack any prominent sedimentary features; layering is outlined by thin micaceous laminations in an otherwise massive pure quartzite layer.

UNIT H2

Unit H2 comprises 1 500 to 2 000 metres of white to dark grey quartzite, interlayered with phyllite, schist, and dark crossbedded siltstone. The lower half, which is exposed only in the southeast corner of the map-area, is predominantly dark grey quartzite and siltstone, the upper half is predominantly schist.

The detailed description of unit H2 in Table 2 is the section of rock units exposed on the ridge northwest from Mount Crawford toward Bluebell Mountain. An unknown amount of the succession is missing due to two layer-parallel faults that cut through this area.

TABLE 2. DETAILED DESCRIPTION OF UNIT H2, HAMILL GROUP

Unit H2	Thickness *metres*	Description
	(top)	
viii	300	epidote-chlorite-amphibole gneiss ('greenstone') with prominent clots of epidote; dark green amphibolite; rare calcareous layers
vii	800	muscovite-chlorite schist, medium grained, light brown; rare white quartzite layers; thin rusted dolomite layer at top
vi	200	dark quartzite; dark, fine-grained, quartz-rich schist; minor green chlorite schist and white quartzite; prominent quartz-rich dolomite layer (2 to 3 metres thick) near centre of unit
v	120	chlorite-muscovite schist, brown weathering; two white quartzite layers 15 metres thick near top of unit
iv	120	quartzite, massive, white, in layers 15 metres thick, interbedded with dark green chlorite schist ('greenstone') and with brown-weathering dolomite layer near centre of unit
iii	200	chlorite schist, dark brown to grey, interlayered with dark siltstone and 2 to 4-centimetre quartzite layers; thick white quartzite layer near centre of unit; cross-bedding common; schists are crenulated
ii	75	chlorite schist, fine grained, light to medium green, with white sugary textured quartz feldspar eyes; some white quartzite layers 0.5 to 1 metre thick; very pronounced crenulation cleavage
i	180	siltstone, dark brown to medium brown, finely laminated; dark green chlorite schist; a few white quartzite layers 1 to 3 metres thick at base of unit; white pure calcite marble 15 to 20 metres thick at top of unit
	(base)	

In the Plaid Lake area, a 200-metre-thick dark green (metavolcanic ?) amphibolite lies at the top of unit H2. It is an epidote-chlorite-hornblende gneiss commonly containing clots of epidote and large (1 centimetre) porphyroblasts of hornblende that are aligned parallel to the prominent mineral foliation. A thin layer of siliceous dolomite, commonly brecciated, occurs near the base of the amphibolite. The amphibolite pinches out north of Tam O'Shanter Ridge.

UNIT H3

Unit H3, a layer of nearly pure white quartzite, is a distinctive marker unit within the Hamill Group. It has been traced from the Crawford Bay road in the south to the Mount Loki area where it is repeated westward by four Phase 2 folds. Its thickness varies from approximately 60 metres in the limbs of the Mount Loki folds to 200 metres on the ridge east of Bluebell Mountain.

The quartzite consists almost entirely of white, crystalline, medium-grained quartz with only rare thin muscovite-rich partings.

UNIT H4

The uppermost unit of the Hamill Group comprises at least 200 metres of fine-grained dark grey biotite-quartz schist and quartzite. Pelitic layers within this unit become more common southward, and on Riondel Peninsula they comprise at least half the exposed section.

In the Mount Loki area, unit H4 is composed primarily of dark grey, fine-grained 'blocky' biotite-rich quartzite interlayered with dark grey, fine-grained, quartz-rich biotite schist. Coarse-grained, micaceous schist and thin white quartzite layers are less abundant.

MOHICAN FORMATION

The Mohican Formation, a gradational unit between the Hamill Group and the Badshot marble, consists predominantly of medium-grained, brown-weathering muscovite schist. Grey dolomite marble layers up to 6 metres thick and, less commonly, micaceous white quartzite layers are interbedded with the schists. A layer of pure or dolomitic white marble several tens of metres in thickness commonly marks the base of the formation.

The formation is well exposed on Crawford Creek on the east limb of the Preacher Creek antiform, but its thickness here is much greater than elsewhere. It consists of alternating thin layers (average thickness less than 2 centimetres) of rusty weathering muscovite schist and impure marble and calcareous schist. Thin quartzitic layers are common within the schists and a few biotite amphibolite layers occur near the top of the section. At least five white calcite-tremolite marble layers occur within the section but not all of these represent distinct stratigraphic horizons. The most westerly of the white marbles is an infold of the overlying Badshot Formation. Detailed mapping has delineated several very attenuated isoclinal folds that thicken the Mohican Formation by repeating parts of the section. Similarly the anomalous thickness of Mohican Formation on Tam O'Shanter and Loki Ridges (on the west limb of the Bluebell Mountain synform) is due to structural repetitions.

A description of the Mohican section exposed on Bernard Ridge on the east limb of the Bluebell Mountain synform is given in Table 3.

TABLE 3. MOHICAN FORMATION STRATIGRAPHY BERNARD RIDGE

Formation	Thickness *metres*	Description
Badshot	----	white calcite marble
Mohican	1	layered grey and green dolomite
	2	schist
	1	fine-grained, grey dolomite
	8	fine-grained, rusted muscovite schist
	4	layered, medium grey, fine-grained dolomite
	5	medium-grained schist
	8	white quartzite with micaceous partings
	16	medium-grained garnet-muscovite schist, brown weathering
Hamill	----	quartzite and schist

BADSHOT FORMATION

The Badshot marble is the most distinctive marker unit within the map-area. It consists of nearly pure, white calcite or dolomite marble and weathers a light grey colour. Accessory minerals include tremolite, phlogopite, and graphite. The Badshot averages 15 to 30 metres in thickness although deformation has locally attenuated it on the limbs of folds (just south of Bluebell Mountain) or considerably thickened it in fold cores (to a maximum of several hundred metres south of Crawford Creek).

Badshot exposed in the Mount Loki area just east of the West Bernard fault is generally more dolomitic and finer grained than elsewhere. It is less pure (quartz, tremolite, and phlogopite are more abundant) and weathers to a light brown colour.

LARDEAU GROUP

Rocks assigned to the Lardeau Group include in excess of 1 000 metres of hornblende gneiss, calc-silicate gneiss, muscovite-biotite schist, and biotite-quartz-feldspar gneiss. The group has been divided into four distinct and mappable units. The youngest of these (L4) is exposed only on the west slope of Bluebell Mountain where the complete Lardeau section outcrops. Unit L3 outcrops on both limbs of the Crawford antiform. Only the lowermost schists (L1) and hornblende gneisses (L2) are exposed in cores of folds to the east. Contacts between these subdivisions of the Lardeau Group are generally quite sharp except near hinges of major folds where isoclinal mesoscopic folding of the units results in apparently 'gradational' contacts.

UNIT L1

A fine to medium-grained muscovite schist or biotite gneiss immediately overlies the Badshot marble. The unit varies from north to south as follows: in the Mount Loki area it is a medium to coarse-grained pelitic schist containing garnet and staurolite porphyroblasts; at Tam O'Shanter Creek, it is more calcareous with a 2-metre layer of rusty weathering siliceous marble near the centre; and east of Bluebell Mountain (in the Preacher Creek antiform), it is a micaceous schist containing quartzite layers.

UNIT L2

Dark grey to black hornblende gneiss and amphibolite comprise unit L2. They crop out along the Kootenay Lake shoreline north and south of Riondel. Unit L2 also contains diopside-rich calc-silicate layers, thin rusty weathering calcite marble layers, and, less commonly, hornblende-biotite gneiss and micaceous quartzite layers. A fairly pure, white calcite marble, several tens of metres thick, occurs near the centre of unit L2 and resembles the Badshot marble. East of Riondel this marble layer is highly attenuated and is cut by a number of sphalerite-galena-pyrite veins.

A fine layering, defined by laminations a few millimetres thick of variable hornblende or calc-silicate mineral content, is ubiquitous in the amphibolite and hornblende gneiss. The layering is believed to reflect compositional variations in the original sedimentary rock; the calc-silicate layers were more calcareous sediments and the biotite gneiss and schist, more pelitic.

UNIT L3

The succession within unit L3 is summarized in Table 4. Unit L2 is overlain by quartzite containing interlayers of biotite schist (L3i), then thinly laminated amphibolite (L3ii), and thin rusty weathering siliceous marble layers (L3iii). The marble grades upward into well-layered calc-silicate gneiss (L3iv) that contains local schist, biotite gneiss, and rusty weathering siliceous marble interbeds.

TABLE 4. LITHOLOGIC SUCCESSION OF MAP UNIT L3

Unit	Thickness *metres*	Description
L4	-----	biotite-quartz-feldspar gneiss
L3iv	230 – 300	calc-silicate gneiss with amphibolite, schist, and marble layers
L3iii	30 – 60	rusted calcite marble with calc-silicate, amphibolite, and schist layers
L3ii	0 – 60	amphibolite
L3i	15 – 30	micaceous to pure white quartzite interlayered with biotite schist and gneiss
L2	-----	amphibolites, hornblende gneisses

The basal quartzite (L3i) is exposed on the ridge west of Preacher Creek. It is light grey, quite pure, containing only thin muscovite partings. Exposures in Tam O'Shanter and Loki Creeks are less pure and are interlayered with some schist and biotite-muscovite gneiss. The quartzite was not observed in the west limb of the Crawford antiform, but a fine-grained sugary textured feldspathic quartzite in the same stratigraphic position may be a westerly, more feldspathic facies of the quartzite. The amphibolite (L3ii) is massive and fine grained. It lies stratigraphically above the quartzite on the east limb of the Crawford antiform.

The calc-silicate gneisses (L3iv) are light grey/green in colour. A pronounced layering, varying in scale from thin laminations to layers at least 8 metres thick, is parallel to the dominant mineral foliation. The layering consists of variations in mineral assemblages and proportions and is believed to reflect variations in bulk composition of the original sedimentary beds. Sections of muscovite-rich schist and biotite gneiss and layers of rusty siliceous marble are common within unit L3iv.

The contact of unit L3 with the stratigraphically overlying biotite gneiss of unit L4 has been mapped where the last calc-silicate layer appears in the gneiss. Part of the area mapped as L3iv in the hinge zone of the Crawford antiform contains some tight infolds of unit L4. As this stratigraphic horizon is followed southward, the interfingering of units L3iv and L4 decreases until on Crawford Peninsula the contact is sufficiently sharp to measure offsets of several tens of metres in late southeast-trending faults.

UNIT L4

Unit L4 is the youngest stratified rock sequence exposed in the area. It is a rusty weathering paragneiss which forms the core of the Crawford antiform. It is generally medium grained and consists mainly of microcline, plagioclase, biotite, muscovite, and hornblende. Amphibolite bodies form large widely spaced boudins within the less competent gneiss (Plate XII).

STRATIGRAPHIC CORRELATIONS

Proposed stratigraphic correlations in the Kootenay Arc are summarized in Table 5. Positioning of the composite Riondel section is based on the lithologic similarities and homotaxial relations of the rocks. No fossils have been discovered in the Riondel area.

The stratigraphic succession in the Riondel area provides a basis for detailed correlations along the Kootenay Arc between the Duncan Lake area (Fyles, 1964) and the Salmo area (Fyles and Hewlett, 1959). The broad outlines of the correlation are relatively straightforward because in each area the same succession of three broad rock-stratigraphic units can be recognized: quartzites and interbedded pelitic rocks, overlain by a persistent and widespread carbonate unit which, in turn, is overlain by pelitic rocks and interbedded carbonates.

Quartzite and schist assigned to the Hamill Group in the Riondel area are correlated with the lithologically similar combined Quartzite Range and Reno Formations in the Salmo area. A massive white quartzite near the centre of the Hamill Group is a distinctive marker horizon in both areas (the Upper Nevada and unit H3). The Mohican Formation in the Riondel and Duncan Lake areas is similar to the Truman member of the Laib Formation in the Salmo area, and the overlying Badshot limestone is similar to and homotaxial with the Reeves member. The Badshot forms a distinctive, persistent limestone-marble unit throughout the Kootenay Arc. It separates the more quartzitic units of the Hamill Group from the overlying Lardeau Group.

Correlation of post-Badshot rocks is more tenuous. The Index Formation in the Duncan Lake area has been divided into a lower more calcareous part (the Lower Index) and an upper more siliceous, noncalcareous part (Fyles, 1964). These subdivisions resemble the hornblende gneiss—calc-silicate gneiss (units L1, L2, and L3) and the overlying biotite-hornblende gneiss (unit L4) respectively, of this study. The more calcareous 'uppermost few hundred feet' of the Lower Index (Fyles, 1964, p. 26) may be the equivalent of the calc-silicate unit (L3iv) in the Riondel area. The Emerald member of the Laib Formation in the Salmo area is probably a less calcareous equivalent of the Lower Index. The basal part of the 'Upper Laib' may correlate with the biotite-hornblende gneisses of unit L4 (Table 5).

The stratigraphic successions established as a result of studies of several other parts of the Kootenay Arc are shown in Table 5. Crosby (1968) tentatively correlated his 'middle' and 'upper' Lardeau rocks (not shown in Table 5) with the Triune, Ajax, and Sharon Creek Formations and the Jowett and Broadview Formations respectively, but remapping

TABLE 5. REGIONAL CORRELATION

SALMO [1]	CENTRAL KOOTENAY LAKE [2]	RIONDEL [3]	AINSWORTH–KASLO [4]	DUNCAN LAKE [5]	POPLAR CREEK [6]
			KASLO MILFORD		MILFORD
EMERALD	LARDEAU	LARDEAU – INDEX – UPPER: L4	LARDEAU: 2C	LARDEAU: BROADVIEW JOWETT SHARON CREEK AJAX TRIUNE	LARDEAU: BROADVIEW JOWETT SHARON CREEK AJAX TRIUNE
			2B	INDEX – UPPER: (GREENSCHIST)	INDEX: 5 4
		INDEX – LOWER: L3 L2 L1	2A EARLY BIRD PRINCESS	INDEX – LOWER: (GREY SCHIST)	3 2 1
REEVES	BADSHOT	BADSHOT	BADSHOT	BADSHOT	BADSHOT
TRUMAN	HAMILL: UPPER HAMILL	HAMILL: MOHICAN	HAMILL	HAMILL: MOHICAN	
HAMILL: RENO		H4		MARSH ADAMS	
QUARTZITE RANGE: UPPER NEVADA		H3			
LOWER NEVADA		H2			
NUGGET	LOWER HAMILL	H1		MT. GAINER	
HORSETHIEF CREEK GROUP					

[1] Fyles and Hewlett (1959); [2] Crosby (1968); [3] this paper; [4] Fyles (1967); [5] Fyles (1964); [6] Read (1973).

of these units in this study indicates that his 'lower' and 'middle' Lardeau rocks belong to the Lower Index. Both the Ainsworth-Kaslo (Fyles, 1964) and Poplar Creek (Read, 1973) sequences have been correlated to the Duncan Lake sequence and hence can be correlated with the Riondel area.

Plate V. A large block of calc-silicate gneiss within the Shoreline stock along Kootenay Lake shoreline (photograph width is approximately 3 metres).

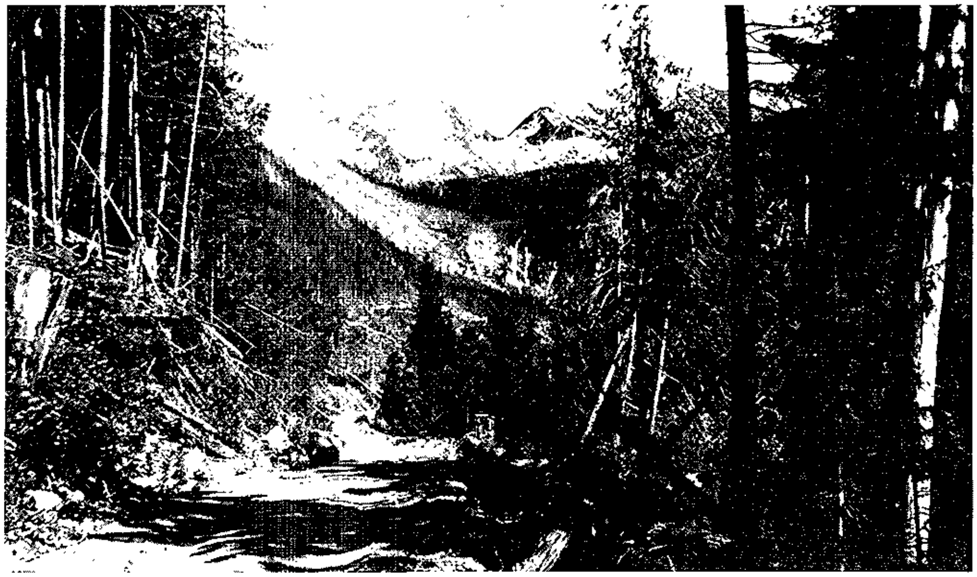


Plate VI. Exposures of the Fry Creek batholith in the distance, viewed toward the east from a logging road following Bernard Creek.

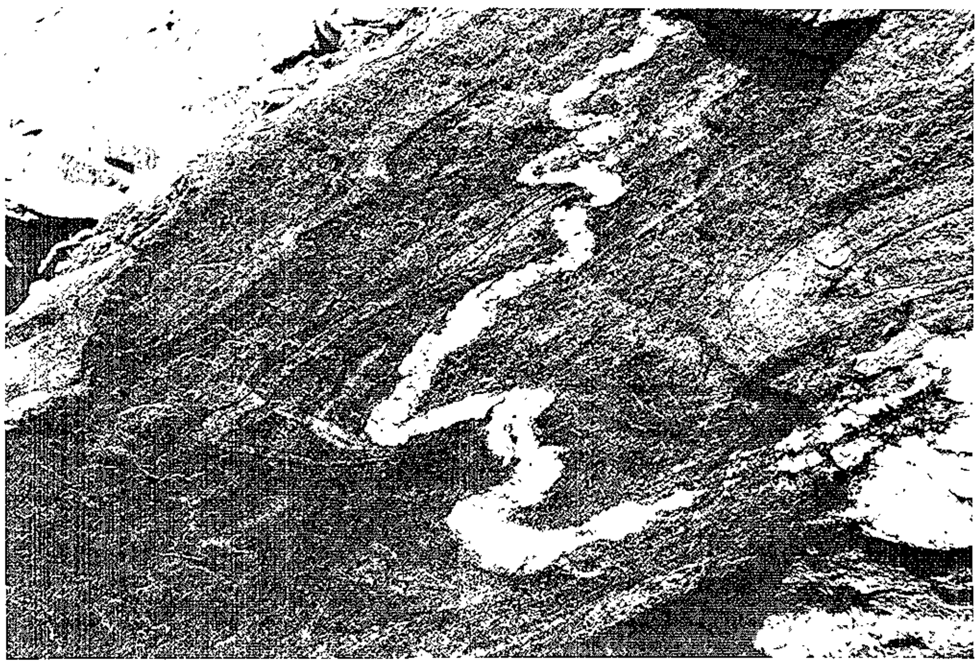


Plate VII. Felsite vein emplaced during Phase 2 deformation and folded with the enclosing calc-silicate gneiss (unit L3iv), Riondel road, 4 kilometres south of Riondel.

INTRUSIVE ROCKS

Quartz monzonite intrusions underlie a large part of the area north of Loki Creek. They include the informally named Shoreline stock and a southwestern extension of the Fry Creek batholith. Aplite and pegmatite sills of variable thickness are common in the western part of the area, particularly south of Tam O'Shanter Creek.

SHORELINE STOCK

The Shoreline stock is exposed along the Kootenay Lake shoreline north of Loki Creek (Plate V). It is a semiconcordant westward-dipping quartz monzonite intrusion which is elongated approximately parallel to the trend of the Phase 2 fold structures. Its contact zone, which is more than 300 metres wide, consists of mixed pegmatite and aplite sills, foliated and layered quartz monzonite, and country rock. Toward the core of the intrusion the amount of included country rock gradually decreases, and the granitic sills become more common finally giving way to a layered (due to variations in grain size) and foliated quartz monzonite. The most westerly exposed part of the stock is massive, medium-grained, equigranular biotite-quartz monzonite (Table 6).

TABLE 6. MODAL ANALYSES OF REPRESENTATIVE HAND SPECIMENS OF GRANITIC ROCKS

Intrusion	Grain Size *mm*	Points	qz *per cent*	Ks *per cent*	pl *per cent*	Mafic *per cent*	Description
Shoreline stock	2 – 5	1 826	30.7	30.2	34.3	4.5	quartz monzonite
Shoreline stock	1 – 2	856	25.7	33.6	38.0	2.5	quartz monzonite
Fry Creek batholith	2 – 4	665	31.4	30.2	35.9	2.5	quartz monzonite
Fry Creek batholith	2 – 3	1 122	29.1	32.7	33.7	4.5	quartz monzonite

FRY CREEK BATHOLITH

Exposures of the Fry Creek batholith (Plate VI) are predominantly massive, medium-grained biotite-quartz monzonite (Table 6). Where observed, the contact of the batholith with the metasedimentary rocks is sharp; the batholith truncates regional structures at a high angle, yet does not appear to deform them.

QUARTZ FELDSPAR SILLS AND DYKES

Numerous small plutons ranging in outcrop size from several hundred square metres to approximately 2 square kilometres and many pegmatite and aplite sills and dykes are distributed throughout the western part of the map-area. Only the very largest of these have been shown on the map (Fig. 4, in pocket).

Granite pegmatite sills are widespread on the western slope of Bluebell Mountain. They are composed dominantly of quartz, white potassic feldspar, albite, and muscovite with minor biotite and rare garnets. Many of these pegmatite bodies were isoclinally folded along with the metasedimentary rocks; others were emplaced during the latter stages of the Phase 2 folding and have only been partially folded (Plate VII) while some of the pegmatites were emplaced after the Phase 2 deformation. No pegmatite bodies have been discovered cutting Phase 3 structures.

The larger of the pegmatite bodies are generally coarser grained and more massive. A large concordant pegmatite body exposed on the ridge north of Crawford Bay has a pronounced foliation and near its contact includes xenolithic blocks of calc-silicate gneiss with layering approximately parallel to the regional layering. The pegmatite body becomes more massive and coarser grained away from its contact.

TECTONIC IMPLICATIONS

The distribution of the 'granite-pegmatite' bodies coincides with the locus of highest grade of regional metamorphism. Some pegmatites are discontinuous and 'rootless' and some include remnant concordant metasedimentary layers. They were emplaced during and after the Phase 2 deformation, but prior to the latest Phase 3 deformation.

The Shoreline stock may have been emplaced during the culmination of the regional metamorphism. Regional metamorphic isograds do not appear to be truncated against this stock but warp around it approximately paralleling its contact. The high degree of mixing of country rock with intrusive rocks and pegmatites in its contact zone, its concordant nature, and its strongly foliated border zone suggest emplacement at depth during the regional deformation. Its massive unfoliated core suggests that cooling and final solidification may have post-dated Phase 2 deformation. D. A. Archibald (personal communication, 1979) suggested, however, that the Shoreline stock is a 'post-tectonic' stock, similar in age (~100 Ma) to a number of intrusives in the southern Kootenay Arc (for example, parts of the Bayonne batholith, the Lost Creek stock, and Rykhert batholith). He has obtained a Tertiary K/Ar date (50.8±1.4 Ma) on the Shoreline stock. He does not believe that this is the age of the intrusion, but rather may be due to (1) Tertiary reheating, (2) slow cooling followed by rapid uplift in Tertiary time, or (3) heating and argon loss due to late shearing.

Features of the discordant Fry Creek batholith suggest post-tectonic emplacement at shallower depth. The batholith consists of massive unfoliated quartz monzonite (except for a local indistinct foliation near the border), with sharp contacts and narrow contact metamorphic aureoles superimposed on the regional metamorphic country rocks.

3
METAMORPHISM

INTRODUCTION

The regional metamorphic grade in the Kootenay Arc ranges from lower greenschist to upper amphibolite facies. An elongate belt of higher grade metamorphism approximately parallels the regional trend of the arc (Fig. 5). The highest grade occurs in a belt centred on Kootenay Lake and extending north toward Duncan Lake. The Riondel area is essentially in the centre of this metamorphic culmination and, as such, is an ideal location for the study of high-grade regional metamorphism in both calc-silicate gneisses and pelitic schists, 1974a, 1976). Within the Riondel area, the metamorphic grade ranges from upper greenschist facies in the east to upper amphibolite facies in the west. Metamorphic isograds trend northward approximately parallel to the dominant structural trends, but cut across them locally as well as regionally.

Isograds mapped in the Riondel area are traces of surfaces across which the observed mineral assemblages are related by means of a specific metamorphic reaction (compare Carmichael, 1970). The isograds have been delineated from both the lower grade and higher grade side by plotting all occurrences where the complete reactant and product assemblages are observed. The isograds are named according to the product assemblage of the reaction. A zone is named according to the product assemblage of the reaction which defines its lower boundary.

PELITIC ISOGRADS

Four pelitic isograds have been identified in widely scattered localities. The isograds are poorly defined due to scarcity of rocks of suitable bulk composition; pelitic units are common only near the top of the Hamill Group (in unit H4 and the Mohican Formation), within the basal Index Formation (unit L1), and in the Upper Index (unit L4). Furthermore, extensive retrograde metamorphism has overprinted the lower temperature assemblages making identification of the prograde assemblages difficult.

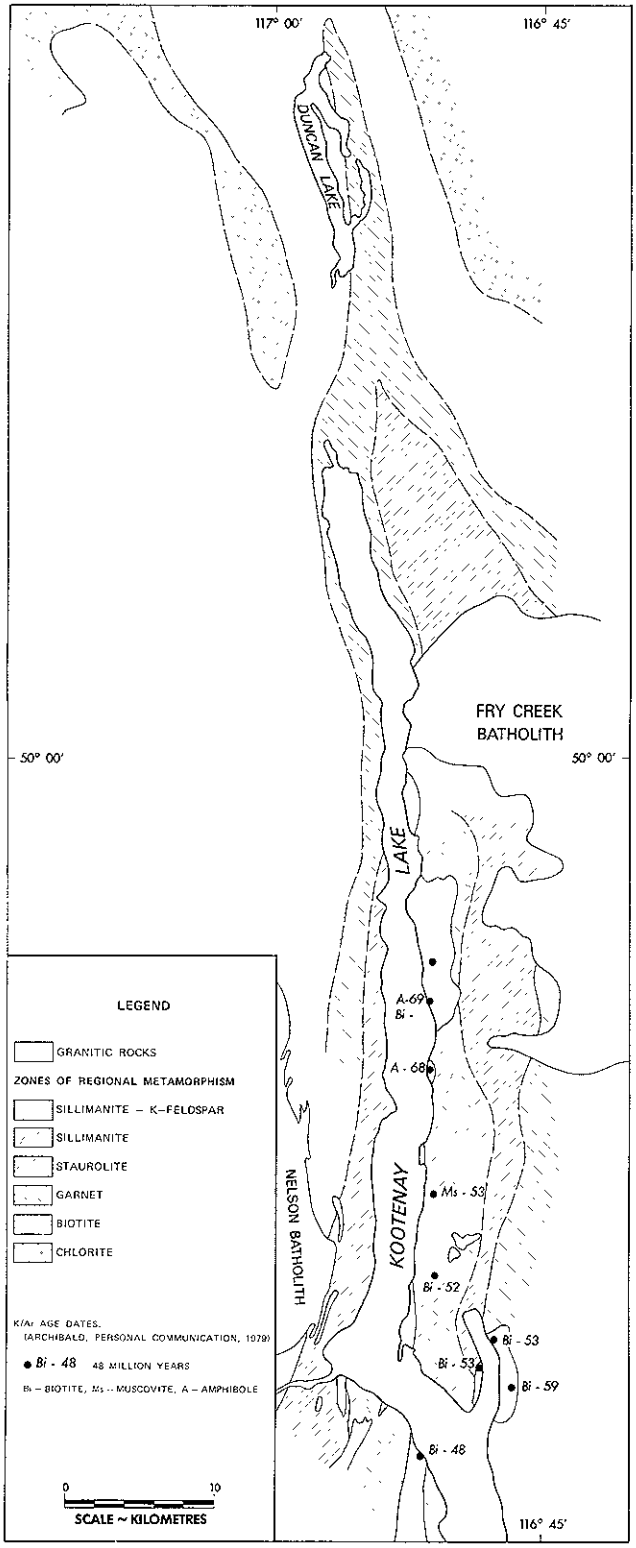


Figure 5. The distribution of regional metamorphic zones and granitic rocks in the Riondel area, from Fyles (1964, 1967), Crosby (1968), Read (1973), Reesor (1973), and this study.

The pelitic isograds are based on the following reactions:

(1) chlorite + muscovite + garnet = staurolite + biotite + quartz + H_2O
(2) staurolite + muscovite + quartz = aluminum silicate + garnet + biotite + H_2O
(3) kyanite = sillimanite
(4) muscovite + quartz = sillimanite + microcline + H_2O

The distribution of these isograds is shown on Figure 6.

Metamorphic assemblages and reactions in pelitic rocks can be graphically plotted on an AFM diagram (Thompson, 1957; Winkler, 1967), a plot which includes the components Al_2O_3, FeO, and MgO (Fig. 7). Muscovite and quartz also occur in any assemblage plotted on this AFM diagram.

STAUROLITE–BIOTITE–QUARTZ ISOGRAD

Reaction (1), which defines the staurolite-biotite-quartz isograd, is shown in steps a and b of Figure 7, in which the tie-line joining garnet and chlorite (plus muscovite) is broken and replaced by the biotite-staurolite tie-line. The st-bi-qz* isograd is only constrained in the northern part of the map-area (Fig. 6) by four occurrences of the lower grade reactant assemblage, chl-ms-gt, and six widely scattered occurrences of the higher grade product assemblage. Two rock samples contained the complete assemblage of reaction (1). Only the reactant assemblage occurs in the southern part of the area.

ALUMINUM SILICATE–GARNET–BIOTITE ISOGRAD

Reaction (2), which defines the Alsi-gt-bi isograd, is graphically illustrated in steps c and d of Figure 7. In the southern part of the map-area (Fig. 6) at the northwest head of Crawford Bay, the complete assemblage of reaction (2), with kyanite, locates the isograd. Approximately 100 metres north, this assemblage, with sillimanite, indicates that the ky-bi-gt zone is very restricted in the Riondel area. Crosby (1968) identified the complete assemblage with both kyanite and sillimanite on 'the west shoreline of Crawford Bay 0.25 mile from head of bay' (p. 13), indicating coincidence of the sillimanite and Alsi-bi-gt isograds. The assemblage was also identified in the northern part of the area, thus locating both the sillimanite and the Alsi-gt-bi isograds. A number of occurrences of the reactant assemblage of the Alsi-gt-bi isograd and one occurrence of the product assemblage (in which the aluminum silicate was completely altered to white mica) further constrain the isograd.

SILLIMANITE ISOGRAD

Only two occurrences of sillimanite and two occurrences of kyanite have been found in the Riondel area where these minerals are not completely altered to 'white mica.' These

*Alsi — aluminum silicate; bi — biotite; chl — chlorite; gt — garnet; ky — kyanite; ms — muscovite; qz — quartz; sil — sillimanite; st — staurolite.

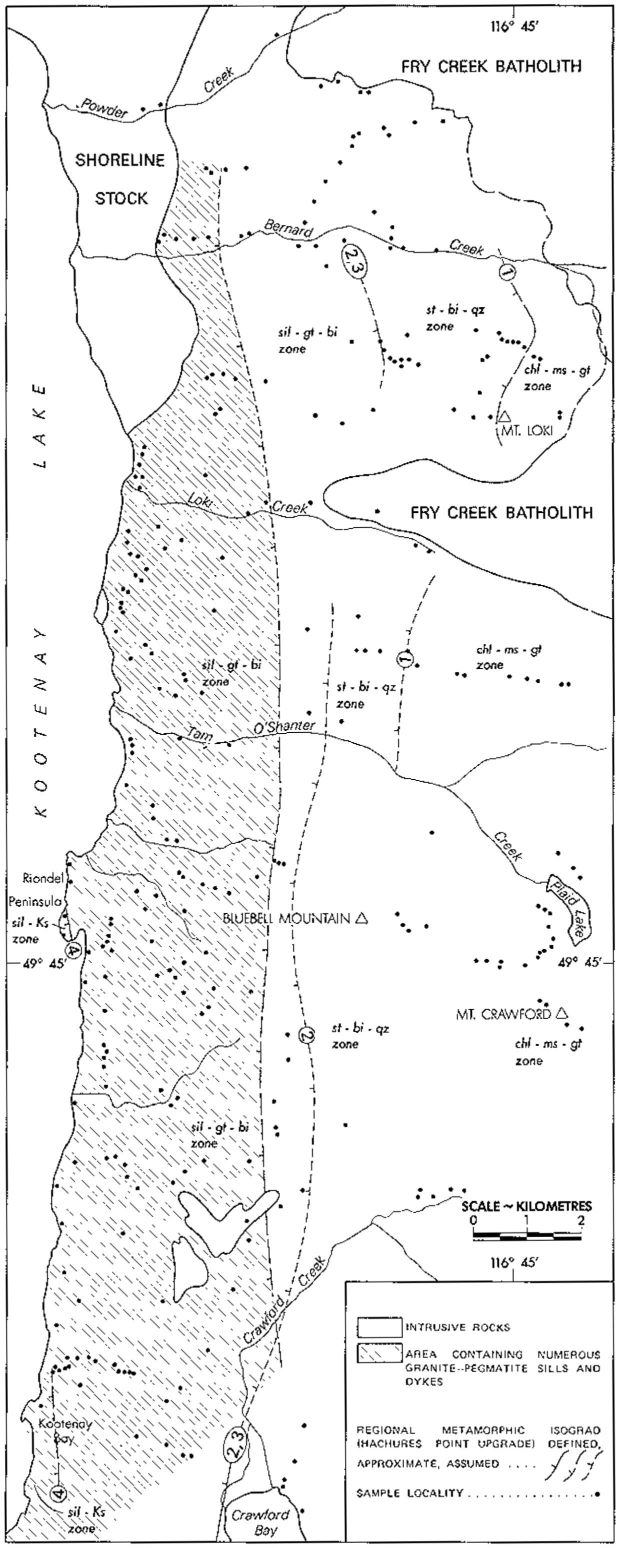


Figure 6. The distribution of pelitic isograds and granite-pegmatite sills and dykes in the Riondel area.

occurrences, described in the previous section, define the position of the isograd in two localities on Figure 6. In addition, many pelite samples contain concentrations of very fine-grained 'white mica' commonly in the form of radiating bunches of fibrous crystals. These mica concentrations are interpreted as being pseudomorphic after sillimanite and have been used to further define the isograds containing sillimanite.

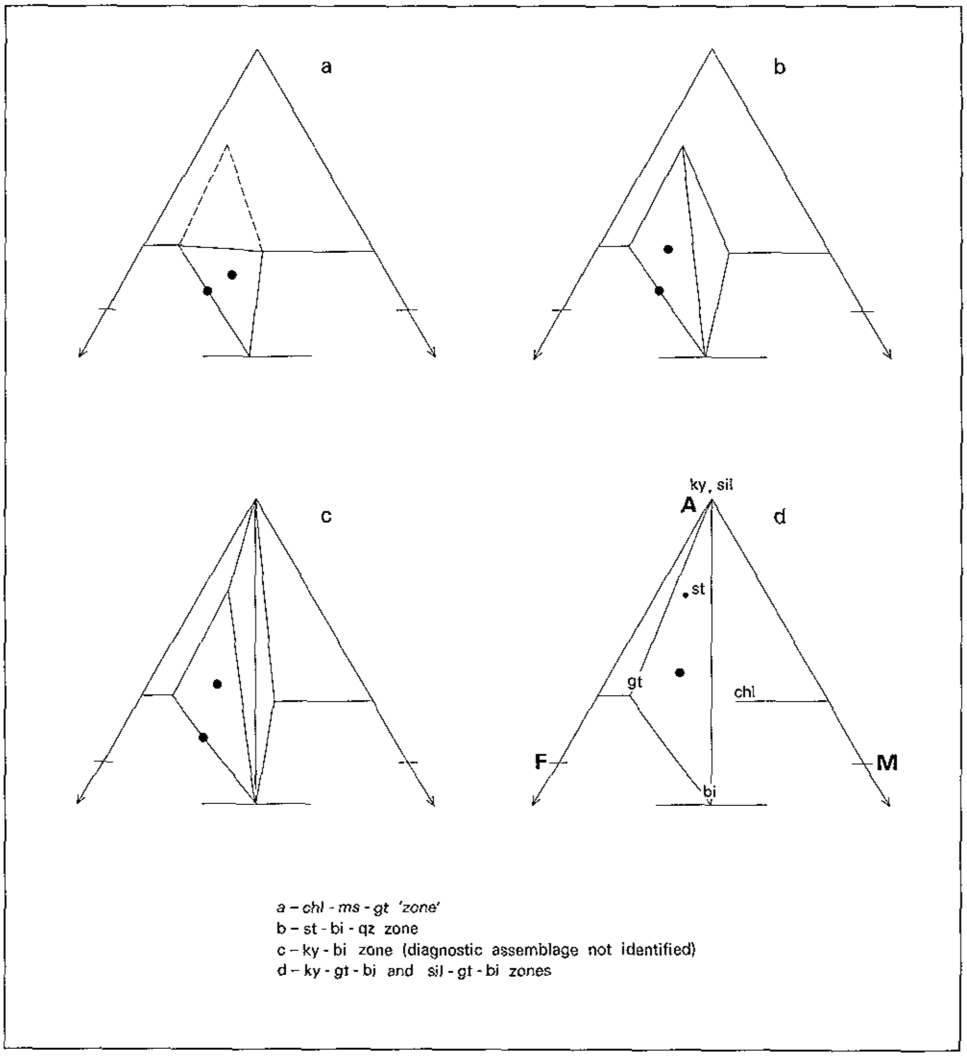


Figure 7. The topology of the reactions in pelites shown on the AFM projection. The observed mineral assemblages in each zone are represented by dots in the appropriate stability fields.

SILLIMANITE–MICROCLINE ISOGRAD

The reactant assemblage of reaction (4), ms-qz, is common throughout the area. The product assemblage, sillimanite (altered to white mica)–K-feldspar, was identified in only one locality (coexisting with ms-qz), on the southwest shore of Riondel Peninsula (Fig. 6). Crosby (1968) also identified coexisting sil-Ks* (orthoclase) just south of Kootenay Bay. These two occurrences define the isograd in two localities and indicate that the highest grade of regional metamorphism is in the most western part of the Riondel area.

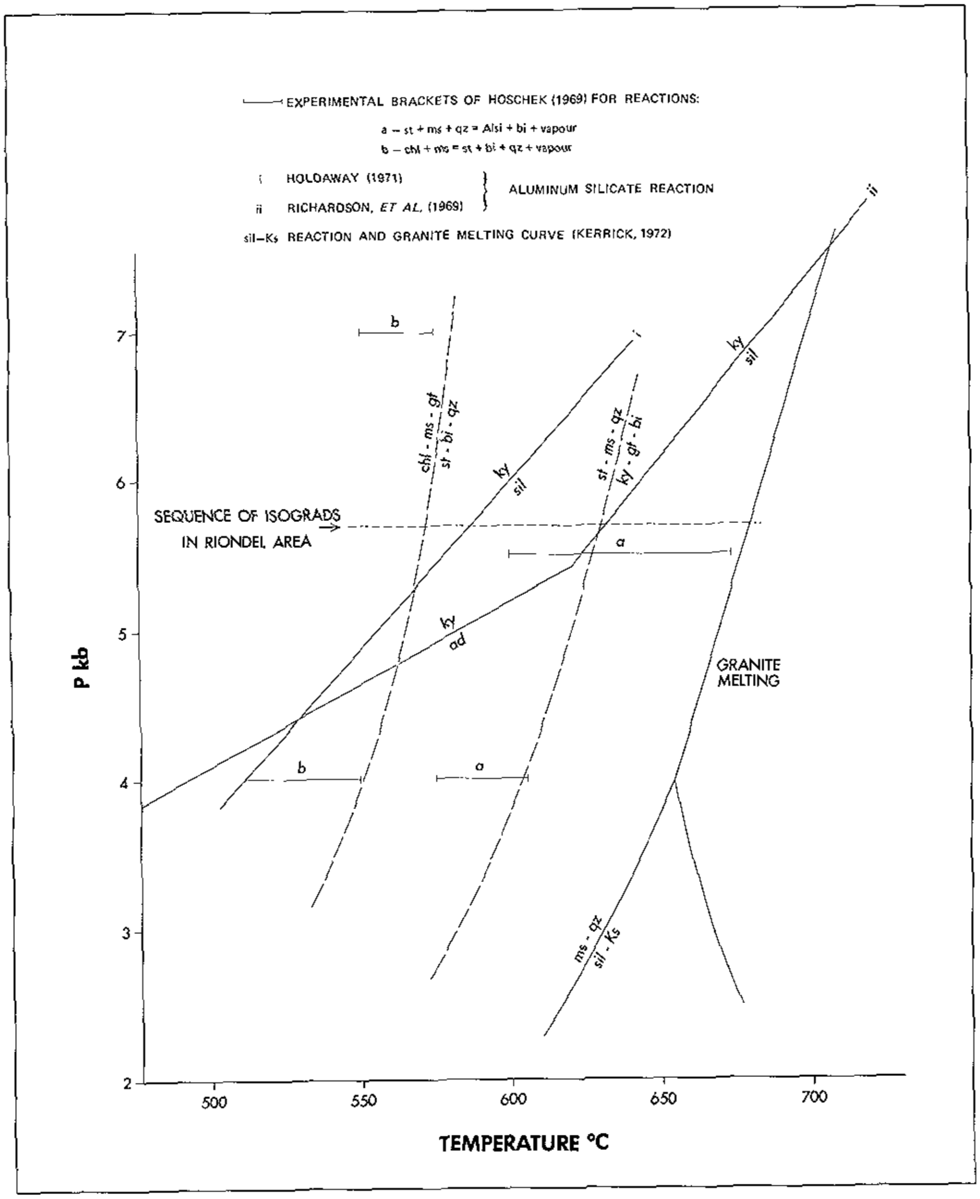


Figure 8. A pelitic grid illustrating reactions upon which the isograds mapped in the Riondel area are based.

*Ks – K-feldspar.

TEMPERATURE, PRESSURE, AND FLUID COMPOSITION ESTIMATES

Experimental data on reactions relevant to the pelitic isograds are plotted on Figure 8.

Within the Riondel area, the ky-bi-gt and the sillimanite isograds approximately coincide. Reactions (2) and (3), which define these isograds, intersect at a point on Figure 8, and define both pressure and temperature: approximately 5.5 kilobars and 625 degrees centigrade according to the data of Hoschek (1969) and Richardson, *et al.* (1969).

At pressures of 5 to 6 kilobars, reactions which define the pelitic isograds are restricted to the temperature range 550 to 650 degrees centigrade. Since the granite-pegmatite bodies, which are inferred to have formed by partial melting of the metasedimentary rocks, extend well into the ms-qz 'zone' in sillimanite-bearing rocks (Fig. 6), pore fluids in these rocks must have had compositions of $X_{H_2O} < 0.5$, as indicated on Figure 5 of Kerrick (1972).

CALC–SILICATE ISOGRADS

Calc-silicate isograds mapped in the Riondel area are based on the reactions*:

(5) $8\ qz + 5\ dol + H_2O = tr_{(act)} + 3\ ca + 7\ CO_2$

(6) $tr_{(act)} + 3\ ca + 2\ qz = 5\ dp + 3\ CO_2 + H_2O$

(7) $6\ qz + 3\ ca + phl_{(bi)} = 3\ dp + Ks + 3\ CO_2 + H_2O$

(8) $2\ dp + phl_{(bi)} + 4\ qz = tr_{(act)} + Ks$

(9) $6\ cz_{(ep)} + tr_{(act)} + 2\ qz = 5\ dp + 9\ an_{(pl)} + 4\ H_2O$

The distribution of these isograds is shown on Figure 9.

The ca-act isograd, based on reaction (5), marks the first appearance of actinolite. It is constrained north and south of Loki Creek by two occurrences of the assemblage qz-dol-act-ca, and to within 1.5 kilometres in the southern part of the area by three occurrences of the reactant assemblage qz-dol and 11 occurrences of the product assemblage ca-act.

The diopside isograd, based on reaction (6), is closely constrained throughout the Riondel area by seven occurrences of the assemblage act-ca-qz-dp, 12 occurrences of the reactant assemblage, and 40 occurrences of the product assemblage. The diopside isograd also delineates four north-trending elongate zones of retrograde alteration within higher grade areas to the west. These zones are defined by the occurrence of the assemblage act-ca-qz-dp, in which the actinolite commonly occurs rimming diopside grains (Plate VIII). Locally within these retrograde zones, the diopside is completely replaced by the lower grade ca-act-qz assemblage.

*act — actinolite; an — anorthite; ca — calcite; cz — clinozoisite; dol — dolomite; dp — diopside; ep — epidote; phl — phlogopite; pl — plagioclase; tr — tremolite.

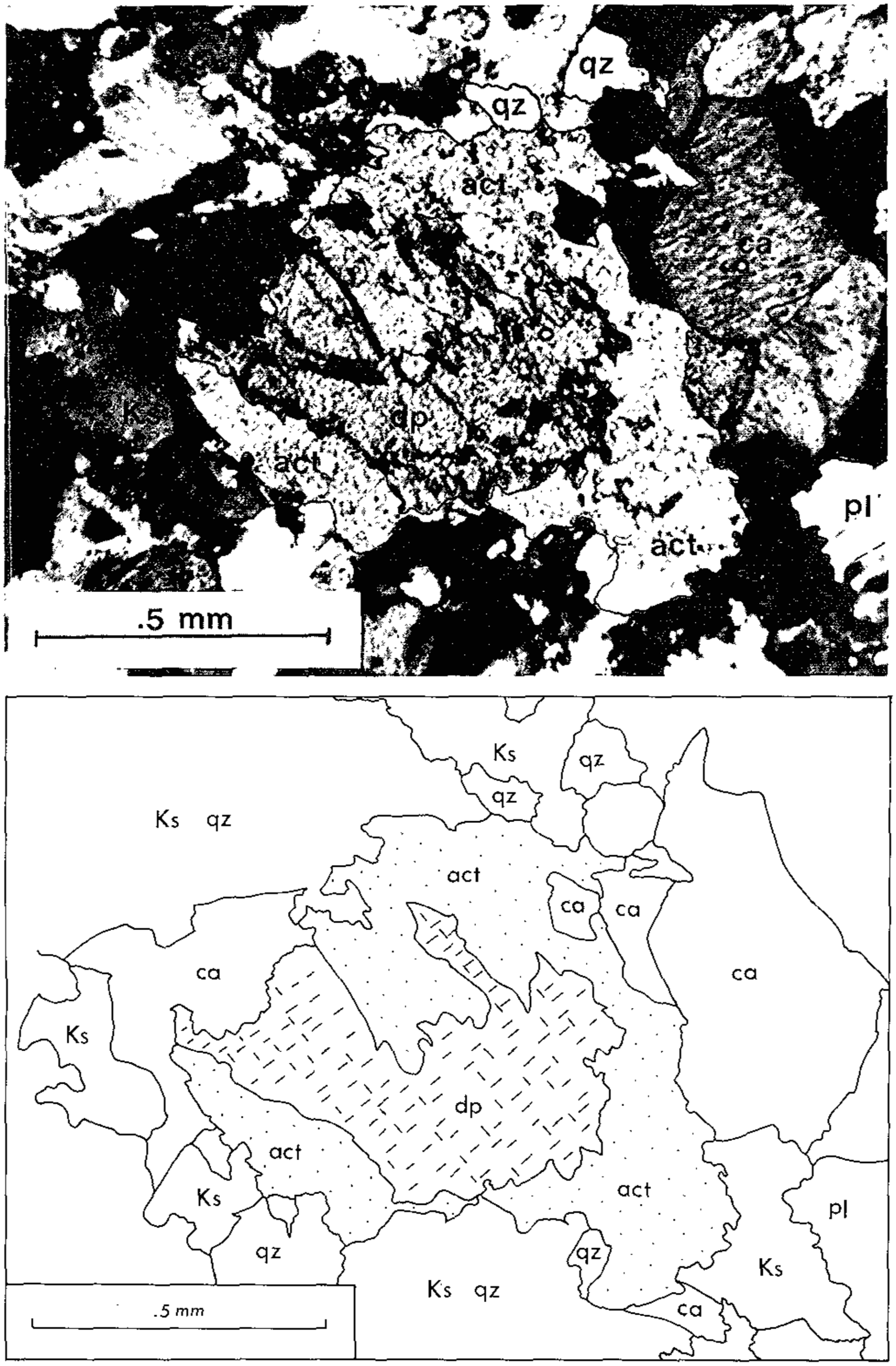


Plate VIII. Photomicrograph of a diopside grain (dp) rimmed by actinolite (act). Microcline (Ks), quartz (qz), and calcite (ca) are also visible.

A plot of all occurrences of the reactant and product assemblages of (7) locates the dp-Ks isograd. The isograd is defined south of Loki Creek by two occurrences of the assemblage ca-bi-qz-dp-Ks. The most northerly of these also contains actinolite and is therefore a field occurrence of the invariant assemblage (Höy, 1976). The dp-Ks isograd also defines a metamorphic 'high' that intersects the diopside isograd in the Mount Loki area and hence locates two additional field positions for the ca-bi-qz-Ks-act-dp 'invariant' point (Höy, 1976).

The Ks-act isograd (Fig. 9) is based on solid-solid reaction (8). The product assemblage Ks-act is common throughout the area; the reactant assemblage is located only north of Riondel (in nine places). The complete assemblage dp-bi-qz-Ks-act is common throughout the area to the west of the isograd, perhaps due to retrograde alteration or to partitioning of additional components between phases; the equilibrium constant of a solid-solid reaction is very sensitive to slight changes in the activity of components in the participating phases. The isograd has therefore been defined as the first appearance of the product assemblage Ks-act.

The reactant and product assemblages of reaction (9) overlap a wide range of grade and the complete five mineral phase assemblages are common. This reaction is not defined at a specific surface line or trace, but rather occurs over a wide zone suggesting that a component is strongly partitioned between one or more of the minerals. A study of the compositions of plagioclase in the ep-act-qz-dp-pl assemblage indicates that the anorthite component in the plagioclase increases with increasing metamorphic grade (Fig. 9).

PHYSICAL CONDITIONS OF METAMORPHISM

The distribution of calc-silicate isograds and the systematic variation in plagioclase compositions is best explained with the aid of a phase diagram that relates the metamorphic variables, temperature and gas composition. The diagram, illustrated on Figure 10, is calculated at 5 000 bars pressure. This estimate of confining pressure during regional metamorphism is based on the following data:

(1) an estimate of 5.5 kilobars and 625 degrees centigrade from experimental data on reactions defining the pelitic isograds in the Riondel area (*see* p. 41).

(2) a minimum pressure estimate of 4 700 bars calculated by Jones (1972) from a metamorphic assemblage observed in the Ainsworth-Kaslo area on the west side of Kootenay Lake.

Metamorphic reactions that involve a gas phase (CO_2 or H_2O) plot as curves on a $T-X_{CO_2}$* diagram, indicating the effect that variable gas composition has on the reaction. Reaction (9) is contoured according to the percentage of anorthite in plagioclase.

*P — pressure (bars); Pf — fluid pressure (bars); P_{H_2O} — partial pressure of H_2O; T — temperature (°C); Xi — mole fraction of species i.

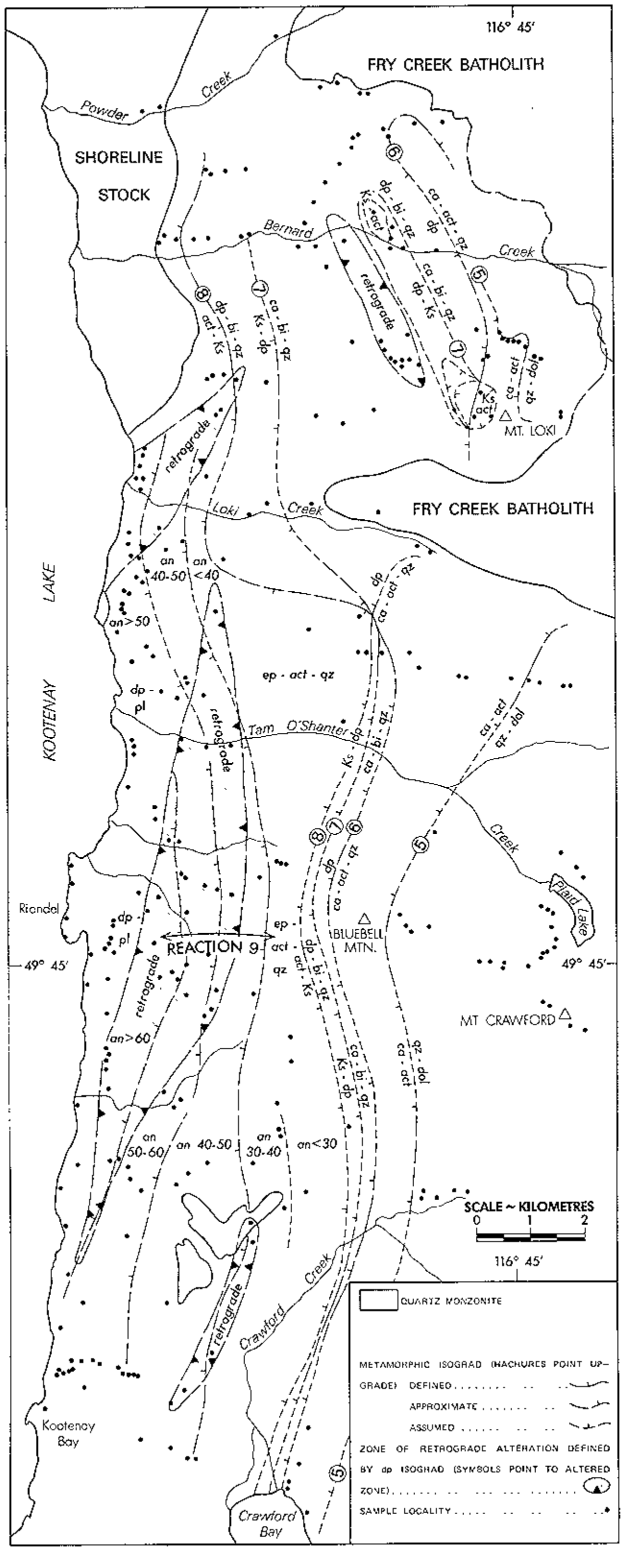


Figure 9. Distribution of calc-silicate isograds in the Riondel area. The grade of regional metamorphism increases toward the west.

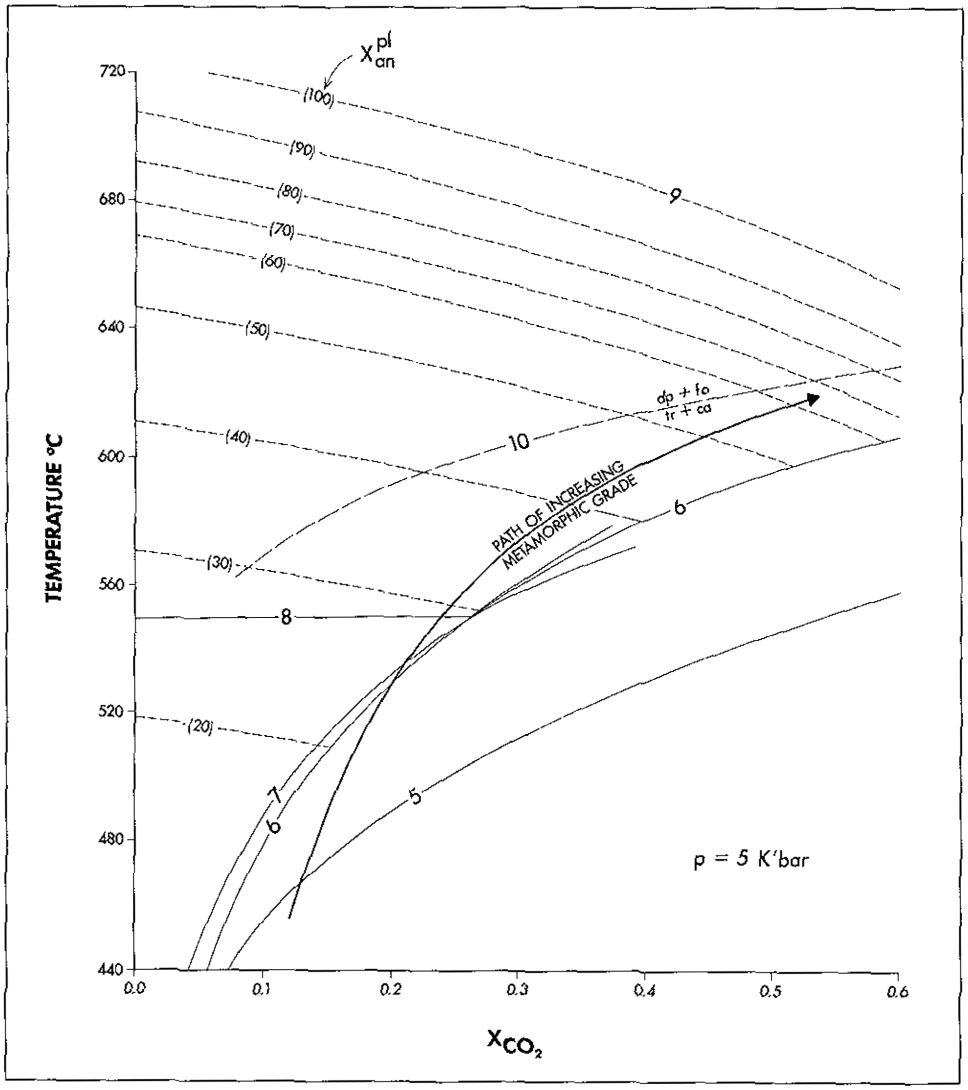


Figure 10. A temperature-gas composition phase diagram that includes reactions that define calc-silicate isograds in the Riondel area (*see* page 41). X_{an}^{pl} refers to the anorthite component in plagioclase in reaction (9). Reaction (10) marks the first appearance of forsterite in regionally metamorphosed marbles: 4 tremolite + 5 calcite = 11 diopside + 2 forsterite + 5 CO_2 + 3 H_2O.

Comparison of Figures 9 and 10 provides an estimate of the distribution of T and X_{CO_2} at the time of metamorphic quenching. In the lower grade areas, below the Ks-act isograd, the fluid phase was rich in H_2O ($X_{CO_2} < 0.25$). With increasing grade, plagioclase in the assemblage ep-act-qz-dp-pl becomes increasingly anorthite-rich. Plagioclase compositions above An_{60}, and below the stability field of olivine [reaction (10)], are stable at temperatures above approximately 600 degrees centigrade and X_{CO_2} values approximately equal to 0.5 to 0.6 (Fig. 10). (Olivine was not encountered in the present study.) This temperature estimate is lower than the estimate of 625 degrees centigrade based on the 'invariant' pelitic assemblage located at the northwest end of Crawford Bay. If a higher pressure were used in calculating the grid, closer to the 5.5 kilobars estimate based on the pelitic assemblage, the temperature discrepancy between the calc-silicate estimate and the pelitic estimate would decrease as the temperature of dehydration and decarbonation reactions increases with increasing pressure.

The regional metamorphic grade in the Riondel area increases from the qz-dol and gt-chl-bi 'zones' in the east to a zone along the shoreline of Kootenay Lake where sillimanite and K-feldspar coexist. Pressures in excess of 5 kilobars and temperature above 620 degrees centigrade during the regional metamorphism are indicated by the bi-gt-ky assemblage identified at the head of Crawford Bay. Extensive retrograde alteration in the western part of the Riondel area probably results from 'de-gassing' of syntectonic granitic stocks, sills, and dykes during cooling from the peak of the regional metamorphic temperatures.

The Riondel area is within the central part of an elongate, north/south-trending metamorphic culmination. The metamorphic grade decreases rapidly from a central sillimanite-K-feldspar zone along the west shore of Kootenay Lake to 'garnet grade' approximately 8 kilometres to the east and west. North of the Riondel area, metamorphic zones form an 'arrow-shaped pattern on the map that broadens southward and narrows to a point near the head of Duncan Lake' (Reesor, 1973, p. 98). The 'staurolite' and 'staurolite-kyanite' zones extend to approximately 8 kilometres north of the north end of Kootenay Lake, and the 'garnet-biotite-muscovite' zone to Duncan Lake, 70 kilometres north of Riondel (Fig. 5). Very limited data indicate that the grade also decreases southward from the Riondel area along the axis of the metamorphic high; the sil-Ks zone on the east shore of Kootenay Lake (Fig. 5) was not recognized by Crosby (1968) to the south, suggesting that the highest grade of regional metamorphism in the central Kootenay Arc occurs in the southwestern part of the Riondel area.

4

STRUCTURE

INTRODUCTION

The structure of the Riondel area can be interpreted in terms of three phases of deformation on the basis of interference and crosscutting relationships and, more tenuously, on the form of individual structures and their relationships to individual mineral species (Table 7). The most conspicuous structures are a set of very tight to isoclinal folds with subhorizontal axes and steeply west-dipping axial surfaces (Phase 2). These folds are imposed on a stratigraphic succession which is overturned and represents the underlimb of the large westward-closing, Phase 1 Riondel nappe. The latest discernible deformation (Phase 3) caused faulting and gentle folding of the earlier structures. The Sherraden Creek fold is the only Phase 3 fold large enough to be shown on the map (Fig. 4, in pocket).

Two west-dipping faults that parallel the regional foliation and transect the entire area from south to north are inferred to be reverse faults. To the east of the faults the stratigraphic succession is right-side-up and Lardeau rocks form synclines in older Hamill rocks; to the west, as mentioned above, the succession is inverted.

Two north-trending faults cut the Lower Hamill rocks east of the reverse faults. The faults are steep, and, although locally parallel with the bedding, cut up-section to the north. They appear to be late normal faults, but the magnitude of the displacement on them is not known. Steeply dipping, southeast-trending faults with small right-lateral displacements are conspicuous just north of Crawford Peninsula. They cut all other structures.

MESOSCOPIC FABRIC ELEMENTS

The main fabric elements in the area are a compositional layering which appears to represent bedding (S_0) that has been accentuated by metamorphic differentiation, a penetrative mineral foliation (S_2) that is parallel to the axial surfaces of isoclinal Phase 2 folds and is subparallel to the compositional layering except in the hinge zones of Phase 2 folds, and a mineral lineation (L_2) that is parallel to the hinge lines of Phase 2 folds and to the intersection of S_0 and S_2.

TABLE 7. CHARACTERISTICS OF THE PHASES OF DEFORMATION

F	Minor Structures			Major Structures	
	Foliation	Lineation	Minor Folds	Folds	Related Faults
1	not recognized	not recognized	rootless, isoclinal folds; generally not distinguishable from Phase 2 folds	westward-closing recumbent anticline, the Riondel nappe	none recognized
2	S_2 – preferred dimensional orientation of platy minerals; mineral segregations	L_2 – alignment of elongate minerals; augen structures; elongate boudins	tight to isoclinal; S_2 parallel to axial planes; L_2 parallel to fold axes	most conspicuous structures, from west to east– Crawford antiform Bluebell Mountain synform Preacher Creek antiform Loki West anticline Loki syncline Loki East anticline	west-dipping reverse faults including the West Bernard fault and the East Bernard fault
LATE STRUCTURES	S_3 – axial plane jointing; crenulation cleavage	L_3 – intersection of S_2 and crenulation cleavage	open, southwest-plunging upright folds	Sherraden Creek fold, a southwest-plunging antiform/synform pair	high-angle, northeast-trending lineaments (faults ?), transecting north/south structural grain eastern normal faults; western late faults

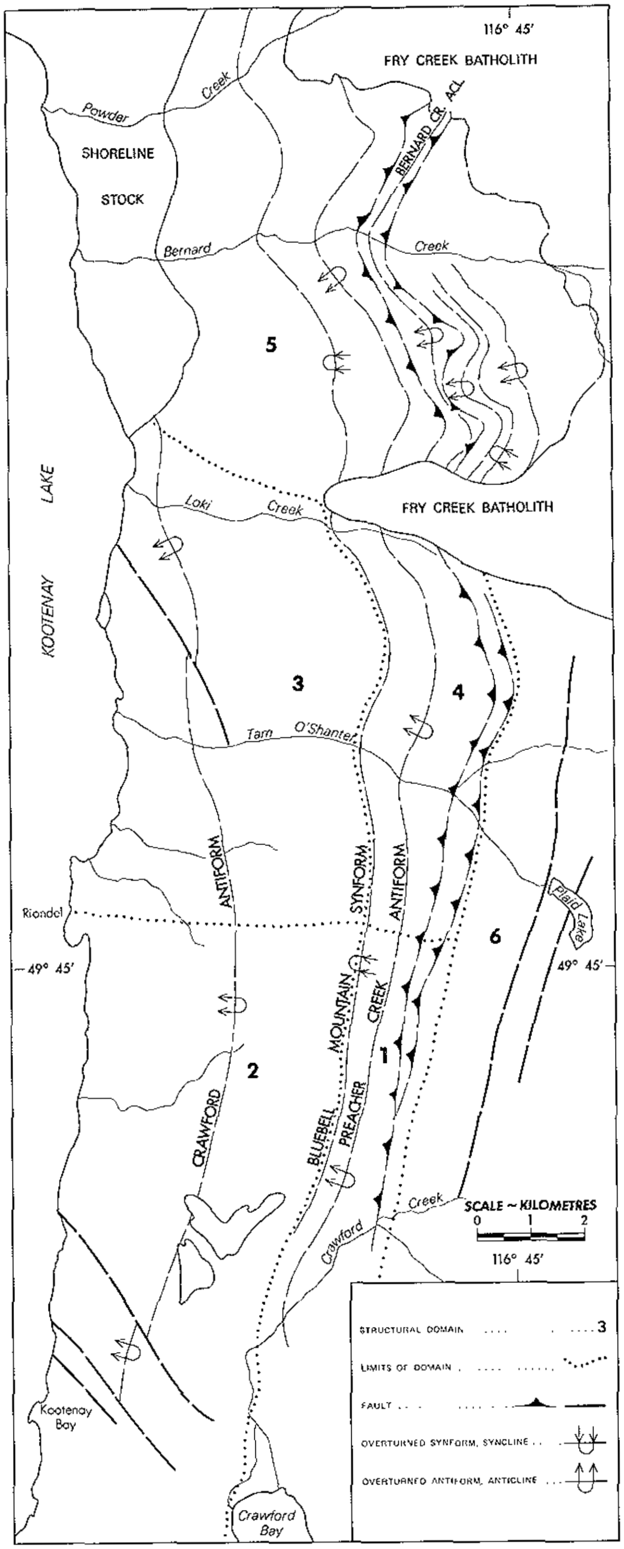


Figure 11. Structural domains in the Riondel area.

The area has been divided into six structural domains, each of which includes a major Phase 2 fold or a number of Phase 2 folds and is statistically homogeneous with respect to the orientation of S_2 foliations or L_2 mineral lineations. Domains 1 and 4 (Fig. 11) include the hinge zone and limbs of the Preacher Creek antiform; domains 2 and 3, the Crawford antiform. The northern third of the area is within domain 5, an area largely underlain by quartz monzonite intrusions, and the low grade and least deformed southeastern part of the area is within domain 6. In general, the S_2 foliation changes in strike from north/northeast in the southern domains (1 and 2) to north/northwest in the more northern domains (3, 4, and 5). S_2 dips to the west in the western domain and steepens through the vertical and becomes east-dipping east of the East Bernard fault (domain 6). L_2 generally plunges at a low angle to the north although locally it plunges gently southward. It trends north to north/northeast in the more eastern domains and north/northwest in the western domains.

BEDDING AND COMPOSITIONAL LAYERING (S_0)

Bedding in Hamill and Mohican rocks consists of interlayering of quartzites, schists, marbles, and calc-silicate rocks. Lithological layering, which appears to be bedding accentuated by metamorphic differentiation, is readily discernible in the calc-silicate gneiss unit (L3iv) of the Lardeau Group. In this unit, thin calc-silicate layers less than a centimetre to several centimetres in thickness commonly separate amphibolite and marble layers. In a similar manner, amphibolite may separate calc-silicate layers from schist layers.

Compositional layering in the Riondel area shows a strong preferred orientation striking approximately north and dipping west at 35 degrees (Fig. 12A), essentially parallel with that for the S_2 foliation (Fig. 12B). In domains 1, 2, 3, and 5, S_0 is statistically parallel with S_2 (compare Figs. 13 and 14), whereas in domains 4 and 6, where the metamorphic grade is lower, poles to S_0 define girdles about axes plunging northeast or south at low angles, parallel with the mineral lineations in these domains (compare Figs. 13 and 15).

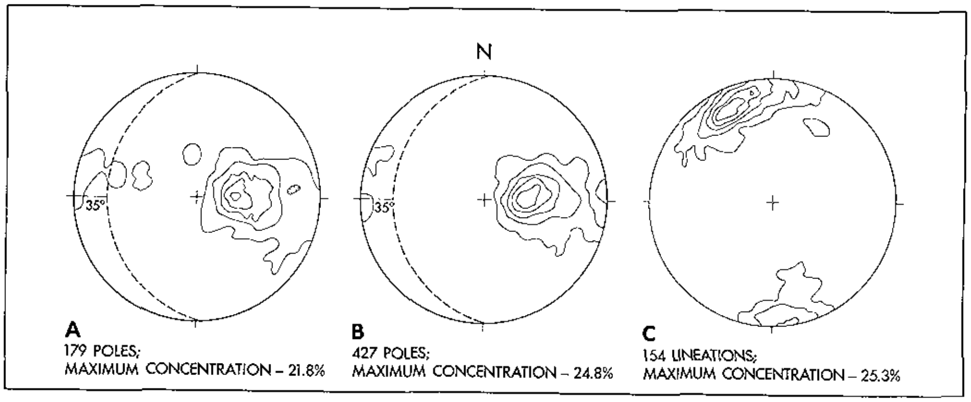


Figure 12. Equal-area projection from the lower hemisphere of: (A) poles to layering; (B) poles to foliation; and (C) mineral lineations. Contour intervals – 1 per cent, 5 per cent, 10 per cent, 15 per cent, and 20 per cent.

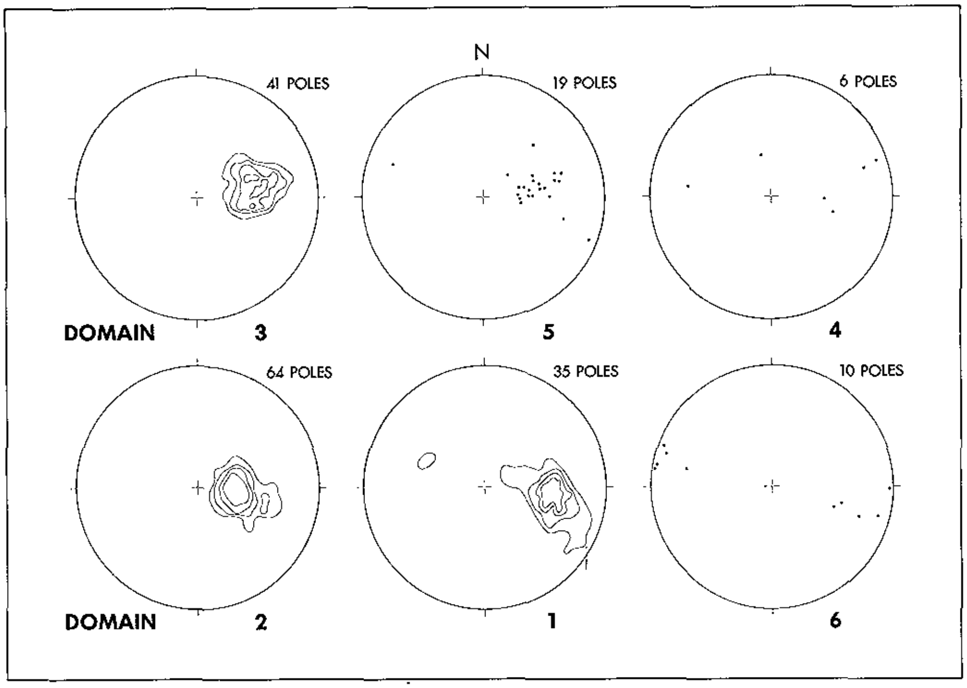


Figure 13. Equal-area projection from the lower hemisphere of poles to layering (S_0); contours — 5 per cent, 10 per cent, 15 per cent, and 20 per cent.

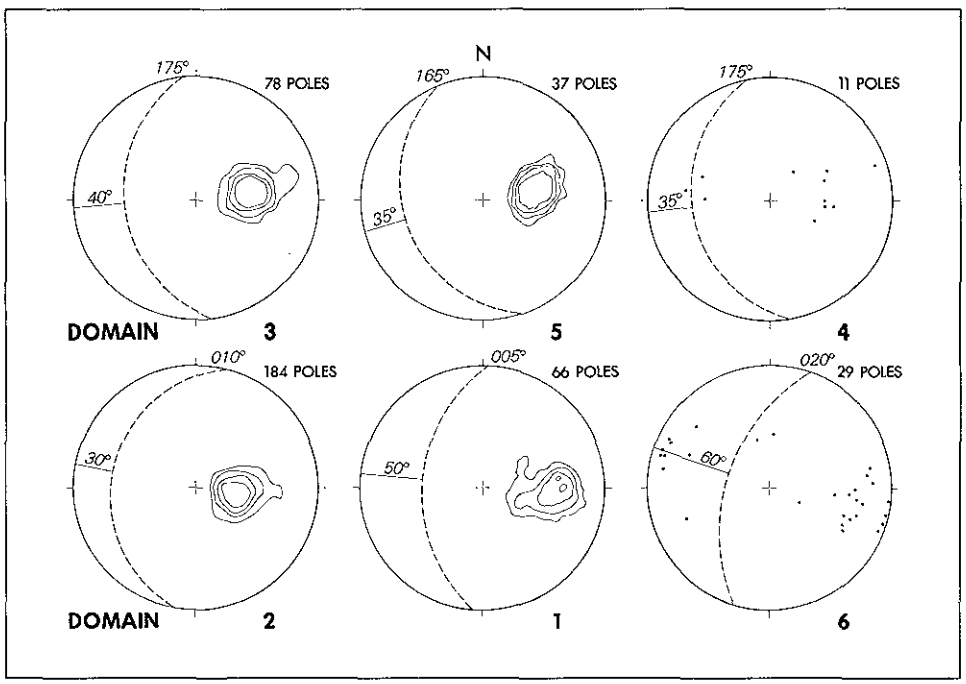


Figure 14. Equal-area projection from the lower hemisphere of poles to foliation (S_2); contours — 5 per cent, 10 per cent, 15 per cent, and 20 per cent.

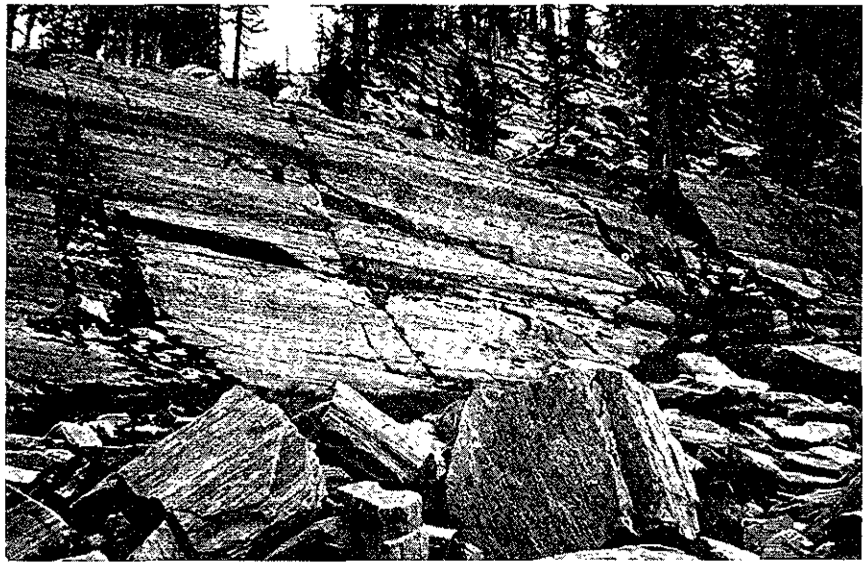


Plate IX. South-plunging lineations (L_2) in Lower Hamill quartzite (unit H1i), east of Mount Crawford.

Plate X. Tight Phase 2 minor fold in impure Hamill Group quartzite, Mount Crawford area.

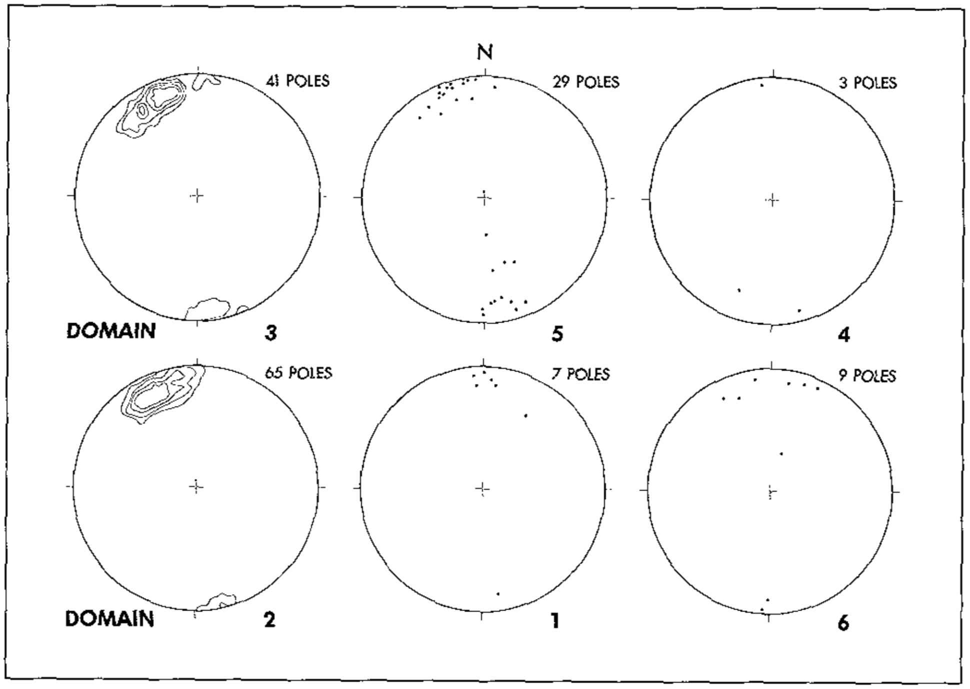


Figure 15. Equal-area projection from the lower hemisphere of mineral lineations; contours — 5 per cent, 10 per cent, 15 per cent, and 20 per cent.

FOLIATION (S_2)

Most rocks in the area have a well-developed penetrative foliation, S_2, which is due to a preferred orientation of platy minerals and augen-like lenticular segregations of quartz, microcline, or plagioclase. In rocks in which these augens are abundant, they may be joined to form thin (less than 0.5 centimetre thick) monomineralllic (most commonly of quartz) discontinuous layers. Alignment of phlogopites and some of the actinolites defines S_2 in calcareous rocks. In schists, S_2 is due to the alignment of micas and chlorites. Quartz grains in quartzites in areas of lower metamorphic grade are elongate parallel to S_2; in higher grade areas, only the rare micaceous partings define S_2.

S_2 is parallel to the axial planes of many tight to isoclinal Phase 2 minor folds. It parallels the compositional layering in the limbs of these folds and cuts the layering at a shallow angle in the hinge zones (*see* Plate XI).

S_2 generally dips to the west throughout the area, although in the eastern domains it becomes more variable and locally may steepen through the vertical to east dipping. The general curvature of the Kootenay Arc in the Riondel area is reflected by a change in trend of S_2 from north/northeast south of Riondel (domains 1 and 2) to northerly east of Riondel (domains 3 and 4) and north/northwesterly further north (domain 5). The more westerly trend of S_2 in the north is accompanied by a flattening of dips.

Plate XIA. Phase 2 minor fold showing intersection of axial surface foliation (S_2) and layering (S_0) in hinge zone, unit H4, Hamill Group, Riondel Peninsula; down plunge, viewed to the north.

Plate XIB. Phase 2 minor fold showing intersection of axial surface foliation (S_2) and layering (S_0) in hinge zone, unit H4, Hamill Group, Riondel Peninsula; detail of fold nose.

LINEATIONS (L_2)

A penetrative mineral lineation (L_2) is defined by a preferred orientation of elongate amphibole grains, actinolite needles, elongate augen in calc-silicate rocks, elongate clusters of micaceous minerals in various rock types, and rodding in quartzites (Plate IX). It is most conspicuous in the well-foliated rocks. It generally plunges at low angles to the north (Figure 12C) parallel with the hinge lines of Phase 2 folds (Fig. 16). South of the Riondel area, deformed cobbles in conglomerates of the Horsethief Creek Group have their long axes aligned with the mineral lineation and fold hinges (M. G. Lis, 1974, personal communication) suggesting that this is the direction of maximum finite elongation.

The orientation of L_2 varies only slightly across the map-area (Fig. 15). In the north (domain 5) it trends north/northwest and is essentially horizontal. Further south (domains 2 and 3), it trends more westerly, plunging at low angles toward the northwest. Further east (domains 1, 4, and 6), fewer measurements are available but the lineations appear to trend more northerly and to be essentially horizontal.

MINOR FOLDS

Tight to isoclinal Phase 2 minor folds are fairly common (Plates X and XI). Their morphology and orientation are similar to those of megascopic Phase 2 folds and their vergence, where determined, most commonly indicate that they are congruent with the megascopic folds. Most are rootless, consisting of an appressed hinge zone with very extended and separated limbs, and with the compositional layering entirely transposed into the foliation plane, even in the hinge zone.

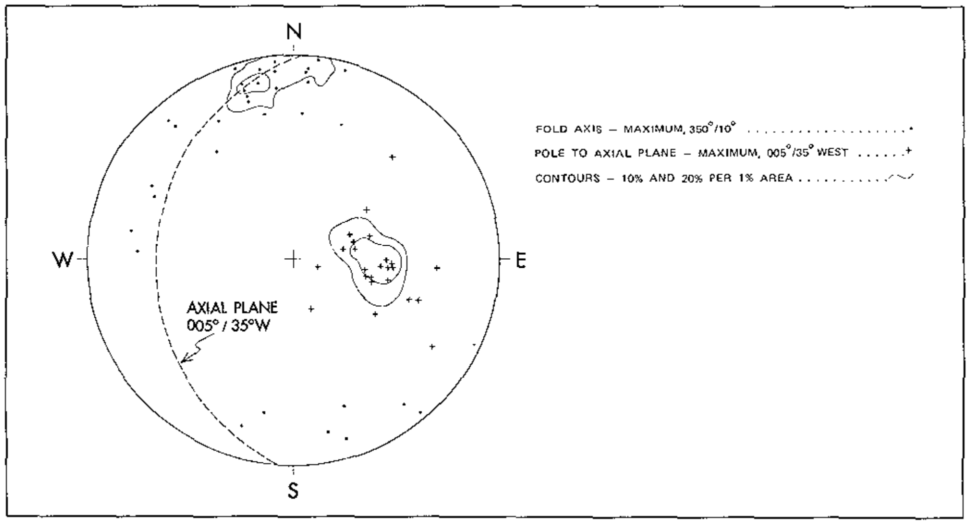


Figure 16. Phase 2 minor folds, all domains; equal-area projections from the lower hemisphere.

In general, the folds plunge at shallow angles to the north/northwest and their axial planes strike northerly and dip to the west (Fig. 16).

BOUDINS

Boudinage is common throughout the area. The short axes of boudins are invariably perpendicular to S_2 and their long axes are generally parallel with L_2. Amphibolites commonly form boudins in less competent marbles, calc-silicates, and schists (Plate XII). Pegmatite bodies emplaced in the plane of the foliation show varying stages of boudin development; some appear unaffected, some have a pinch-and-swell structure, while others have been separated into widely spaced boudins.

From measurements of boudin separations, a minimum estimate of finite strain in the plane of the bedding (S_0) has been obtained on the west limb of the Crawford antiform, just west of the contact of units L3 and L4 (for method *see* Ramsay, 1967, p. 80). The maximum elongation in the plane of the bedding is toward 330 degrees, roughly parallel with the preferred orientation of mineral lineations. Furthermore, all directions within the plane of the bedding have undergone extension, which necessitates a large component of flattening perpendicular to S_0.

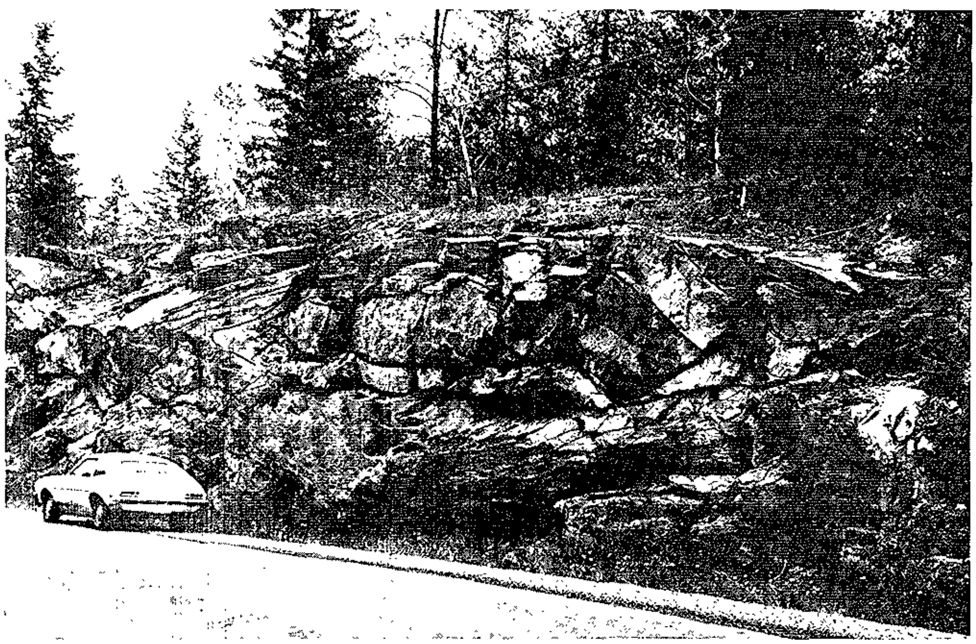


Plate XII. Large amphibolite boudin in biotite gneiss (unit L4), just east of the Riondel road junction on Highway 3.

PHASE 2 FOLDS

Large Phase 2 folds dominate the structure of the area. The folds are characteristically tight to isoclinal with attenuated limbs and complex hinge zones. They are overturned to the east with axial surfaces dipping moderately to steeply to the west and hinge lines generally plunging at low angles to the north or south. Individual Phase 2 folds can be traced readily from Crawford Bay in the south to the northern part of the area where they are truncated by the Fry Creek batholith. West of the West Bernard fault, Phase 2 folds are developed in an inverted panel of rocks and have been named, from west to east, the Crawford antiform, the Bluebell Mountain synform, and the Preacher Creek antiform (Fig. 11). East of the West Bernard fault, Phase 2 folds have developed in a right-side-up sequence of rocks. These include the Bernard Creek anticline, the Loki West anticline, the Loki syncline, and the Loki East anticline.

CRAWFORD ANTIFORM

The youngest rocks within the map-area, unit L4, are exposed in the core of a fold on the west slope of Bluebell Mountain. Hamill Group rocks are exposed in its west limb on Riondel Peninsula and in its east limb in the Bluebell Mountain area. North of Loki Creek, only the east limb is exposed; the Shoreline stock occupies its core.

The hinge zone of the Crawford antiform consists of a set of very tight folds in the layering over a width of several hundred metres. The layering has been entirely transposed into the plane of axial plane foliation, and the recognition of individual fold hinges in the hinge zone is difficult. The contact between units L3 and L4 is marked by an interval of extensive interlayering of both units with the proportion of unit L4 gradually increasing toward the core. The contact on the map (Fig. 4, in pocket) is placed at the last recognizable outcrop of unit L3 toward the core. Similarly, the extensive interlayering of marbles and calc-silicates north of Tam O'Shanter Creek results from extensive infolding of units L3iii and L3iv in the hinge zone of the tightly appressed Crawford antiform.

Northward, the antiform becomes tighter, trends more westerly, and its axial plane steepens. South of Riondel (Fig. 17B), it has an interlimb angle of about 25 degrees and its axial plane strikes just east of north (approximately 005 degrees) and dips west at 30 to 40 degrees. North of Riondel (Fig. 17A), the interlimb angle is less than 10 degrees, the axial plane trends just west of north (approximately 350 degrees) and has steepened to 40 degrees. North of Loki Creek, only the east limb is exposed; the Shoreline stock occupies the core of the antiform; layering (S_0) and foliation (S_2) are virtually parallel, striking approximately 345 degrees and dipping west at 25 to 35 degrees.

Mineral lineations, parallel with the fold axis, generally plunge at 10 to 20 degrees toward the north/northwest. To the west, these lineations progressively trend more westerly. On Crawford Peninsula, the antiform plunges southwesterly and lineations, though very scattered, generally trend southwesterly (M. G. Lis, personal communication, 1974). This curvature in the orientation of L_2 defines a local doming that coincides with the regional metamorphic culmination. Within the metamorphic culmination, west-dipping Phase 2 structures (minor folds, S_2, and the axial plane of the Crawford antiform) all dip less steeply while linear elements (lineations and fold axes) have a more westerly trend.

Phase 2 minor folds usually consist only of a single hinge zone with sheared out limbs and therefore their vergence cannot generally be determined and used to indicate the closure of the Crawford antiform. The evidence that indicates that the fold is actually an antiformal structure and hence must have developed in an inverted sequence of rocks (as the youngest rocks are exposed in its core) is summarized below:

(1) The fold closes northward and mineral lineations which parallel axes of Phase 2 folds generally plunge north.
(2) The adjacent fold immediately to the east is a synformal structure (the Bluebell Mountain synform).

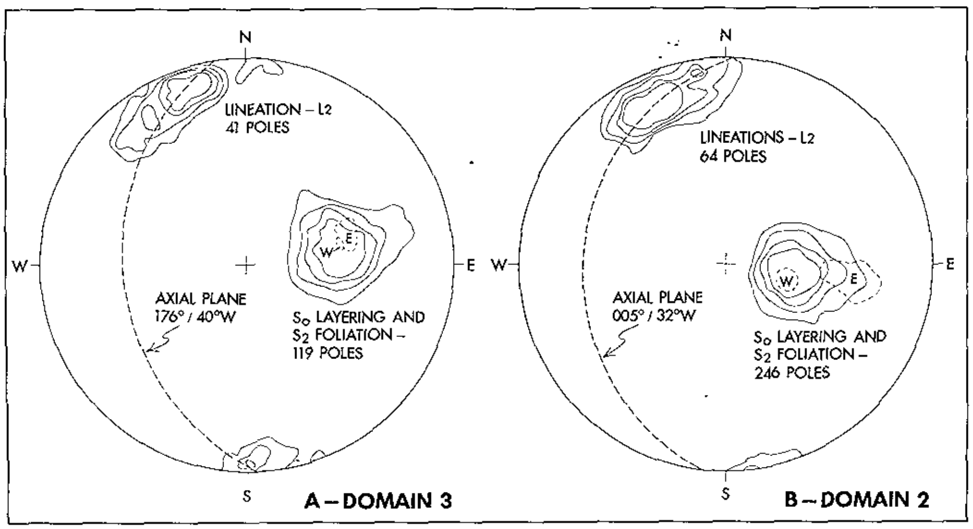


Figure 17. Structural elements of the Crawford antiform in domains 2 and 3; equal-area projections from the lower hemisphere.

BLUEBELL MOUNTAIN SYNFORM

The Bluebell Mountain synform is continuous the entire length of the map-area (approximately 30 kilometres). Hamill rocks are exposed in its core over most of its length and younger Badshot and Index rocks in its limbs. On the southeast-facing cliff north of Crawford Creek, Badshot marble in its core closes southward in the opposite direction of plunge of mineral lineations and axes of Phase 2 minor folds, indicating that the fold is a synform. Furthermore, minor folds in Badshot marble on its limbs (two of these are large enough to be shown on section B-B', Fig. 4, in pocket) have the correct sense of vergence for minor folds on the limbs of a synform.

The fold generally plunges to the north at angles less than 20 degrees. However, there is a culmination in the crest line just north of Crawford Bay and at the northwest head of the bay two Badshot horizons have been mapped (Fig. 4) indicating that the synform opens southward and hence must plunge south. Both limbs dip west over its entire length with a decrease in dip north of Tam O'Shanter Ridge, perhaps due to a 'bowing-up' effect of the intrusion of the underlying Fry Creek batholith (Fig. 4, section A-A').

Structures within the core of the synform are complex. A rootless, tightly appressed layer of Badshot in a thickened Mohican section (Plate XIII and Fig. 4, section B-B') is an antiform pinched off during folding. Just east of this structure, Mohican rocks appear to be in fault contact with Middle Hamill rocks (unit H2), and in the core on Loki Ridge massive quartzite layers may be fault or fold repetitions of unit H3.

Plate XIII. Appressed nose of a Phase 2 (?) antiform within the Bluebell Mountain synform on Tam O'Shanter Ridge; view to south. Note offset on a west-dipping reverse fault.

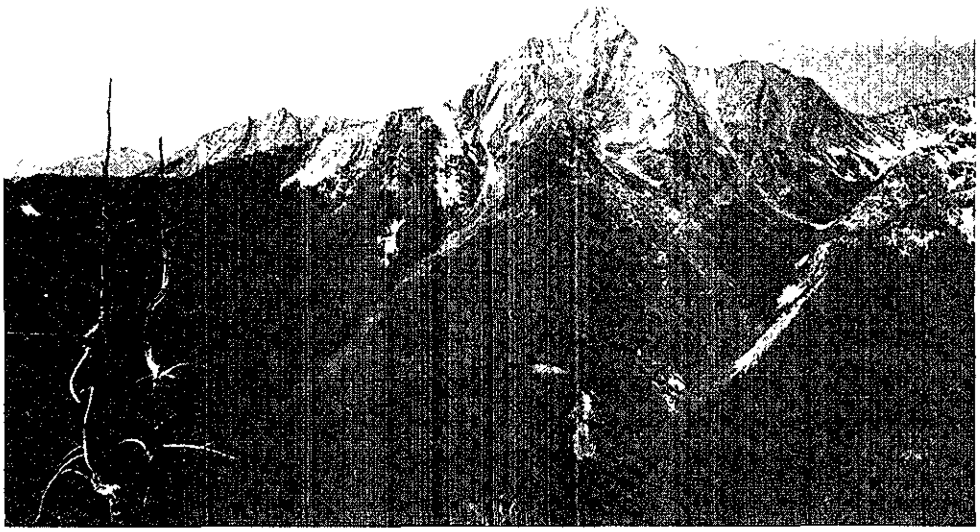


Plate XIV. Mount Loki, viewed from the south. Fry Creek batholith is exposed east of the peak. Details of the geology of the ridge north of Mount Loki are shown in Plate XV.

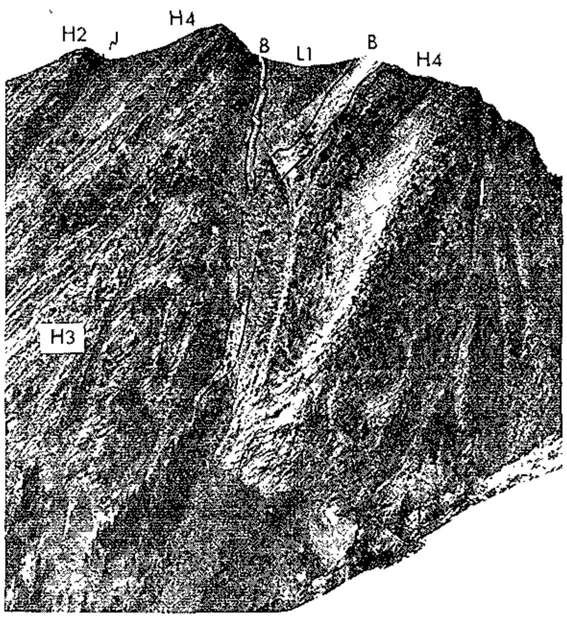


Plate XV. The Loki syncline with Lower Lardeau (L1) in its core, and the Loki West anticline exposed on the ridge just north of Mount Loki, viewed from the south. The fault west of the anticline, the East Bernard fault, is a west-dipping reverse fault that here juxtaposes unit H2 of the Hamill Group on younger Hamill rocks (unit H4).

PREACHER CREEK ANTIFORM

The Preacher Creek antiform is a tight, overturned, eastward-closing antiform, plunging north or south at low angles (Fig. 15, domains 1 and 4). Lower Lardeau rocks (units L1 and L2) are exposed in its core and Upper Hamill in its limbs indicating that the fold is an antiformal syncline.

On Tam O'Shanter Ridge, the east limb of the antiform is inferred to have been cut by a west-dipping reverse fault with a dip separation approaching 1 000 metres (Fig. 4, section B-B'). The fault dies out to the north and south, its displacement accommodated by attenuation of the east limb. It is believed to have developed synchronously with the Phase 2 folding.

FOLDS BETWEEN THE PREACHER CREEK ANTIFORM AND THE WEST BERNARD FAULT

A synform and antiform are outlined by Badshot and Lardeau rocks just east of the Preacher Creek antiform along Bernard Creek (Fig. 4, section A-A'). On Tam O'Shanter Ridge (section B-B'), a thickened section of Badshot marble flanked on both sides by Upper Hamill rocks is interpreted to be the highly appressed hinge of the antiform. The fold was not recognized on Bluebell Mountain Ridge (section C-C'). There, the hinge at the level of the Badshot Formation may be below the level of exposure. Massive white Badshot marble that occurs just south of the Crawford Creek road is also flanked on both sides by Upper Hamill quartzites and schists (unit H3) and may represent the hinge of the same antiformal syncline. If so, the crestline of the antiform must reach a culmination in the vicinity of Tam O'Shanter Ridge, plunging north at approximately 5 degrees north of the ridge and plunging south, south of the ridge.

FOLDS EAST OF WEST BERNARD FAULT

Several conspicuous folds east of the West Bernard fault in the Mount Loki area (Plate XIV) are tight, easterly verging, overturned folds with tightly appressed hinge zones. At Mount Loki, Badshot marble and Lardeau schist form the core of a syncline and Hamill quartzite forms the cores of anticlines. Thus, although these folds are aligned with the Phase 2 folds in the inverted panel west of the West Bernard fault, the succession of stratigraphic units in these folds shows that they involve a right-side-up structural panel.

The Bernard Creek anticline occurs between the west-dipping West Bernard and East Bernard faults. Hamill quartzites and schists are in its core and Badshot dolomite and Lower Lardeau amphibolite (unit L2) in its limbs.

Massive white quartzite of unit H3 outlines the anticlines east of the East Bernard fault. The Badshot marble, which occurs in the core of the Loki syncline just east of Mount Loki and on the ridge north of Mount Loki, outlines the long (400-metre) attenuated hinge of the syncline (Plate XV and Fig. 4, section A-A').

Southward from the Mount Loki area, successively lower stratigraphic levels are exposed (Fig. 18). For example, Lardeau rocks are exposed in the core of the Loki syncline at Loki Ridge, whereas only the Badshot limestone is exposed in this structure at Tam O'Shanter Ridge and only Hamill rocks at Bluebell Mountain Ridge. The Loki West anticline and the west limb of the Loki syncline are progressively truncated against the East Bernard fault southward from the Mount Loki area.

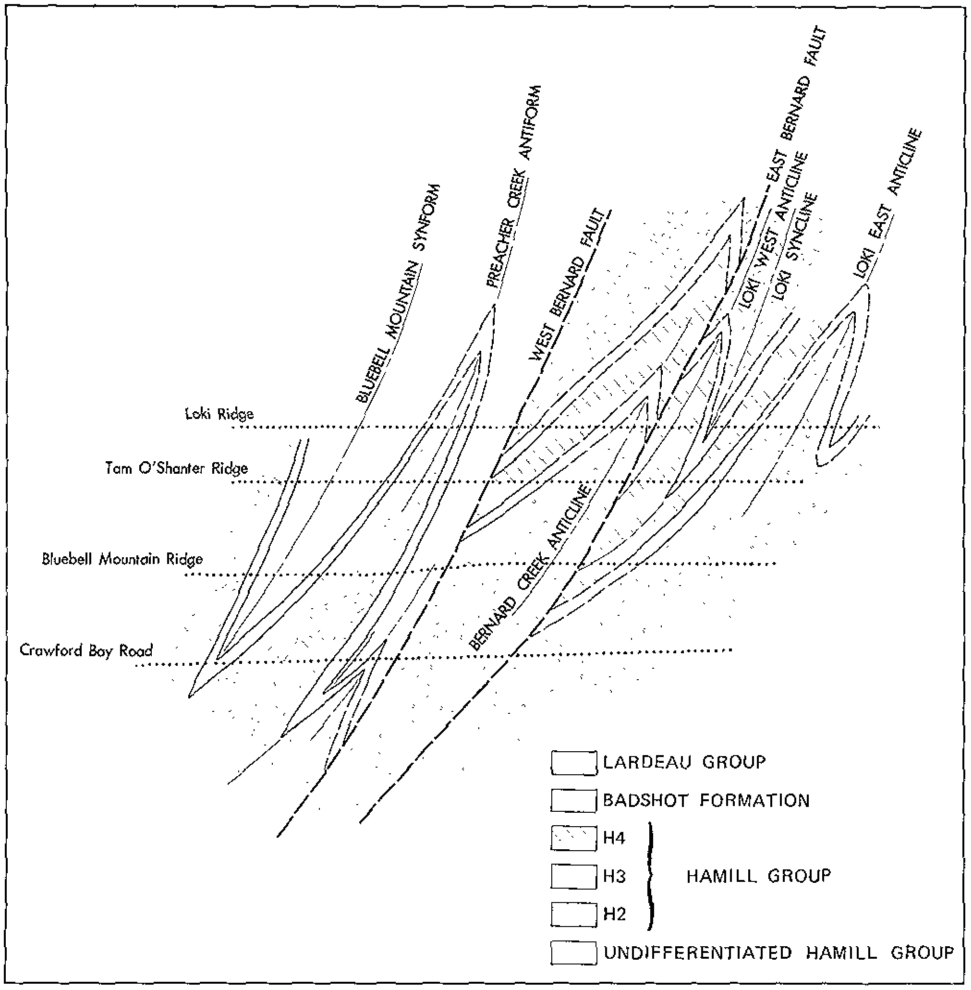


Figure 18. Schematic down plunge projection of Phase 2 folds on the east side of the West Bernard fault. Dotted lines show levels of exposure along various east-west sections.

The west-dipping section in the area around Plaid Lake (Fig. 4) extending along the Bluebell Mountain Ridge, extending from unit H3 to the Horsethief Creek Group in the east appears to be right-side-up and homoclinal with few structural complications other than late normal (?) faults. Large Phase 2 folds were not observed in the area; if they occur, they are restricted to individual units within the Hamill Group. Unit H3 is not repeated in the area and unit H1 and the Horsethief Creek Group outcrop only in the eastern part. Tight minor folds with axial plane foliation (S_2) are common, however. *In exposures of the Horsethief Creek Group along Crawford Bay road, the S_2 foliation* commonly cuts across the compositional layering at angles up to 20 degrees, indicating that the folds in this region are more open.

RIONDEL NAPPE

Phase 2 structures west of the West Bernard fault have developed in an inverted panel of Hamill, Badshot, and Lardeau rocks. This panel is interpreted by the author to be the underlimb of a recumbent anticline, the Riondel nappe (Fig. 19).

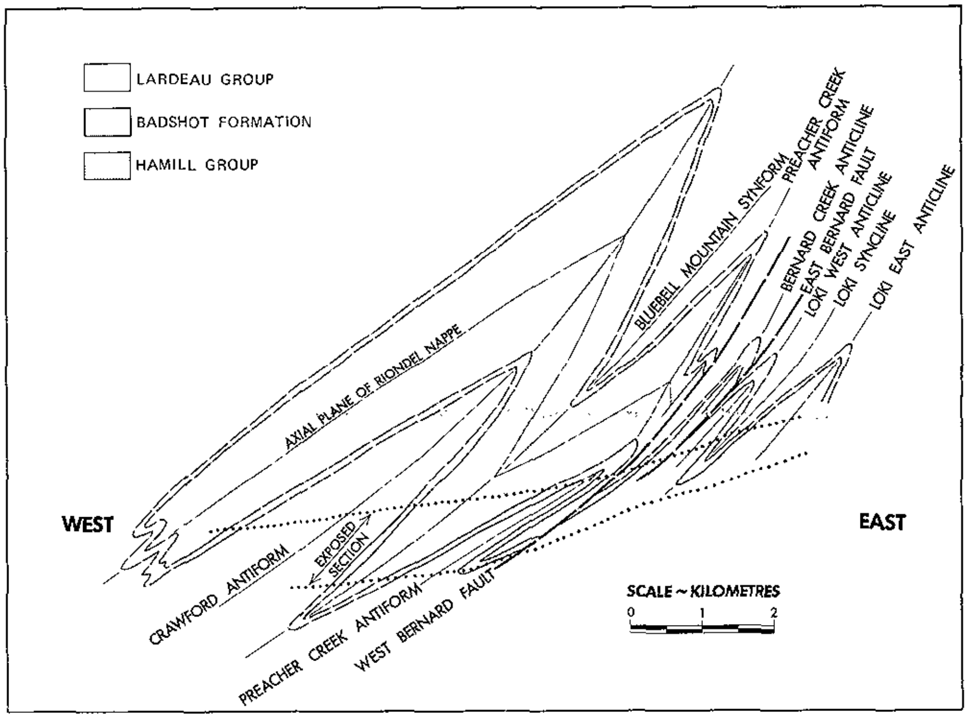


Figure 19. The Riondel nappe, a composite section.

The inverted limb of the Riondel nappe extends under Kootenay Lake in the west and is bounded on the east by the West Bernard fault. Consequently, determination of the direction of closure of the nappe is based primarily on comparison to similar nappe structures north of the Riondel area. In the Duncan Lake area, recumbent anticlines cored by Hamill Group rocks open in the east, are overturned to the west by Phase 2 folds, and close to the west (Fyles, 1964). Similarly, the Riondel nappe is interpreted to open (root) in the eastern part of the area, east of the West Bernard fault, and to close west of the most western exposure in the Riondel map-area. Hamill Group rocks on the west shore of Kootenay Lake north of Kaslo (Fyles, 1967) which are flanked on both sides by Badshot marble and Lower Lardeau phyllite may be part of the structurally complex synformal nose of the Riondel nappe. A large Phase 1 minor fold on the west limb of the Phase 2 Bluebell Mountain synform on Tam O'Shanter Ridge (Fig. 4, section B-B') provides additional evidence that the nappe closes to the west because the sense of rotation with this fold is opposed to that for the limb of the Phase 2 synform on which it occurs but compatible with the underlimb of a westward-closing nappe.

It is possible that the Riondel nappe is the southern extension of the Meadow Creek anticline (Fyles, 1964) of the Duncan Lake area. The Meadow Creek anticline closes on the west shore of Kootenay Lake and is rooted on the east shore. It plunges at a low angle to the north and hence a lower structural level should be exposed to the south. This lower structural level may be the underlimb of the Riondel nappe. Later folding of the Meadow Creek anticline in the Duncan Lake area (Fyles, 1964) is not as intense as Phase 2 folding of the Riondel nappe, and the Phase 2 folds in the Duncan Lake area cannot be directly correlated with Phase 2 folds in the Riondel area. The West Bernard and East Bernard faults, however, are roughly on strike with the root of the Meadow Creek anticline.

As the structurally highest rocks exposed in the Riondel nappe belong to the Hamill Group and as the Hamill Group forms the cores of the recumbent anticlines in the Duncan Lake area, these structures are thought to have developed above a décollement zone which separates the Horsethief Creek Group (and perhaps the lower part of the Hamill Group) from the younger Hamill and Lardeau Groups.

EASTERN FAULTS

Two west-dipping faults that parallel the regional foliation in Hamill rocks east of the Preacher Creek antiform appear to be closely related to the Phase 2 folding. The most westerly of these, the West Bernard fault, separates the right-side-up panel of rocks on the east from the inverted section to the west. The East Bernard fault separates the Bernard Creek and Loki West anticlines and appears to have developed during the Phase 2 folding in the place of a syncline. It is a reverse fault with a minimum dip separation of at least 1 kilometre. A third west-dipping fault, also parallel with the regional foliation, cuts the *eastern limb of the Preacher Creek antiform in the Tam O'Shanter Ridge area.* It also separates two antiforms and appears to be a reverse fault with a dip separation of approximately 1 kilometre.

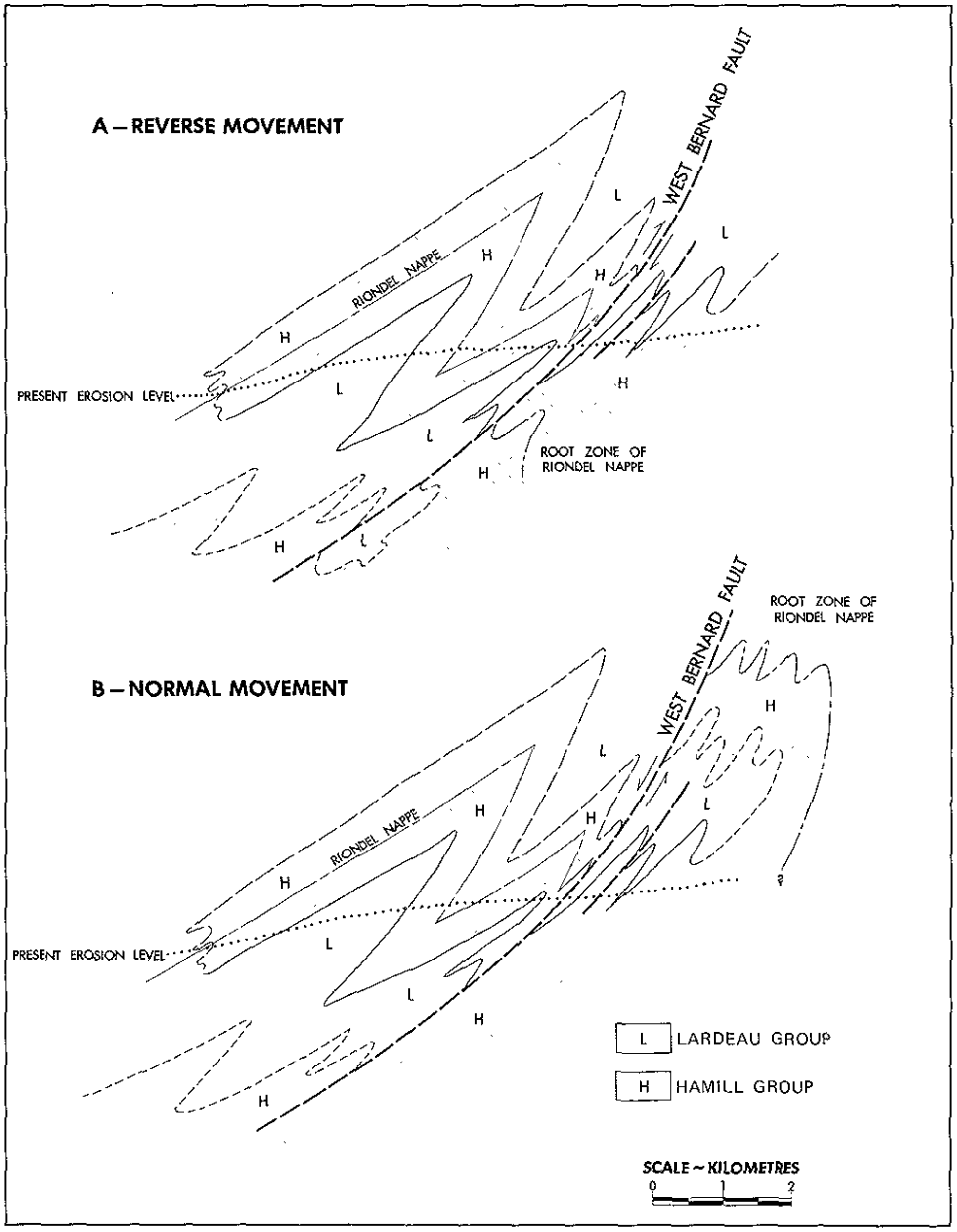


Figure 20. Schematic structure sections of the Riondel nappe illustrating two alternative interpretations of the sense of dip slip on the West Bernard fault.

WEST BERNARD FAULT

The West Bernard fault has been traced from the Loki stock to just south of Bluebell Mountain. Further south the exact position of the fault is unknown, although it probably merges with the East Bernard fault and lies just east of the antiformal fold in which an overturned succession of Badshot limestone is exposed near Crawford Creek. Only on Loki Ridge are there good exposures of the fault surface. Here it separates hornblende gneiss and micaceous schist (units L1 and L2) of the Lower Lardeau from Hamill quartzites. The gneiss immediately adjacent to the fault is more fissile and rusted. Northward (down-dip), the fault cuts across layering at a low angle and unit L2 and the Badshot Formation are progressively truncated by the fault.

The West Bernard fault separates the inverted structural panel in the west from the right-side-up panel in the east, and is thus inferred to cut across both limbs of the Riondel nappe, separating the limbs and hinge of the nappe from its root. This could be effected by either a normal or reverse displacement; however, the inferred location of the root zone of the nappe differs substantially in each case (Fig. 20). If the displacement on the fault is normal, the exposed right-side-up section east of the fault is the normal section below the lower limb of the Riondel nappe and the root zone of the nappe should be exposed further east in the Purcell Mountains (Fig. 20B). If the displacement on the fault is reverse, the exposed section must be part of the upper limb of the Riondel nappe and the root of the nappe must be buried beneath the West Bernard fault (Fig. 20A).

Although conclusive evidence bearing on the direction of displacement on the West Bernard fault is lacking, reverse displacement is favoured. The antiformal root zone of the nappe is not evident east of the fault, either in the homoclinal west-dipping Hamill sequences mapped in the southeastern part of the Riondel area or in the essentially homoclinal Horsethief Creek sequence to the southeast (M. G. Lis, personal communication, 1974). Hence, the root zone may be buried beneath the West Bernard fault. Furthermore, the regional metamorphic grade decreases eastward across the fault zone (Höy, 1976), suggesting that the rocks there are from a shallower structural level, rather than a deeper level demanded by normal movement.

EAST BERNARD FAULT

The East Bernard fault dips west, subparallel with the regional foliation. It has been traced from the Fry Creek batholith to south of Bluebell Mountain where it may merge with the West Bernard fault. The lower and middle units of the Hamill Group (H2 and H3) occur in the hangingwall and the middle and upper Hamill units (H3 and H4) occur along the footwall. On Loki Ridge it separates the overturned east limb of the Bernard Creek anticline from the upright limb of the Loki West anticline, replacing the intervening syncline. On this basis it is considered to be a reverse fault. Only a minimum dip separation can be estimated. On Tam O'Shanter Ridge (Fig. 4, section B-B'), the highest exposure of H3 in the hangingwall is approximately 1 kilometre above the lowest exposure of H3 in the footwall. As H3 is on the west limb of an anticline in the hangingwall (Fig. 18), the unit cannot be extrapolated, with constant dip, to the fault surface. Hence, a maximum separation cannot be estimated.

On Tam O'Shanter Ridge, where the fault coincides with a pronounced gulley, it is marked by 2 metres of sheared, rusty schist.

PHASE 3 FOLDS

The youngest folding discernible in the area is a small-scale gentle to open folding of the limbs of the earlier folds. Phase 3 minor folds are particularly common in the western part of the area in the amphibolites and amphibole gneisses (unit L2) south of Riondel Peninsula (Plate XVI) and in the Hamill quartzites (unit 4) on the peninsula. Axial planes of Phase 3 minor folds are steep, and the axes plunge southwesterly at shallow angles. The folds are symmetrical to nonsymmetrical with most commonly a sinistral shear sense. The only Phase 3 fold large enough to be plotted on Figure 5 is the Sherraden Creek fold, developed in the west limb of the Crawford antiform.

Minor structures associated with Phase 3 folds include: widely spaced joints that parallel the axial planes; occasional crenulation cleavage on the limbs of some of the minor folds; and rare linear structures parallel with fold axes.

LATE FAULTS

EASTERN NORMAL (?) FAULTS

Two strike faults, both marked by pronounced air photograph lineaments, cut Lower Hamill rocks in the southeastern part of the area.

The lineament corresponding to the most westerly of the faults, the 'Orebin Creek fault,' can be traced from Loki Creek to well south of Crawford Creek. The fault strikes north/northeast, is vertical, or dips west at a very steep angle, and in general is parallel with the layering in the east block but cuts up-section northward at a low angle in the west block. It is, however, entirely restricted to the Lower Hamill (unit H2). Stratigraphic units are cut out across the fault. Where exposed on Bluebell Mountain Ridge, the fault is a 2 to 4-metre-wide zone of rusty, sheared schist with some fault gouge.

A second fault, approximately 500 metres east of the Orebin Creek fault, is also restricted to the Lower Hamill (unit H2), is subparallel with the layering, and is marked by a shear and gouge zone.

The prominent lineaments, associated shearing, and development of gouge suggest that they are late faults and the inferred gaps in the stratigraphic succession across the faults suggest that movement on them is normal (downthrown to the west).

Plate XVIA. Phase 3 fold in unit L2 (Lardeau Group) exposed along the Kootenay Lake shoreline just south of Riondel.

Plate XVIB. Structurally higher, the fold of Plate XVIA is replaced by a small reverse fault.

TRANSVERSE FAULTS

Layering and Phase 2 structures are offset by several transverse faults near the head of Crawford Peninsula. Prominent southeast-trending lineaments mark these fault zones. The faults most commonly have a right-hand strike separation of about 150 to 300 metres, but the most southerly of these has a left-hand strike separation of 200 metres. Two pronounced air photograph lineaments which extend northeastward from the Kootenay Lake shoreline south of Riondel may be transverse faults, although no marker horizons which clearly display an offset have been found.

SUMMARY AND CONCLUSIONS

STRUCTURES WITHIN THE KOOTENAY ARC

The Kootenay Arc has undergone intense polyphase deformation. In general, the earliest recognized structures are tight to isoclinal, north-trending recumbent anticlines. More open, Phase 2 folds with upright to steeply west-dipping axial surfaces and north-trending fold axes are superposed on the Phase 1 folds. In the Akolkolex River area near Revelstoke, a large recumbent fold, the Akolkolex anticline, is a nappe structure that closes to the northeast (Thompson, 1979). Coaxial warps and upright open folds are superposed on the nappe. In the Duncan Lake area, recumbent, isoclinal folds root in a westerly direction and are sharply overturned to the west by large upright to west-dipping Phase 2 folds (Fyles, 1964).

In the Riondel area the oldest recognized structure is the Riondel nappe, a recumbent fold that closes west of the most western exposure in the area. Its root is inferred to lie beneath the West Bernard fault, a west-dipping reverse fault that separates an inverted panel of rocks in the west, the lower limb of the Riondel nappe, from a right-side-up panel in the east. Tight to isoclinal northerly trending folds with west-dipping axial surfaces and subhorizontal fold axes are superposed on the Riondel nappe. Small-scale southwesterly trending warps and folds are overprinted on the earlier folds and a number of southeast-trending transverse faults displace the north/south fold trends.

EVOLUTION OF THE RIONDEL NAPPE

Two models are proposed to explain the development of the Riondel nappe. The basic difference between the models relates to the relative age of the first and second phases of deformation. The first model assumes that both phases are part of one protracted deformational event in Mesozoic time. The second model assumes that there is a finite time interval between the Phase 1 folding (producing the Riondel nappe) and the second phase (deformation of the nappe).

In both models, Phase 1 and Phase 2 structures are interpreted to have developed preferentially in the thin-bedded Hamill and Lardeau Groups, separated from the underlying, more massive Horsethief Creek Group and perhaps lowermost Hamill strata by a décollement zone. Horsethief Creek rocks have not been recognized in the core of the Riondel nappe nor in the cores of Phase 1 folds in the Duncan Lake area (Fyles, 1964).

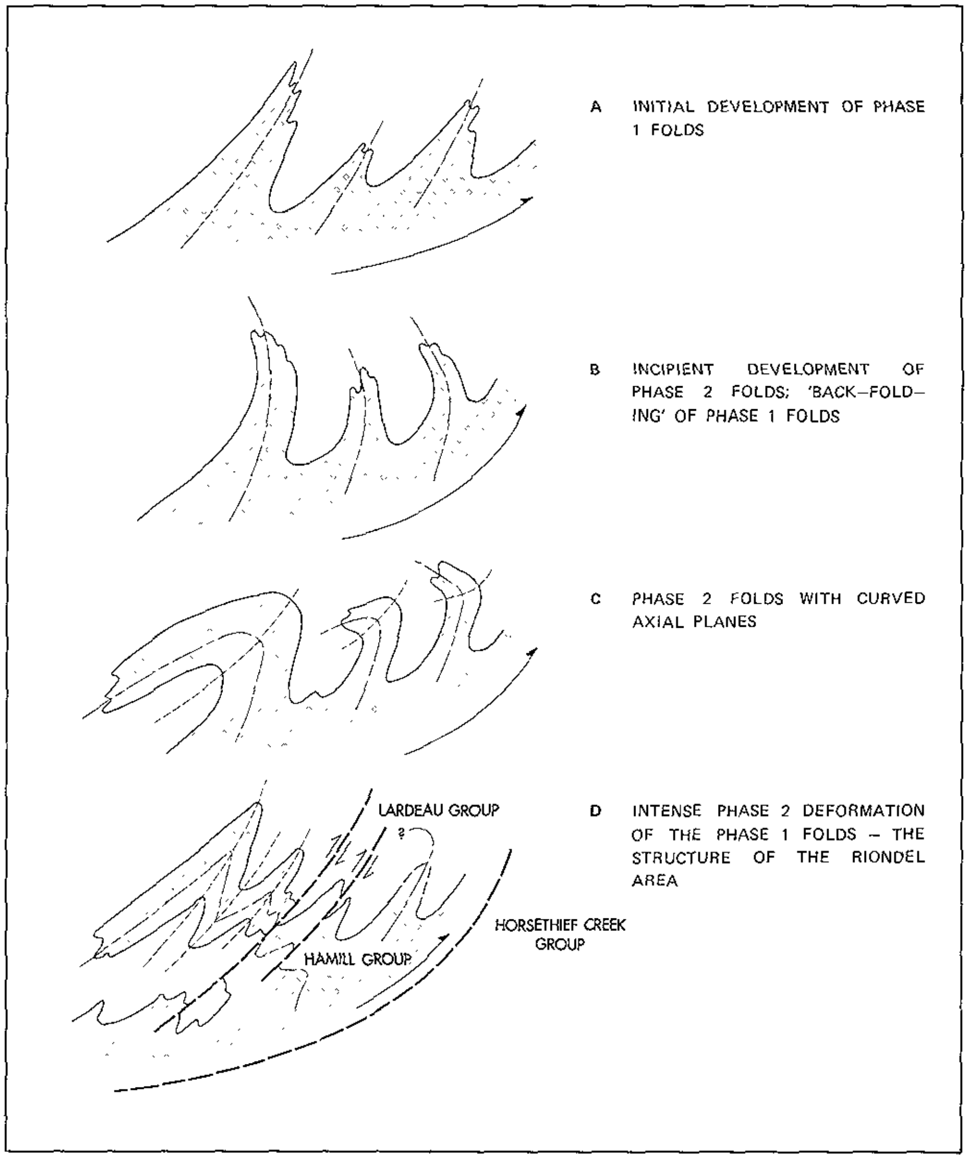


Figure 21. Postulated stages in the evolution of the Riondel nappe, assuming a model in which the first and second phases of deformation are parts of one protracted deformational event (see text).

In the first model, the folding of the limbs of the Riondel nappe is a continuation of the deformation that produced the nappe structure itself. The Riondel nappe (and Phase 1 structures in the Duncan Lake area to the north) developed as eastward-verging structures above a west-dipping décollement zone (Fig. 21A) that probably dipped progressively less steeply to the west (a pattern displayed by other planar features in the Riondel area). The nappe overturned to the west (back folded), forming the Phase 2 folds (Fig. 21B and C). In the Riondel area (as well as in the Duncan Lake area), the west-dipping Phase 2 folds show evidence of a rotational component of strain. Axial planes are curved, becoming more upright at higher levels and to the east (Fig. 21D).

The reverse displacements on older strike faults suggest an initial overriding of western structures toward the east. With increased horizontal shortening and vertical extension, back folds may have developed resulting in relative translation of higher structural levels to the west and perhaps accompanying normal displacement on west-dipping strike faults. It is possible that strike faults with normal displacement in the higher structural levels in the Ainsworth-Kaslo area (Fyles, 1967) reflect this westward component of rotational strain. The conspicuous layer-parallel faults above the basal Hamill in the eastern part of the Riondel area may be in the zone of decollement. Postulated west-side-down displacement on these faults may be a late feature reflecting relaxation.

This suggested sequential development of the Riondel nappe (model 1) may be displayed at various stages of development in other parts of the Kootenay Arc. Tight to isoclinal west-dipping to upright folds, comparable to those in stage a of Figure 21, predominate in the eastern part of the Ferguson area near the north end of the Kootenay Arc (Fyles and Eastwood, 1962). 'Overturned' and isoclinal west-dipping folds in the Salmo area (Fyles and Hewlett, 1959) are similar to folds in the higher structural level of stage b on Figure 21, and the recumbent, refolded Phase 1 folds in the Duncan Lake area (Fyles, 1964) illustrate stage c in the development of the Riondel nappe.

In the second model a westward-closing recumbent anticlinal structure, rooted in the east, developed prior to initiation of Phase 2 folding. West-dipping Phase 2 folds are superposed on the limbs of the Phase 1 nappe, and a finite time interval is assumed to separate the two phases.

There is some evidence further north in the Kootenay Arc that indicates that the earliest structures developed during the Caribooan orogeny in pre-Late Mississippian time and hence are separated in time from the intense Phase 2 deformation of Mesozoic age. In the Ferguson area, a Phase 1 syncline in Lower Paleozoic Lardeau Group rocks is truncated by an unconformity at the base of the Upper Mississippian to (?) Permian Milford Group (Read, 1976). Large Phase 2 folds, however, are conspicuous in both the pre and post-Mississippian rocks. Further evidence of a Devono/Mississippian (?) tectonic event in the Lardeau west map-area includes the occurrence of a conglomerate (first described by Wheeler, 1968, 1972) at the base of the Milford Group that 'contains clasts of the underlying Broadview Formation with the earliest foliation varying from clast to clast' (Read, 1975, p. 29). Furthermore, the occurrence of polymetamorphic textures in the Lardeau Group and their absence in the Milford Group indicates that an early metamorphic event was restricted to pre-Milford Group rocks (Read, 1971).

In summary, there is no conclusive evidence within the Riondel area that provides an absolute age for the development of the Riondel nappe. However, as the earliest deformation elsewhere in the arc may be of Devono/Mississippian age, it is possible that the nappe may have developed as a recumbent anticline during the Cariboonan orogeny and subsequently been deformed by Phase 2 folding in Mesozoic time (model 2). Alternatively, it is possible that both phases in the Riondel area are part of one protracted deformational event in Mesozoic time (model 1).

AGE OF DEFORMATION, METAMORPHISM, AND INTRUSIVE EVENTS IN THE KOOTENAY ARC

In the Lardeau area to the north, the 'culminating Mesozoic orogeny' is bracketed between 164 Ma with the emplacement and consolidation of the Mount Toby stock and 97 Ma with the emplacement of the Fry Creek batholith (Reesor, 1973). The Mount Toby stock 'apparently recrystallized synchronously with the deformation of the surrounding rocks' (Reesor, 1973, p. 108), and the Fry Creek batholith, although generally unaffected by the deformation, may have been deformed by Fyles' Phase 2 structures in its northwest corner (Reesor, 1973, p. 93). Read and Wheeler (1975), however, restrict the second phase of deformation in the Lardeau area to an interval between 178 Ma, a radiometric date from the core of the pre to syntectonic Kuskanax batholith, and 164 Ma, a date for the post-tectonic, northern part of the Nelson batholith and Mount Carlyle stock. In the southern Kootenay Arc, Archibald, *et al.* (1979) report dates of 155 Ma (K/Ar) and approximately 170 Ma (Pb^{206}/U^{238}) on the mine stock. The intrusion of the stock 'was syn- to late-kinematic with respect to the penetrative fabric' (Archibald, *et al., op. cit.*) indicating a Middle Jurassic (pre 170 Ma) age of deformation and associated metamorphism here as well.

A minimum age of 97 Ma for the Phase 2 deformation in the Riondel area is provided by the age of the post-tectonic Fry Creek batholith. A date on the Shoreline stock might restrict further the age of the Phase 2 deformation. The 50.8-Ma date reported (p. 34) is not believed to represent an intrusive date on the stock (D. A. Archibald, 1979, personal communication).

Regional metamorphic isograds are not folded by Phase 2 structures (Höy, 1976) yet Phase 2 foliation and lineation are defined by preferred orientations of platy metamorphic minerals. This suggests that the metamorphism occurred during the Phase 2 deformation.

The age of the Riondel nappe cannot be determined from the present study. Phase 2 deformation and associated regional metamorphism culminated during Middle Jurassic (to Early Cretaceous ?) time. By Middle Cretaceous time intense deformation had ceased, although thermal events such as retrograde metamorphism and intrusion of discordant stocks may have continued into Paleocene or Eocene time.

5

MINERAL DEPOSITS

INTRODUCTION

The Riondel area is within an important lead-zinc metallogenic province that extends from northern Idaho and Montana through southeastern British Columbia to north of Revelstoke in the northern Selkirk Mountains (Fyles, 1970; Höy, 1977b). Included in this province are shale-hosted deposits (such as Sullivan) within the Purcell Supergroup of Late Proterozoic age, Shuswap deposits of probable Late Proterozoic to Early Paleozoic age (Fyles, 1970; Höy, 1979), stratiform and stratabound deposits in Early Cambrian limestone and dolomite with the Kootenay Arc (including the Bluebell deposit), and numerous late lead-zinc-silver vein deposits in a variety of rock types of various age (*see*, for example, descriptions of properties in the Ainsworth-Kaslo area; Fyles, 1967). The Bluebell deposit, a replacement lead-zinc deposit in the Lower Cambrian Badshot Formation, is the only important producer within the Riondel area. It milled in excess of 5 million tonnes of lead-zinc-silver ore during the periods of 1895 to 1927 and from 1952 until its closure in 1971 (Table 8). A more complete history of exploration and mining in the Riondel area is outlined in Chapter 1.

TABLE 8. PRODUCTION FROM THE BLUEBELL MINE, 1895–1971

Year	Tonnage		Gross Contents				
	Mined	Milled	Gold *oz.*	Silver *oz.*	Copper *lb.*	Lead *lb.*	Zinc *lb.*
1895–1927	542,203	480,636	----	669,913	--------	49,359,420	6,260,671
1952	136,212	136,212	----	225,995	--------	15,672,897	15,838,897
1953	216,401	216,401	----	340,722	388,840	25,010,402	26,059,973
1954	163,134	163,134	----	246,226	276,387	18,247,076	21,077,328
1955	241,788	241,788	----	345,905	345,241	24,972,006	28,353,216
1956	249,126	252,523	----	368,632	349,833	26,190,433	30,876,281
1957	256,118	256,118	----	361,189	298,892	25,925,392	31,079,628
1958	255,859	255,859	----	363,156	320,757	27,545,899	31,792,649
1959	251,366	251,366	----	307,951	246,000	21,215,525	30,171,642
1960	255,571	255,571	----	354,397	368,000	25,688,460	29,904,260
1961	252,821	252,821	----	318,159	320,600	22,428,228	29,146,290
1962	237,742	237,742	----	297,191	211,600	21,164,684	23,572,471
1963	256,484	256,484	----	350,370	408,800	24,869,808	29,301,241
1964	257,871	257,871	----	324,023	355,600	22,158,400	28,429,800
1965	256,332	256,332	----	329,907	388,400	24,495,860	27,953,480
1966	246,390	246,390	----	341,228	402,000	25,157,920	29,118,600
1967	255,536	255,536	----	314,760	377,000	22,196,400	28,341,600
1968	251,497	251,497	60	345,896	339,600	22,017,400	26,498,600
1969	230,956	230,956	69	304,927	288,000	20,649,400	24,157,000
1970	242,997	246,529	81	308,583	311,000	21,006,000	25,369,800
1971	256,797	260,343	75	281,759	298,600	29,328,800	25,364,400
Totals	5,313,201	5,262,109	285	7,130,889	6,294,950	515,300,410	548,667,827

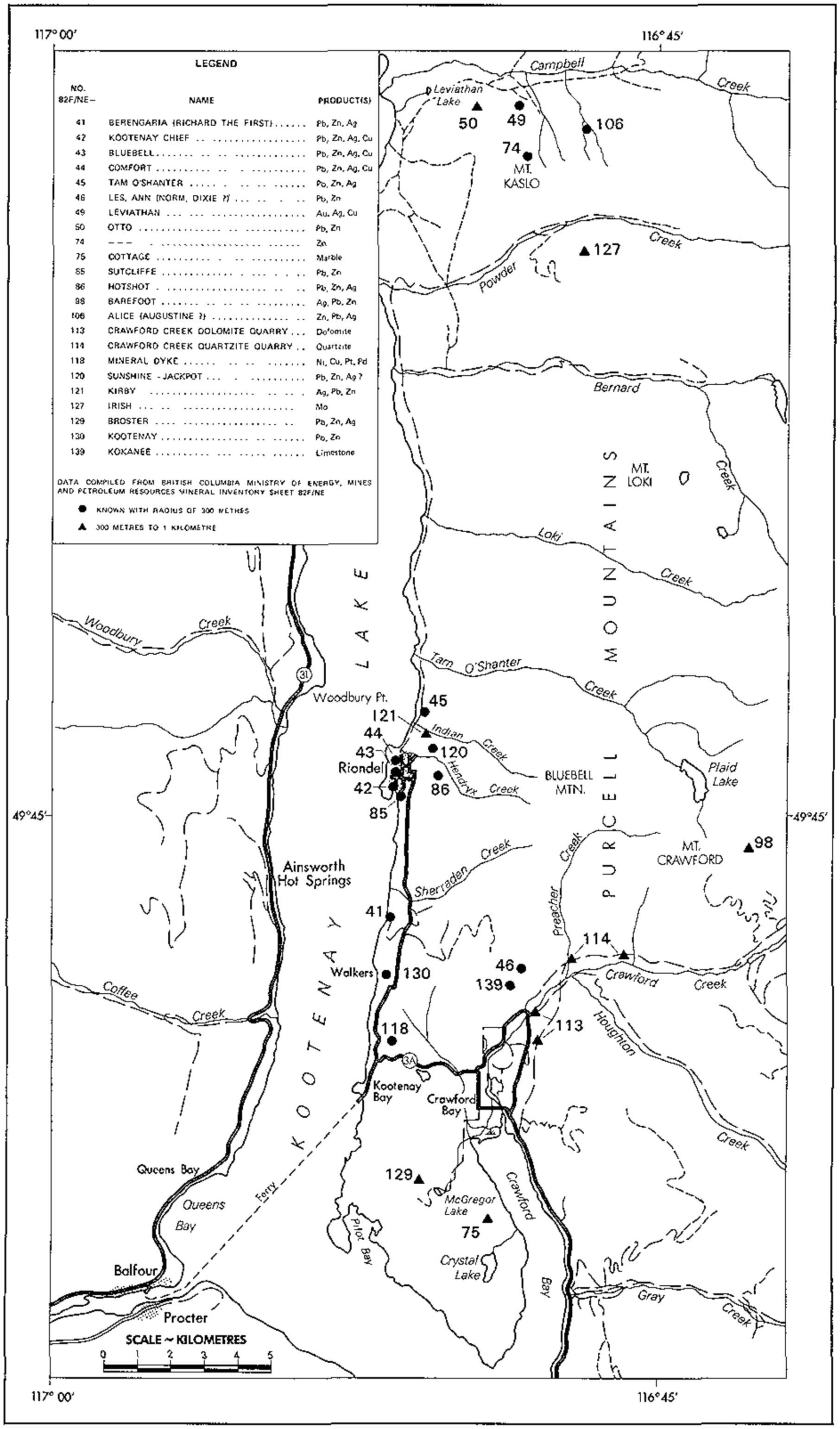


Figure 22. Location of mineral occurrences in the Riondel area; from British Columbia Ministry of Energy, Mines and Petroleum Resources Mineral Inventory Map 82F/NE.

DEPOSIT TYPES

Fyles (1966) classified lead-zinc deposits in British Columbia into two main types, concordant and transgressive. In the Kootenay Arc, the concordant deposits are exemplified by Salmo-type deposits, stratiform deposits in isoclinally folded, Lower Cambrian (Badshot Formation) dolomitized limestone. Transgressive deposits are divided into two main types: replacement deposits, such as the Bluebell, and 'veins and lodes,' such as occur in the Ainsworth camp.

TABLE 9. LIST OF MINERAL PROPERTIES IN THE RIONDEL AREA

No. (MI 82F/NE)	*Name*	*Commodity*	*Type*	*Status*
41	Berengaria (Richard the First)	Pb, Zn, Ag	massive sulphide	past producer
42	Kootenay Chief	Pb, Zn, Ag, Cu	replacement	Bluebell mine – past producer
43	Bluebell	Pb, Zn, Ag, Cu	replacement	Bluebell mine – past producer
44	Comfort	Pb, Zn, Ag, Cu	replacement	Bluebell mine – past producer
45	Tam O'Shanter	Pb, Zn, Ag	vein	minor production (1918, 1920)
46	Les, Ann (Norm, Dixie ?)	Pb, Zn	vein	occurrence
49	Leviathan	Au, Ag, Cu	vein	occurrence
50	Otto	Pb, Zn	replacement (?)	occurrence
74	------	Zn	------	occurrence
75	Cottage	marble	------	------
85	Sutcliffe	Pb, Zn	------	occurrence
86	Hotshot	Pb, Zn, Ag	vein	occurrence
98	Barefoot	Ag, Pb, Zn	vein	occurrence
106	Alice (Augustine ?)	Zn, Pb	vein, replacement	minor production (1915)
113	Crawford Creek Dolomite quarry	dolomite	------	producer
114	Crawford Creek Quartzite quarry	quartzite	------	producer
118	Mineral Dyke	Ni, Cu, Pt, Pd	disseminated in diorite sill	occurrence
120	Sunshine–Jackpot	Pb, Zn, Ag	------	------
121	Kirby	Ag, Pb, Zn	vein	minor production (1920)
127	Irish	Mo	------	------
129	Broster	Pb, Zn, Ag	vein	occurrence
130	Kootenay	Pb, Zn	vein	occurrence
139	Kokanee	limestone	------	------

Lead-zinc deposits and occurrences in the Riondel area include the Bluebell deposit and a number of lead-zinc-silver vein or replacement deposits within the Badshot or overlying calcareous schists of the Index Formation. Several of these occurrences are located within a few kilometres of the Bluebell deposit at Riondel (Fig. 22 and Table 9), and are probably related to the same late fracture system controlling mineralization at Bluebell and in the Ainsworth camp across Kootenay Lake from the Bluebell deposit (Le Couteur and Sinclair, in preparation). Fyles (1970) described the vein systems in the Ainsworth area and concluded (p. 50) that:

Plate XVII. Riondel Peninsula, the site of the Bluebell mine, on the east shore of Kootenay Lake.

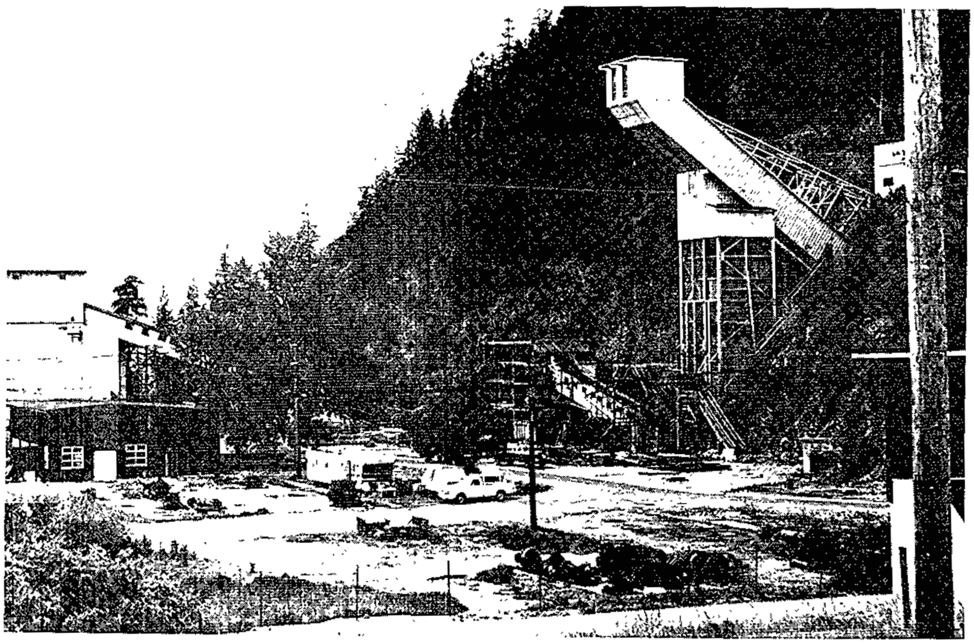


Plate XVIII. Demolition of the Bluebell minesite in August 1975, approximately four years after its closure.

(1) there are three dominant vein attitudes striking generally north, northwest, and west/northwest and dipping variably toward the west or southwest;

(2) 'the vein fractures have been the locus of small and repeated movements' (Fyles, *op. cit.*, p. 51); and

(3) the fracture system and mineralization post-dates the regional deformation, metamorphism, and granitic intrusions.

PROPERTY DESCRIPTIONS

All known mineral occurrences in the Riondel area are listed in Table 9 and located and identified by British Columbia Mineral Inventory numbers on Figure 22. The following descriptions are, in large part, summarized from published data. The Bluebell mine was closed before the period of this study.

BLUEBELL
(KOOTENAY CHIEF, MI 82F-42; BLUEBELL, MI 82F-43; COMFORT, MI 82F-44)

INTRODUCTION

The Bluebell deposit at Riondel comprises three main ore zones, the Kootenay Chief, Bluebell, and Comfort, located on a peninsula on the east shore of Kootenay Lake (Plate XVII). It is one of the oldest mines in British Columbia, first staked in 1882 by Robert E. Sproule, and worked intermittently from 1895 to its closure in 1971 (Plate XVIII). Intermittent production from 1895 to 1927 included 540,000 short tons containing 6.5 per cent lead and 8.2 per cent zinc, and by Cominco Ltd. from 1952 to 1971, 4,777,000 tons containing 5.1 per cent lead and 6.1 per cent zinc (Table 8). The ore also contained 1 to 2 ounces silver per ton (28 to 56 grams per tonne), 0.1 per cent copper, and 0.03 per cent cadmium. The known unrecoverable mineralization includes approximately 385,000 tons containing 4.9 per cent lead, 5.6 per cent zinc, and 1.4 ounces silver per ton (40 grams per tonne) (Ransom, 1977).

The general geology description in the following section is summarized from previous chapters in the bulletin. The geology of the Bluebell deposit has been described by Irvine (1957), Shannon (1970), Ohmoto and Rye (1970), and Ransom (1977). The descriptions of ore controls and sulphide mineralogy are based largely on these published reports, as well as personal communications with Paul Ransom and E. W. Muraro of Cominco Ltd.

GENERAL GEOLOGY

STRATIGRAPHY

Rocks on Riondel Peninsula comprise a north-trending and west-dipping succession of Lower Cambrian quartzites, pelitic schists, calcareous schists, and marble. The succession is inverted; the older rocks of the Hamill Group outcrop along the western shoreline of Riondel Peninsula and overlie successively younger rocks of the Mohican Formation, the Badshot marble which hosts the sulphide mineralization, and schists of the Index Formation. As these rocks are described in detail in Chapter 2, they will be described only briefly here.

The upper part of the Hamill Group (unit H4) consists of at least 200 metres of fine-grained, dark grey biotite-quartz schist and quartzite. Pelitic micaceous schist layers comprise at least half the Upper Hamill succession on Riondel Peninsula, and thin white quartzite layers are common. Calcareous schist, pelitic schist, quartzite, and marble characterize the stratigraphically overlying Mohican Formation. On Riondel Peninsula the Mohican is represented by a basal limestone (the Upper Limestone) and overlying micaceous schist. The Badshot Formation is a 30 to 50-metre-thick white calcite marble. Accessory minerals include tremolite, phlogopite, and graphite. It is stratigraphically overlain by calcareous and pelitic schist and gneiss of the Index Formation (unit L1). These rocks are the youngest metasedimentary rocks on Riondel Peninsula, and comprise the footwall of the Badshot-hosted sulphide ore.

Granitic pegmatite dykes and sills are common throughout the mine area. The most noticeable is a laterally extensive pegmatite sill, 1 to 3 metres thick, that occurs in the top 10 metres of the Badshot Formation (Ransom, 1977). Lamprophyre dykes a few centimetres to a metre in thickness cut both the metasedimentary rocks and the pegmatites (Irvine, 1957). The dykes are porphyritic containing phenocrysts of plagioclase (labradorite to andesine), olivine, pyroxene, hornblende, and biotite which have been largely replaced by calcite, epidote, chlorite, and magnetite (Ohmoto and Rye, 1970).

STRUCTURE

The structure of the Riondel area is dominated by a large, recumbent Phase 1 anticlinal fold, the Riondel nappe. It closes west of the Riondel area, probably beneath Kootenay Lake. The rocks in the western part of the Riondel area are the inverted stratigraphic panel of the lower limb of the nappe. North-trending isoclinal Phase 2 folds are superposed on this panel. The Bluebell deposit is on the western limb of a Phase 2 fold, the Crawford antiform, that has in its core the youngest rocks within the map-area. The intense regional metamorphism culminated during Phase 2 deformation and many of the coarse-grained granitic pegmatite bodies were intruded as sills or dykes during various stages of development of Phase 2 folds.

Phase 3 folds warp the limbs of earlier folds. They are not conspicuous on a regional scale, but are common as fairly open to tight S-shaped folds in the vicinity of the Bluebell deposit.

OREBODIES

The Bluebell ore deposit consists of three main zones spaced approximately 500 metres apart along the strike of the Badshot marble: the Comfort zone at the north end of Riondel Peninsula, the Bluebell zone in the centre, and the Kootenay Chief at the south end (Fig. 23). The zones are localized along steep cross-fractures that trend west/north-westerly (north 62 degrees west to north 75 degrees west) and dip 80 to 90 degrees north (Irvine, 1957). Within the zones are tabular ore shoots that are transverse to the bedding and plunge westward following the intersection of the fractures with the marble.

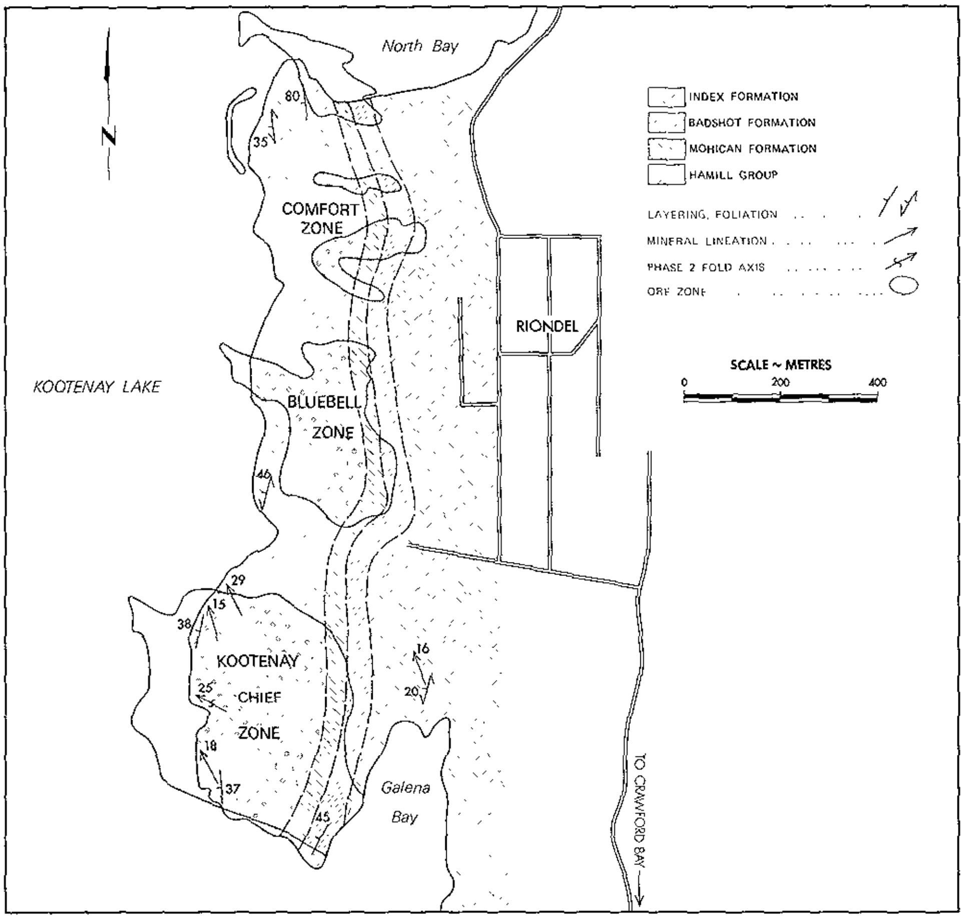


Figure 23. Sketch map of Riondel Peninsula showing distribution of formations and Bluebell ore zones, projected to surface; modified from Shannon (1970).

Ransom (1977) described the geometry of individual ore shoots. They:

'ranged in size from irregular pods of a few thousand tons to continuous masses of up to one million tons that extended down-dip as much as 500

m. In cross-section, an average ore shoot was mushroom-shaped, the stem representing cross-cutting keels 1 to 30 m wide and the cap representing a bedding-conformable horizon up to 6 m thick that extended laterally as much as 50 m from the keel zone. The keel zones extended below the conformable ore some 10 to 20 m, narrowing and grading into a series of steep mineralized fractures that became uneconomical to mine. Some of the fracture zones and keels of the larger ore shoots extended to the footwall. A few ore shoots also developed along the footwall in a style complementary to hangingwall ore shoots. Depressions along the footwall and arches along the hangingwall were particularly favourable areas for ore accumulations. Ore shoots more than doubled in thickness and spread out laterally as 'runs' along strike on the down-dip side of displaced lamprophyre dyke segments. Very little ore occurred on the up-dip side of these segments and not until 30 m further up-dip did ore attain normal thicknesses' (Ransom, 1977, p. 41).

Each of the three main ore zones comprise a number of individual orebodies, as described by Irvine (1957, p. 100). (Subsequent exploration and mining increased the number of ore shoots and their strike length, as indicated in square brackets.)

'In the Comfort ore zone, at the north end of the mine, there are at least five known orebodies, all more or less tabular, occupying transverse fracture zones and raking steeply down the dip of the beds. These occur along a strike length of 1,200 feet, and are separated by completely barren limestone. In general, the Comfort orebodies follow only cross-fractures, but the principal and central body of the group, which is known to be continuous for at least 600 feet down dip from surface, spreads out along beds under the hanging-wall quartzite and again under a pegmatite sill just below the quartzite. As it follows cross-fractures toward the stratigraphically central portion of the limestone, the orebody narrows and almost pinches out, then spreads to a greater width as it approaches the footwall of the limestone formation. The north boundary of this orebody is here marked by a steeply dipping green dyke, transverse to the bedding in strike.

'The Bluebell ore zone, from which all the ore was mined prior to Cominco acquiring the property, lies south of the Comfort zone, and is separated from it along the strike of the limestone formation by a 1,000-foot barren interval. Three [five] ore shoots occur as stubby keels, clustered close to the hanging-wall of the limestone and occupying a strike length of 400 [700] feet. The ore has been mined 800 feet down dip from the surface, and may go deeper. In the central portion of the zone, the ore follows limestone beds just below the hanging-wall quartzite, and in the main it follows cross-fractures for only a small stratigraphic distance below the hanging-wall. In this respect, the Bluebell ore zone differs from the other ore zones in the mine, where the ore following cross-fractures goes much deeper into the limestone formation.

'The Kootenay Chief ore zone, from which most of the recent production has come, is south of the Bluebell zone, and is separated from it by about 900 feet of barren limestone. Orebodies in this zone are known to occur along a strike length of 1,200 feet in the limestone formation, and have been traced for at least 1,200 feet down dip from the surface. Five principal orebodies have been identified, and the general pattern is one of ore spreading out along beds near the hanging-wall of the limestone from mineralized cross-fractures which may penetrate as deep as the footwall. The bedding-type ore shoots have somewhat irregular shapes when viewed in the plane of the bedding, but follow the rake of the cross-fractures faithfully down the dip of the beds. One large orebody near the central portion of the ore zone is composed of a number of closely spaced mineralized cross-fractures extending from footwall to hanging-wall of the limestone. This body has swelled out in places to a width of 100 feet, and is the largest and most continuous so far encountered in the mine.'

ORE MINERALOGY

The mineralogy of the most southern of the ore zones, the Kootenay Chief zone, is described in detail by Westervelt (1960). Two types of mineralization are identified, referred to as the knebelite (an Fe-Mn olivine) zone and the siliceous zone.

Sphalerite, occurring either in coarse-grained masses or in veins, is the most abundant sulphide in the knebelite zone. Galena, and less commonly arsenopyrite and chalcopyrite, occur as scattered grains enclosed within the sphalerite or in other sulphides, and pyrrhotite is common as disseminated flakes and blebs within a siliceous gangue. The gangue is a highly altered rock containing abundant chlorite, and knebelite largely altered to chlorite, serpentine, and carbonate. Minor quartz, rare magnetite, and varying amounts of carbonate are also present in the knebelite zone gangue.

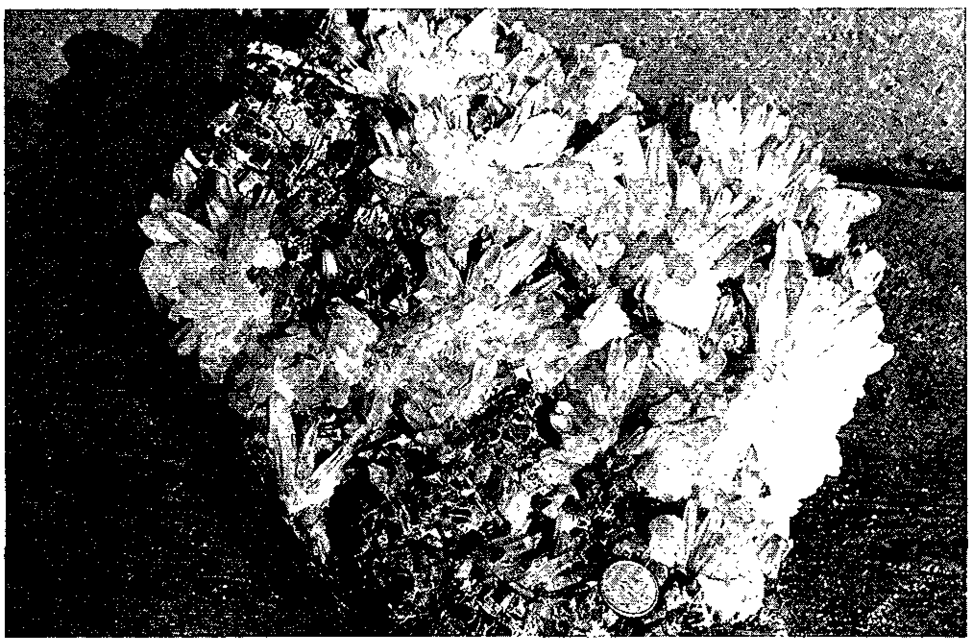


Plate XIX. Coarse quartz and galena crystals from a vug in the Bluebell deposit.

The siliceous zone is characterized by an abundance of quartz and pyrrhotite, and the development of spectacular crystal growths in vugs and cavities (Plate XIX). Pyrrhotite occurs as large well-developed crystals and as masses within other sulphides. Dark sphalerite and coarsely crystalline galena are abundant. Chalcopyrite, arsenopyrite, pyrite, and marcasite occur in small euhedral crystals or intergrown with each other or other sulphides. Coarsely crystalline quartz and carbonate are the common gangue minerals in the siliceous zone.

Muraro (personal communication, 1979) described stratiform lead-zinc mineralization in the Bluebell deposit suggesting that the obvious late fracture-controlled mineralization may in large part represent *in situ* remobilization of an older stratabound deposit.

OXIDATION AND THERMAL WATERS

Oxidation of the Bluebell ore is common, and occurred to depths in excess of 300 metres below surface (Shannon, 1970). The sequence of oxidation appears to be:

(1) alteration of pyrrhotite to lacy or spongy pyrite.
(2) alteration of pyrite to hematite or limonite.
(3) oxidation of arsenopyrite, sphalerite, and then knebelite.

An unusual geological feature of the Bluebell mine was CO_2 charged thermal water which flowed from fissures encountered at depth and commonly produced various forms of $CaCO_3$ deposits in caves and adits.

ORIGIN OF THE BLUEBELL DEPOSIT

The alignment of ore shoots with steep tensional cross-fractures, the crosscutting nature of the ore shoots, and the occurrence of sulphides in both Badshot marble and structurally overlying marble in the Mohican Formation argue strongly that the deposits formed as fracture-controlled replacement bodies. The common occurrence of coarsely crystalline sulphide minerals, associated with well-formed quartz crystal clusters in numerous vugs and cavities in the siliceous zones, is evidence of late deposition, post-regional metamorphism and deformation.

Lead isotope data from deposits in the Kootenay Arc clearly differentiate between 'concordant' deposits, such as occur in the Salmo camp and 'transgressive' deposits, exemplified by deposits in the Ainsworth and Slocan camps (Le Couteur and Sinclair, in preparation; Reynolds and Sinclair, 1971). Analyses of Bluebell leads have similar ratios to deposits in the Ainsworth camp but dissimilar to the system that includes Slocan and Slocan City. Therefore a common origin of the lodes of the Bluebell mine and the vein deposits in the Ainsworth camp is fairly certain.

A detailed study of fluid inclusions in ore and gangue minerals of the Bluebell deposit by Ohmoto and Rye (1970) showed that the late development of crystals in vugs was associated with saline brines of probable meteoric rather than magmatic origin, and that temperatures of 320 degrees centigrade to 450 degrees centigrade were indicated. The temperature and salinity of fluids associated with earlier deposition of massive sulphide-quartz-carbonate ores were both probably higher. They also concluded that the depth of the Bluebell marble at the time of ore deposition was probably 6±2 kilometres.

In summary, the distribution and geometry of the Bluebell ore deposits, the nature of the sulphide and gangue mineralogy, and the isotopic and fluid inclusion data indicate that the bulk of the deposits were emplaced as late fracture-controlled replacement bodies within the Badshot and, to a lesser extent, Mohican marbles. The fractures and related mineralization may have developed during the Phase 3 deformation which cannot be directly dated, but is probably related to a Tertiary thermal event recognized by Archibald (personal communication, 1979). The emplacement of mineralization in its present form is certainly younger than the intense Phase 2 deformation of Middle Jurassic age. The possibility that the deposit represents *in situ* remobilization of an older stratabound deposit will be investigated in a future paper.

BERENGARIA (MI 82F-41)

LOCATION: Lat. 49° 43' Long. 116° 52' (82F/10W)
SLOCAN M.D. On the Kootenay Lake shoreline, 4 kilometres south of Riondel.

METALS: Lead, zinc, silver.

DESCRIPTION:

Walker (1928, p. 134) described the Berengaria property as a 'large boulder about 30 by 20 by 10 feet and standing on end.' 'It consisted of heavy alternating bands and masses of pyrrhotite, galena, and zinc-blende, with small amounts of chalcopyrite, in a limestone gangue' (*Minister of Mines, B.C.,* Ann. Rept., 1928, p. C302).

'Small fragments of mineral are reported to have been found neaby and such fragments have been found as far south as Crawford Bay peninsula. The mineral fragments as well as the boulder are very like the Blue Bell ores and the fact that they are found in glacial material south of the Blue Bell, strongly suggests that they have been plucked and carried by the ice from the Blue Bell outcrop to their present position' (Walker, 1928, p. 134).

Production from the property is summarized (from Annual Reports of the Minister):

Year	tons	Ag oz./ton	Pb per cent	Zn per cent
1927	114	3.6	8.5	11
1927	240	. . . . . 'rather better grade'*		
1957	124	3.3	7.36	7.9
1964	9	2.28	10.04	9.65

**Minister of Mines, B.C.,* Ann. Rept. 1928, p. C302.

TAM O'SHANTER (MI 82F-45)

LOCATION: Lat. 49° 47′ Long. 116° 51′ (82F/15W)
SLOCAN M.D. On the Kootenay Lake road, 2 kilometres north of Riondel.

METALS: Lead, zinc, silver.

DESCRIPTION:

Lead-zinc veins in a limestone within unit L2 of the Index Formation have been explored intermittently since 1896. Production in 1918 and 1920 totalled 94 tons containing 17.7 ounces silver per ton.

LES, ANN (NORM, DIXIE) (MI 82F-46)

LOCATION: Lat. 49° 43′ Long. 116° 48′ (82F/10W)
SLOCAN M.D. At 975 metres (3,200 feet) elevation on the southeast-facing slope west of Crawford Creek, 4 kilometres northeast of Crawford Bay post office.

METALS: Lead, zinc.

DESCRIPTION:

Galena, sphalerite, and pyrite mineralization occurs in a number of narrow veins that both parallel and crosscut grey/white crystalline limestone of the Badshot Formation (Assessment Report 1249; *Minister of Mines, B.C.,* Ann. Rept., 1956, 1964). The limestone strikes north 5 degrees east and dips 45 degrees southwest; the attitude of a crosscutting vein is north 60 degrees west/65 to 75 degrees northeast.

Open cut excavations and three diamond-drill holes, totalling 98 metres, explored the prospect in 1957. The prospect was re-examined with geological mapping and a soil geochemical survey in 1967 for Nelway Mines Ltd. (Assessment Report 1249).

LEVIATHAN (MI 82F-49)

LOCATION: Lat. 49° 56′ Long. 116° 48′ (82F/15W)
SLOCAN M.D. *On the south side of Campbell Creek, 4 kilometres from Kootenay Lake.*

METALS: Gold, silver, copper.

DESCRIPTION:

A quartz-rich schist, interlayered with calcareous rocks, is mineralized adjacent to a granite-pegmatite with pyrrhotite, minor pyrite, and trace chalcopyrite. Mineralization is also concentrated along fractures in both the schists and a pegmatite dyke. The only assay recorded from the property contained 1.41 ounces gold and 2.9 ounces silver per ton (*Minister of Mines, B.C.,* Ann. Rept., 1952, p. 190).

Development of the property, mainly prior to 1925, included approximately 100 metres of underground work, and several large surface trenches.

HOTSHOT (MI 82F-86)

LOCATION: Lat. 49° 46′ Long. 116° 50′ (82F/15W)
SLOCAN M.D. One to 2 kilometres due east of Riondel.

METALS: Lead, zinc, silver.

DESCRIPTION:

A number of veins striking northwest and dipping to the north cut schists of the Lower Index Formation. The veins contain galena, sphalerite, pyrite, and ruby silver. The largest is approximately 1 metre wide and 10 metres in length (Rice, 1941, p. 81). It has been explored by an adit.

ALICE (MI 82F-106)

LOCATION: Lat. 49° 49′ Long. 116° 47′ (82F/15W)
SLOCAN M.D. *South of Campbell Creek at an elevation of 1 300* metres, 6 kilometres from Kootenay Lake.

METALS: Lead, zinc, silver.

DESCRIPTION:

Galena, sphalerite, pyrite, and pyrrhotite occur in crosscutting and layer-parallel veins or replacement bodies in limestone, calcareous schist, and micaceous schist surrounded by granite (Assessment Report 3803).

In 1915, 16 tons of ore containing 15 per cent lead and 82.7 ounces silver per ton was produced. The property was most recently explored in 1972 (geological mapping, geophysical survey, and soil geochemistry) by Canex Aerial Exploration Ltd. (Assessment Report 3803).

MINERAL DYKE (MI 82F-118)

LOCATION: Lat. 49° 41' Long. 116° 52' (82F/15W)
SLOCAN M.D. Less than 1 kilometre northwest of the junction of the Riondel road with the Kootenay Bay/Crawford Bay road.
METALS: Nickel, copper, platinum, palladium.
DESCRIPTION:
Pyrrhotite and chalcopyrite are disseminated in a 'flat-lying diorite dyke or sill, probably 40 to 50 feet thick, intruded into Lardeau sediments' (Rice, 1941, p. 60). Platinum and palladium are associated with the sulphides. An 80-metre-long adit was driven in 1930 to test the mineralization below the 'superficial zone' (*Minister of Mines, B.C.,* Ann. Rept., 1930, p. 254).

KIRBY (MI 82F-120, 121)

LOCATION: Lat. 49° 46' Long. 116° 51' (82F/15W)
SLOCAN M.D. One to 2 kilometres northeast of Riondel.
METALS: Lead, zinc, silver.
DESCRIPTION:
The Kirby property is described by Gunning (1928, p. 134) as follows:

'The principal veins, three in number, occur as distinct bedding fissure veins, principally in the schist but in places cutting granitic dykes or sills. In a few places the calcareous schists are sparingly impregnated with sulphides, principally pyrite. A series of steep fissures connect the main veins, cutting across the strike of the sediments.

'The ore minerals, pyrite, sphalerite, and galena, occur with quartz and some carbonates in bedded shear zones, along with fragments of the country rock.'

Nine tons of ore was shipped from the property in 1920, containing 21.8 per cent lead and 27 ounces silver per ton.

BROSTER (MI 82F-129)

LOCATION: Lat. 49° 39' Long. 116° 51' (82F/15W)
SLOCAN M.D. On Crawford Peninsula.
METALS: Lead, zinc, silver.
DESCRIPTION:
A vein occurrence of galena and sphalerite cutting limestone was explored by tunnelling in 1928 (*Minister of Mines, B.C.,* Ann. Rept., 1928).

A number of occurrences of boulders containing galena, sphalerite, and pyrrhotite in the vicinity of the Broster showing were investigated by Cominco Ltd. (Assessment Reports 4132, 4814, 6247). Four holes, drilled in 1977 and totalling approximately 330 metres, failed to locate the source of the sulphide mineralization.

KOOTENAY (MI 82F-130)

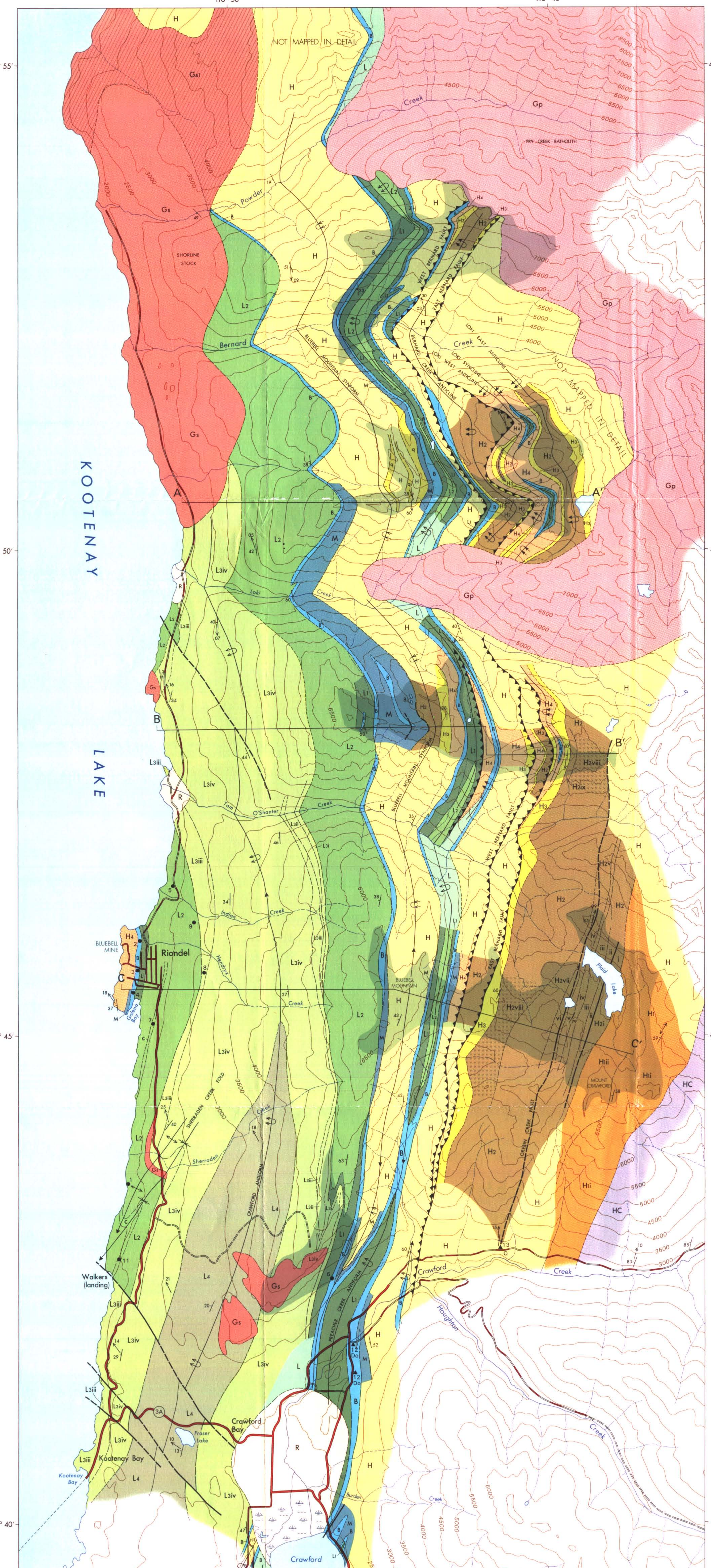
LOCATION: Lat. 49° 42' Long. 116° 52' (82F/15W)
SLOCAN M.D. Within a few hundred metres of the Kootenay Lake shoreline, 3 kilometres north of Kootenay Bay.

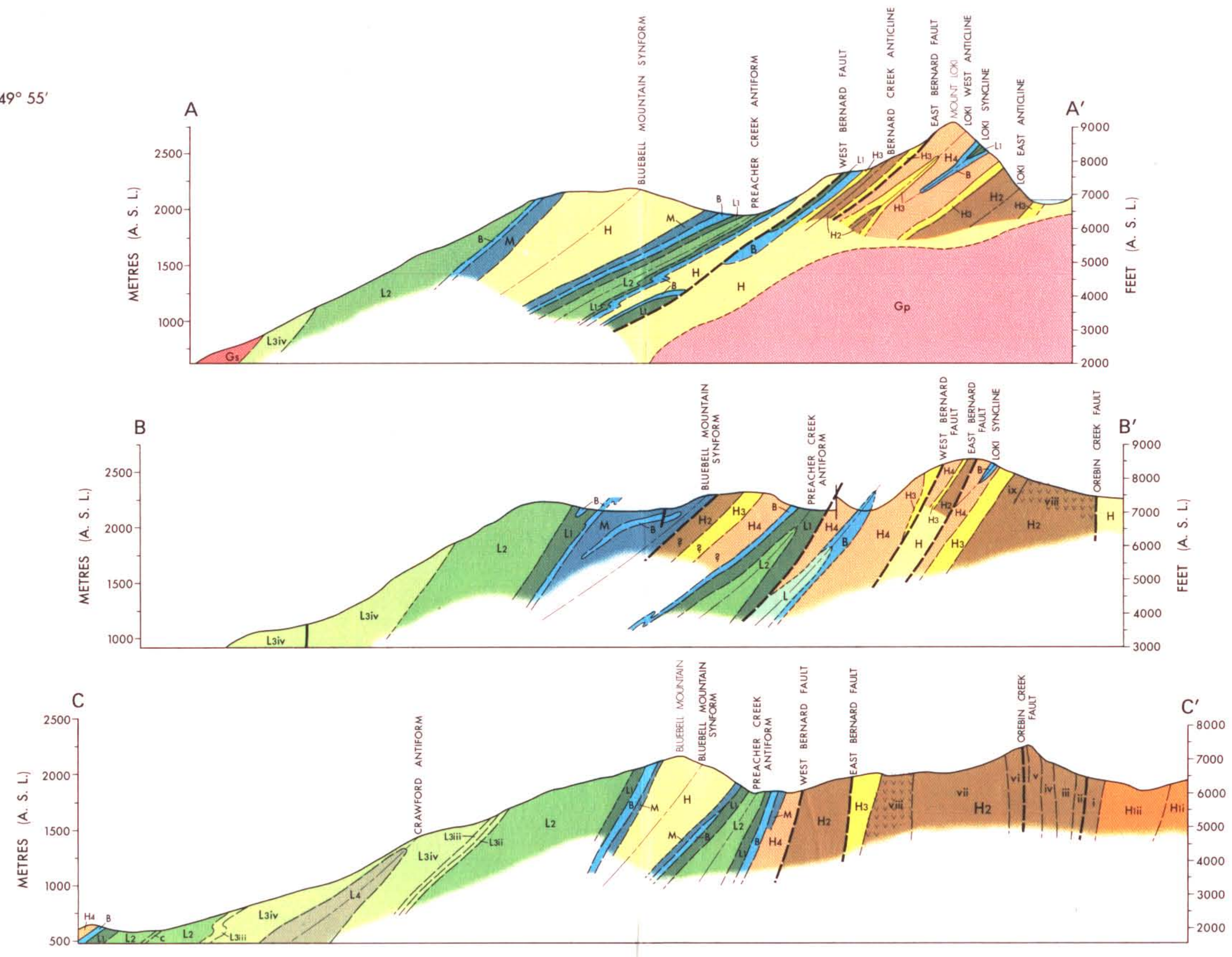
METALS: Lead, zinc.

DESCRIPTION:

'The mineral occurrence consists of four parallel narrow quartz veins striking north 36 degrees east and dipping 68 degrees southeast. Occasional transverse quartz stringers connect adjoining veins' (*Minister of Mines, B.C.*, Ann. Rept., 1958, p. 42). The main vein 'ranges in width erratically from nil to 6 inches, and is mineralized with galena, sphalerite, and pyrite in vuggy quartz.... Four assays taken along the vein at its wider and better mineralized points assayed as follows:'

No.	Width *cm*	Au *oz./ton*	Ag *oz./ton*	Pb *per cent*	Zn *per cent*
1	6	0.06	4.1	5.73	6.1
2	8	0.02	13.3	24.65	0.2
3	3	0.01	11.2	6.44	1.4
4	15	0.01	0.2	0.04	1.5





VERTICAL STRUCTURE SECTIONS A, B, C

Province of British Columbia
Ministry of Energy, Mines and Petroleum Resources

GEOLOGICAL MAP OF THE RIONDEL AREA

Geology by T. Höy, 1972, 1973.

SCALE ~ KILOMETRES

1 0 1 2 3 4

CONTOUR INTERVAL 500 FEET

LEGEND

QUATERNARY

R — PLEISTOCENE AND RECENT ALLUVIAL DEPOSITS

JURASSIC–CRETACEOUS (?)

GRANITIC ROCKS

Gp — 'POST–TECTONIC' QUARTZ MONZONITE

Gs — 'SYNTECTONIC' QUARTZ MONZONITE, PEGMATITE; GS1: MIXED ZONE OF INTRUSIVE, PEGMATITE, AND METASEDIMENTS

MIDDLE CAMBRIAN

LARDEAU GROUP

L — UNDIFFERENTIATED

INDEX FORMATION

L4 — BIOTITE – QUARTZ – FELDSPAR ± GARNET GNEISS; MINOR AMPHIBOLITE

L3 — iv. CALC – SILICATE GNEISS WITH AMPHIBOLITE, SCHIST, AND MARBLE LAYER; MAY INCLUDE UNITS L3i, L3ii, AND L3iii
iii. CALCITE MARBLE WITH CALC–SILICATE, AMPHIBOLE, AND SCHIST LAYERS
ii. AMPHIBOLITE
i. MICACEOUS QUARTZITE

L2 — HORNBLENDE GNEISS, AMPHIBOLITE: c = CALCITE MARBLE

L1 — BIOTITE – MUSCOVITE SCHIST AND GNEISS

LOWER CAMBRIAN

BADSHOT FORMATION

B — CALCITE MARBLE, DOLOMITE

MOHICAN FORMATION

M — CALCAREOUS SCHIST, QUARTZITE, MARBLE

HAMILL GROUP

H — UNDIFFERENTIATED

H4 — DARK QUARTZITE, QUARTZ–RICH SCHIST

H3 — WHITE QUARTZITE: q = MASSIVE WHITE QUARTZITE WHICH MAY IN PART BE UNIT H3

H2 — MUSCOVITE–BIOTITE–CHLORITE SCHIST, QUARTZITE, SILTSTONE
ix. DARK MUSCOVITE SCHIST, DARK QUARTZITE
viii. EPIDOTE – CHLORITE – AMPHIBOLE GNEISS (GREENSTONE ?)
vii. MUSCOVITE – CHLORITE SCHIST
vi. DARK QUARTZITE; MINOR CHLORITE SCHIST, DOLOMITE
v. CHLORITE–MUSCOVITE SCHIST; MINOR QUARTZITE
iv. MASSIVE WHITE QUARTZITE, DARK GREEN CHLORITE SCHIST
iii. DARK BROWN TO GREY CHLORITE SCHIST, DARK SILTSTONE
ii. LIGHT TO MEDIUM GREEN CHLORITE SCHIST
i. BROWN SILTSTONE, DARK GREEN CHLORITE SCHIST; MINOR QUARTZITE AND CALCITE MARBLE

H1 — QUARTZITE
ii. MASSIVE WHITE QUARTZITE, MICACEOUS QUARTZITE
i. GREY–GREEN FELDSPATHIC QUARTZITE

HADRYNIAN

HORSETHIEF CREEK GROUP

HC — MUSCOVITE – CHLORITE SCHIST AND PHYLLITE; QUARTZ PEBBLE CONGLOMERATE

SYMBOLS

GEOLOGICAL CONTACT: DEFINED, APPROXIMATE, ASSUMED*
THRUST FAULT: DEFINED, APPROXIMATE
'LATE' FAULT: DEFINED, APPROXIMATE
ANTIFORM, SYNFORM – AXIAL SURFACE TRACE
OVERTURNED ANTIFORM, ANTICLINE – AXIAL SURFACE TRACE
OVERTURNED SYNFORM, SYNCLINE – AXIAL SURFACE TRACE
FOLIATION (S_2) PARALLEL TO LAYERING (S_0)
MINERAL LINEATION (L_2)
LEAD–ZINC OCCURRENCE
QUARRY: Do = DOLOMITE; Q = QUARTZITE
AREAS OF EXTENSIVE OUTCROP
LOCATION OF VERTICAL STRUCTURE SECTION
HIGHWAY
SECONDARY ROAD (ALL WEATHER)
TWO–WHEEL–DRIVE VEHICLE ROAD (DRY WEATHER)
FOUR–WHEEL–DRIVE VEHICLE ROAD
CONTOUR — 2500

* DEFINED CONTACT – observed and walked out in the field; APPROXIMATE – constrained between adjacent outcrops; ASSUMED – projected from defined or approximate contacts.

MINERAL SHOWINGS IN THE RIONDEL AREA

NO.	NAME	LOCATION
1.	BERENGERIA	SHERRADEN CREEK
2.	COMFORT ZONE } BLUEBELL MINE	
3.	BLUEBELL ZONE } BLUEBELL MINE	RIONDEL PENINSULA
4.	KOOTENAY CHIEF } BLUEBELL MINE	
5.	TAM O'SHANTER	INDIAN CREEK
6.	LES–ANN	2 MILES (3 KM) NNE OF CRAWFORD BAY
7.	SUTCLIFFE	¼ MILE (.4 KM) SE OF RIONDEL
8.	HOTSHOT	½ MILE (.8 KM) E OF RIONDEL
9.	JACKPOT	1 MILE (1.5 KM) NE OF RIONDEL
10.	BROSTER	CRAWFORD PENINSULA
11.	KOOTENAY	WALKER'S LANDING
12.	CRAWFORD CREEK DOLOMITE	CRAWFORD CREEK
13.	CRAWFORD CREEK QUARTZITE	CRAWFORD CREEK

#73 ①