A1 Fieldtrip Guidebook, GAC/MAC Victoria '95

DEPOSITIONAL ENVIRONMENT, ALTERATION AND ASSOCIATED MAGMATISM, SULLIVAN AND RELATED MASSIVE SULPHIDE DEPOSITS, SOUTHEASTERN B.C.

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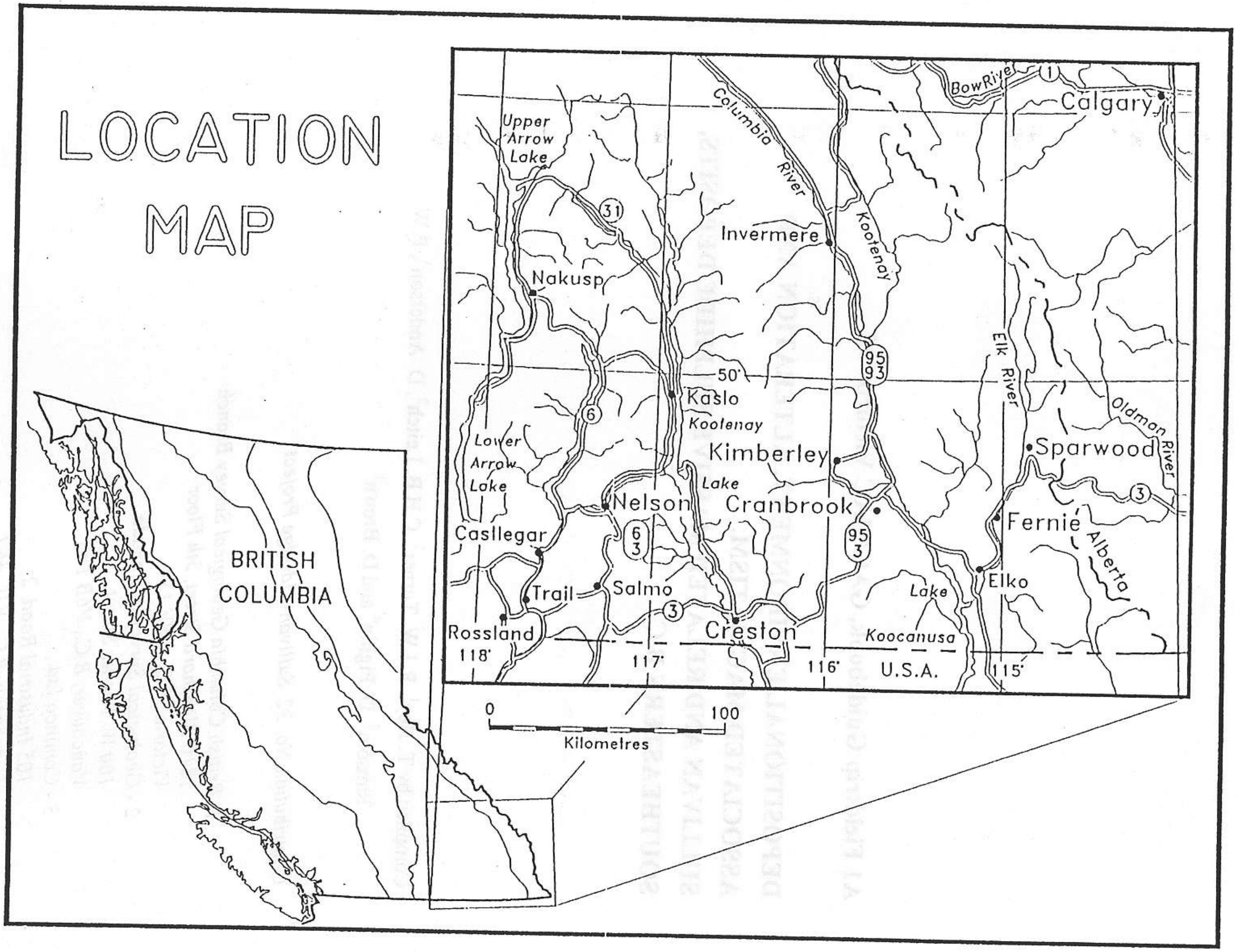
LOCATION MAP
Upper Arrow Lake
Columbia River
Bow River
1
Calgary
31
Invermere
Kootenay
Nakusp
50°
95
93
Kaslo
Kootenay Lake
Elk River
Oldman River
Lower Arrow Lake
6
Kimberley
Sparwood
3
Nelson
Cranbrook
Fernie
Casllegar
6
3
95
3
Alberta
Trail
Salmo
Elko
Lake Koocanusa
Rossland
Creston
118°
117°
116°
U.S.A.
115°
0
100
Kilometres
BRITISH COLUMBIA

INTRODUCTION

The focus of GAC/MAC field trip A1 is the depositional and tectonic setting of Sullivan and other base metal deposits in the Purcell Supergroup in southeastern B.C. Sullivan is a giant Pb-Zn-Ag sedex deposit that formed within a Middle Proterozoic intracontinental rift, coincident with deep water turbidite deposition, emplacement of voluminous amounts of gabbro, syndepositional faulting and widespread hydrothermal activity. The depositional, tectonic, magmatic and hydrothermal history of this basin, and the geology and setting of the Sullivan deposit, has been the focus of the Sullivan-Aldridge Project, a 5-year collaborative research program involving over a dozen researchers from the Geological Survey of Canada, the B.C. Geological Survey Branch, United States Geological Survey, industry and several universities. The trip will complement the GAC/MAC symposium entitled "Continental rifting and the formation of SEDEX deposits: Sullivan and other giants".

The objectives of the trip are to examine the Sullivan deposit and its setting within the basin. Specifically, we will examine a number of deposits, including Sullivan, Vine and Fors, and address:

- Middle Proterozoic tectonics
- Aldridge sedimentology
- the Moyie gabbro sill complex, and
- the nature of hydrothermal alteration, including regional tourmaline, albite, sericite and sulphide alteration.

The first day will focus on the paleogeography of the Belt/Purcell basin and the stratigraphy of the Aldridge Formation, with emphasis on the gabbro sill complex and its interaction with the host sedimentary succession.

The second day will examine basin metallogeny with a number of stops in recently discovered or actively explored mineral deposits. We will also examine the Sullivan-North Star corridor, a 7 km long zone of fragmental rocks and intense alteration that hosts Sullivan and a number of other sulphide prospects. The final day includes an underground tour of the Sullivan mine.

The route begins and ends, each day, in Kimberley. Field trip stops are shown on Figure 1.

ACKNOWLEDGEMENTS

The field guide draws heavily from previously published guides (e.g., Turner *et al.*, 1993; Höy *et al.*, 1993) and the authors gratefully acknowledge those that contributed to these publications. We thank Consolidated Ramrod Gold Corp. and Cominco Ltd. for permission to examine their properties; without their cooperation this trip would not be possible. Numerous geologists participating in the Sullivan-Aldridge Project have generously lent their help, guidance and expertise; they are gratefully thanked. Finally, we would like to acknowledge those involved in helping to put together the guide. D. MacIntyre and V. Preto of the Geological Survey Branch organized and coordinated the field trip component of the GAC/MAC meeting; M. Fournier and P. Stinson helped prepare figures, and L. Hitchen was responsible for layout and typesetting.

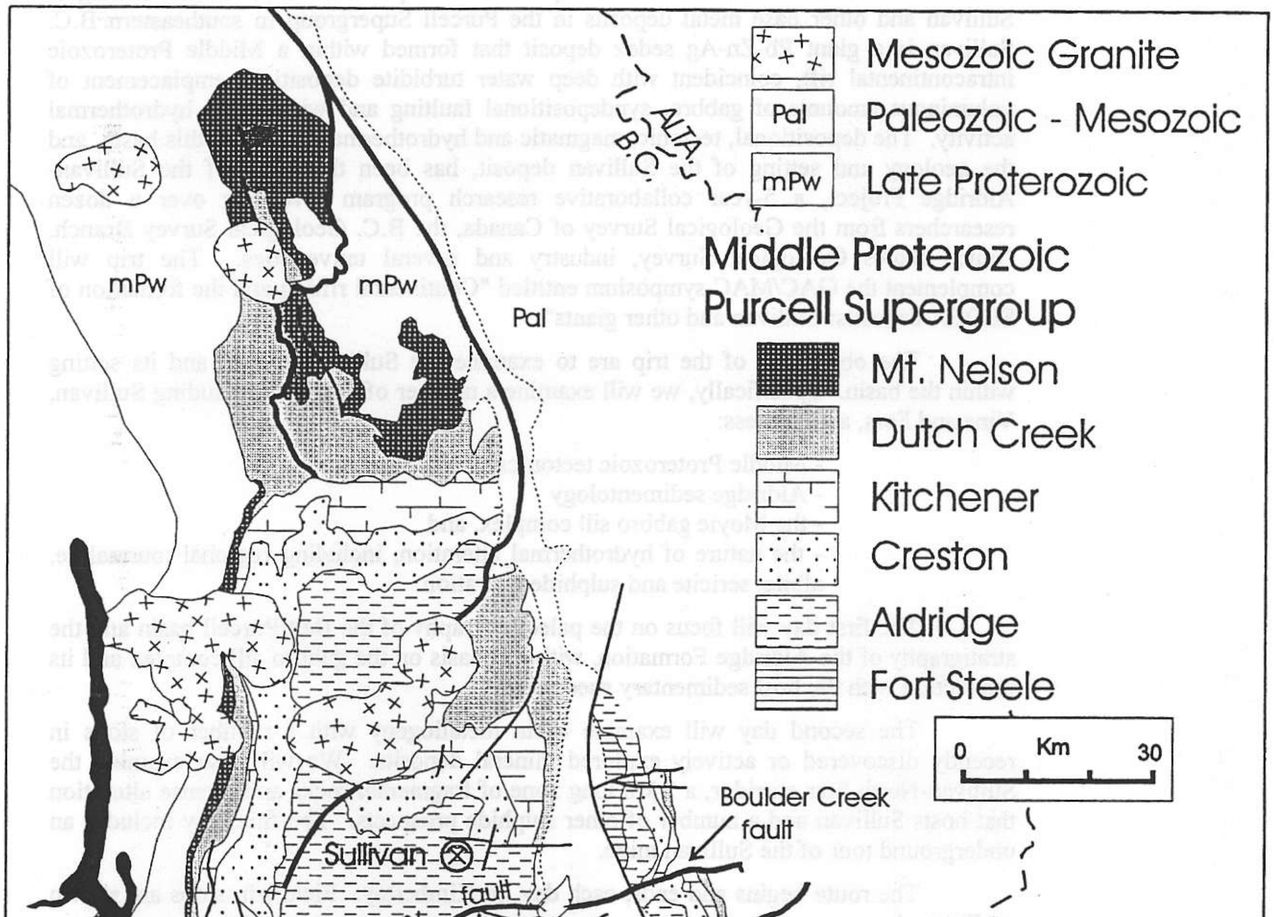

Figure 2. Geological map of the Purcell Supergroup, southeastern British Columbia.

REGIONAL OVERVIEW

The Sullivan deposit, one of the world's largest massive sulphide deposits, occurs within a thick sequence of Middle Proterozoic turbidites in southeastern British Columbia (Figure 2). It is within the Foreland Thrust and Fold belt (Monger *et al.*, 1982), characterized by shallow, easterly verging thrust faults and broad open folds.

The structure of the western part of the Foreland Thrust belt, west of the Rocky Mountain trench is dominated by the Purcell anticlinorium, a generally north-plunging structure that is cored by the Middle Proterozoic Purcell Supergroup and the late Proterozoic Windermere Supergroup and flanked by Paleozoic miogeoclinal rocks. The anticlinorium is allochthonous, carried eastward and onto underlying cratonic basement by generally north trending thrust faults during the Laramide orogeny in late Mesozoic and Early Tertiary time (Price, 1981; Cook and Van der Velden, in press). The anticlinorium is cut by prominent northeast trending faults, including the Moyie and St. Mary faults, and its eastern edge by north trending, west-side down normal faults, such as the Gold Creek and Rocky Mountain trench faults.

The northeast trending structures are within or parallel to a broad structural zone that cuts the Purcell anticlinorium, crosses the Rocky Mountain trench and extends northeastward across the Foreland Thrust belt. The zone is marked by a conspicuous change in the structural grain, from northward north of the zone to northwestward to the south, and by pronounced and fundamental changes in thickness and facies of sedimentary rocks that range in age from Middle Proterozoic to early Paleozoic. Changes in Middle Proterozoic rocks reflect tectonism during early development and infilling of the Purcell basin.

The Purcell Supergroup succession and its correlation with Belt Supergroup rocks is illustrated in Figure 3. It comprises dominantly turbidite deposits of the Aldridge Formation, overlain by shallow-water to locally subaerial clastic and carbonate rocks. The Nicol Creek lavas are a prominent marker succession of subaerial basalts that are centred near the present position of the Rocky Mountain trench. Within the Aldridge Formation and in correlative rocks east of the trench, the Fort Steele Formation, is a thick sequence of gabbroic sills and dikes referred to as the Moyie sills. These sills were intruded locally into wet, unconsolidated sediments (Höy, 1989; 1993). A U-Pb zircon age of 1445 Ma on one of these sills (Höy, *op cit.*) provides a minimum age for Aldridge sedimentation and formation of the Sullivan deposit. Recent dating of Moyie sills suggest a slightly older age of emplacement (*circa* 1465 Ma; Anderson and Davis, *in press*)

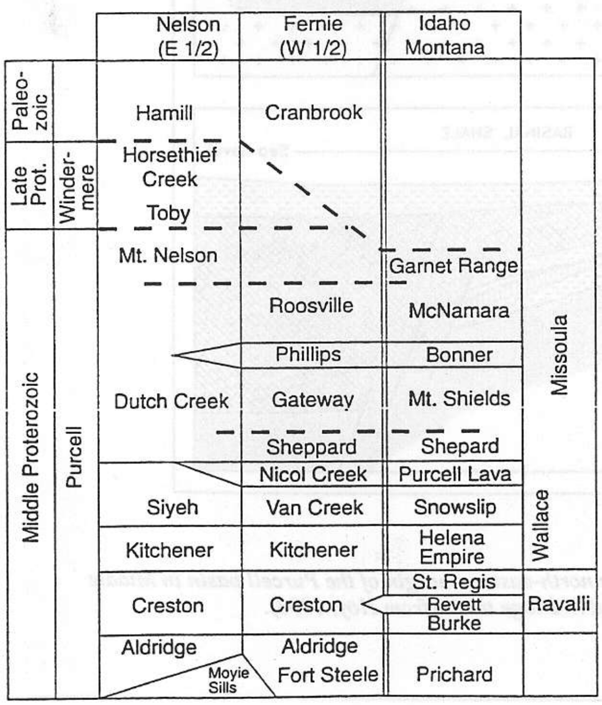

Figure 3. Table of formations, Purcell Supergroup, and correlation with Belt Supergroup in the United States.

The Purcell Supergroup has been affected by several episodes of deformation in middle and late Proterozoic time. The earliest event, recorded in the Purcell stratigraphy, is schematically shown in Figure 4. It comprised extensional tectonics resulting in prominent block faulting along the margin of the Purcell basin during deposition of the Fort Steele and Aldridge formations (Höy, 1993). The Boulder Creek fault and the segment of the Rocky Mountain trench fault north of Boulder Creek coincide with a marked change in the character of lower Purcell rocks, from dominantly fluvial and deltaic (Fort Steele Formation), shallow-water and minor turbidite deposits in the Northern Hughes Range to a thick succession of Aldridge turbidites west of the trench. In late middle Aldridge time, turbidite deposition extended over the basin margin (Figure 4b); evidence of growth faulting is not apparent in late Aldridge time as upper Aldridge rocks extend across the basin margin. Thus, the Boulder Creek fault and a segment of the Rocky Mountain trench fault outline a block of Purcell rocks in the Northern Hughes Range that marks the faulted eastern edge of the Purcell basin.

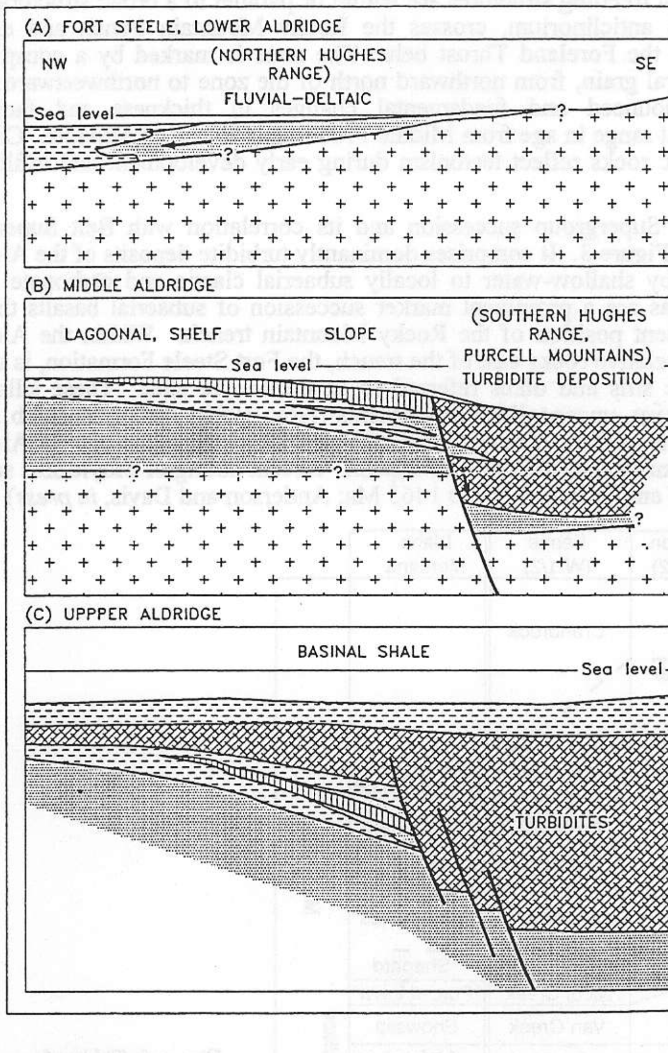

Figure 4. Tectonic evolution of the north-eastern margin of the Purcell basin in Middle Proterozoic Fort Steele and Aldridge times (from Höy, 1993).

The north to north-northwest trending growth faults are parallel to the depositional axis of the Purcell basin as defined by isopachs of the middle Aldridge turbidite package (Höy, 1993) and unit G of the Prichard Formation in the United States (Cressman, 1989); (Figure 5). Correlative formations to the east, including the Fort Steele, Altyn and Neihart, are dominated by shelf, deltaic or fluvial facies, separated from the basin by marginal growth faults (Price, 1964; Höy, 1993; Winston and Link, 1993). The axis of the basin coincides approximately with the thickest accumulation of Moyie sills (Figure 6), supporting a rift model for the basin.

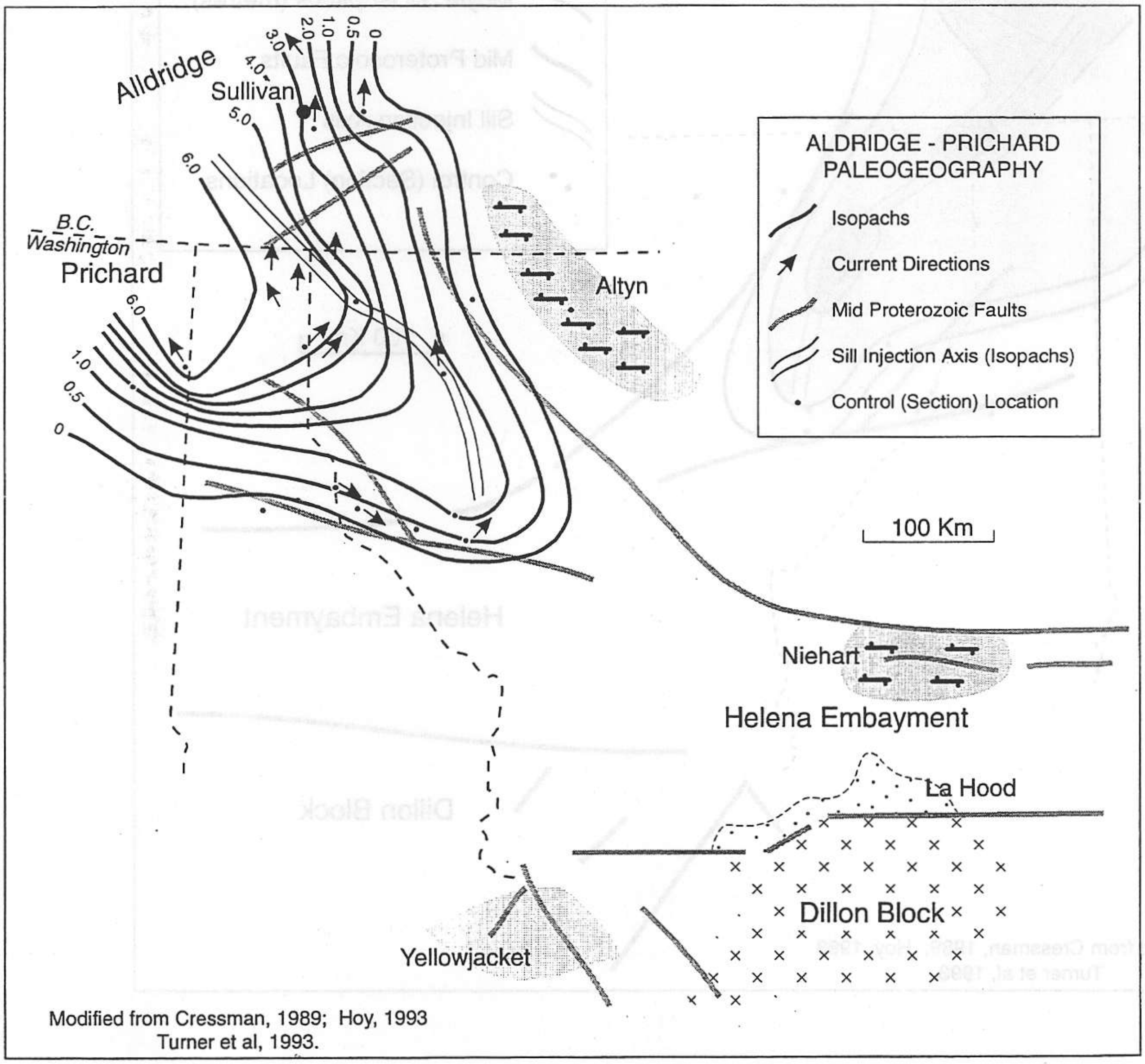

Figure 5. Isopach map of dominantly turbidites of the middle Aldridge and unit G, Prichard Formation, showing northwest-trending depositional axis for the Purcell/Belt basin (data from Cressman, 1989; Höy, 1993 and Turner et al., 1993).

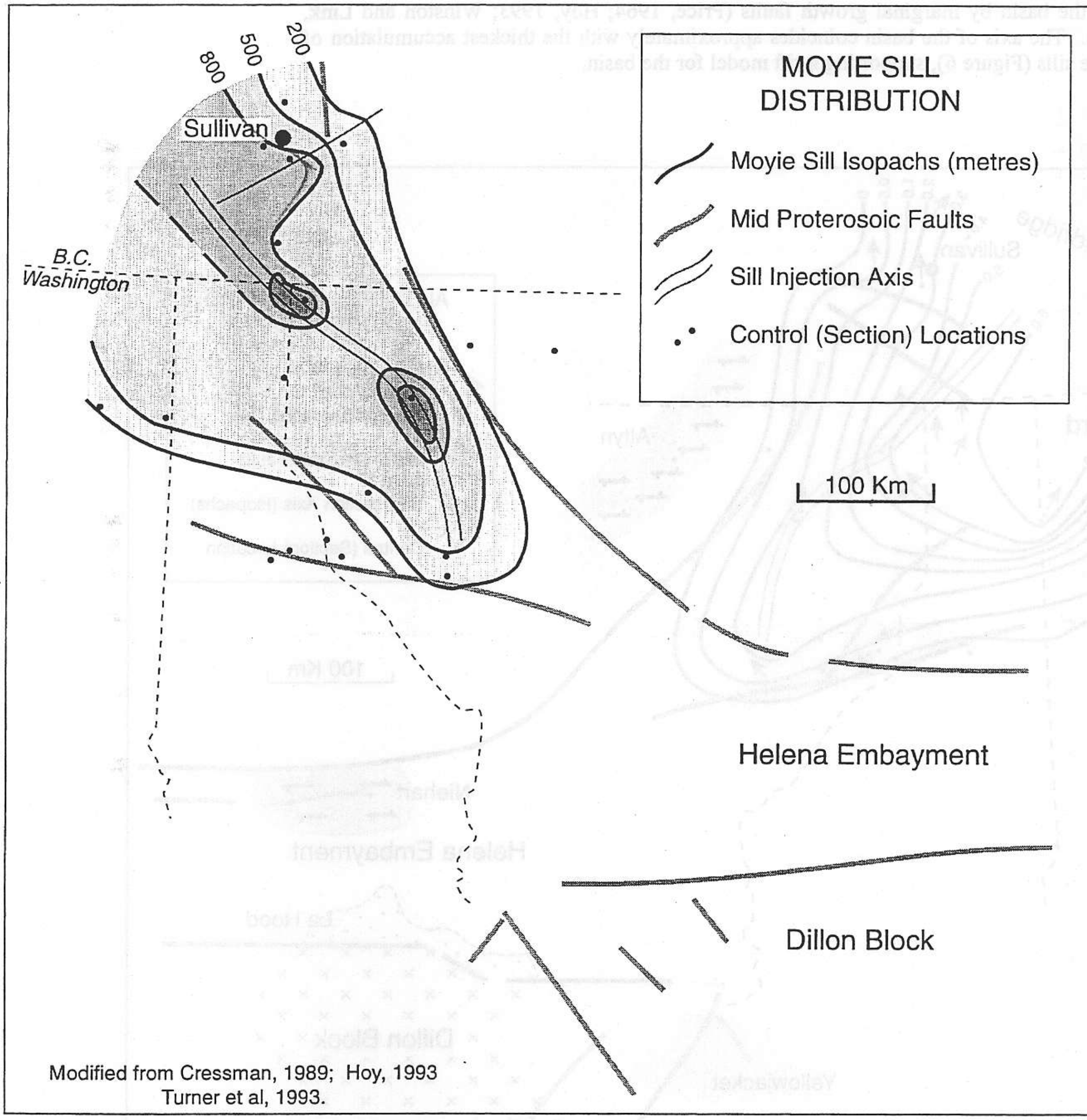

Figure 6. Isolith map of Moyie sills, Prichard and Aldridge Formations. Note correlation between basin axis, as defined by turbidite accumulations (Figure 5), and thickness of sills (data from Cressman, 1989; Höy, 1993 and Turner et al., 1993).

North and northeast-trending extensional growth faults, recognized by distribution of fragmentals, emplacement of Moyie dikes or prominent facies or thickness changes of Aldridge Formation rocks, occur within the basin. Their intersections commonly control the distribution of hydrothermal alteration and sulphide mineralization. For example, Sullivan occurs at the intersection of the Sullivan-North Star corridor with the Kimberley fault and the Vine deposit occurs near the intersection of the northwest-trending Hagen fault and the Moyie fault.

Tectonism continued along the Purcell basin margin during deposition of younger Purcell Supergroup rocks. The most voluminous extrusion of basaltic lavas of the Nicol Creek Formation (Figure 7) occured along the eastern margin of the basin centered close to the present position of the Rocky Mountain trench (Höy, 1993). In the Skookumchuck area 30 kilometres northeast of Sullivan, dramatic changes in thickness and facies of the Sheppard and Gateway formations are caused by extensional growth faults and resultant subsidence. The overlying Phillips Formation, a regional mauve-coloured marker unit in both Belt and Purcell Supergroup rocks, dies out here, supplanted to the north by green facies in the Dutch Creek Formation (Carter and Höy, 1987). Southeast of Cranbrook in the Gold Creek area, an unconformity within the Sheppard Formation, marked by a prominent basal conglomerate, has locally cut through and removed up to several hundred metres of the Nicol Creek Formation (Höy and Diakow, 1982). This unconformity appears to have locally controlled sulphide deposition: stratabound copper occurs in coarse quartzitic sands of the basal Sheppard at the Roo property and replacement Pb-Zn-Ba mineralization occurs at Mineral King in immediately overlying dolomite of the Dutch Creek Formation (*see* Figures 2 and 7).

In summary, the Purcell Supergroup in the Sullivan area was deposited near a tectonically active basin margin. Dramatic thickness and facies variations record Purcell-age growth faults and contrast with gradual changes characteristic of most Purcell and Belt rocks elsewhere. These faults reflect deep crustal structures, structures that modified incipient Purcell rifting, and led to the development of an intracratonic basin in Middle Proterozoic time. They also formed conduits that localized many of the Middle Proterozoic base and precious metal deposits.

STRATIGRAPHY

The Middle Proterozoic Purcell Supergoup comprises a thick accumulation of dominantly turbidites and associated deep-water basinal shales and argillites of the Aldridge Formation overlain by shallow-water to locally subaerial clastic and carbonate rocks. The Aldridge Formation is divided into three divisions (Figure 7). The lower Aldridge consists mainly of rusty-weathering, thin-bedded argillaceous siltstone with occassional sections of coarse, more massive turbidite wackes. It is overlain by the middle Aldridge, comprising up to 3000 metres of grey-weathering, thick to thin-bedded turbidites with some intercalated, well laminated siltstone marker units. The upper Aldridge comprises 500 metres of massive to faintly laminated argillite and argillaceous siltstone. The Sullivan deposit occurs at the transition between the lower and the middle Aldridge.

The Aldridge Formation is overlain by shallow-water to locally subaerial argillite, siltstone and quartzite of the Creston Formation (Figure 7), interpreted to represent mudflats and alluvial apron deposits that were fed from braided streams in the south, southwest and northeast (Winston and Link, 1993). These latter deposits are recognized in the Northern Hughes Range and are characterized by clean white, crossbedded and flat-laminated quartz sands. Overlying carbonate rocks of the Kitchener Formation are dominantly shallow-water deposits; prominent cyclical sedimentation in correlative rocks of the Helena Formation in Montana are interpreted to record periodic expansion and shrinkage of a Purcell (Belt) lake (Winston and Link, 1993).

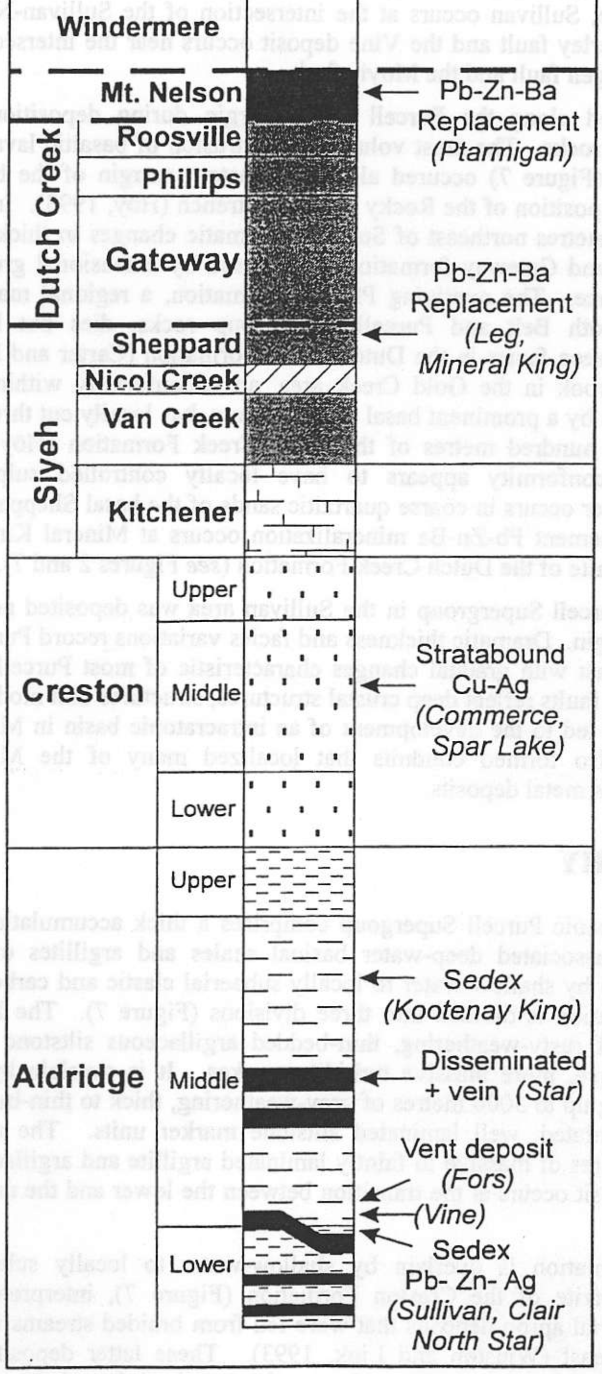

Figure 7. Stratigraphic column of the Purcell Supergroup, showing the position of important base and precious metal deposits.

Upper Purcell rocks include shallow-water carbonate and clastic rocks, deposited in a similar setting to those of the Creston and Kitchener formations and, along the eastern margin of the Purcell-Belt basin, a sequence of dominantly subaerial basalts of the Nicol Creek Formation (McMechan *et al.*, 1980; Höy, 1993). South of the Moyie fault, Purcell Supergroup rocks are overlain unconformably by Devonian carbonates of the Fairholme Group; north of the Moyie fault, Lower Cambrian shale and quartzite overlie the Purcell Supergroup.

DAY 1 - ALDRIDGE STRATIGRAPHY AND MAGMATISM; HYDROTHERMAL ACTIVITY AND MINERAL DEPOSITS

Kimberley to Creston and return

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INTRODUCTION

The first day will provide a regional setting for the Purcell basin in Canada, overview tectonics and structures, and outline the detailed stratigraphy of the Aldridge Formation, emphasizing regional correlations, source areas, and paleogeographic reconstructions. The location of stops are illustrated on Figures 8 and 13 and their stratigraphic position on the detailed stratigraphic column of Figure 9. Magmatism, specifically the thick accumulation of largely synsedimentary gabbroic sills, will be examined and related to regional hydrothermal alteration and mineral deposition.

Note that all distances are given from the traffic lights at Ross and Wallinger Streets, the main intersection in downtown Kimberley.

START POINT

0.0 km Ross and Wallinger Street, Kimberley; drive west on Ross Street (which becomes Gerry Sorenson Way) following signs to Kimberley ski area, passing Happy Hans campground.

STOP 1-1:

VIEW OF ROCKY MOUNTAIN TRENCH, ROCKY MOUNTAINS.

4.0 km This stop provides an overview and introduction to the regional geological setting of the Aldridge Formation and the Sullivan deposit. The comments below are largely summarized from the previous general geology section.

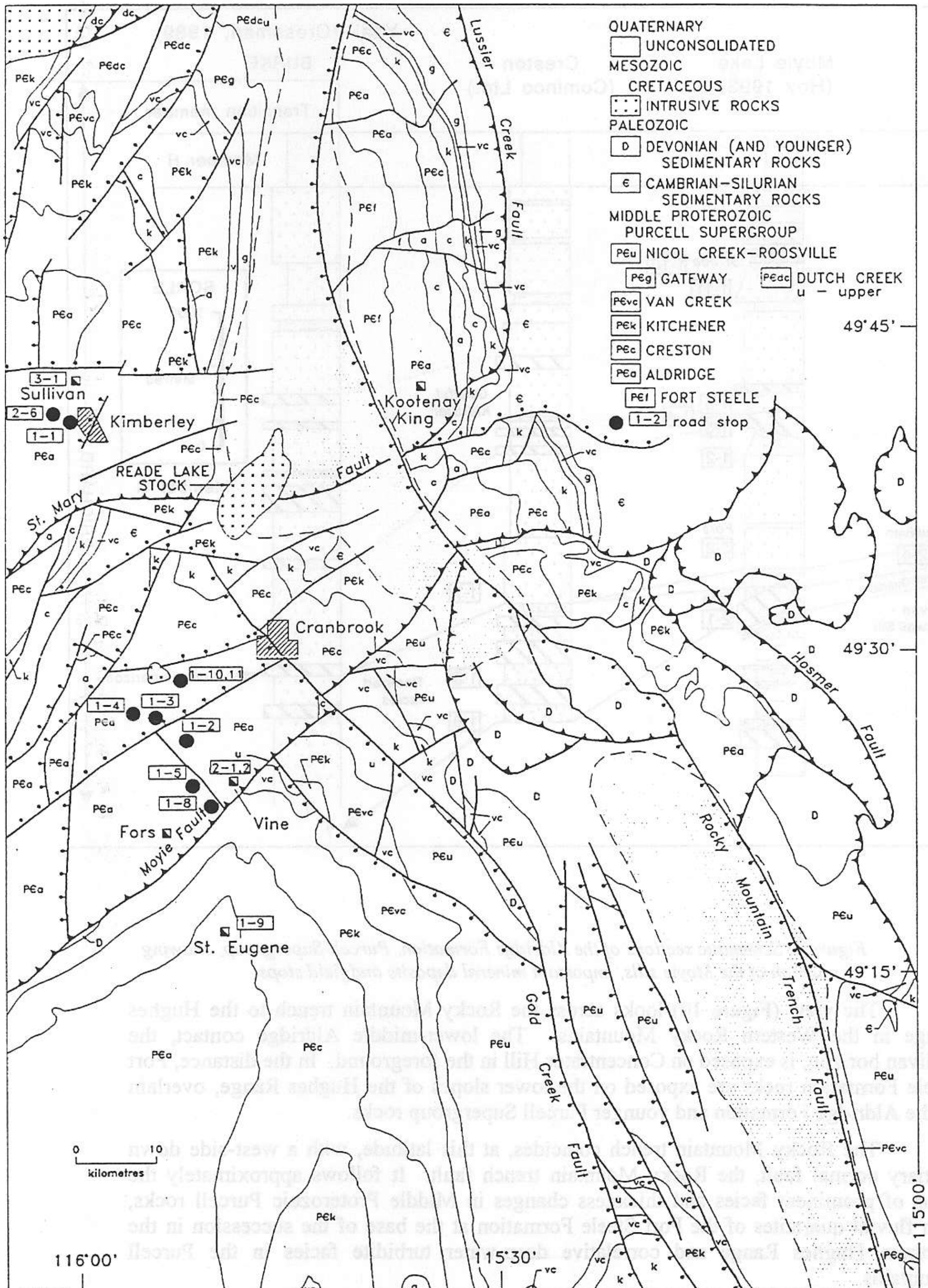

Figure 8. Geological map of the northeast portion of the field trip area (from Höy, 1993), showing location of field stops.

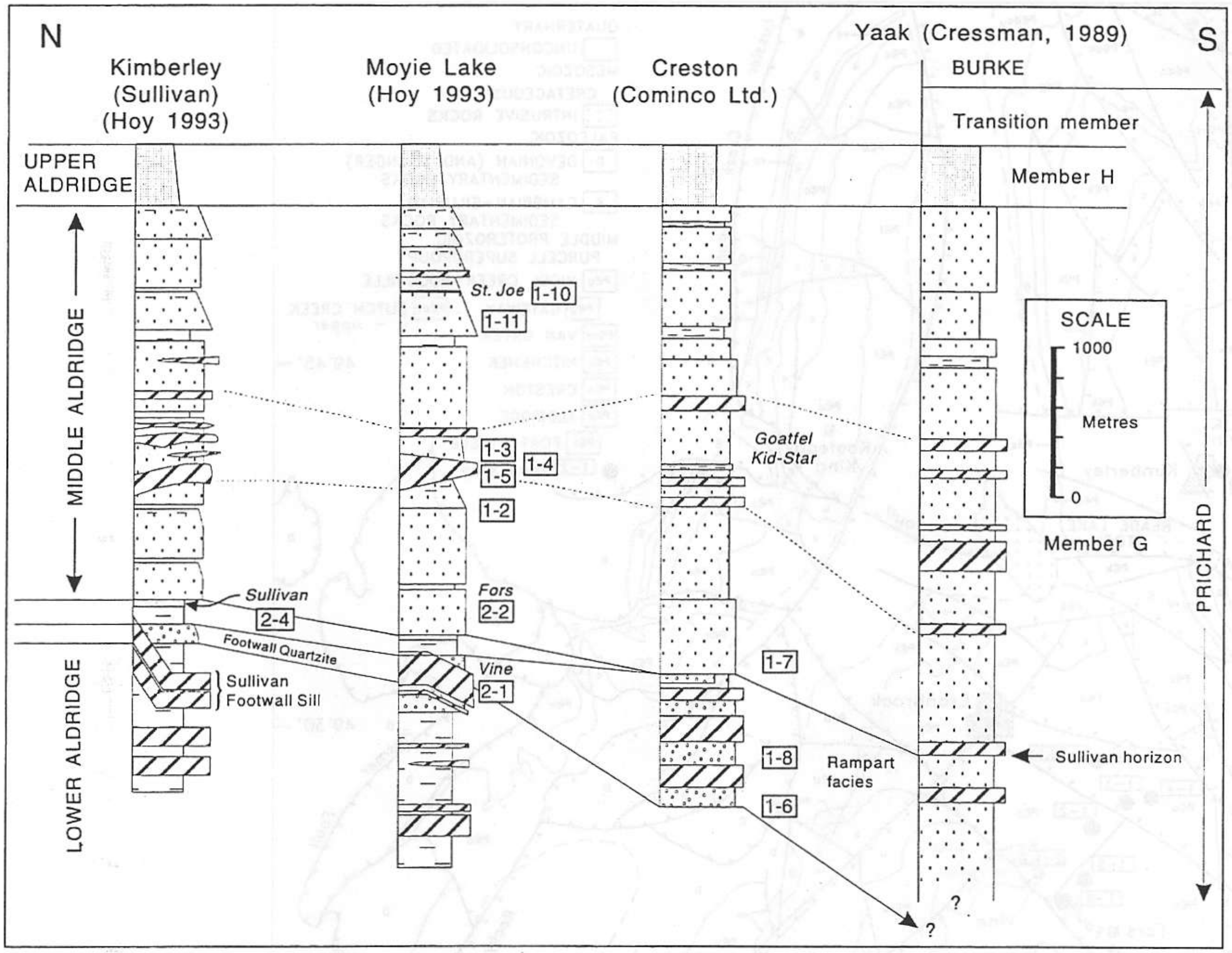

Figure 9. Schematic sections of the Aldridge Formation, Purcell Supergroup, showing position of the Moyie sills, important mineral deposits and field stops.

The view (Figure 10) looks across the Rocky Mountain trench to the Hughes Range in the Western Rocky Mountains. The lower-middle Aldridge contact, the Sullivan horizon, is exposed on Concentrator Hill in the foreground. In the distance, Fort Steele Formation rocks are exposed on the lower slopes of the Hughes Range, overlain by the Aldridge Formation and younger Purcell Supergroup rocks.

The Rocky Mountain trench coincides, at this latitude, with a west-side down Tertiary normal fault, the Rocky Mountain trench fault. It follows approximately the locus of prominent facies and thickness changes in Middle Proterozoic Purcell rocks, with fluvial quartzites of the Fort Steele Formation at the base of the succession in the Northern Hughes Range and correlative deep-water turbidite facies in the Purcell Mountains.

The Boulder Creek fault, which occurs in the valley just north of Mount Fisher (Figure 10), also follows the locus of a Middle Proterozoic structure. To the south, turbidites similar to those in the Purcell Mountains are exposed. Thus, the Boulder Creek fault and a segment of the Rocky Mountain trench fault define the faulted northeastern margin of the Belt/Purcell basin.

Retrace route towards Kimberley.

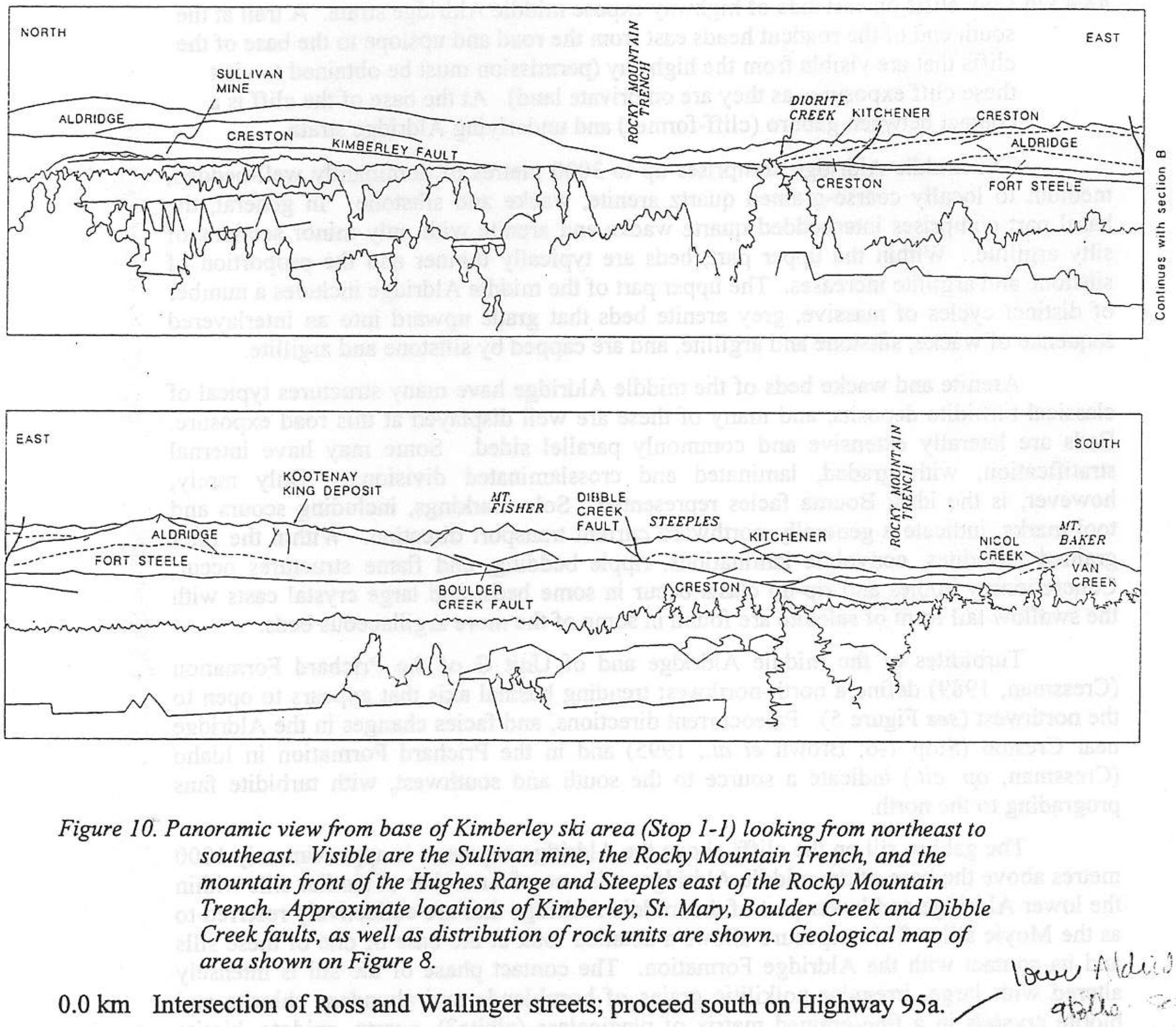

Figure 10. Panoramic view from base of Kimberley ski area (Stop 1-1) looking from northeast to southeast. Visible are the Sullivan mine, the Rocky Mountain Trench, and the mountain front of the Hughes Range and Steeples east of the Rocky Mountain Trench. Approximate locations of Kimberley, St. Mary, Boulder Creek and Dibble Creek faults, as well as distribution of rock units are shown. Geological map of area shown on Figure 8.

0.0 km Intersection of Ross and Wallinger streets; proceed south on Highway 95a.

6.7 km Marysville.

12.9 km Hill to west (Lone Pine Hill) is underlain by irregular bodies of gabbro (Höy, 1984).

15.3 km Junction, Wycliffe Road.

15.9 km View across St. Marys River. Bluffs on south side expose Pliestocence gravels and sands.

21.0 km Bridge over St. Marys River.

28.3 km Junction of Highways 95a and 95/3; proceed west on Highway 95/3 through Cranbrook.

37.4 km Travel Information Center and Jim Smith Road.

42.4 km Bluffs to west expose Moyie sill gabbro.

STOP 1-2:

MIDDLE ALDRIDGE FORMATION AND MOYIE SILL; LUMBERTON ROAD TURNOFF.

48.4 km Low cliffs on east side of highway expose middle Aldridge strata. A trail at the south end of the roadcut heads east from the road and upslope to the base of the cliffs that are visible from the highway (permission must be obtained to visit these cliff exposures as they are on private land). At the base of the cliff is a contact between gabbro (cliff-former) and underlying Aldridge strata.

The middle Aldridge comprises up to 3000 metres of dominantly well-bedded, medium to locally coarse-grained quartz arenite, wacke and siltstone. In general, the basal part comprises interbedded quartz wacke and arenite with only minor sections of silty argillite. Within the upper part, beds are typically thinner and the proportion of siltstone and argillite increases. The upper part of the middle Aldridge includes a number of distinct cycles of massive, grey arenite beds that grade upward into an interlayered sequence of wacke, siltstone and argillite, and are capped by siltstone and argillite.

Arenite and wacke beds of the middle Aldridge have many structures typical of classical turbidite deposits, and many of these are well displayed at this road exposure. Beds are laterally extensive and commonly parallel sided. Some may have internal stratification, with graded, laminated and crosslaminated divisions. Only rarely, however, is the ideal Bouma facies represented. Sole markings, including scours and tool marks, indicate a generally northward current transport direction. Within the finer grained turbidites, convolute laminations, ripple bedding, and flame structures occur. Concretionary bodies and rip-up clasts occur in some beds, and large crystal casts with the swallow tail form of selenite are found in some of the more argillaceous beds.

Turbidites of the middle Aldridge and of Unit G of the Prichard Formation (Cressman, 1989) define a north-northwest trending basinal axis that appears to open to the northwest (*see* Figure 5). Paleocurrent directions, and facies changes in the Aldridge near Creston (Stop 1-6; Brown *et al.*, 1995) and in the Prichard Formation in Idaho (Cressman, *op. cit.*) indicate a source to the south and southwest, with turbidite fans prograding to the north.

The gabbro sill on the cliffs above the Aldridge exposure is approximately 1000 metres above the base of the middle Aldridge; it is one of a number of similar sills within the lower Aldridge and lower part of the middle Aldridge that are collectively referred to as the Moyie sills. This exposure allows a detailed look at the base of one of these sills and its contact with the Aldridge Formation. The contact phase of the sill is intensely altered with large, irregular poikilitic grains of hornblende and abundant chlorite and biotite crystals in a fine-grained matrix of plagioclase (albite?), quartz, epidote, biotite and calcite. This alteration, including biotite, albite and hydrothermal minerals, is typical of contact sill alteration and is supportive evidence of intrusion into wet sediments. Stops 1-5, 1-7 and 1-8 will also examine alteration and structures associated with emplacement of other Moyie sills.

Turn onto Lumberton road.

STOP 1-3:

SUNDOWN MARKER, LUMBERTON ROAD

51.8 km Marker laminae in the upper part of the middle Aldridge occur in a small exposure on the north side of the road.

DAY 2 P.M. - SULLIVAN - NORTH STAR CORRIDOR

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The final part of the field trip will focus on ore formation and sediment alteration associated with hydrothermal processes by reviewing the geology of the Sullivan-North Star corridor (Day 2, P.M.), a graben characterized by fragmentals and intense alteration that extends 6 kilometres south of the Sullivan mine, and by an underground tour of the Sullivan Mine (Day 3, A.M.). Finally, on the last afternoon of the trip, we will examine in detail, a number of drill intersections through the Sullivan deposit, the footwall alteration zone, and the corridor.

0.0 km Intersection of Ross and Wallinger streets, Kimberley. Follow Gerry Sorensen Way to North Star ski area. Park at base of blue ski lift, and walk northwest past gates to first outcrops.

4.3 km Sullivan Deposit; Sullivan - North Star corridor

SULLIVAN-NORTH STAR CORRIDOR

North Star Hill

Altered and fragmented rocks of the Sullivan-North Star corridor are exposed on the lower part of North Star mountain and their distribution is marked by the brown iron-stained soils visible on the cleared ski runs. At the base of the slope, altered rocks of the corridor are covered by terraces of Pleistocene sediments, now site of the lodge and condominium complexes. Gabbro underlies the Pliestocene sediments below the elevation of the ski lodge (Figure 26).

The uppermost slopes of North Star Hill are underlain by unaltered east-dipping lower Aldridge strata cut by a variably developed steep, west-dipping cleavage. The western (upper) boundary of the alteration corridor occurs near north-trending mineralized structures (Midnight, Kellogg and Quantrell veins) and the stratiform and discordant orebodies at the North Star mine (Figures 26, 27 and 28). East (downslope) of this line, fragmental or massive unbedded units are common and rock variably altered and mineralized. The mine dumps of the North Star mine have largely been recontoured but are still visible south of the chairlifts. A 400 m2 area of patchy tourmalinite and elevated base metal content underlies the area above the Ski lodge. This tourmalinite zone is on strike and semi-continuous with tourmalinite that forms an envelope on the north-trending Stemwinder vein (Figures 26 and 28). The Stemwinder mine area is just out of view on the south side of Mark Creek.

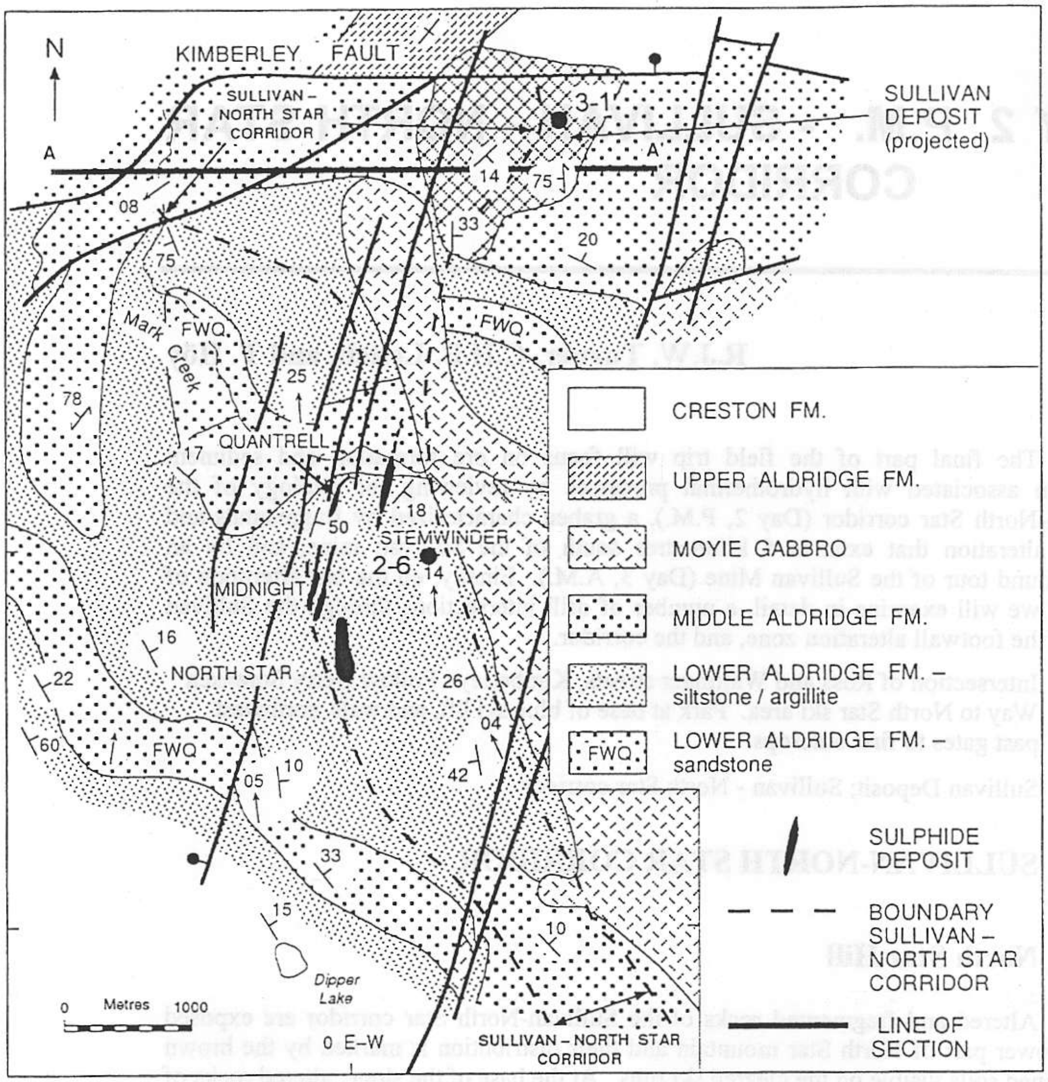

Figure 26. Geological map of the Sullivan-North Star corridor (modified from Hagen, 1985 and Höy, 1993); note field stops.

OVERVIEW

Geology of the Sullivan-North Star Corridor

The Sullivan-North Star corridor is an elongate, north-south-trending graben with abundant fragmental and disrupted sedimentary rocks that are variably altered and mineralized (Hagen, 1983; Höy, 1984). The corridor extends 6 km in length, 1-3 km in width, and over 500 metres in stratigraphic thickness (Figures 27-30). The Kimberley Fault truncates the corridor to the north while at the southern end, the corridor terminates in outcrops north of the Quaternary deposits of the St. Mary Valley (Figure 24). The corridor is widest adjacent to the Kimberley fault

Three gabbro sills with an aggregate thickness of 650 metres have been intersected in drilling below the Sullivan deposit (Figure 27). These sills are the upper part of a widespread sill complex intruded into the lower Aldridge Formation. The uppermost gabbro sill ("Footwall Sill") forms a discordant arch-like feature roughly coincident with the corridor and contains a core of plagioclase-quartz-biotite

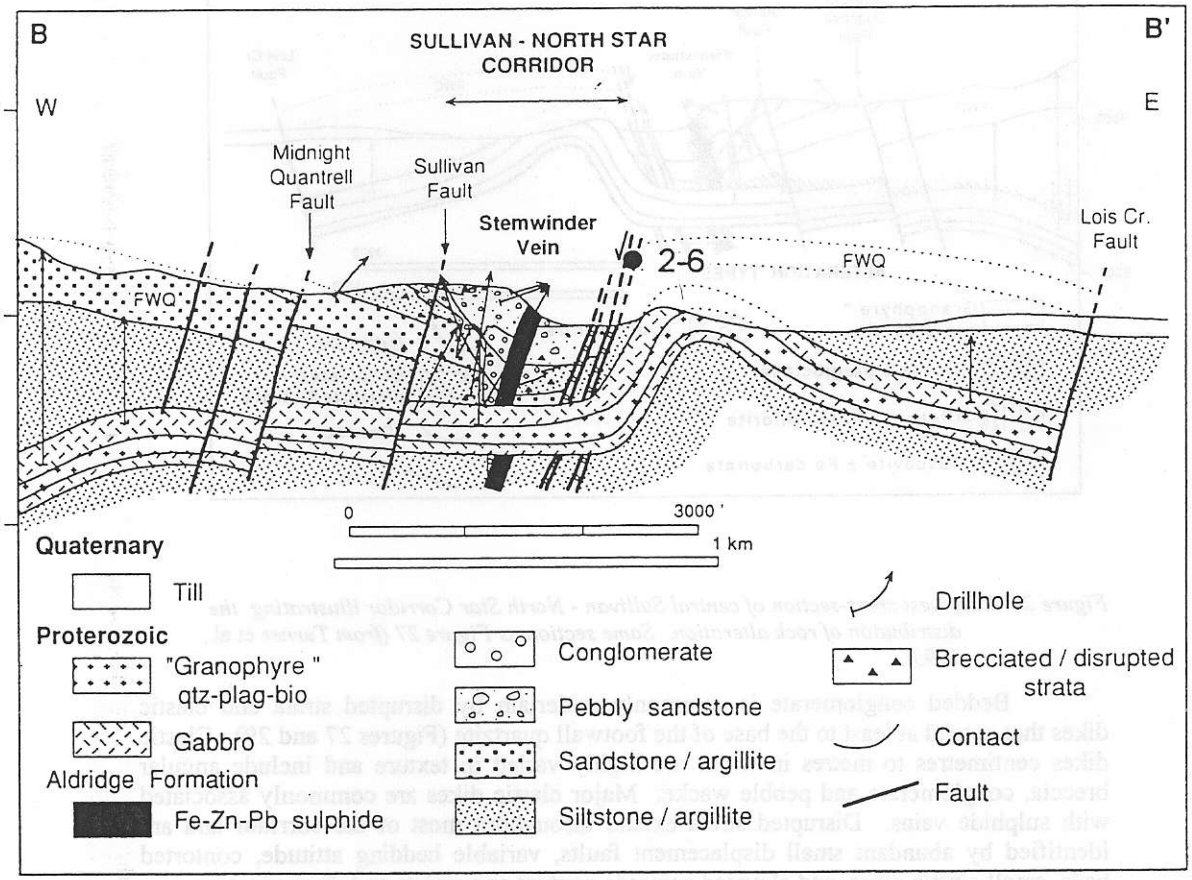

Figure 27. East-west cross-section of central Sullivan - North Star Corridor illustrating the distribution of stratigraphic units, intrusions and the Stemwinder vein. Location of section is shown on Figure 26. (from Turner et al.*, 1993).*

"granophyre". This biotite granophyre may represent injection of a differentiated silicic melt produced by assimilation and melting of Aldridge sediments, or the *in situ* reconstitution of sediment trapped between two gabbro sills by magmatic fluids. The top of the arch coincides with the stratigraphic level of the Sullivan orebody.

Fragmental rocks

Fragmental rocks include bedded conglomerate, semi-concordant bodies of massive pebble wacke, clastic dikes of conglomerate and breccia, and disrupted strata. Bedded conglomerate immediately underlies the Sullivan deposit, extends across the width of the corridor, and is composed of beds up to 5 metres thick and with graded tops. The original distribution of conglomerates is unclear as this stratigraphic level is only preserved in the northern part of the corridor near the Kimberley fault. The bedded conglomerate unit is typically 30 to 50 metres thick, but exceeds 300 metres in thickness west of the Sullivan deposit (Figure 27).

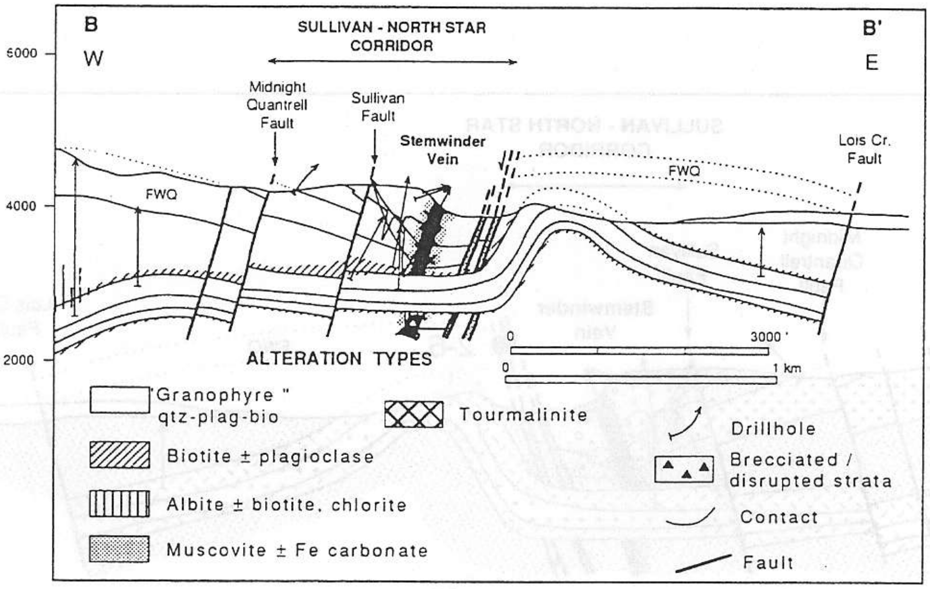

Figure 28. East-west cross-section of central Sullivan - North Star Corridor illustrating the distribution of rock alteration. Same section as Figure 27 (from Turner et al.*, 1993).*

Bedded conglomerate is commonly underlain by disrupted strata and clastic dikes that extend at least to the base of the footwall quartzite (Figures 27 and 29). Clastic dikes centimetres to metres in width are highly varied in texture and include angular breccia, conglomerate and pebble wacke. Major clastic dikes are commonly associated with sulphide veins. Disrupted strata extend throughout most of the corridor and are identified by abundant small displacement faults, variable bedding attitude, contorted beds, small clastic dikes, and elevated sulphide content as veinlets and disseminations.

Pebble wacke is composed of small rounded lithic fragments up to 10 mm scattered in a wacke matrix. Pebble wacke occurs as massive units that are conformable or semi-conformable, 10s to 100s of metres thick, and transitional laterally into disrupted strata. The Stemwinder vein cuts a semi-conformable body of pebble wacke that is transitional laterally and down into disrupted strata (Figure 27).

Rock alteration

Sandstone and siltstone of the Aldridge Formation is typically composed of 15-20% detrital plagioclase. Altered rocks in the Sullivan-North Star graben are distinguished from unaltered equivalents by the near absence of feldspars and the combined abundance of muscovite, sulphides, chlorite, epidote and garnet (Leitch *et al.*, 1991). Sulphides include abundant pyrite and pyrrhotite, lesser sphalerite and galena, and trace chalcopyrite and arsenopyrite. Major alteration types include tourmalinite, muscovite-pyrite, garnet, albite-biotite-chlorite, biotite-plagioclase hornfels, and quartz-plagioclase-biotite granophyre (Figures 28 and 30). There is no evidence for addition of hydrothermal silica to altered rocks. Intensity of alteration is highly variable within the corridor and related to a number of discrete hydrothermal centers, the major ones being the Sullivan deposit (Figure 30) and the Stemwinder vein system (Figure 28).

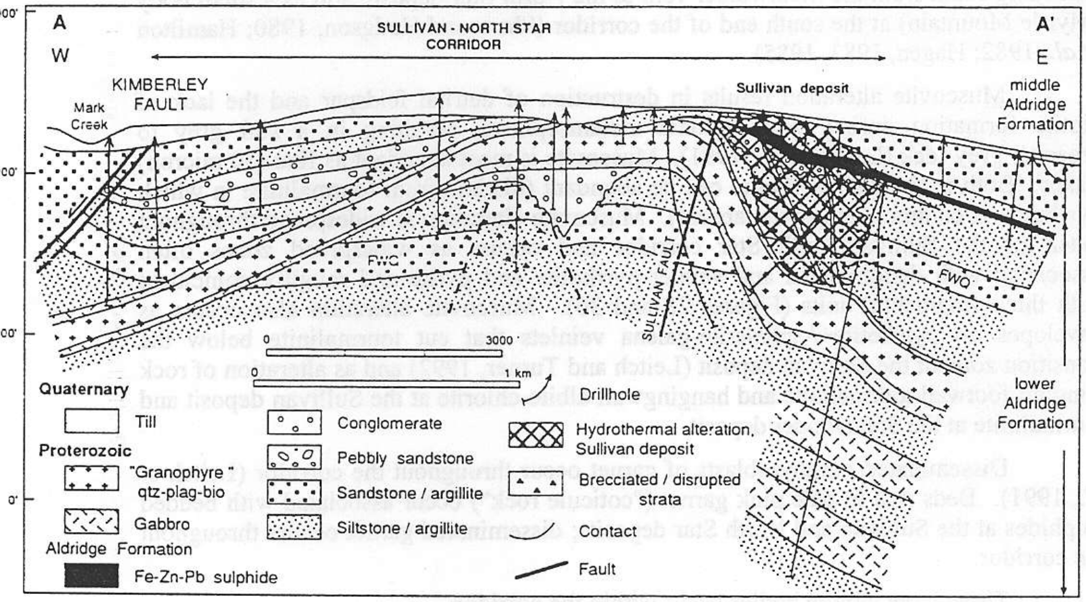

Figure 29. East-west cross-section of northern Sullivan - North Star Corridor illustrating the distribution of stratigraphic units, intrusions and the Sullivan deposit. Location of section is shown on Figure 26 (from Turner et al., *1993).*

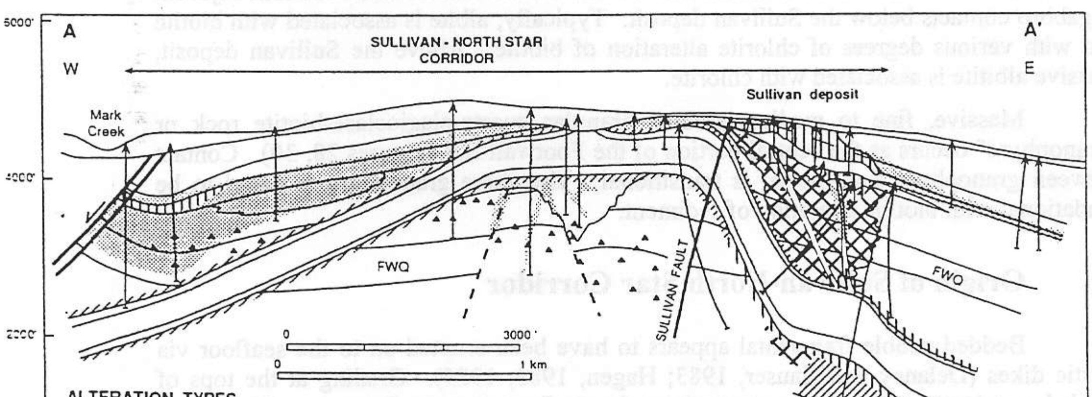

Figure 30. East-west cross-section of northern Sullivan - North Star Corridor illustrating the distribution of rock alteration. Same section as Figure 29. Location of section is shown on Figure 26 (from Turner et al., *1993).*

Tourmalinite alteration bodies occur as a pipe underlying the western part of the Sullivan deposit, as an envelope on the Stemwinder vein, as a cluster of small bodies extending south from the Stemwinder vein to the North Star deposit, and as a small body (Myrtle Mountain) at the south end of the corridor (Shaw and Hodgson, 1980; Hamilton *et al.*, 1982; Hagen, 1983, 1985).

Muscovite alteration results in destruction of detrital feldspar and the lack of biotite formation during later regional metamorphism, resulting in a soft grey to greenish-grey rock (Leitch *et al.*, 1991). Muscovite is most abundant as fine (50 micron) flakes. Both pyrite and pyrrhotite can be abundant (distinct from tourmalinite in which pyrrhotite is common and pyrite absent). Muscovite alteration is widespread throughout much of the Sullivan-North Star corridor and occurs as widespread zones often associated with disseminated and veinlet pyrrhotite and pyrite and roughly coincident with thick fragmental units (Figures 28 and 30). Muscovite alteration also occurs as envelopes on pyrrhotite+/-sphalerite-galena veinlets that cut tourmalinite below the transition zone of the Sullivan deposit (Leitch and Turner, 1992) and as alteration of rock fringing footwall tourmalinite and hangingwall albite-chlorite at the Sullivan deposit and tourmalinite at the Stemwinder deposit.

Disseminated porphyroblasts of garnet occur throughout the corridor (Leitch *et al.*, 1991). Beds rich in pale pink garnet ("coticule rock") occur associated with bedded sulphides at the Sullivan and North Star deposits; disseminated garnet occurs throughout the corridor.

Three large albitite bodies occur within the corridor:

(1) overlying the western Sullivan orebody (Shaw and Hodgson, 1980; Hamilton *et al.*, 1982)

(2) a kilometre west of the Stemwinder vein immediately overlying the footwall gabbro (Turner and Leitch, 1992); and

(3) 3 km west of the Sullivan deposit within the conglomerate horizon.

Smaller occurrences of albitic rock are associated with altered sediment adjacent to gabbro contacts below the Sullivan deposit. Typically, albite is associated with biotite and with various degrees of chlorite alteration of biotite. Above the Sullivan deposit, massive albitite is associated with chlorite.

Massive, fine to medium-grained granular quartz-plagioclase-biotite rock or "granophyre" occurs as the central portion of the Footwall Sill (Figures 28, 30). Contact between granophyre and gabbro is transitional; elsewhere granophyre is noted to be gradational with biotitic alteration of sediment.

Origin of Sullivan-North Star Corridor

Bedded pebble fragmental appears to have been erupted on to the seafloor via clastic dikes (Delaney and Hauser, 1983; Hagen, 1983, 1985). Grading at the tops of bedded conglomerates suggests transport on the seafloor as mass flows, possibly due to collapse of an eruptive pebble fragmental mound. The well sorted and rounded nature of the conglomerate yet local derivation precludes simple collapse of strata on a fault scarp; instead conglomerate dikes indicate rounding and winnowing occurred below the seafloor during upward movement. The lack of bedding in pebbly wackes suggests subsurface disaggregation and freezing of silt and sand-rich sediments due to liquifaction rather than seafloor transport and deposition. Disturbed sediments could represent collapse due to evacuation of underlying sediment during eruption (Hagen, 1983, 1985).

The energy required to disrupt and erupt sediment may come from rapid release of overpressured fluids within permeable horizons (*eg.* footwall quartzite), possibly due to heating by gabbro intrusion at depth, or liquifaction induced by seismic energy from fault movement. The coincidence of some clastic dikes and large sulphide veins in the corridor suggest common structural controls for sediment eruption and later hydrothermal upflow. Conglomerate eruption was closely followed by mainstage hydrothermal activity at the Sullivan deposit.

Of the alteration types, tourmalinite appears to be most closely linked to ore formation. Tourmalinite is spatially associated with the two major sulphide systems at Sullivan and Stemwinder, and based on stratigraphic evidence at Sullivan is also temporally associated with ore formation (Leitch and Turner, 1992). The widespread distribution of muscovite alteration around but not directly associated with the major sulphide occurrences suggests it reflects lower temperature fluid-rock interaction away from focused discharge areas. At the Sullivan deposit, muscovite alteration postdates tourmalinite formation and is associated with the waning stages of hydrothermal activity (Leitch and Turner, 1992). Garnet-rich beds associated with bedded sulphides appear to reflect Mn-rich sediments exhaled on the seafloor (Slack, 1993). Disseminated garnet reflects Mn enrichment of wallrock during alteration of the corridor (Leitch *et al.*, 1991). The close association of some albite-chlorite and albite-biotite-chlorite alteration with gabbro dike and sill contacts below Sullivan deposit and elsewhere in the corridor indicate this type of alteration was synchronous with or postdated gabbro emplacement and is later than ore formation (Turner and Leitch, 1992).

Structural controls

The north-south alignment of fragmental and altered rocks, sulphide veins and discordant zone of the Footwall Sill indicate north-trending faults define a graben structure that has informally been referred to as the corridor. The widening of the corridor along the Kimberley fault is in part an artifact of preservation of higher stratigraphic levels such as widespread bedded conglomerates and associated conformable alteration adjacent to the fault. However, the distribution of pebble wacke and disrupted sediments between the footwall quartzite and Sullivan horizon is also significantly wider adjacent to the Kimberley fault than it is farther south (this stratigraphic interval is exposed in drilling throughout the corridor). This distribution suggests an ancestral Kimberley fault was active during formation of the Sullivan deposit. The location of the Sullivan deposit may well reflect a high permeability zone along the intersection of these two fault zones. Early fault movement resulted in fragmentation and eruption of sediments, followed by widespread hydrothermal activity within the corridor. Focused discharge resulted in formation of a large seafloor sulphide body (Sullivan), as well as a smaller sulphide vein (Stemwinder deposit) and overlying seafloor deposit, now largely eroded (North Star deposit). Emplacement of gabbro intrusions was locally controlled by faults within the corridor; hydrothermal alteration associated with gabbro emplacement was focused along discordant limbs of intrusions.

STOP 2-6:

ALTERATION AND FRAGMENTALS ALONG WESTERN MARGIN OF SULLIVAN - NORTH STAR CORRIDOR

4.3 km Sullivan - North Star corridor.

This stop is a walking tour of the lower portion of the ski road that provides a transect across the eastern margin of the central part of the Sullivan-North Star corridor (Figure 26) and provides a look at representative alteration types and fragmental rocks. This stop is several hundred metres south of the section B-B' illustrated in Figures 27 and 28. In general, the stop traverses the down-to-west faults immediately west of the gabbro arch. Based on the presence of clastic dikes that occur within this fault zone, and alteration and mineralization that was focused along some clastic dikes, it is likely that the fault zone was active during Middle Proterozoic hydrothermal activity within the corridor. The discordant western side of the gabbro arch subcrops just down slope from the parking lot.

The least altered strata occur at the base of the hill. Upslope are tourmalinite bodies, fragmental rocks and muscovite alteration of lower Aldridge strata. Steeply dipping conglomeratic zones are interpreted as important fault structures (Figures 27, 28) that localized hydrothermal alteration.

0 m Weak alteration: Gate, base of access road (reset odometer). The rocks exposed in outcrop are biotitic siltstone, similar to regional Aldridge strata. Muscovite-altered strata lack biotite; it appears that during metamorphism, muscovite-altered strata lacked available iron for biotite formation. Therefore, the presence of biotite suggests the rock is largely unaltered, though the presence of some dark chlorite suggests weak alteration. This rock may represent less altered rock marginal to the corridor. A north-trending spaced cleavage is conspicuous.

30 m Mixed altered float: A pile of rock on west side of road provides a view of the range of rock types within the corridor. Rocks include: weakly altered conglomerate, intensely muscovite-pyrite altered conglomerate, gossanous breccia, tourmalinite matrix fragmental and gabbro.

100 m Tourmalinite: Road traverses cleared area. Low outcrops are on the west side of the road at edge of the forest. The cutcrop closest to road is a weakly biotitic (*i.e.* brownish color) muscovite-pyrite altered rock. This rock is more altered than biotitic siltstone at gate (*i.e.* more sulphide, muscovite).

At the edge of the trees is a small tourmalinite body, distinguished by its hardness, black color and prominent northwest-trending quartz veins. Quartz veins may reflect brittle nature of tourmalinite during deformation. Just upslope are shallow-dipping muscovite-pyrite altered siltstones. Pyrite is distinctly more abundant than in adjacent tourmalinite.

Ten metres upslope along the tree line is another small tourmalinite body surrounded by muscovite-pyrite altered strata. Some tourmalinite is distinctly soft due to the presence of some muscovite. Timing relationships of tourmalinite and muscovite are unclear but at the Sullivan deposit, tourmalinite is cut by later muscovite-sulphide alteration (Leitch and Turner, 1992). As many tourmalinite bodies within the corridor are surrounded by muscovite-pyrite altered rock, this detourmalinization process may be widespread.

130 m Muscovite altered tourmalinite: Road continues through forest. There is a low rib of outcrop 30 metres north of the edge of the clearing on west side of road. Dark, shallow northwest-dipping strata are altered to a tourmalinite-muscovite assemblage. Early tourmalinite may be partially altered by later muscovite alteration (*i.e.* detourmalinized).

160 m Clastic dike: Continue to low rib of outcrops 60 metres north of tree line on west side of road. A shallow north-dipping sequence of fine-grained sandstone and thin argillite beds is cut along a steep north-trending contact by a matrix-rich pebble wacke to conglomerate. The discordant contact is exposed on the north side of the largest outcrop.

Map distribution of units within lower Aldridge Formation suggest a down to the west fault in this vicinity (Figure 26); this clastic dike along with others exposed farther up the road may represent an early fault zone, active prior to lithification of the rock.

180 m Clastic dike and alteration: Continue to low rib and bench of outcrops 80 metres north of tree line on west side of road. A shallow north-dipping bedded sequence is altered to tourmalinite and muscovite (tourmalinite later altered to

muscovite?). Bedded sequence is cut by pebble clastic dike exposed on the flat bench on the north side.

230 m Intensely altered clastic dike. Continue to the bold north-trending rib with fresh roadcut exposures on west side of road. Rock has been intensely altered to muscovite with abundant disseminated pyrrhotite and minor sphalerite and galena. A steep north-trending foliation is well developed. A weak fragmental texture is preserved in some fresh surfaces; alteration has largely destroyed the original textures.

This clastic dike was a locus of hydrothermal fluid flow and is likely a north-trending fault. This fault set is a part of the structural control of alteration within the Sullivan-North Star corridor. These clastic dikes are similar to the north-trending fragmental bodies described by Hamilton *et al.* (1982) underlying the Sullivan orebody.

Return to Kimberley.

DAY 3 - SULLIVAN DEPOSIT

Kimberley, B.C.

C.H.B. Leitch, R.I Turner, P.W Ransom and Sullivan Mine Staff

This morning we will have an underground tour of the Sullivan mine. In the afternoon, we will visit the regional exploration office of Cominco Ltd., in Cranbrook, to look in detail at representative diamond drill core intersections through the deposit and corridor.

0.0 km From the traffic lights at intersection of Ross St. and Wallinger St., Kimberley, drive north on Wallinger St., turning left then immediately right at first stop sign. Follow street past switchback up hill. Continue past hospital and turn left at sign to Sullivan mine. Continue through gates and up to the mine.

STOP 3-1:

SULLIVAN MINE

4.5 km Sullivan Mine

Introduction

The Sullivan deposit, one of the largest massive sulphide base metal deposits in the world, is a stratiform sediment-hosted (sedex) deposit characterised by bedded iron, zinc and lead sulphides formed as hydrothermal sediments on the seafloor. It has been well described in a number of papers including Ethier *et al.* (1976) and Hamilton *et al.* (1982, 1983) and in guidebooks (Ransom *et al.*, 1985). The deposit is the focus of recent studies by a joint project involving the Geological Survey of Canada, British Columbia Geological Survey Branch, U.S. Geological Survey, industry, and a number of universities.

The Sullivan deposit has produced 137 million tonnes of ore (to September, 1993) from a deposit estimated to have originally contained more than 160 million tonnes of 6.5% lead, 5.6% zinc, 25.9% iron and 67 g/tonne silver. The Sullivan orebody comprises a broadly stratiform, upwardly convex lens and lesser bands covering an area of 1.6 x 2.0 km across composed mainly of pyrrhotite, sphalerite, galena and lesser pyrite. Contacts with enclosing sediments are sharp and conformable; the orebody is truncated on the north by the Kimberley fault. The deposit is divided by an irregular transition zone into two parts, western massive sulphides and an eastern zone of interbedded sulphides and silicate sedimentary rocks (Figure 31). Thus, the Sullivan deposit is a classic example of a stratiform deposit composed of a vent complex overlain and flanked by bedded sulphides.

The western massive sulphide body is part of an extensive vent complex, which includes: (a) the massive pyrrhotite replacement body; (b) an underlying tourmalinite pipe consisting of breccia, altered and fragmented strata and disseminated or veinlet

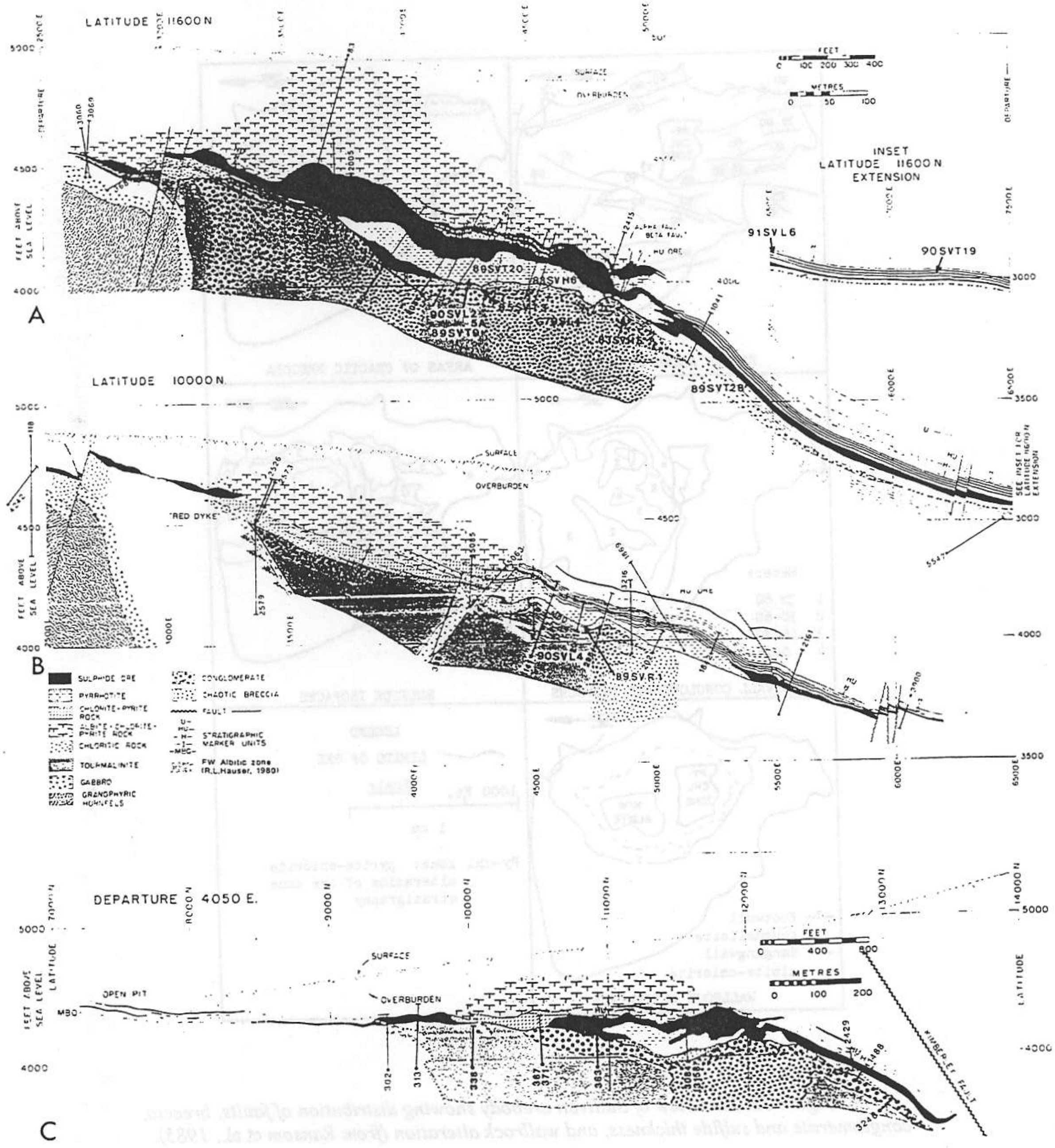

Figure 31. Geologic cross-sections through the Sullivan deposit (modified after Hamilton et al., *1982). (A) East-west cross-section at 11600 N (looking north). (B) East-west cross-section at 10000 N (looking north). (C) North-south cross-section at 4050 E (looking west).*

sulphides; and (c) albite-chlorite altered sediments in both footwall and hangingwall (Figures 31 and 32). The vent complex represents the feeder zone, or zone of hydrothermal fluid upflow and discharge at the seafloor during formation of the sulphide sediments.

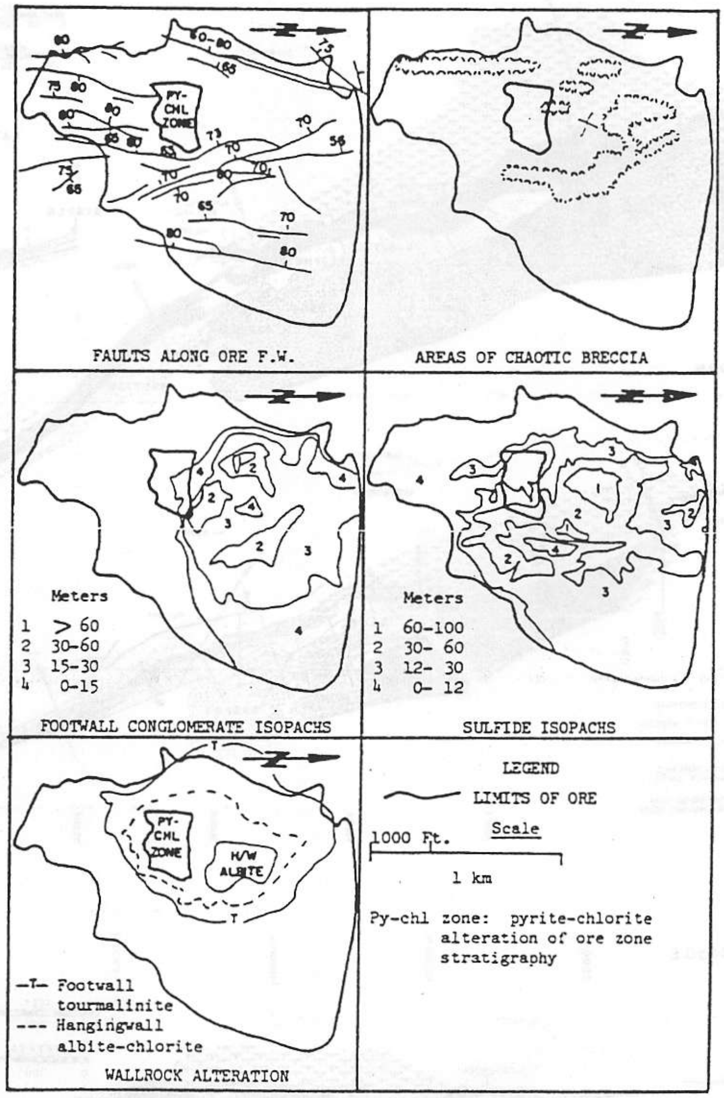

Figure 32. Plan view of Sullivan orebody showing distribution of faults, breccia, conglomerate and sulfide thickness, and wallrock alteration (from Ransom et al., *1985).*

The eastern bedded ores include five distinct conformable layers of generally well-laminated sulphides separated by clastic sediments. The sulphide layers thin to the east away from the transition zone. Sub-ore grade sulphide layers of pyrite and pyrrhotite with subordinate sphalerite and galena persist beyond the eastern limits of the ore-grade sulphides. Bedded sulphides are interpreted as sulphidic sediments deposited on the basin floor adjacent to the vent complex of the western orebody.

Fragmental rocks

A wide range of coarse clastic rocks including breccias, pebble dikes and conglomerates are associated with the Sullivan mine; collectively these are referred to as fragmentals by mine geologists. Two distinct varieties are recognized on the basis of textures (Delaney and Hauser, 1983): (1) pebble fragmental composed of subangular to subrounded, granule to pebble-sized clasts; and (2) breccia that consists of angular, granule to boulder-size clasts forming an intact to locally disrupted framework.

Underlying the western orebody is a fragmental body of breccia and pebble fragmental. This discordant body is almost 1 km in diameter and cuts at least 150 metres of thin and medium-bedded, fine wackes of the lower Aldridge Formation (Figures 31 and 32; Delaney and Hauser, 1983). Within the complex, Jardine (1966) mapped north-trending zones of breccia up to 150 metres wide and 1000 metres long (Figure 32). Where unaltered, the clasts and matrix are indistinguishable in composition from enclosing lower Aldridge strata. The top of the fragmental body is a pebble fragmental ("footwall conglomerate") that extends to the east as an eastward-thinning concordant sheet. Below the western orebody, the footwall conglomerate merges downward into underlying breccias and pebble fragmental dikes. The footwall conglomerate is up to 50 metres thick below the western orebody, where it is overlain by and separated from ore by up to 12 metres of laminated wacke, to less than 15 metres in the east where it directly underlies ore (Ransom *et al.*, 1985). The hanging wall conglomerate, a conformable pebble fragmental up to 4 metres thick and containing some ore grade clasts, underlies the H sulphide laminations (see below) and has been traced for 1000 metres along the southern margin of the orebody. A discordant, north trending pebble dike extends up to the hangingwall conglomerate and probably represents the feeder.

Discordant fragmentals are interpreted to have resulted from violent release of pore overpressure in the sedimentary pile (Delaney and Hauser, 1983), possibly caused by heat from magma bodies at depth. Rounding of clasts of local derivation may be explained by abrasion during ascent in a turbulent slurry. Erupted conglomerate may have accumulated as a mound that slumped eastward; accumulation may also have occurred in north trending structural depressions, parallel to the chaotic breccia bodies that fed the conglomerate bodies, related to withdrawal of material at depth. Bedded wacke between the conglomerate and sulphide body represent resedimented fine sediments related to sediment eruptive processes. The discharge pipes became the major conduits for rising hydrothermal solutions; the fragmentals are evidence that cross-stratal permeability developed prior to sulphide deposition.

Massive sulphides

The western massive portion of the Sullivan orebody, approximately 1000 metres in diameter, ranges from 10 to 100 metres thick with an average of about 50 metres; it is about twice as thick as the eastern part of the orebody (Figure 31). The lower portion consists of (a) a massive pyrrhotite lens up to 35 metres thick and 350 metres long in which sphalerite and galena are confined to disseminations, fracture fillings and wispy laminae (especially towards the margins of the lens); overlain by (b) massive layered galena-sphalerite-pyrrhotite, and (c) uppermost laminated sphalerite, galena and pyrrhotite plus minor pyrite intercalated with silicate laminae or layers of clastic sediment. Massive pyrrhotite grades upward and laterally into more continuous layers up to 10 metres thick rich in galena and sphalerite and interbedded with clastic sediments, both of which are extremely deformed in places. The thick section of massive sulphides with only minor clastic component in the western orebody is indicative of rapid accumulation which may have produced a sulphide mound over the vent zone. Ongoing hydrothermal activity produced the massive pyrrhotite lens over the vent zone by replacement of previously bedded or slumped sulphides. Remobilization of Pb, Zn and other minor metals as they were flushed out of the massive pyrrhotite zone, probably accompanied this replacement in a process of "zone refinement".

The eastern bedded ores average about 30 metres in thickness and consist of five laterally persistent sulphide layers called "bands" in sharp conformable contact with interbedded wacke (Figures 31 and 33). From base to top the sulphide bands are named Main, A, B, C and D bands. The basal Main band consists of a series of fine-grained pyrrhotite, sphalerite and galena beds generally less than 3 but up to 30 centimetres thick. The upper Main band and the overlying bands have up to 50% interbedded wacke; sulphide layers are almost monomineralic laminae up to 10 millimetres thick that persist laterally over 100 metres. Eastern bedded ore was probably deposited by one or more of three processes: distal accumulation of sulphides by fallout from a hydrothermal plume within a brine pool or open basin water column, or resedimentation of sulphide material from the vent mound area.

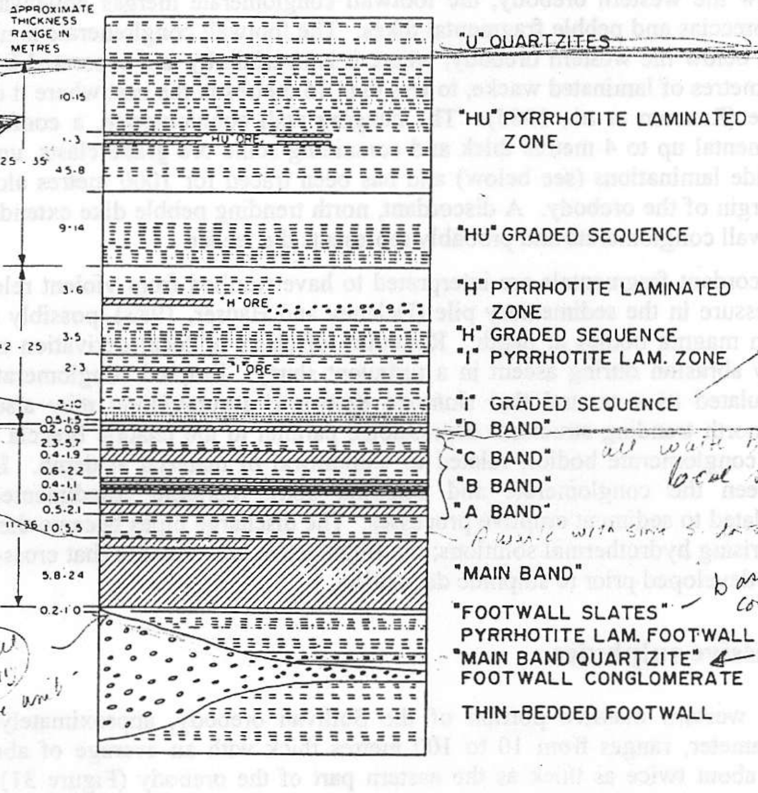

Figure 33. Ideal geological column, eastern part of Sullivan orebody (from Ransom et al., *1985).*

The ore bands are interbedded with massive wacke beds ("waste beds") up to 5.7 metres thick that make up to 40% of sequence of the eastern bedded ores (Figure 33). Unlike turbidite beds in the overlying middle Aldridge, the waste beds are not graded. These wacke beds terminate abruptly to the west at the transition zone and generally taper to the east. The wacke beds include a variety of sulphide and non-sulphide clasts, typically angular or irregular in shape. The most significant clast type are sheets of well-laminated pyrrhotite and wacke up to several meters long and one meter thick that lie subparallel to the contacts of the wacke bed (Ransom, 1989). Pyrrhotite laminations terminate abruptly at clast margins. Small adjacent clasts suggest disintegration of a large clast during transport within the wack bed; other clasts are folded suggesting plastic deformation during transport. The laminated pyrrhotite in the clasts is similar to the pyrrhotite-rich fringe of the Sullivan orebody. Waste beds are interpreted as debris flows derived from the marginal parts of the bedded ores (Ransom, 1989). A possible slump scar area 200 by 800 metres in area where laminated sulphides are missing has been identified by drilling in the southern marginal area beyond the mining limit of the orebody.

The eastern bedded ores and parts of the western orebody are overlain by three distinct stratigraphic intervals, the I, H and HU (Figure 33). These consist of a basal thick (1 to 5 metres) bed graded from quartz wacke to argillite and an upper 2 to 6 metre-thick argillite characterized by disseminated and laminated pyrrhotite ± sphalerite and rare galena. Distinctive laminae can be matched over 1000 metres (Freeze, 1966); zinc and lead content increase up dip and southwards into ore grade material above the western part of the orebody. The texture and graded nature of quartz wacke beds in the I, H and HU intervals are similar to regional turbidites; however these beds are anomalously thick (3-15 metres) in the vicinity of the Sullivan mine relative to the thickness of equivalent turbidites east of the mine (0.2-0.3 metres). This thickening of turbidites in the mine area may reflect ponding of passing turbidity flows by the bathymetric depression of the Sullivan deposit.

Overlying the HU interval is the U quartzite which is regarded as the base of the middle Aldridge (Figures 31, 33). Middle Aldridge sediments are typically thicker, coarser turbidites (silt to sand-sized wackes) than those found in the lower Aldridge.

Trace metal and gangue distribution

Within the Sullivan orebody, there are minor amounts of arsenopyrite, chalcopyrite, argentian tetrahedrite (freibergite), magnetite, ilmenite, rutile, sphene, hypogene goethite and in places cassiterite, stannite, bismuthian or antimonian boulangerite and/or jamesonite, native Bi-Sb alloy, gudmundite, bournonite and traces of molybdenite. Ruby silver (pyrargyrite) and scheelite are also reported (Hamilton *et al.*, 1982). The main gangue minerals, found especially as interbedded waste in the layered eastern ore, are quartz, muscovite, chlorite, biotite, carbonate and garnet; in places, tourmaline, albite to anorthite, minor tremolite, epidote, clinopyroxene, scapolite, and rare axinite are present.

The deposit is zoned, with lead plus silver values decreasing toward the margin in the eastern part. Tin and arsenic are concentrated in the western part; antimony appears to halo the arsenic (Figure 34). In general, metal distribution patterns appear to be related to proximal chaotic breccia and the transition zone, with higher absolute values of lead and silver and higher Pb/Zn and Ag/Pb ratios over the breccia zones (Freeze, 1966; Hamilton *et al.*, 1982; Ransom *et al.*, 1985). Vertical metal distribution patterns in the western orebody show increasing Pb and Zn and decreasing Fe upwards; in contrast, patterns in the eastern ore sequence show a general decrease in Pb, Zn and Ag and increase in Fe upsection (Hamilton *et al.*, 1983).

The transition zone, the boundary between the western massive orebody and the eastern bedded ores, is an arcuate zone up to 75 metres across that overlies the eastern margin of the footwall tourmalinite-pyrrhotite vent zone. It is characterized by thinning and complex folding of the ore. Several minor minerals (cassiterite, stannite, freibergite, arsenopyrite, bismuthian boulangerite and jamesonite, gudmundite, bournonite, ?bismuthinite, Bi-Sb alloy) rich in Sn, Ag and the semi-metals, As, Sb and Bi, appear concentrated near the transition zone in veins and disseminations with associated muscovite alteration (Leitch, 1992b). The distribution of Sb peripheral to that of As and Sn (Freeze, 1966; Figure 34) may be explained by the abundance of boulangerite and lesser jamesonite in and near the transition zone; tetrahedrite probably broadens the Sb distribution since it is more common and widespread than boulangerite and jamesonite. Silver is concentrated over the footwall vent zone inside the transition zone. Microprobe analyses suggest the principal locus of silver is in freibergite and in solid solution in galena as suggested by Freeze (1966) and Hamilton *et al.* (1982). Scheelite probably controls the distribution of tungsten.

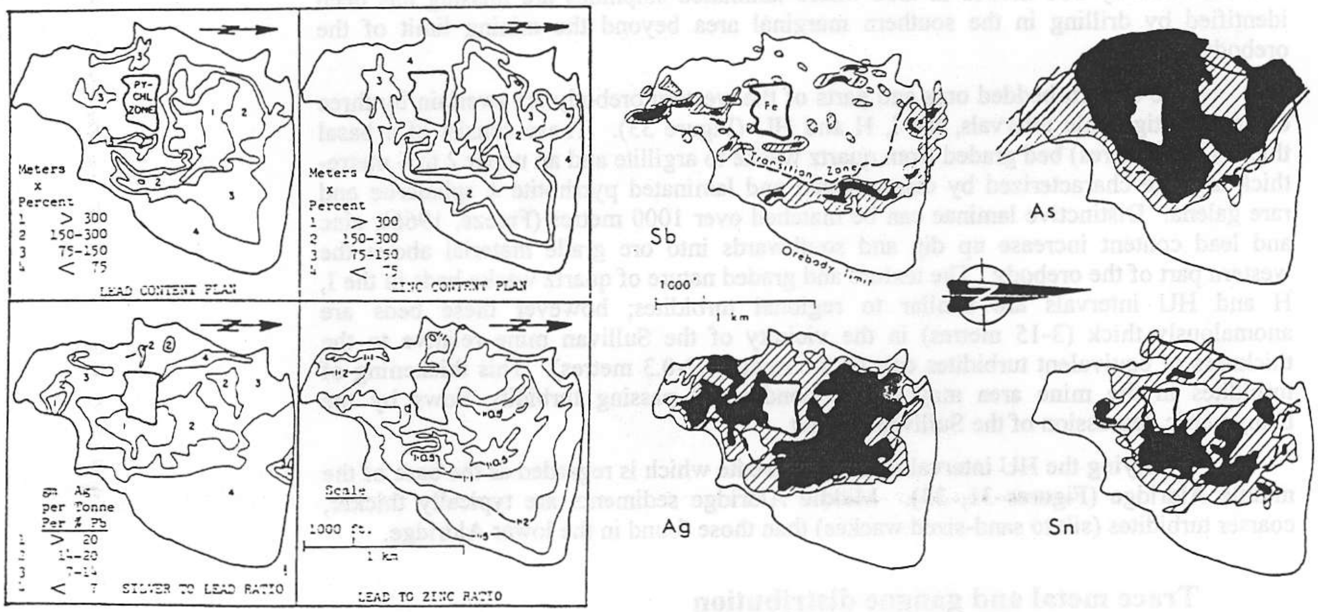

Figure 34. Plan view showing distribution of metals within Sullivan orebody (after Ransom et al, 1985 and Freeze, 1966). For Sb, As, Ag and Sn the white, hachured, and dark areas indicate increasing levels of each element. Fe = central pyrite-chlorite-calcite zone.

The distribution of Bi probably lies inside that of Sb, since it is found in bismuthian boulangerite and jamesonite, and native Bi-Sb alloy, within the area delimited by the transition zone. It thus may mimic the distribution of arsenic (Figure 34); the occurrence of the Bi-Sb alloy with arsenopyrite supports this hypothesis. Tin, recovered during mining of the western orebody, is primarily in cassiterite (less in stannite) and is concentrated in an annular zone inside the transition zone coincident with higher arsenic contents (Freeze, 1966; Figure 34). Most tin is associated with the pyrrhotite-rich zone at the base of the orebody within an area bounded by the transition zone, with values falling off towards the hangingwall (Freeze, 1966). The association of tin-bearing minerals with muscovite or arsenopyrite-bearing cross-cutting structures suggests that Sn, along with As, Bi, and possibly Sb, is related to late-stage upflow of hydrothermal fluids in the transition zone (Figure 35; Leitch and Turner, 1992).

Cd, In, Tl, Hg and a portion of the Mn in the Sullivan deposit are probably contained within and controlled by the distribution of sphalerite. Up to 0.3 wt% Cd is present in sphalerite; low levels of In (0.05-0.08%) and Hg (0.4%) are detected.

Coincidence of maximum concentrations of Tl with Zn-rich areas confirms that Tl occurs in sphalerite. Ga and Ge recovered in minor quantities at the Trail smelter probably are also hosted in sphalerite.

Microprobe analyses indicate two varieties of chlorite in the deposit: 1) a widely distributed Mg-rich variety and 2) a peripheral Fe-rich variety present mainly in the eastern bedded ores. The Fe content of type 1) chlorite is highest in the center of the deposit, but for type 2) it increases towards the fringe of the deposit. There is also a zonation in carbonate, garnet and chlorite to higher Mn toward the fringes of the Sullivan deposit. Carbonates vary from calcite to manganoan calcite, ankerite or siderite (C.H.B. Leitch, unpublished data). Garnets are spessartine rich (Barnett, 1982). Manganese enrichment occurs peripheral to other stratiform sediment-hosted Zn-Pb deposits, such as Meggen in Germany (Gwosdz and Krebs, 1977) or Tynagh in Ireland (Russell, 1974), and is known to concentrate distally in the Red Sea muds (Zierenberg and Shanks, 1988). This suggests elevated Mn content peripheral to the Sullivan and North Star deposits is due to Mn-rich exhalations. Garnet formed preferentially during metamorphism in the Sullivan-North Star altered corridor because of elevated Mn content of the altered strata (Leitch *et al.*, 1991). Metamorphic recrystallization has concentrated the Mn into certain preferred phases such as garnet and carbonate and, to a lesser extent, tremolite, diopside, chlorite, biotite and epidote. Thus the simple picture of a manganese "halo" surrounding the Sullivan deposit has been modified and blurred by widespread exhalation from several centers surrounding the deposit, and by local metamorphic redistribution. Whole-rock analyses for Mn around the Sullivan deposit and in the Aldridge show complex trends possibly due to mobilization of Mn into carbonates (J. Hamilton, personal communication, 1991).

Trends are also apparent in Fe content of epidote and possibly biotite in the Sullivan-North Star corridor. The Fe content of epidote increases from regional unaltered rocks to the altered corridor. Also, Fe contents in chlorites are highest in massive sulphide samples, associated with minor occurrences of Fe-rich chlorite (chamosite) and biotite (lepidomelane). This is in contrast to the observed decrease in the Fe content of most silicates towards the center of other metamorphosed massive sulphide deposits, predicted due to greater affinity of sulphides for Fe in the competition between sulphides and silicates during recrystallization (Nesbitt, 1986).

Footwall sulphide network

The western massive sulphide portion of the Sullivan deposit is underlain by an extensive, in places intensely developed stringer network of pyrrhotite-quartz-Fe carbonate veins in tourmalinite (Figure 36; McAdam, 1978, Leitch and Turner, 1992). These sulphide veinlets, as well as sulphide disseminations and sulphide matrix in pebble fragmentals are abundant within 50 metres of the base of the deposit. The veinlets may also contain minor sphalerite, galena and rare arsenopyrite, chalcopyrite, cassiterite, tourmaline and scheelite. The sulphide network ranges from wispy, irregular veinlets that likely formed within weakly indurated sediments at relatively early stages, to planar veins with increasingly abundant quartz and carbonate that appear to have formed at later stages in more indurated parts of the feeder zone. Massive veins are locally up to 1 metre thick, and major stringer zones are up to several tens of meters wide.

A crescent-shaped zone around the margins of the tourmalinite pipe is characterized by the presence of sphalerite and galena in the veinlets (Figure 36), with associated tourmaline-destructive muscovite or chlorite alteration. This may represent the site of late-stage fluid flow after sealing of the main central conduit (Figure 35, Stage 2).

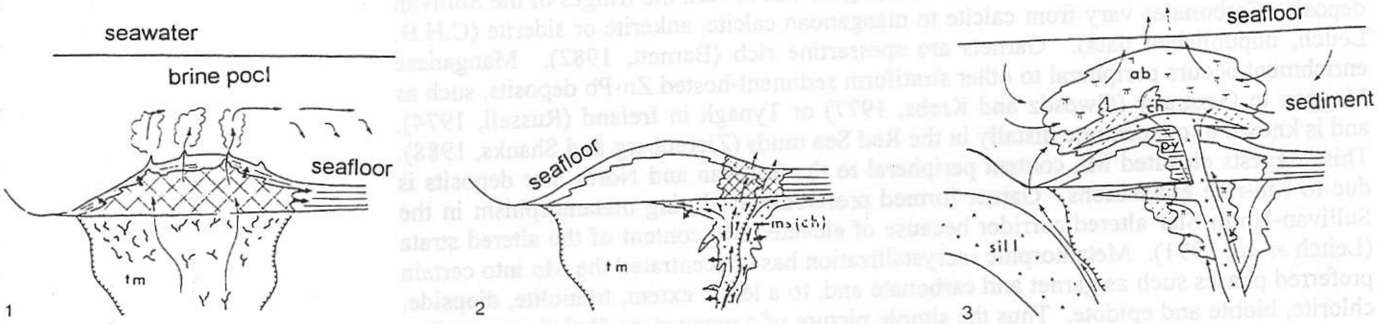

Figure 35. Postulated evolution of the hydrothermal system, Sullivan deposit (Leitch and Turner, 1992). (1) Main stage hydrothermal flow results in sulfide sedimentation in a brine pool, with progressive replacement of early-formed sulfides by massive pyrrhotite and underlying pyrrhotite network and tourmalinite alteration (tm). (2) Late-stage hydrothermal flow is concentrated at the periphery of the main vent zone giving rise to pyrrhotite-sphalerite-galena-sulphosalt veinlets in the transition zone, accompanied by muscovite and ?later chlorite (ms, ch). (3) Post-mineral fluid flow set up by magma body feeding Moyie sills and focused by vertical structures results in albite-chlorite-pyrite alteration (ab = albitite alteration; ch = chlorite-pyrite-pyrrhotite alteration; pyrite = pyrite-carbonate-chlorite alteration).

Fluid inclusion studies

Within the network veinlets, quartz and, to a lesser extent, sphalerite and carbonate in the network veins contain abundant secondary or pseudosecondary fluid inclusions, many of which contain halite at room temperature (Leitch, 1992a; Leitch and Turner, 1991). Inclusions are not seen in wallrock detrital quartz grains, which do not appear to be significantly recrystallized by the greenschist metamorphism. Fluids trapped in the inclusions are probably samples of the mineralizing fluids, in places diluted and/or reset by metamorphism. Mineralizing fluids are characterized as moderately saline 15-32 wt% ($NaCl+CaCl_2+?MgCl_2$) brines; homogenization temperatures (Th) range from 200-300°C. Due to the high confining pressures (1-2 kb) during metamorphism, it is unlikely that many of the inclusions were reset, so the observed Th values probably do not reflect metamorphism. If the observed Th does represent mineralization temperature, the pressure correction of 20-30°C for 0.2 kb (2000 metres water depth) would give trapping temperatures of 220-330°C (Roedder, 1984). Primary fluids trapped in 0.5 millimetre tourmaline recrystallized by chlorite-pyrrhotite alteration (8-18 wt% NaCl±?KCl, Th=225-300°C) are similar to secondary fluids trapped in quartz associated with albite-chlorite-pyrite alteration (14-20 wt% NaCl±?KCl, Th=165-250°C), suggesting late-stage fluids were less saline and contained no significant Ca or Mg. Late fluids associated with Mesozoic deformation, characterized by low salinities of <5 wt% NaCl, with variable but significant CO_2+CH_4, are found as secondary inclusions with Th 200-350°C (Leitch, 1991). Lower temperature secondary inclusions in quartz, albite and sphalerite range from 3 to 20 wt% NaCl, Th 90-150°C. Saline (halite-saturated) fluids are found at several other prospects (North Star, Quantrell, St. Joe and Kid-star) in Aldridge rocks and in veins in Moyie gabbro sills (Leitch, unpublished data).

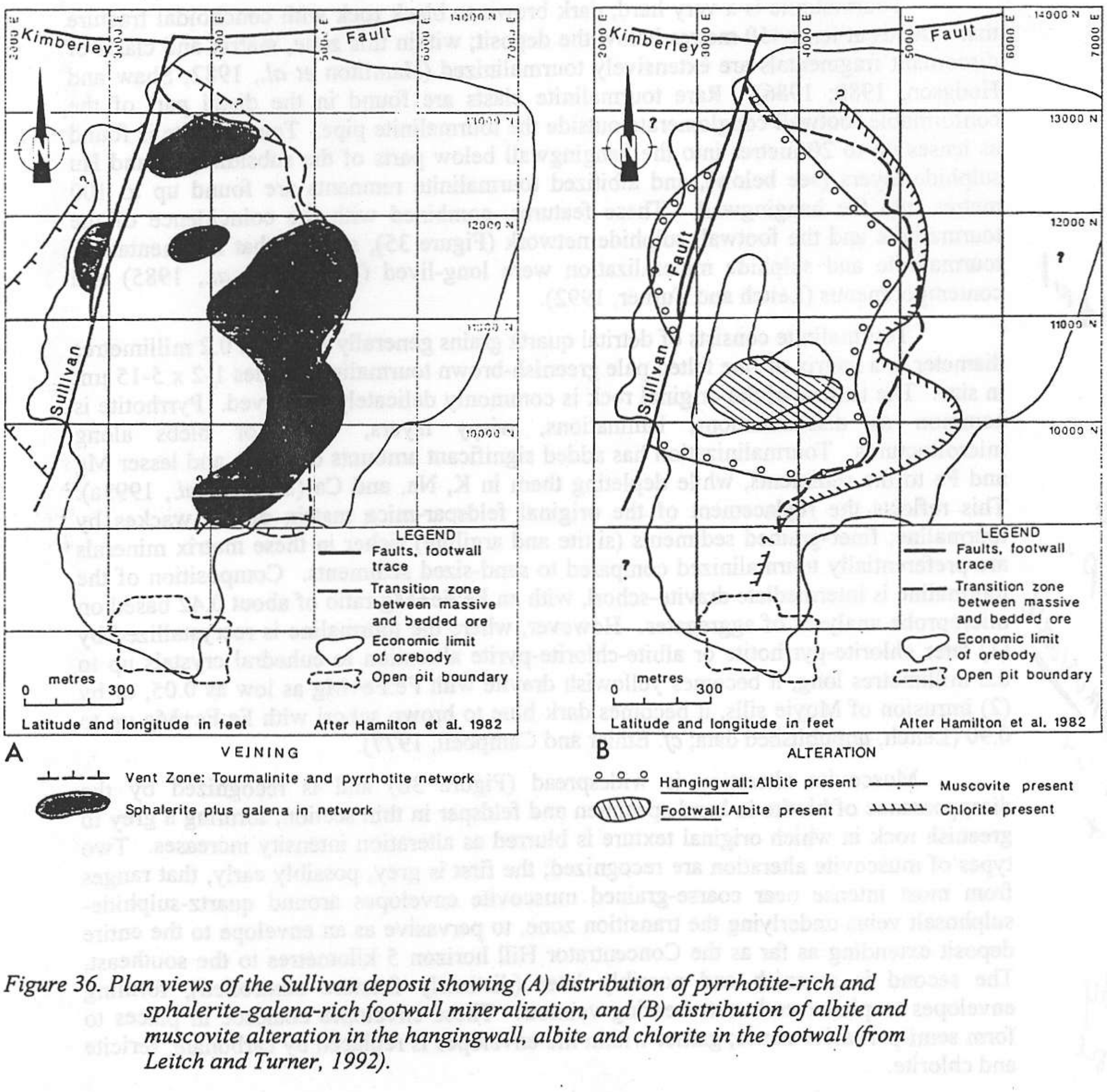

Figure 36. Plan views of the Sullivan deposit showing (A) distribution of pyrrhotite-rich and sphalerite-galena-rich footwall mineralization, and (B) distribution of albite and muscovite alteration in the hangingwall, albite and chlorite in the footwall (from Leitch and Turner, 1992).

Alteration

Alteration at Sullivan is very well developed compared to most sedex deposits due to the abundance of detrital feldspar relative to quartz. Four main types of alteration are recognized at Sullivan, in temporal order from early to late: tourmalinite, muscovite (or sericite), chlorite-pyrrhotite, and albite-chlorite-pyrite. Both muscovite and chlorite may have had various pre-metamorphic clay mineral precursors, and increase at the expense of feldspar, biotite and even quartz. Also, both muscovite and chlorite are tourmalinite destructive. Albite and chlorite occur up to 150 metres stratigraphically above the orebody, and so are post-mineral.

The composition of unaltered rocks is difficult to estimate due to metamorphism and the interlayering of variable amounts of mud-rich and sand-rich rocks. Away from the mineralization, background rock consists mainly of detrital quartz in a matrix of biotite, muscovite and/or sericite, feldspar (mainly plagioclase of about albite to ?oligoclase composition and minor microcline), with lesser garnet, epidote, chlorite, carbonate, and minor sphene, tourmaline, rutile, pyrrhotite or pyrite, carbonaceous matter, allanite, apatite and zircon (Edmunds, 1977; Leitch, 1992b).

Tourmalinite is a very hard, dark brown to black rock with conchoidal fracture that extends at least 450 metres below the deposit; within this zone, matrix and clasts of discordant fragmentals are extensively tourmalinized (Hamilton *et al.*, 1982; Shaw and Hodgson, 1980; 1986). Rare tourmalinite clasts are found in the distal part of the conformable footwall conglomerate outside the tourmalinite pipe. Tourmalinite is found as lenses up to 20 metres into the hangingwall below parts of the subsidiary H and Hu sulphide layers (see below), and albitized tourmalinite remnants are found up to 100 metres into the hangingwall. These features, combined with the coincidence of the tourmalinite and the footwall sulphide network (Figure 35), suggest that fragmentation, tourmalinite and sulphide mineralization were long-lived (Ransom *et al.*, 1985) and contemporaneous (Leitch and Turner, 1992).

Tourmalinite consists of detrital quartz grains generally less than 0.2 millimetres diameter in a matrix of fine felted pale greenish-brown tourmaline needles 1-2 x 5-15 μm in size. The texture of the original rock is commonly delicately preserved. Pyrrhotite is common as disseminations, laminations, wispy layers, veins, or blebs along microfractures. Tourmalinization has added significant amounts of boron and lesser Mg and Fe to the sediments, while depleting them in K, Na, and Ca (Shaw *et al.*, 1993a). This reflects the replacement of the original feldspar-mica matrix of the wackes by tourmaline; finer-grained sediments (siltite and argillite) richer in these matrix minerals are preferentially tourmalinized compared to sand-sized sediments. Composition of the tourmaline is intermediate dravite-schorl, with an Fe:Fe+Mg ratio of about 0.42 based on microprobe analyses of aggregates. However, where the tourmaline is recrystallized by (1) later chlorite-pyrrhotite or albite-chlorite-pyrite alteration to euhedral crystals up to 0.5 millimetres long, it becomes yellowish dravite with Fe:Fe+Mg as low as 0.05, or by (2) intrusion of Moyie sills, it becomes dark blue to brown schorl with Fe:Fe+Mg up to 0.90 (Leitch, unpublished data; *cf.* Ethier and Campbell, 1977).

Muscovite alteration is widespread (Figure 36) and is recognized by the disappearance of biotite in hand specimen and feldspar in thin section, forming a grey to greenish rock in which original texture is blurred as alteration intensity increases. Two types of muscovite alteration are recognized; the first is grey, possibly early, that ranges from most intense near coarse-grained muscovite envelopes around quartz-sulphide-sulphosalt veins underlying the transition zone, to pervasive as an envelope to the entire deposit extending as far as the Concentrator Hill horizon 5 kilometres to the southeast. The second is greenish and possibly later (distinctly fracture controlled), forming envelopes to planar carbonate-bearing veinlets. These envelopes coalesce in places to form semi-pervasive zones; garnet within the envelopes is replaced by carbonate, sericite and chlorite.

Chlorite alteration is mainly found inboard of the transition zone (Figure 36) and may be divided into early chlorite-pyrrhotite and later chlorite-pyrite assemblages; the former is confined to the footwall of the deposit and the ore zone, whereas the latter is found both below and above the deposit. Chlorite-pyrrhotite occurs mainly immediately below the massive pyrrhotite zone at the centre of the orebody in a conformable zone up to 10 metres thick. Accessory minerals in this zone are quartz, muscovite, sphene, carbonate and tremolite (Leitch, 1991) with minor but significant allanite (Campbell and Ethier, 1984; Schandl and Gorton, 1992). Chlorite-pyrite occurs at the top of the sulphide body in a semi-conformable zone separating ore from albitite, as crackle breccia matrix to albitite, and as crosscutting zones in the footwall, some of which are cored by albite alteration (see below). A cylindrical pipe of pyrite-chlorite-calcite 350 x 250 metres across replaces the central portion of the western orebody; in the core of this zone pyrrhotite is replaced by pyrite, and sphalerite and galena are absent. In the hangingwall, a 300 metre diameter core of albitite, composed of albite-chlorite-sphene and minor quartz, pyrite and calcite, and extending at least 120 metres above the deposit, is surrounded by variably albite-chlorite altered rocks over a 1000 x 600 metre area (Shaw *et al.*, 1993b). This hangingwall core of albite shows an apparent displacement 240 to 300 metres north relative to the center of pyrite-chlorite-calcite alteration of the ore zone (McClay, 1983; but see Paakki *et al.*, 1995 for evidence against a single translation). Chlorite-pyrite veins and alteration envelopes in the footwall and ore zone, and albite-chlorite-pyrite alteration in the hangingwall appear to be late, related to hydrothermal flow generated by the emplacement of mafic magma at depth below Moyie sills and dikes that are unusually abundant in the footwall of the deposit (Figure 35, Stage 3).

Relationship of albite-chlorite-pyrite alteration to gabbro intrusions

The Sullivan deposit is underlain by a major sequence of Moyie gabbro sills, the uppermost of which comprises a 15 metre thick upper gabbro separated from a lower 60 metre gabbro by 90 metre of granophyric rocks that may represent recrystallized sediment and gabbro. This sequence lies 450 metres below the ore horizon except on the western side where it abruptly cuts up-section to form a 1 kilometre wide north trending, gently north plunging arch, the crest of which is in contact with the western orebody (Figure 31). The root zone of chlorite-albite-pyrite ± calcite alteration coincides with a set of dikes and sills, apophyses of this larger footwall gabbro sill (Turner and Leitch, 1992). Altered tourmalinite adjacent to gabbro is zoned from proximal albite-chlorite to chlorite-pyrite; alteration postdates intrusion as some dikes and sills are locally altered. The position of the dike set may have localized a plume of rising hydrothermal fluids; zoned alteration envelopes on individual dikes indicate fluid flow was channeled along intrusion margins (Figure 35; Turner and Leitch, 1992).

Höy (1989) suggested that the Moyie sills were intruded into unconsolidated Aldridge sediment and proposed the Guaymas sedimented rift basin as a modern analogy. Basalt sill complexes are known to intrude modern sediments to within tens of metres of the present seafloor (Einsele, 1982; Gieskes *et al.*, 1982; Zierenberg *et al.*, in press). A model for intrusion by Einsele (1982) assumes upward-younging sills as each subsequent magma injection rises to the top of previously altered sediment, achieves neutral bouyancy and spreads laterally. Such sills are only slightly younger than the sediments they intrude. One might speculate therefore, that the minimum age of the two gabbro sill complexes exposed southwest of the Sullivan mine (Leech, 1957) can be dated by the stratigraphic level of the uppermost sill of each complex; an older intrusive event up to the time of formation of the Sullivan deposit, and a younger event during Middle Aldridge time. The upward termination or "silling out" of small gabbro dikes within or immediately above the Sullivan orebody, and the intrusion of the footwall sill up to the base of the orebody suggests that local gabbro intrusion took place when the Sullivan sulphide body was only buried a short distance below the seafloor, as suggested by Hamilton *et al.* (1982). During early burial, the indurated footwall sediments and thick sulphide mass of the Sullivan deposit would have had a higher density than overlying turbidite sediments. Magma rising through the indurated tourmalinized footwall sediments and massive sulphide body achieved neutral buoyancy at the base of overlying partly lithified silts and muds and did not rise farther.

During emplacement of the Moyie syn-rift intrusive complex, hydrothermal circulation driven by intrusions below those presently exposed (sedimentary rocks adjacent to most sills in the Aldridge Formation are not significantly altered) is interpreted to have moved laterally at the base of overlying sill sheets, and ascended along fault zones such as the west side of the Sullivan sub-basin. At Sullivan, these fluids appear to have followed the steep contacts of the footwall sill and branching dike apophyses, resulting in the hydrothermal plume focusing upwards on the orebody and overlying strata. Maximum alteration occurs at sill contacts and diminishes away from them, suggesting fluid flow along and upward from the contact. Steeply dipping albite veinlets in the altered rocks indicate that subvertical fluid flow was important, possibly related to a fault that breached the sills and allowed heated fluids from below the sills to rise into overlying sediments. This suggests that the source magma for the Moyie sills may have been a heat engine of fluids that formed the Sullivan orebody, as suggested by Hamilton (1984).

Albite-chlorite alteration is distinguished by elevated Na_2O (7%); chlorite-pyrite by elevated MgO (13%) and total Fe (29%) (Shaw *et al.*, 1993b). Both alteration types are significantly depleted in SiO_2, K_2O and CaO relative to unaltered Aldridge strata (Hamilton *et al.*, 1982). Formation of Mg-silicates in seafloor hydrothermal systems relate to high temperature mixing of Mg-bearing seawater and Mg-depleted silica-rich hydrothermal fluids (Seyfried *et al.*, 1988). Mg uptake by secondary phases makes it unlikely that seawater-derived Mg will penetrate significantly into the high temperature regions of submarine geothermal systems. The chloritic alteration at Sullivan therefore was likely produced by a seawater dominant system. Experiments by Bischoff *et al.* (1981) monitored the reaction of greywacke with seawater and brines at 350°C and 500 bars and indicate that an assemblage of chlorite-smectite±albite can form from heated seawater. However, the formation of extensive bodies of massive albite (i.e. albitite) with little chlorite likely requires brines enriched in sodium (Bischoff *et al.*, 1981) and significantly depleted in Mg and Ca, unlike seawater (Seyfried *et al.*, 1988). Sodium fixing through albitization is expected in upflow zones of seafloor hydrothermal systems in which Na and Si-rich, Mg-free and Ca-depleted fluids are derived from high-temperature reactions at depth that form epidote-quartz-chlorite assemblages (Seyfried *et al.*, 1988). At Sullivan, early formed proximal albite occurs along hydrothermal conduits surrounded by chlorite-rich assemblages, and is locally overprinted by late chlorite veins. This suggests albitic alteration reflects the core of the upflow zone of high Na/(Mg+Ca) brines, and this is supported by fluid inclusion observations. On the margins of this hydrothermal plume, mixing with entrained Mg-rich seawater-derived intersitial fluids resulted in chlorite-dominant alteration. During the late stages, collapse of the hydrothermal plume allowed penetration of Mg-rich seawaters into the altered rock body along fractures, particularily at the base of the massive albite causing chloritic alteration to overprint albite.

In summary, the ascent of Na-rich, Mg-depleted hydrothermal fluids followed dikes in the Sullivan orebody localizing albitic alteration (Figure 35). These fluids may be related to deep gabbro intrusions below the Moyie sill complex. Mixing with Mg-rich seawater caused peripheral chloritic alteration, and late collapse of the hydrothermal system caused chloritic alteration to overprint earlier-formed albitite. Southwest of the Sullivan mine, albite-chlorite alteration extends 200 metres above the contact of a gabbro sill. The absence of base metals suggests this albite-chlorite-pyrite alteration is not directly related to ore-forming processes.

Structural and metamorphic history

Regional metamorphism is interpreted as biotite-Mn garnet middle greenschist facies at 400°C (McMechan and Price, 1982) and 2.0 kb (5.8-7.6 km depth of burial; Edmunds, 1977), and is related to the East Kootenay Orogeny of Middle Proterozoic age.

The Sullivan deposit also shows evidence of moderate deformation and recrystallization during Mesozoic eastward-directed thrusting. The ductility contrast between massive pyrrhotite-galena rich sulphides, which have flowed, and the enclosing brittle clastic rocks, has caused strain to be localized in the orebody (Paakki *et al.*, 1995). Offset of the hangingwall albitite from its postulated roots in the pyrite-chlorite-calcite pipe in the orebody, segmentation of gabbro dikes in the orebody, and recumbent isoclinal folds in the sulphides, suggest overriding of the hangingwall toward the east (McClay, 1983). Continued deformation caused asymmetric folds, commonly overprinting isoclinal folds, and thrust faults at the boundaries of the orebody. This phase of deformation probably included the latest displacement on the Kimberley fault; subsequently, lamprophyre dikes were intruded. West-verging thrust faults offset the lamprophyres and other earlier structures. Eocene crustal extension (Price *et al.*, 1981) resulted in steeply west-dipping normal Sullivan-type faults that offset the ore by up to 30 metres (Figure 31), along an important north-trending ancestral structure subparallel to the axis of the Sullivan-North Star corridor and the Belt basin. Early development of the Kimberley fault is also suggested by albite alteration along it west of the deposit where the fault bends southward, and pyritic alteration similar to that in the center of the deposit, localized along the fault where it cuts bedded eastern ore.

Deposit model

Sullivan is interpreted to be a hydrothermal synsedimentary sulphide (sedex) deposit that formed in a small submarine basin within a north-trending graben referred to as the Sullivan-North Star corridor. The western part lies directly above the conduit zone, the brecciated and tourmaline altered footwall pipe of the deposit. Interpretation of tourmalinite formation temperatures, based on oxygen isotope studies, range from less than 100°C (Nesbitt *et al.*, 1984) to 200-250°C (Beatty *et al.*, 1988). However, fluid inclusion homogenization temperatures in quartz of the stringer zone that is coextensive with the tourmalinite pipe range from 200-300°C, suggesting that tourmalinite-pyrrhotite formation was not early and low temperature, but main-stage and hot.

The extensive, up to 1 metre thick pyrrhotite veins found in the footwall tourmalinite pipe appear to be main feeders to the Sullivan deposit and show similarities to the Stemwinder vein (Leitch and Turner, 1992). The high ratio of sulphide to gangue in the feeder veins directly underlying the Sullivan deposit, and in the massive sulphides, suggest a concentrated, strong flow of fluid, rich in metals, which combined with a minimal input of detrital material, to the basin where sulphide precipitation and deposition was occurring leading to the formation of a giant deposit. An analagous situation is the Red Sea Deeps, where a brine pool develops because fluids exhaled in restricted basins on the bottom do not mix with overlying seawater (Ramboz *et al*, 1988). Instead, they form one or two density-stratified brine layers that cool by conduction to normal seawater without significant loss of salinity, allowing hot, saline exhaled fluids at up to 300°C and therefore lower density than seawater, to form brine pools; surface waters are at 30°C and bottom water at 22°C in such a restricted sea, compared to open ocean bottom temperatures of 4°C. Temperatures of Red Sea exiting fluids are not known, but inclusions in anhydrite veins beneath the central portion of the deeps show that boiling occurred, at up to 420°C (Ramboz *et al.*, 1988). It is possible that the first discharge of the hydrothermal system would be cooler than main stage discharge due to conductive cooling, giving rise to a higher density fluid and initiation of the brine pool, which could then not be destroyed by later, hotter, more buoyant fluids (McDougall, 1984).

Such a model for the Sullivan deposit is supported by two key observations. The extremely finely laminated nature of the major portion of the bedded ores, in which details of stratigraphy can be followed for up to 2 kilometres (Hamilton *et al.*, 1982) is suggestive of dewatered Red Sea muds (although plume fallout could also account for the laterally continuous nature of the laminae). If brines trapped in fluid inclusions in quartz veins (Leitch, 1992a) represent the mineralizing fluids, the 15-32 wt% salinities are like those in anhydrite veins underlying the Red Sea brine pools, and similar to the salinity of the brine pools (13.5-25.6%: Ramboz *et al.*, 1988). Such elevated salinities are critical for transportation, as chloride complexes, of the large amounts of metal required to form a vast deposit like the Sullivan. Metals were likely derived by widespread convective leaching of lower Aldridge sediments. The high salinities also suggest that the mineralizing fluids passed through evaporites at some point in their circulation. Although evaporites are not known in the Belt-Purcell Basin, they may have been present at the base of the section now preserved only along the eastern margin of the basin (Chandler and Zieg, 1994). The most likely source of thermal energy to drive the convection would be magmatic intrusion (Moyie sill complexes, especially the larger magma chambers at depth that are not exposed; *cf.* Hamilton and Shaw, 1986). Discharge of hydrothermal fluids was clearly concentrated along crustal weaknesses such as proto-Kimberley and proto-Sullivan faults.

BLUEBELL[1]

MINFILE NUMBER: 082FNE043
STATUS: Past Underground Producer

ACCESS: Follow 10 km road from Kootenay Bay to Riondel and mine site.

<table>
<tr><td colspan="3">DEPOSIT TYPE: Polymetallic manto Ag-Pb-Zn - J01</td></tr>
<tr><td colspan="3">LOCATION</td></tr>
<tr><td colspan="2">NTS MAP: 082F15W
UTM ZONE: 11 (NAD 27)</td><td>NORTHING: 5512000
EASTING: 510000</td></tr>
<tr><td colspan="3">MINERALOGY</td></tr>
<tr><td>ORE AND SULFIDES: Galena, Sphalerite, Pyrrhotite, Pyrite, Chalcopyrite, Arsenopyrite, and Marcasite</td><td>GANGUE: Quartz, Calcite, Magnetite, Siderite, Knebelite, and Chlorite</td><td>ALTERATION: Chlorite, Carbonate, Serpentine.</td></tr>
<tr><td colspan="3">COMMODITIES: Silver Zinc Lead Copper Cadmium Gold</td></tr>
<tr><td colspan="3">HOST ROCK: Metasedimentary - Limestone, Quartzite, Argillite</td></tr>
<tr><td colspan="2">TOTAL PRODUCTION:
Milled: 4,774,123 tonnes
Recovery:
Silver: 221,011,383 grams
Gold: 8,864 grams
Cadmium: 1,141,943 kilograms
Copper: 2,855,381 kilograms
Lead: 233,800,528 kilograms
Zinc: 249,022,008 kilograms</td><td>From 1952 to 1971 mined 4.333 million tonnes of ore grading 5.2% Pb, 6.3% Zn and 60 g/t Ag.</td></tr>
</table>

CAPSULE GEOLOGY

In 1825, a botanist discovered sulphide ore at the Bluebell site. In later years, Hudson Bay Company trappers used galena from this site to make bullets. The site was staked by R.E. Sproule in 1882.

The Bluebell occurrence consists of three main zones approximately 500 metres apart along strike of the Lower Cambrian Badshot Formation (Lardeau Group) marble. They are called the Comfort zone at the north end of Rionel Peninsula, the Bluebell zone in the centre, and the Kootenay Chief at the south end. The zones are localized along steep cross-fractures that trend west-northwesterly and dip 80 to 90 degrees north. Within the zones are tabular ore shoots that are transverse to the bedding and plunge westward following the intersection of the fractures with the marbles. The ore occurs as replacement deposits along steep cross fractures in the marbles. Bedding planes and minor structures tend to localize the deposit. The ore consists of galena, sphalerite, pyrrhotite, pyrite, arsenopyrite, and chalcopyrite. The gangue occurring with the sulphides consists of carbonates, coarsely-grained quartz and knebelite (oilvine group, maganiferous fayalite -$(Fe,Mn)_2 SiO_4$). Oxidation of the deposit has occurred to depths well below lake level.

[1] derived from MINFILE, May , 1999