



STRUCTURAL SETTING, MINERAL DEPOSITS, AND  
ASSOCIATED ALTERATION AND MAGMATISM  
SULLIVAN CAMP, SOUTHEASTERN BRITISH COLUMBIA  
(82F, G)

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## INTRODUCTION

The Sullivan deposit is a large, essentially stratiform lead-zinc-silver orebody in late Proterozoic Aldridge Formation turbidites in southeastern British Columbia. It is located near the eastern margin of the Purcell anticlinorium, just west of the Rocky Mountain Trench (Fig. 5). It has been the focus of a number of recent studies, including its geology (Hamilton, *et al.*, 1982, 1983; Hamilton, *in press*), structure (McClay, 1983), alteration (Shaw, *in preparation*), and isotopic signature (Nesbitt, *et al.*, 1982; Campbell, *et al.*, 1978). Recently regional geology in the vicinity of the deposit has been described by Höy (1983), based on fieldwork in 1982 and previously published maps by Schofield (1915), Rice (1937), and Leech (1958, 1960).

The purpose of this paper is to describe in more detail geology in the immediate vicinity of the Sullivan mine. The report focusses on the structural setting of Sullivan and describes a regional Sullivan 'camp' alteration zone. As well, evidence is presented which suggests that the thick accumulation of Moyie gabbroic sills within the Aldridge Formation is a magmatic event in Lower Aldridge and early Middle Aldridge time, in part prior to lithification of the sedimentary pile, rather than a post-lithification intrusive event.

## STRUCTURE

The structure in the vicinity of the Sullivan deposit is dominated by two prominent fault sets that cut shallow-plunging broad open folds. Sullivan-type faults trend north to northeasterly (Fig. 6), dip steeply to the west, and generally have normal, west-side-down offsets of a few tens of metres (faults a, b, c, d, Fig. 7) (Hamilton, *et al.*, 1983; McClay, 1983). Those east of the deposit (c, d) are drawn schematically; they may in fact involve cumulative movements on a number of smaller northeast-trending faults as shown on Figure 2.4 of Hamilton, *et al.* (1983). Sullivan-type faults cut a number of east-west-trending, north-dipping faults. The most prominent of these, the Kimberley fault, cuts the north fringes of the Sullivan deposit at depth (Hamilton, personal communication, 1983). It has an apparent net normal displacement of at least 2 500 metres (Hamilton, *et al.*, 1982; McClay, 1983) and juxtaposes Creston Formation rocks against Middle and Lower Aldridge rocks (Fig. 6).

A steep, generally west-dipping cleavage is prominent throughout the area. The cleavage is widely spaced (approximately 5 centimetres) in competent quartz wacke beds, is more closely spaced in siltites, and locally comprises a penetrative foliation in phyllite (near the southwest corner of the map-area, see Fig. 6). The cleavage is axial planar to broad, generally open folds (illustrated in the sections of Fig. 7). Southwest of Sullivan on North Star Hill (domain 1, Fig. 8), folds are locally tight with fold hinges that plunge variably to the north or south. In general, however, bedding is relatively flat lying to east dipping, cleavage dips steeply west, and bedding/cleavage intersections plunge at low angles to the north or south, parallel to fold hinges. In the Sullivan mine area (domain 2, Fig. 8), regional bedding is also relatively flat lying to east dipping, cleavage dips variably to the west, and cleavage/bedding intersections and fold axes, although

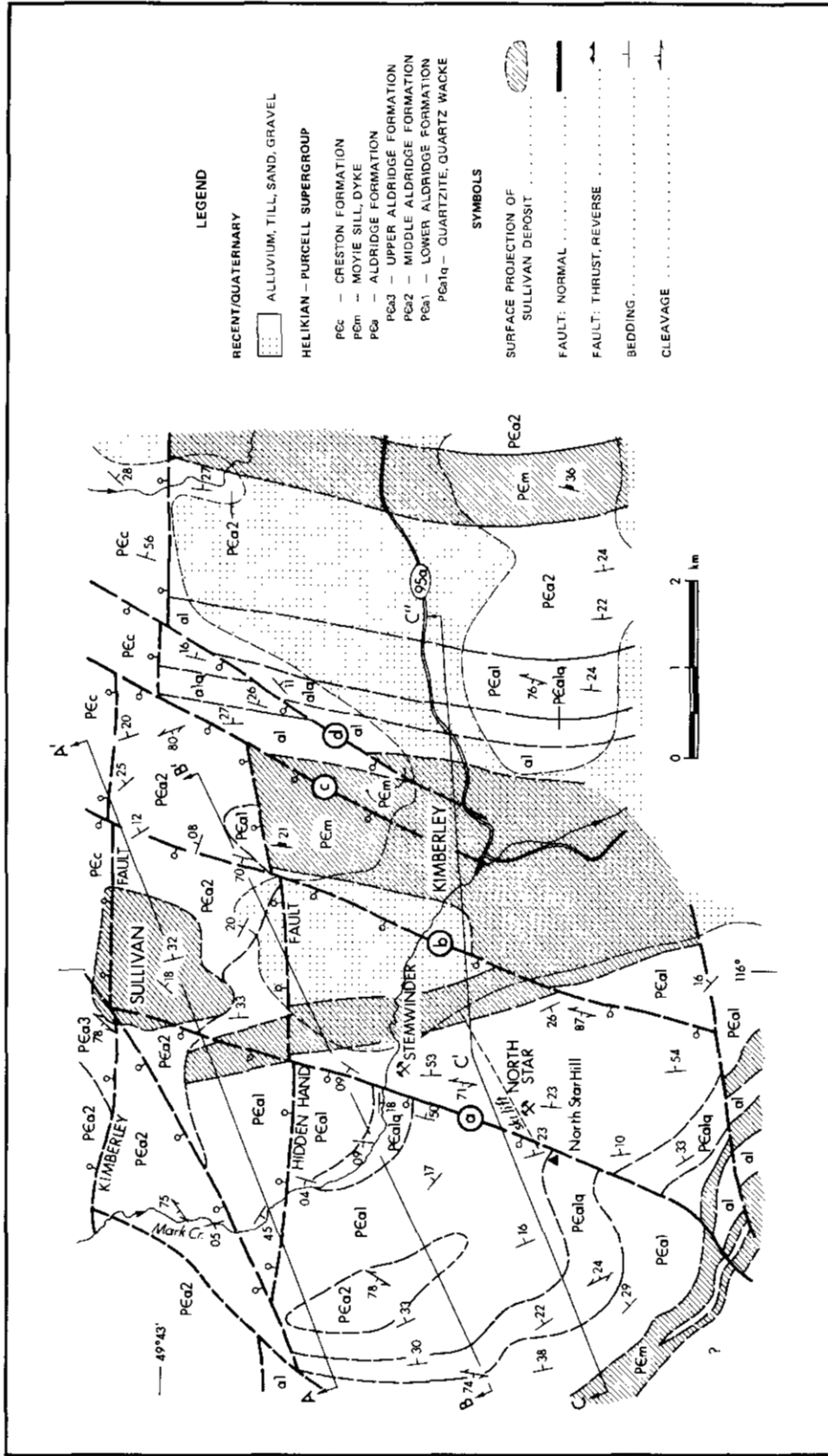


Figure 6. Geology in the vicinity of the Sullivan deposit, Kimberley.

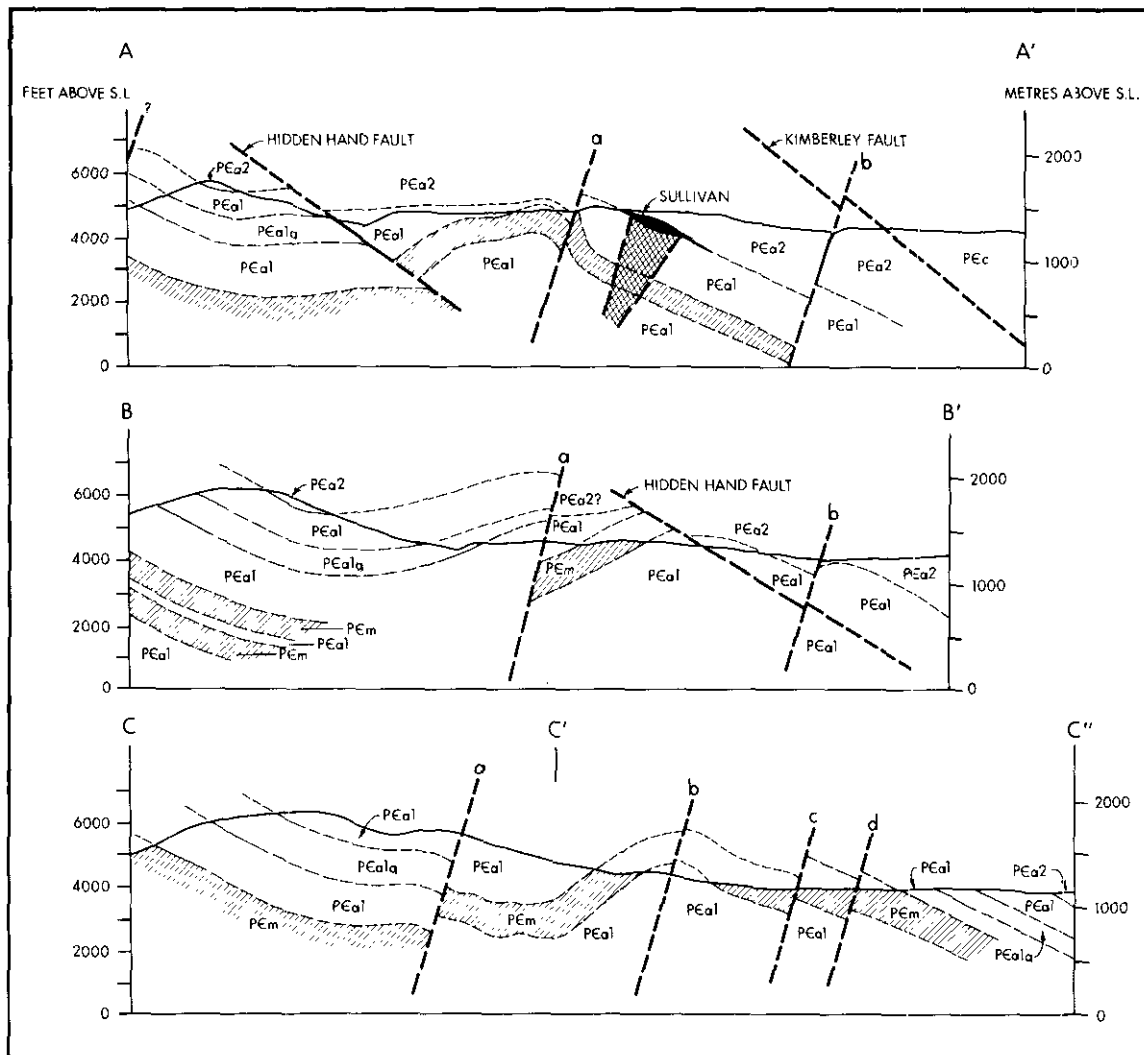


Figure 7. Vertical structural sections, Sullivan deposit area; see Figure 6 for locations.

scattered, generally trend north-northeasterly or south-southwesterly; plunges are up to a few tens of degrees. These folds and associated cleavage are correlative with Phase 2 structures described by McClay (1983) in the Sullivan deposit. The greater scatter of structural elements in the deposit is undoubtedly because of lower competency of the thinly laminated sulphides (compare Fig. 17 of McClay with domain 2 of Fig. 8). East of the Sullivan deposit and in the Concentrator Hill area (domain 3, Fig. 8) bedding trends north and dips 20 to 30 degrees east. Cleavage dips steeply west-northwest; lineations and bedding/cleavage intersections plunge at low angles to the north-northeast.

A late crenulation cleavage locally overprints the pronounced regional fold and associated cleavage.

Regional fold deformation in the Kimberley-Cranbrook area is dominated by large, open to locally tight folds that verge eastward; they are probably related to west-dipping thrust faults and associated east-trending tear faults. These structures deform and offset Paleozoic rocks but appear to predate Late Cretaceous granite bodies (Höy, 1983), and are, therefore, probably related to the regional Mesozoic orogeny as suggested by McClay (1983).

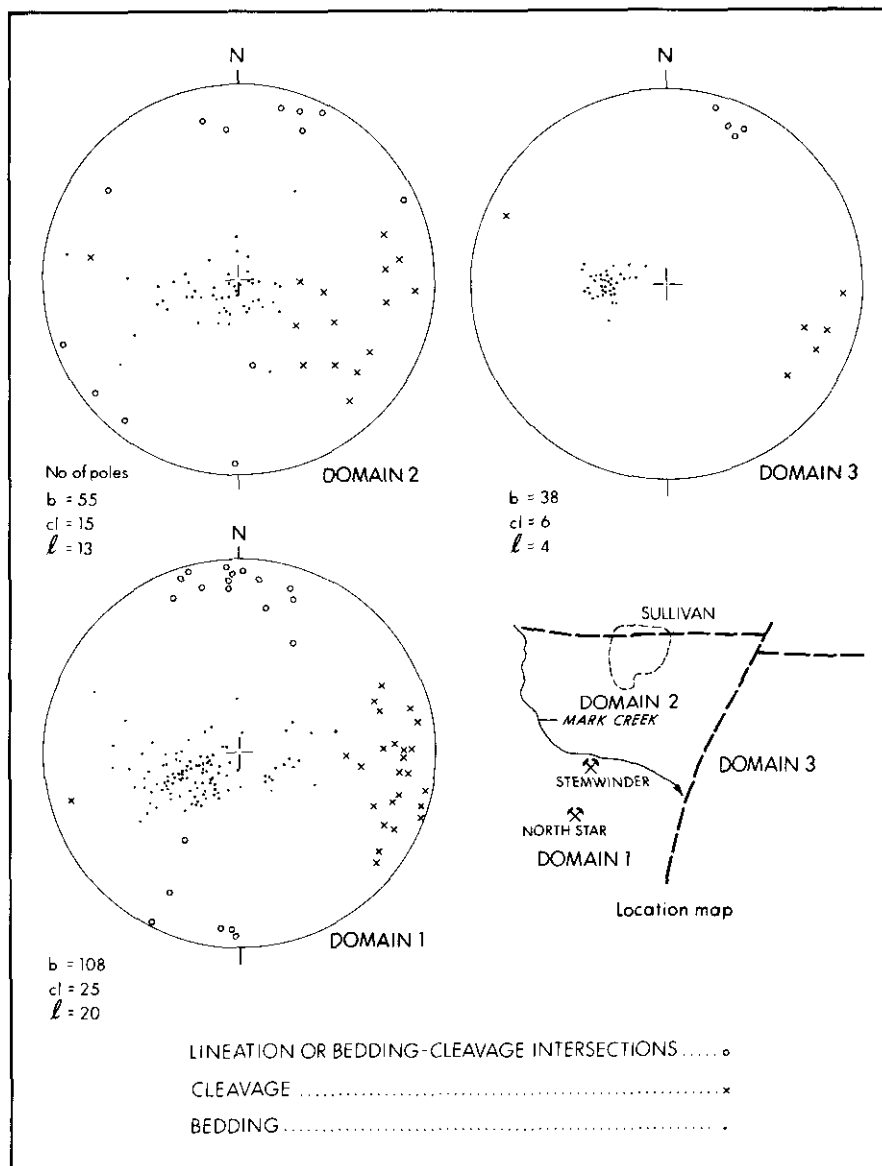


Figure 8. Equal area projections of structural data, Sullivan deposit area.

## PURCELL SUPERGROUP STRATIGRAPHY

The Purcell succession in the Kimberley area has been described recently by Hamilton, *et al.* (1983) and Höy (1983); it will be reviewed only briefly here. Within the thick succession of rusty weathering, generally laminated siltite and argillite of the Lower Aldridge Formation is a 250-metre-thick sequence of grey-weathering quartz wacke and quartz arenite beds (unit P<sub>Ea1q</sub>) that is lithologically similar to the basal part of the Middle Aldridge Formation. This unit crops out on the western and southern slopes of North Star Hill and on the western slope of Concentrator Hill (Fig. 6). The sequence, where exposed in Mark Creek, is more rusty weathering and somewhat thinner bedded. The Lower Aldridge grades up section into grey-weathering quartz wacke, quartz arenite, and more rusty weathering laminated siltite of the Middle Aldridge Formation (unit P<sub>Ea2</sub>). The Lower/Middle Aldridge transition is poorly exposed. Where outcrop allows, it has been placed below the first appearance of prominent blocky, grey-weathering quartz wacke beds.

The Upper Aldridge Formation consists of approximately 300 metres of rusty to dark-grey-weathering laminated argillite and silty argillite. The Creston Formation (Pc) is composed of grey, green, or mauve-coloured siltite and quartzite with numerous shallow water subtidal to intertidal sedimentary structures.

## MINERAL DEPOSITS

The Sullivan deposit, and a number of smaller stratabound lead-zinc-silver deposits, occur in a north-northwest-trending regional alteration zone that extends from Sullivan southward to North Star Hill.

The Sullivan deposit is one of the largest base metal deposits in the world; it has produced 116 million tonnes of ore grading 6.7 per cent lead, 5.8 per cent zinc, and 79 grams silver per tonne. Remaining reserves are approximately 45 million tonnes containing 4.5 per cent lead, 6.0 per cent zinc, and 38 grams silver per tonne. Its geology has been described recently by Hamilton, *et al.* (1982, 1983). In brief, the deposit is a large, generally conformable lens of massive pyrrhotite, galena, and sphalerite that lies near the top of the Lower Aldridge Formation. Its western part, comprising generally massive to irregularly layered sulphides, overlies a brecciated and tourmalinized footwall alteration zone (Fig. 9); the orebody is overlain by an albite-chlorite-pyrite-carbonate alteration halo. Its eastern part consists of a number of thinly laminated sulphide layers separated by fine-grained clastic rocks.

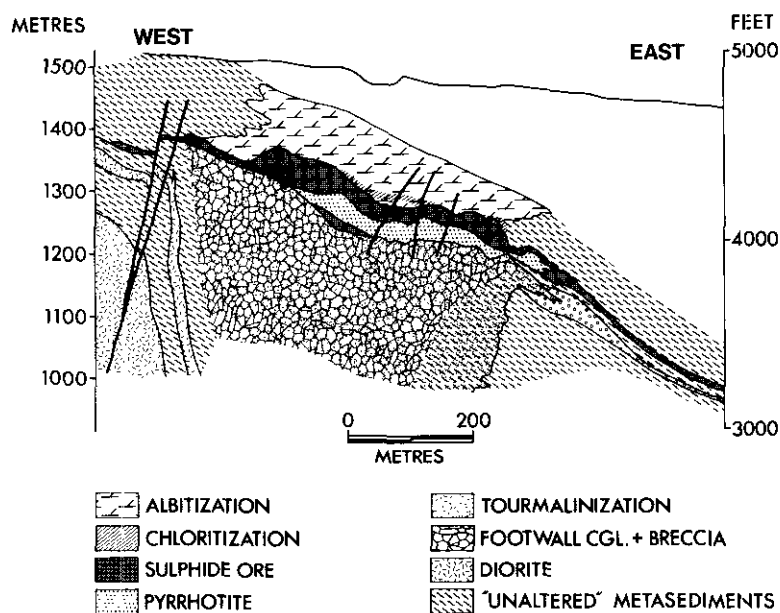


Figure 9. Schematic vertical section through the Sullivan deposit (simplified from Hamilton, *et al.*, 1982).

Numerous small vein occurrences, a few thin stratabound sulphide lenses, and a number of larger stratabound deposits occur within a few kilometres south of Sullivan. The North Star deposit, located approximately 4 kilometres south-southwest of Sullivan (Fig. 6), is a small, but very high-grade, stratiform deposit in Lower Aldridge siltstones. The deposit produced 70 000 tonnes of hand-sorted material containing 46 per cent lead, less than 1 per cent zinc, and about 1 000 grams silver per tonne (Hamilton, *et al.*, 1983, p. 45). It is described (Schofield, 1915) as a conformable lens of massive galena only partly preserved in synformal structures on the eastern slopes of North Star Hill. Construction of the North Star ski hill complex has largely covered the old workings.

The Stemwinder is located between Sullivan and North Star. It produced approximately 25 000 tonnes containing 3.7 per cent lead, 15.6 per cent zinc, and 76.3 grams silver per tonne. Reserves include approximately 125 tonnes of 82 grams per tonne silver, 3 per cent lead, and 16 per cent zinc (Hamilton, *et al.*, 1983, p. 45). The deposit trends northerly and dips steeply west. It is interpreted to be a vein deposit that occurs in a tight, faulted synclinal structure (Freeze, 1966).

#### REGIONAL ALTERATION IN THE SULLIVAN CAMP

Lead-zinc-silver deposits in the Sullivan camp are enclosed within a north-northeast-trending zone of intensely altered Lower Aldridge siltstone and quartzite. The zone is approximately 6 000 metres in length, 1 500 to 2 000 metres wide, and locally, beneath the Sullivan deposit (Hamilton, 1983), extends through a known stratigraphic interval of at least 500 metres. On North Star Hill tourmalinized rock was intersected in drill holes to depths exceeding 200 metres (D. H. Olson, personal communication). The alteration zone appears to be restricted to Lower Aldridge rocks; that is, rocks that stratigraphically underlie the Sullivan deposit. It is characterized by:

- (1) A marked increase in the abundance of disseminated and irregularly laminated pyrrhotite and, to a lesser extent, pyrite. Surface exposures are typically highly oxidized.
- (2) An increase in the number of pyrite, galena, and sphalerite-bearing veins.
- (3) An increase in the number of 'massive' sulphide occurrences, such as North Star, Stemwinder, and a number of other smaller occurrences.
- (4) Zones of pervasive tourmalinized and silicified rock, similar to those described in the footwall of the Sullivan deposit. These alteration zones are commonly irregular in outline with either sharp or gradational contacts; they cross lithologic boundaries. Locally, thin tourmaline-rich laminations occur in siltstone. The tourmalinite is a dark, hard siliceous rock that breaks with a conchoidal fracture.
- (5) Irregular zones of breccia or 'conglomerate'. The conglomerate is generally diamictite with sub-rounded siltite clasts up to 2 centimetres in diameter supported by a siltstone matrix. Pyrite and pyrrhotite with minor amounts of sphalerite and galena typically occur in the matrix. Often, the conglomerate grades into massive (lacking bedding) siltstone or quartzite. The conglomerates may define beds but can form clastic dykes. Similar rocks in the footwall of the Sullivan, termed 'fragmentals' are interpreted to have formed by injection and local surface extrusion, rather than by collapse of fault scarps (Hamilton, in press).
- (6) Obliteration of bedding by intense sulphide alteration, tourmalinization, silicification, or development of 'conglomerate'.

Many of these features extend beyond the limits of the intense alteration zone described previously. For example, thin laminations of tourmalinite occur 3 to 4 kilometres south of the North Star deposit in Lower Aldridge siltite, and a crosscutting conglomerate occurs on a small hill nearby (A. Hagen, personal communication, 1980). As well, anomalous numbers of sulphide laminae occur at the Lower/Middle Aldridge transition (Sullivan horizon) on Concentrator Hill, which is 5 kilometres east of North Star Hill.

#### MOYIE INTRUSIVE ROCKS – A PRELITHIFICATION MAGMATIC EVENT ?

Laterally extensive sills, which are predominantly gabbroic in composition (accompanying table), intrude the Lower and the lower part of the Middle Aldridge Formation. They are generally a few tens to several hundred metres thick, with medium to coarse-grained equigranular central parts and finer grained margins. A thin hornfelsic zone occurs adjacent to some sill contacts. Locally, Moyie intrusions also form dykes. Although Moyie intrusions have isotopic ages indistinguishable from the host Aldridge rocks (approximately

1433 Ma, Zartman, *et al.*, 1982), it has generally been accepted that they are coeval with deposition of the Upper Aldridge Formation or Creston rocks (Zartman, *et al.*, 1982), or perhaps with Nicol Creek lavas (McMechan, 1981). However, Höy (in press) suggested that they are early and were emplaced into water-saturated Aldridge sediments a few tens to a few hundreds of metres below the sediment surface. If this is correct, the Moyie sills may be evidence of a regional igneous/thermal event during deposition of Lower to Middle Aldridge rocks, hence during formation of contained stratiform sulphide deposits. A modern example of intrusion of basaltic sills into highly porous unconsolidated turbidite sediments was described by Einsele, *et al.* (1980) from drill sites in the Guaymas Basin, Gulf of California.

Moyie sills have a number of features in common with Guaymas Basin sills: they are basaltic in composition (accompanying table; Fig. 10), intrude turbidites, and occur in a basin formed by rifting (*see* Sears and Price, 1978; Price, 1981). Intrusion of 2 000 to 3 000 metres of Moyie sills (*see* Reesor, 1958; Höy and Diakow, 1982) into lithified Aldridge rocks could only be accommodated if there were considerable uplift of the surface rocks; no such uplift is evident in post-Aldridge time. If it occurred, major unconformities or coarse clastics would be apparent in the overlying succession of dominantly platformal rocks. Room is not a problem if the sills were injected into unconsolidated, water-saturated sediments; expulsion of pore fluids results in little change in relief of the sea floor (Einsele, *et al.*, 1980). Crosscutting, sheeted fracture zones containing calcite-epidote-chlorite-quartz and, locally, sulphide assemblages and vein concentrations near sill margins are common in Moyie sills. These may be evidence of hydrothermal activity associated with water expulsion and escape through the sills. Transgressive zones of disrupted bedding, such as occurs on Highway 3 at the south end of Moyie Lake, could be large dewatering structures associated with sill injection. Perhaps the best direct evidence that some sills were injected into wet, unconsolidated sediments are local development of flame and load cast structures at the base of some Moyie sills (Plate II); similar structures have been observed by Dave Pighan (personal communication, 1983). As well, a thin (20 to 30-centimetre) contact zone with large hornblende crystals is common at the base of some sills; this suggests hydrothermal growth in a mixed magma-crystal-sediment mush. Other sill contacts have fine-grained chilled margins and hornfelsic country rocks, suggesting intrusion into cool, lithified rocks.

Many of the Moyie sills are alkaline basalts (Fig. 10). Magmatism was essentially restricted to early Aldridge and early Middle Aldridge time, dying out in late Middle Aldridge time at the same time as the volume of coarse turbidites decreased. Their abundance, volume, composition, spatial, and suggested temporal restriction to a stratigraphic interval dominated by turbidite deposition suggests that Lower Aldridge and early Middle Aldridge sedimentation took place during a period of continental rifting.

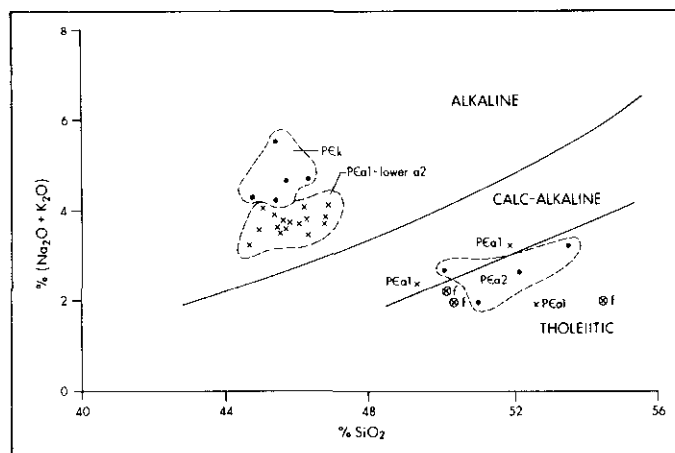


Figure 10. Alkali-silica plot of Moyie gabbroic sills in the Lower Aldridge (PEa1), Middle Aldridge (PEa2), and Fort Steele (f) Formations. A number of sills in younger Kitchener Formation (PEK) are also plotted.

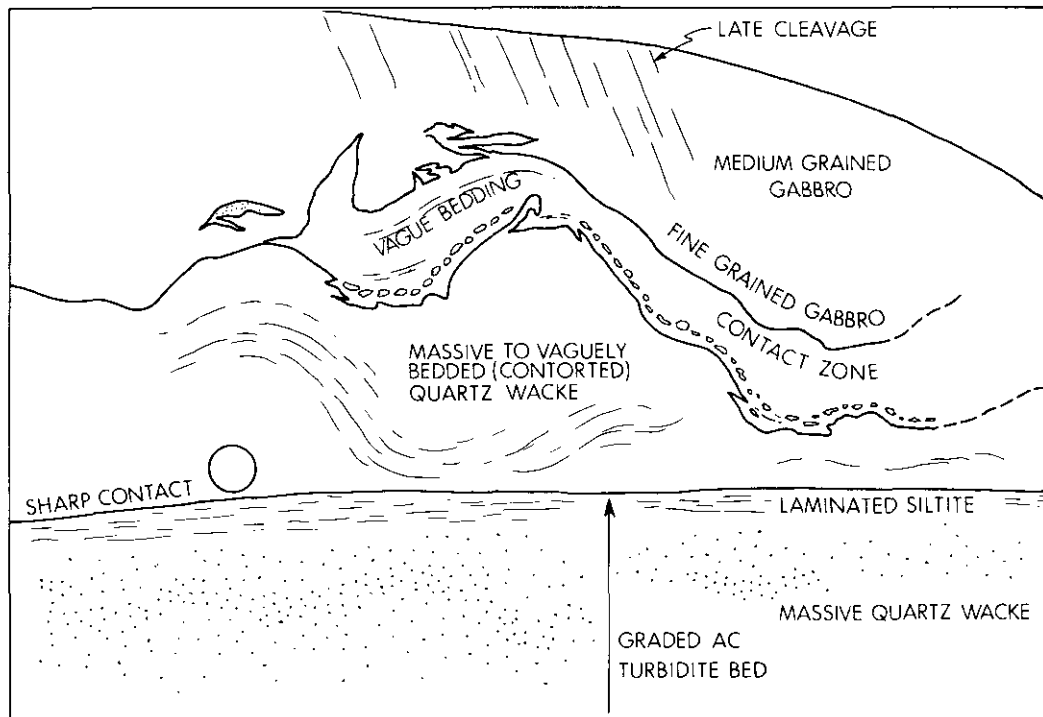
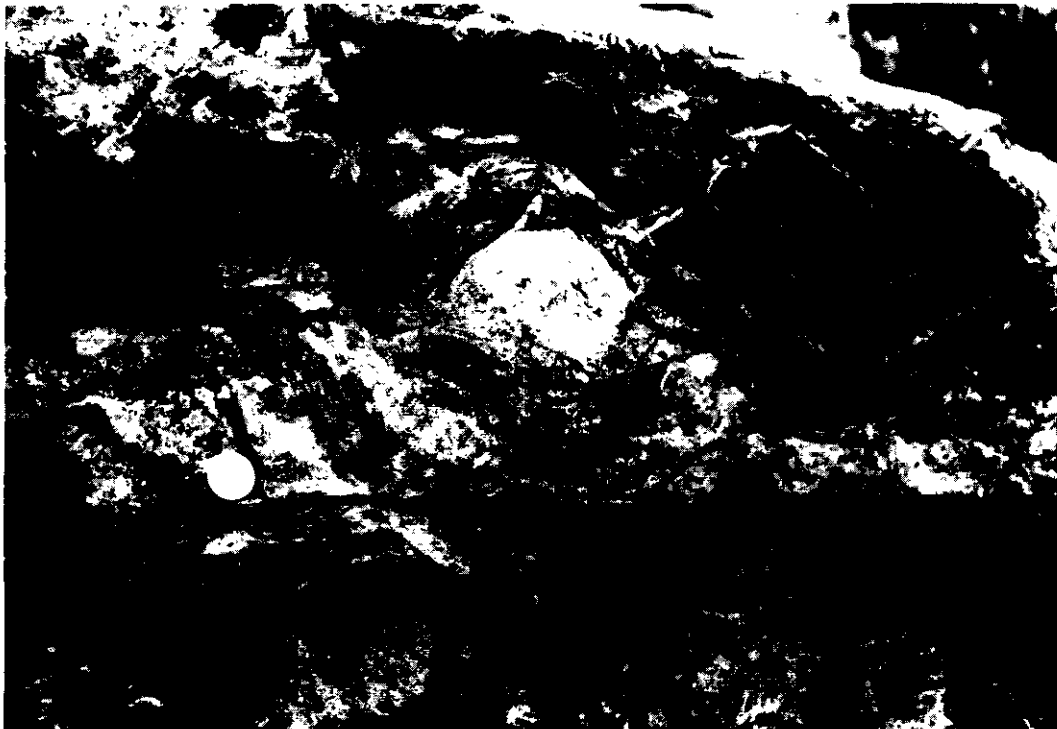


Plate II. Detail of Moyie sill-Middle Aldridge Formation turbidite contact; note features which suggest that the sill was injected prior to lithification of the quartz wacke, such as flame and load cast structures at the base of the sill, and a mixed sediment - coarse-grained hornblende contact zone.



SILICATE ANALYSES OF MOYIE SILLS IN ALDRIDGE AND FORT STEELE FORMATIONS

SAMPLE	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub> T	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	MnO
M1-7	50.80	14.63	9.55	8.25	11.98	1.549	0.322	0.739	0.152
M20-1	50.05	15.94	14.67	5.02	10.06	2.439	0.227	1.108	0.201
E8-15	53.46	14.39	9.83	8.03	2.88	2.430	0.815	0.948	0.113
E75-2	52.04	13.49	11.32	6.83	6.40	2.176	0.461	0.844	0.141
M7-209	46.82	13.77	16.62	5.51	9.07	2.952	1.115	2.606	0.259
M7-214	46.15	13.96	16.56	5.49	10.55	2.746	0.711	2.758	0.249
M7-218	46.68	13.49	16.62	5.52	9.77	2.889	0.823	2.607	0.258
M7-223	46.72	13.76	16.18	5.35	9.85	2.925	0.934	2.628	0.252
M7-228	45.95	13.33	16.68	5.65	9.54	2.786	0.970	2.713	0.257
M7-233	46.17	13.48	16.24	5.61	9.67	2.709	1.078	2.603	0.257
M7-240	44.94	13.81	17.05	5.65	10.25	2.660	0.968	2.854	0.265
M7-241	45.64	13.67	16.88	5.51	9.93	2.768	0.846	2.831	0.268
M7-249	45.50	13.49	16.74	5.47	9.80	2.797	0.801	2.746	0.267
M7-251	45.57	13.48	17.00	5.49	10.04	2.841	0.924	2.791	0.270
M7-256	46.05	13.36	16.64	5.35	9.23	2.602	1.496	2.775	0.262
M7-261	44.88	13.55	17.17	5.37	9.93	2.839	0.753	2.831	0.296
M7-265	44.66	13.12	17.48	5.28	10.25	2.750	0.469	2.729	0.280
M7-270	44.99	13.68	17.67	5.27	8.14	3.208	0.782	2.789	0.282
M12-27	49.25	16.53	9.11	8.33	10.54	1.406	0.992	0.627	0.166
M14-15	60.02	13.28	12.18	0.97	4.86	3.069	2.045	1.312	0.187
K23-2	51.87	14.23	8.88	7.74	9.93	1.476	1.795	0.625	0.149
K38-4	61.04	11.55	6.09	2.64	7.87	4.254	4.484	0.199	0.320
D3-7A	43.87	14.36	12.12	6.73	10.42	2.196	2.753	2.535	0.199
E4-1	54.40	13.98	11.32	6.44	10.96	1.435	0.687	0.736	0.180
E6-1	50.08	14.62	12.62	9.55	2.79	0.263	2.000	1.167	0.141
E55-4	50.30	14.53	9.52	8.13	11.43	1.562	0.429	0.690	0.154

Sample M1-7 - in Middle Aldridge Formation, sheet 82G/5 (Moyie).

Sample M20-1 - in Middle Aldridge Formation, sheet 82G/4 (Yahk).

Samples E8-15 and E75-2 - in Middle Aldridge Formation, sheet 82G/12E, 13E.

Samples M7-209 to M7-270 - in Middle to Lower Aldridge transition, sheet 82G/4 (Yahk).

Samples M12-22 and M14-15 - in Lower Aldridge Formation, sheet 82G/5 (Moyie).

Samples K23-2 and K38-4 - in Lower Aldridge Formation, sheet 82G/12 (Cranbrook).

Samples D3-7A to E55-4 - in Fort Steele Formation, sheets 82G/12E, 13E.

## DISCUSSION

The Sullivan and other smaller stratabound lead-zinc-silver deposits in the Sullivan camp presumably formed by venting of hydrothermal, metal-charged brines onto the sea floor. The deposits occur within a broad area of intense alteration that is restricted to the Lower Aldridge Formation. This suggests that initially a thermal convective cell was operative over a wide area with local well-established discharge points; later it became more localized and in late Lower Aldridge time it formed the Sullivan deposit. The hydrothermal system continued to be active after sulphide deposition ceased; it caused chlorite-pyrite alteration of the central part of the Sullivan massive sulphide lens and albite-chlorite-pyrite-carbonate alteration of overlying Middle Aldridge sediments (Hamilton, *et al.*, 1983).

It is suggested that intrusion of Moyie sills was, at least in part, contemporaneous with deposition of Aldridge turbidites and contained stratiform base metal deposits. It is unlikely that these sills supplied a substantial magmatic component to the source hydrothermal fluids, or that they directly provided a heat source to drive a convective cell. Their presence does, however, indicate an elevated geothermal gradient, and the associated thick accumulation of turbidites probably reflects contemporaneous tectonic activity in the form of crustal extension. Movements on deep-rooted basement faults have been documented in Aldridge rocks just east of the trench (Höy, 1982; in press). This tectonic activity, concentrated near the intersection of a north-trending rifted continental margin (Price, 1981) with a pronounced southwest-trending tectonic zone (Kanasewich, 1968; Höy, 1982), both triggered and localized a thermal convective cell system.

Through Middle Aldridge time, as the Purcell basin was being filled, the rate of turbidite deposition and gabbroic sill intrusion decreased, indicating waning tectonic and magmatic activity. Local tourmalinite and 'conglomerate' occurrences in Middle Aldridge rocks indicate, however, that faulting, rock fracturing, and convective systems continued on a local scale. By Upper Aldridge time only dark fine-grained silts and muds were being deposited, indicating relatively stable tectonic conditions.

## ACKNOWLEDGMENTS

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