802640

R. V. KIRKHAM

THE SULLIVAN OREBODY

J. M. Hamilton, R. L. Hauser and P. W. Ransom

(*From:* Field Guides to Geology and
Mineral Deposits, G.A.C.
Annual Meeting, Calgary, 1981)

Introduction

The Sullivan orebody is a large gently dipping iron-lead-zinc sulphide deposit lying conformably in Helikian clastic metasedimentary rock of the Aldridge Formation of the Purcell Supergroup. The Aldridge Formation is a flysch-like sequence at least 3800 m thick. The orebody is located at the western edge of the Rocky Mountain Trench and on the eastern flank of the Purcell Mountains. Showings of sulphide mineralization were discovered in 1892, but little work was done prior to completion of a rail line to Kimberley in 1899. Early development of the property included a smelter in nearby Marysville in 1903. This venture failed owing to metallurgical difficulties, and the property was acquired in 1909 by the Federal Mining and Smelting Company. The Consolidated Mining and Smelting Company of Canada Ltd. (now Cominco) took a lease and option on the property in late 1909 and completed purchase by 1913.

A main adit at the 3900 foot level, some 200 m below the showings, was started in 1915 and a major effort was directed toward solving the milling and metallurgical problems. In 1920 a differential floatation process was developed that proved successful for obtaining lead and zinc concentrates suitable for smelting. From the date of acquisition by Cominco to the end of 1980 the Sullivan Mine produced approximately 125,500,000 short tons (113,900,000 tonnes) containing 6.7 per cent lead, 5.8 per cent zinc and 2.4 oz. per short ton (81 gms per tonne) silver (Fig. 4). Remaining diluted reserves at the end of 1979 were 54,000,000 short tons (49,000,000 tonnes) containing 4.5 per cent lead, 5.9 per cent zinc and 1.1 oz. per short ton (37 gms per tonne) silver.

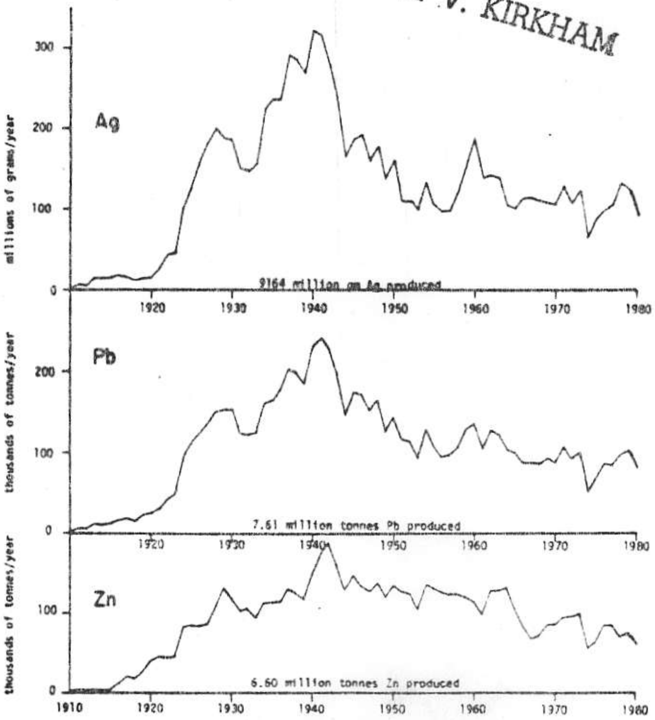

Figure 4. Annual production of silver, lead and zinc from the Sullivan mine, 1910 to 1980.

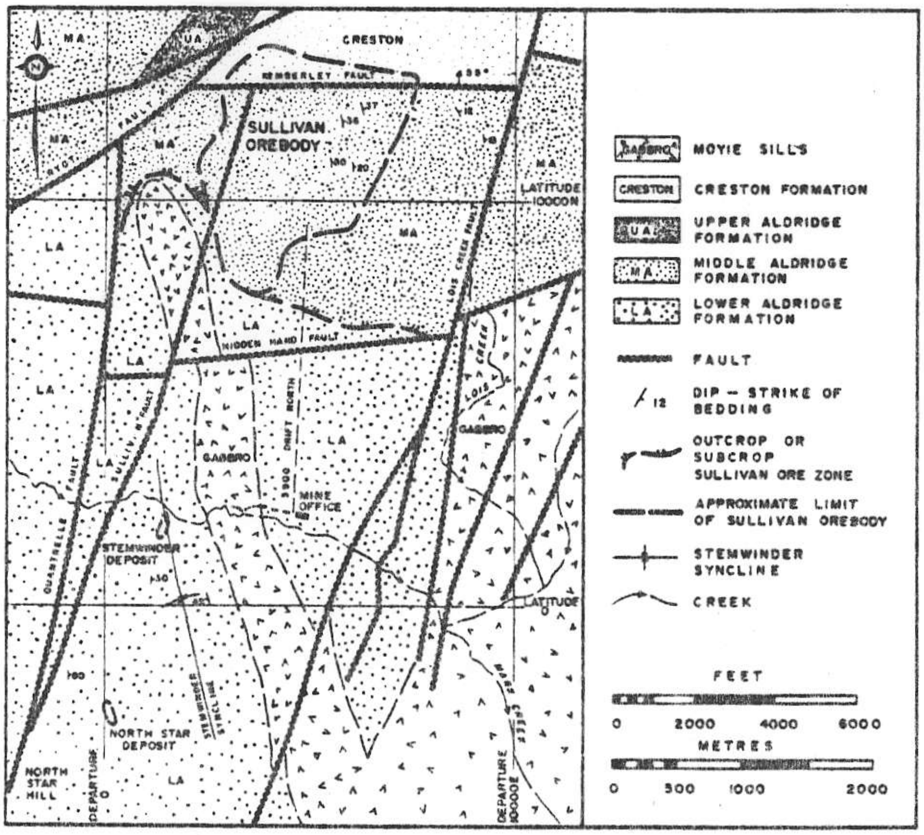

Figure 5. Geology of the Kimberley area.

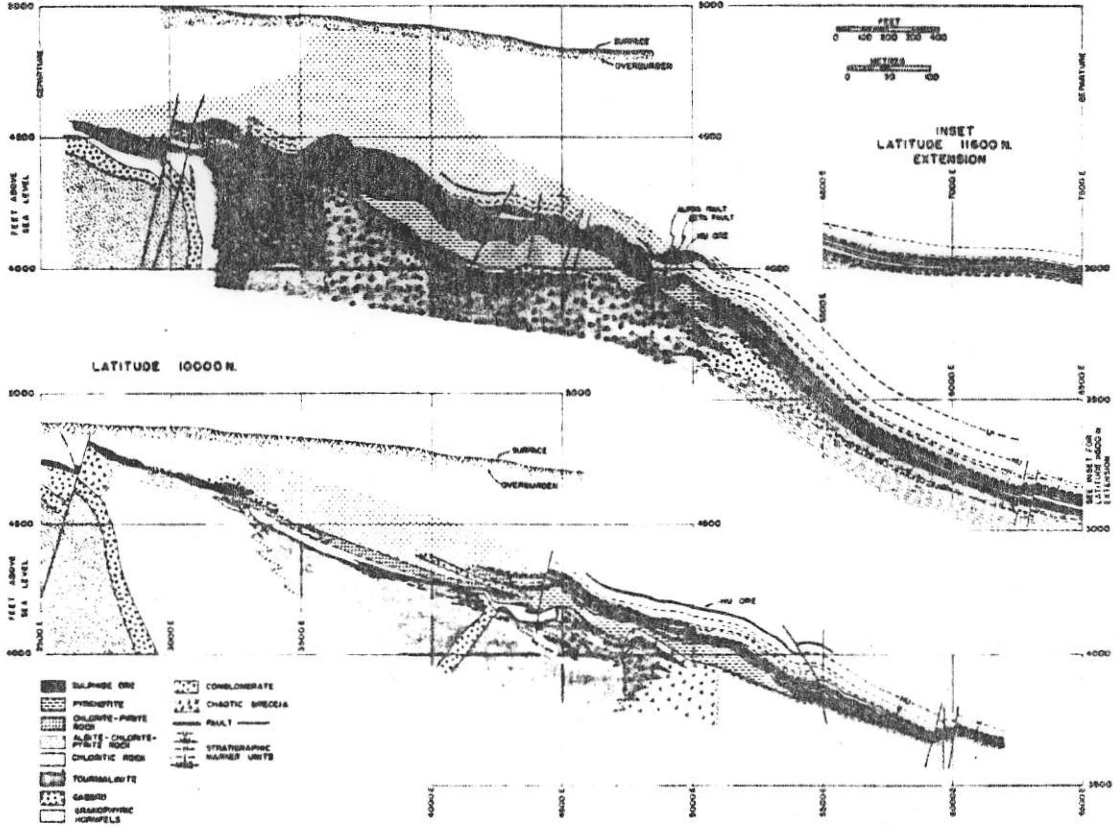

Figure 6. "East-west" vertical sections through the Sullivan orebody.

This discussion draws heavily from earlier works by Cominco geologists, including Freeze (1966), and, in particular, Ransom (1977) and Hamilton, *et al.* (in press).

Geological Setting

The Aldridge Formation in the Purcell Mountains is divided into Lower, Middle and Upper divisions. The Lower division is at least 1500 m thick (base not exposed) and is composed of a rhythmic succession of thin- to medium-bedded very fine grained wacke. The Sullivan orebody is at the top of the Lower division (Fig. 5). The Middle division is 2000 m of medium- to thick-bedded quartzose turbidites. The Upper division is 300 m of thin bedded to laminated mudstones. The Aldridge Formation is metamorphosed to middle to upper greenschist facies.

These rocks have been intruded by the Moyie Sills, gabbroic in composition, which make up 25 per cent of a typical Lower Aldridge section but become less numerous in the Middle Aldridge and are absent in the Upper Aldridge. Zircons from differentiates of a sill near the top of the Lower division provide concordant uranium-lead ages of 1430 ± 20 million years (Zartman, *et al.*, in press).

The Purcell Anticlinorium is the dominant regional structure. It is characterized by open folds plunging gently to the north and to the south. The Sullivan occurs on the east side of this regional structure, on the east limb of an open anticline. The orebody is up to 2000 m north-south by 1600 m east-west. It has flat to gentle easterly dips in the west, moderate easterly to northeasterly dips in the centre, and gentle easterly to northeasterly dips in the east.

The ore zone is truncated on its north side by the Kimberley fault. This east-striking fault dips 55 degrees north, with an apparent stratigraphic displacement of 2000 m, north side down. "Sullivan-type" normal faults also cut the orebody. These faults strike 010°, dip steeply west and exhibit west side down displacements in the ore zone up to 25 m. Larger displacements occur on similarly oriented faults located east of the orebody.

Geology of Footwall Rocks

Bedded Sequence. This unit is at least 150 m thick and is mainly composed of graded quartz wacke beds 10 to 30 cm thick. Cross laminae are rarely observed. The main mineral constituents are quartz, sericite biotite and some carbonate. Pyrrhotite laminations up to 1 mm thick occur in the uppermost 5 to 15 m of the unit, at intervals of about 1 per cm near the base to 5 per cm near the top.

Conglomerate. An intraformational conglomerate occurs near the top of the bedded sequence beneath the northern two-thirds of the orebody (Figs. 6 and 7). Its footwall contact is often disconformable in the west, where conglomerate thickness exceeds 80 m, but often only slightly disconformable or conformable in the east. Its hanging wall contact is generally conformable and is normally about 10 to 15 m below the sulphide footwall.

Clast lithologies and matrix compositions are the same as those of other footwall sedimentary rocks. No foreign clasts have been observed. Clasts are generally 1 to 3 cm in diameter but range from 2 mm to at least 1 m and comprise 10 to 95 per cent of the rock. Pyrrhotite is a typical but variable accessory mineral accentuating either matrix or clasts. Pyrrhotite occurs as laminations in certain clasts and as rims on other clasts. The footwall conglomerate may be extrusive (Shaw and Hodgson, personal communication, 1977) or it may be a slump feature.

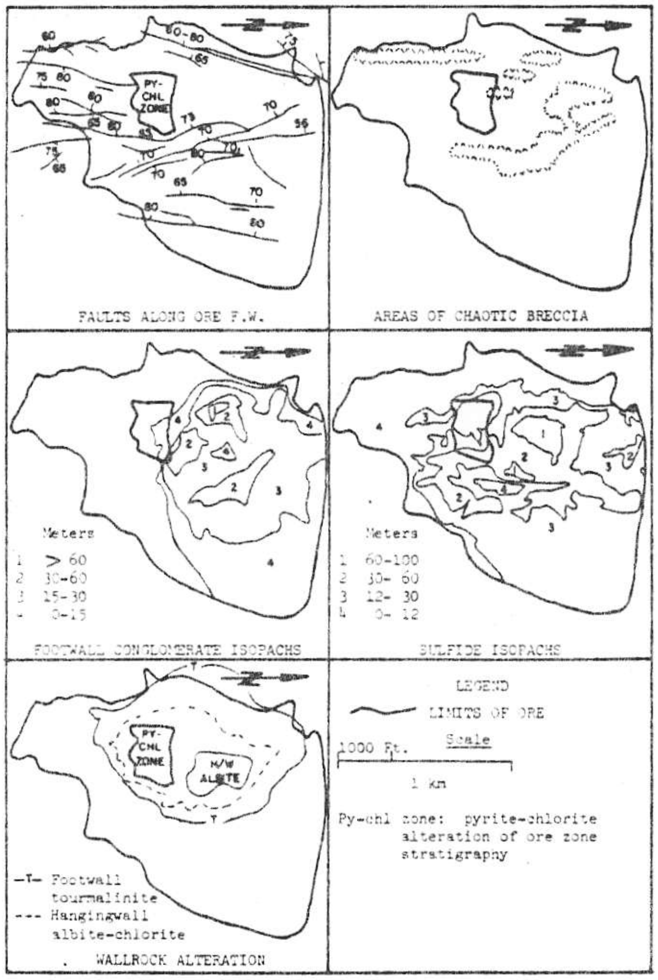

Figure 7. Faults, breccia distribution, conglomerate and sulphide isopachs, and wall-rock alteration, Sullivan deposit.

Chaotic Breccia. Generally north-trending bodies of breccia which have steep dipping contacts are located beneath the western part of the orebody (Jardine, 1966). These extend down unknown distances from the sulphide footwall (Fig. 6). The largest breccia body has dimensions of 120 by 900 m (Fig. 7). Breccia fragments range in size from 1 cm to 10 m, and exhibit a large range of degrees of roundness. Pyrrhotite is a common matrix constituent and galena and sphalerite are locally abundant. Chaotic breccia zones are now interpreted as conduits through which ore-forming fluids passed.

Alteration. The western half of the orebody is underlain by tourmaline rich rock (Figs. 6 and 7). This tourmalinite zone is funnel-shaped and extends at least 450 m below the sulphide footwall. Most tourmalinite appears to be due to metasomatic addition of boron, but the upper 50 m of the zone exhibits some features consistent with syngenetic availability of boron. In hand specimen tourmalinite resembles black or dark brown chert, and it is called chert locally. In thin section, quartz grains with indistinct boundaries are seen to comprise 15 to 50 per cent of the rock and are set in a felted matrix of tourmaline crystals 1 to 10 microns long. Pyrrhotite and subordinate sphalerite comprise 0 to 15 per cent of tourmaline rich rock, as disseminated grains or in delicate laminae.

Intensely chloritic rocks occur locally near the footwall of the western part of the orebody. Chloritic rocks occur along the eastern margin of the footwall tourmalinite zone, in crosscutting zones of large vertical extent below the centre of the orebody and in a comformable zone up to 10 m thick immediately underlying the centre of the orebody (Shaw and Hodgson, 1980*b*). Albite-rich rocks are commonly associated with pyrite-rich chloritic rocks in the area underlying the pyrite-chlorite-calcite assemblage of the ore zone (Shaw and Hodgson, 1980*b*).

Vein Mineralization. Sulphide veins are present in the footwall in and adjacent to the zone of tourmalinite and very rare elsewhere. Irregular veins commonly form networks composed dominantly of pyrrhotite, galena and sphalerite. Generally minor amounts of quartz, arsenopyrite, chalcopyrite, cassiterite, tourmaline or scheelite occur in some veins.

Footwall Intrusive Complex. A pair of gabbro sills 15 to 60 m thick separated by about 90 m of granophyre occur about 450 m below the eastern part of the orebody. This intrusive-granophyre package has the form of a gently north-plunging arch several km long which passes below and west of the western margin of the orebody (Figs. 5 and 6). The sides of the arch have steep to moderate dips. The arch is truncated at its north end by the Kimberley fault. Granophyre is interpreted to be highly altered sedimentary rock. Origin of the arch feature in the footwall intrusive complex is not well understood but intrusion into sedimentary layers draped over a syn-depositional horst is one possibility.

Geology of the Ore Zone

Introduction. The Sullivan orebody can be classified into two distinctive parts joined by a transition zone. The up-dip or western part of the orebody (generally that part underlain by tourmaline rich footwall rock, Fig. 7) is much thicker than the eastern part (Fig. 7). The western part is typified by sulphide layers which are relatively internally homogeneous and which contain relatively little intercalated waste layers. The transition zone up to 75 metres wide, is generally coincident with the eastern margin of footwall tourmalinite. Outboard of the transition zone, in the eastern part of the orebody, ore occurs in five laterally persistent "Bands" intercalated with significant clastic sedimentary rock layers (Fig. 8). Ore Bands in the eastern part of the mine are typified by delicate layering of sulphides.

Western Part. The ore zone averages about 50 m thick but relatively abrupt thickness changes within the 10 m to 100 m range occur. Conformable massive pyrite layers up to 5 m thick occur intermittently at the sulphide footwall and hanging wall. Nearly barren pyrrhotite lenses 10 m or more thick occur. The largest of these is at or near the sulphide footwall; it ranges up to 35 m thick, with a length of 350 m. Layering is not well developed in the barren pyrrhotite. Sphalerite and galena occur as wispy concentrations, disseminated grains, fracture fillings and veins. The top of the main pyrrhotite lens grades into an intermittently developed zone in which wispy layering is defined by galena and sphalerite concentrations. Further up section, layering becomes more pronounced and contorted, and discontinuous intercalated layers of clastic sedimentary rock are present. At the top of the western part of the orebody, thin bedded to laminated sulphide rock may be present.

Thick sections of internally homogenous sulphide containing no intercalated layers of clastic sedimentary rock and only a minor component of non-sulphide grains are thought to be features indicative of relatively rapid accumulation of sulphides. Layering of sulphides and presence of some intercalated waste beds near the top of the western part of the ore zone suggest a gradually decreasing rate of sulphide deposition.

An intensely developed pyrite-chorite-calcite alteration assemblage crosscuts the complete ore zone within the area indicated on Figures 6, 7 and 10. Contact zones between it and adjoining pyrrhotite or ore are 1 to 15 m wide. Fluids which led to development of a hanging wall alteration assemblage are regarded as having created the pyrite-chlorite-calcite assemblage in the ore zone (Shaw and Hodgson, 1980a, 1980b).

Eastern Part. The stratigraphy of the ore zone and enclosing rocks in the eastern part of the orebody, down dip from the transition

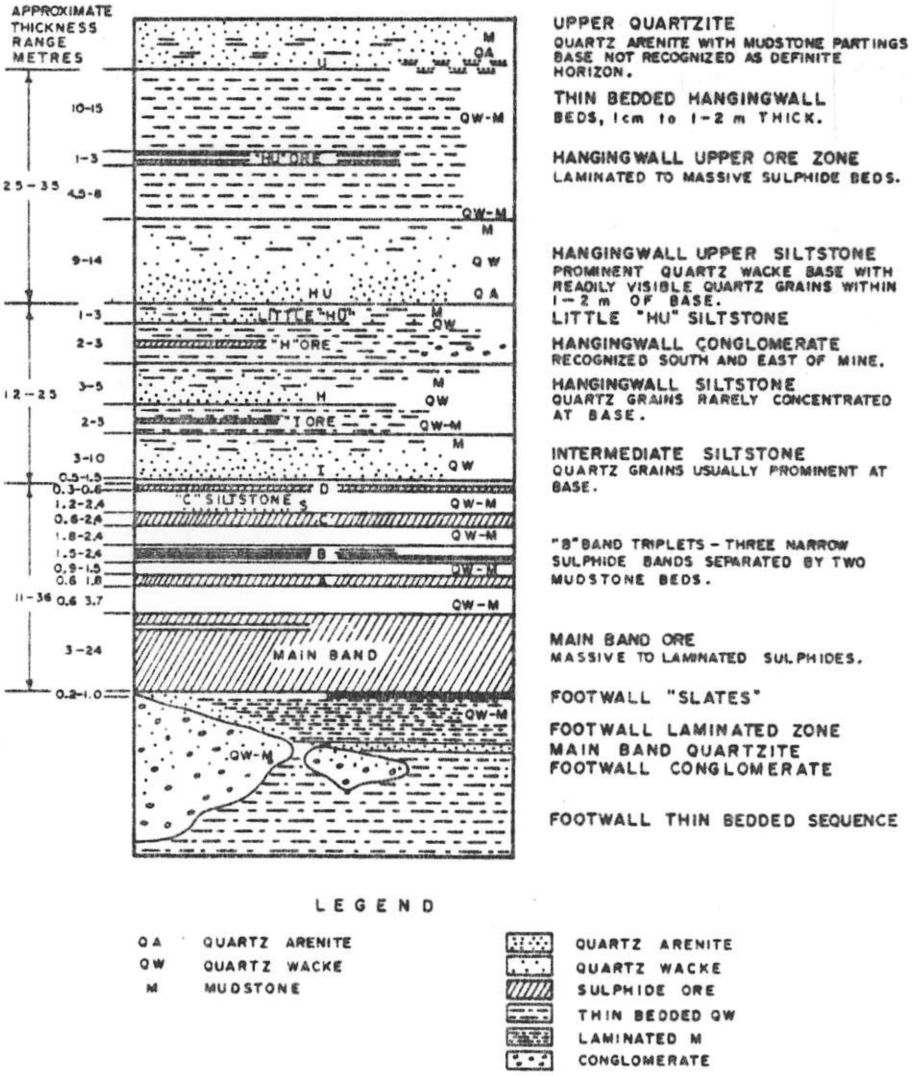

Figure 8. Ideal section of the bedded ore, Sullivan deposit.

zone, is shown in Figure 8. Ore extends from the base of the Main Band to the top of the D Band.

The Main Band rests on the Footwall "Slates" with a very sharp conformable contact. The basal half to two-thirds of the Main Band is different from over-lying sulphides. It consists of a succession of fine grained pyrrhotite, sphalerite and galena beds without intercalated clastics. The sulphide beds contain different proportions of the three sulphide minerals, and while generally less than 3 cm thick, range up to 30 cm thick. In some areas, notably the eastern fringes of the orebody, the basal part of the Main Band contains megascopic fragments and inclusions which together make up to 20 per cent of the rock. These are generally less than 1 cm across, but the fragments may range up to 1 m across. The common fragment types are altered and unaltered clastic sedimentary rock, carbonate rock and granular quartz-rich rock. Monomineralic inclusions of pyrite, calcite, quartz, sphalerite, scapolite and garnet are more numerous but volumetrically not greatly more significant than lithic fragments.

The upper portion of the Main Band, and overlying Bands contain up to 40 per cent of thin, closely spaced interbeds of mudstone and quartz wacke. Grain size of the sulphide layers is coarser but more variable than in the basal part of the Main Band. Sulphide beds are generally thinner and have a greater tendency to be monomineralic. Sections several cm thick composed entirely of delicate nearly monomineralic sulphide lamellae 0.3 to 5 mm thick are common in this part of the ore zone.

Four graded beds of intercalated waste rock separate the five Bands and make up 25 to 40 per cent of the ore zone, or about 50 per cent of that portion of the ore zone which overlies the Main Band. These four beds are similar to but thicker than those in the footwall bedded sequence.

Metal Distribution. Vertical distribution of metals in a portion of the eastern part of the orebody is shown on Figure 9. Iron concentration is roughly constant at 20 to 25 per cent. Zinc concentration ranges from about 20 per cent in the Main Band to about 7 per cent in the D Band. Lead concentration is greater at the top of the Main Band than at the bottom, reaching a maximum of about 14 per cent, decreasing to 1.4 per cent in the D Band. Vertical distribution of silver is similar to that of lead, decreasing from 50 to 5 gms per tonne.

Distribution of metals in plan is shown on Figure 10. Lead and zinc distribution maps show products of thickness times grade for those metals. Not surprisingly, most lead and zinc is located where the orebody is thickest. However, distribution maps for silver and tin show grade only. In general, highest grade areas for these metals are located in the western portion of the orebody. Of particular interest are the silver to lead ratio and lead to zinc ratio

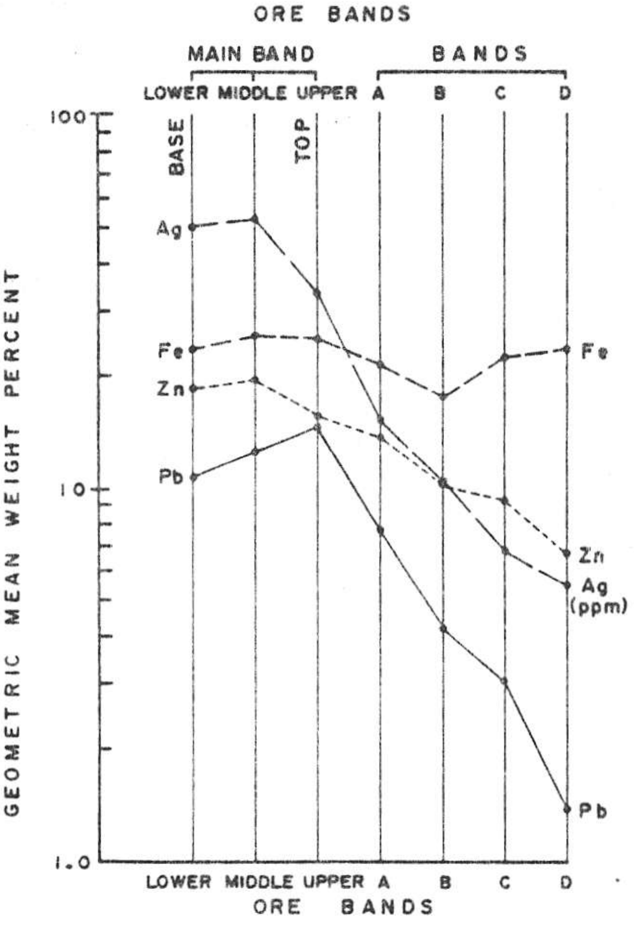

Figure 9. Vertical metal distribution in ore bands, Sullivan deposit.

plans. The silver to lead ratio plan shows that silver is enriched with respect to lead in the western part of the orebody. Similarly, the lead to zinc ratio is highest there.

These data are consistent with deposition of lead, silver and tin preferentially in the area of the orebody proximal to the vent zones, thought to be represented by areas of chaotic breccia (Fig. 7). Zinc is more concentrated than lead in more distal area.

Sulphur Isotopes, Geothermometry and Geobarometry. Detailed sulphur isotope investigations (Campbell, Ethier, Krouse and Both, 1978; Campbell, Ethier and Krouse, 1980) show that within the ore zone there is a general increase in relative abundance of ^{32}S with increasing stratigraphic position. Campbell, Ethier and Krouse (op. cit.) ascribe this variation to changing conditions affecting the supply of H_2S in the basin and temperature gradients existing in the basin, and conclude that Proterozoic seawater was the sulphur source.

Ethier, Campbell, Both and Krouse (1976) studied mineral relationships to obtain values for metamorphic temperatures and pressures. Arsenopyrite data provide a temperature estimate of 400° to 490°C; fractionation of sulphur isotopes suggests temperatures of 300° to 340°C; oxygen isotope fractionation between quartz and magnetite indicates a 400° to 560°C range. Sphalerite geobarometry work suggests pressures of 5 kilobars. As they point out, this figure is at least double that consistent with the known post-ore succession.

Structural History. Detailed structural mapping (McClay, in preparation) has revealed three phases of folding. Phase 1 is characterized by isoclinal folds with axial planes parallel to bedding planes and north-trending fold axes. Phase 2 is characterized by relatively open folds with gentle north or south plunges and with moderately west-dipping axial planes. Both Phase 1 and Phase 2 folds indicate easterly vergence. Phase 3 folds are associated with east-dipping thrusts; axial planes have steep dips and folds have variable plunges to NW or SE. Synsedimentary slump features occur but are extremely rare. East-dipping low angle thrusts associated with Phase 3 folds offset early Cretaceous lamprophyre dykes.

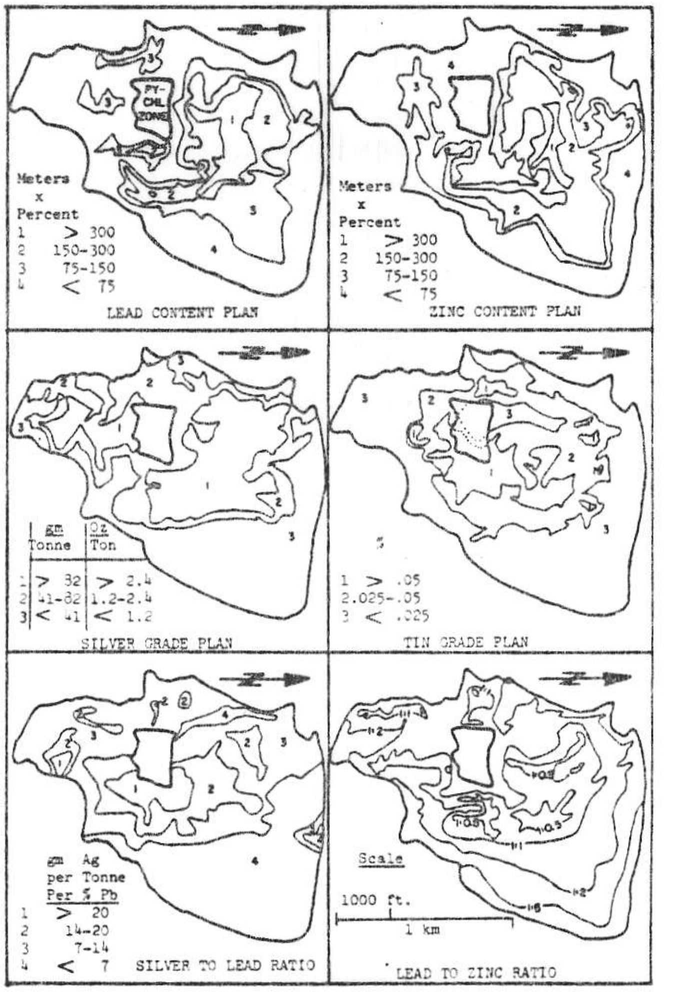

Figure 10. Metal distribution maps, Sullivan deposit.

Geology of Hanging Wall Rocks

Stratigraphy. The ore zone is overlain by four distincitive graded series: the I, H, Little HU and HU series. Each has a graded quartz wacke bed at the base which grades upward to a thick mudstone top. The top of the mudstone portions are commonly pyrrhotite-laminated. Distinctive pyrrhotite-laminated sections have been matched over distances of up to 1500 m. Up dip and to the south, these pyrrhotite-laminated sections grade into ore. The I, H, Little HU and HU series are not well documented outside the immediate mine area. They are regarded as products of largely post-ore infilling of the sub-basin in which the Sullivan orebody was deposited.

A hanging wall conglomerate averaging 4 m thick occurs stratigraphically beneath the H sulphide laminations. This conglomerate has been traced for about 1000 m along the southern margin of the orebody. Like the footwall conglomerate, the hanging wall conglomerate contains no foreign clasts. However, in contrast, it does contain some ore-grade clasts. It appears to correlate with the top of a largely post-ore breccia located in the southwest part of the orebody. Evidence for an extrusive origin for the hanging wall conglomerate is persuasive.

The HU series is overlain by 10 to 15 m of graded quartz wacke beds, and then by the U Quartzites which are regarded as the base of the Middle division of the Aldridge Formation.

Alteration. Hanging wall rocks above the western portion of the orebody are intensely altered to an albite-chlorite-pyrite assemblage up to 125 m thick (Fig. 6). Massive albitite in which original sedimentary textures have been obliterated forms a core that grades outward to an envelope of albitic and chloritic rock in which original gross sedimentary layering is preserved. The massive albitite core is located about 225 m northeast of the centre of the pyrite-chlorite-calcite alteration assemblage in the ore zone. Structural interpretation suggests that the hanging wall is displaced to the northeast (McClay, in preparation); crosscutting dykes assumed to be apophesies to the footwall intrusive complex are offset in that direction. Accordingly, it seems reasonable that the hanging wall alteration assemblage was once centred over the pyrite-chlorite-calcite assemblage that crosscuts the ore zone.

Geological History

The Sullivan orebody is interpreted as a hydrothermal synsedimentary deposit which formed in a sub-basin on the Aldridge marine floor. It is located directly over conduits through which mineralizing fluids passed. Cross-strata permeability developed along synsedimentary faults and fractures; fluid escape along these led to development of chaotic breccia zones. Footwall conglomerate was extruded from breccia pipes (Shaw and Hodgson, personal communication, 1977), or was laid down when locally oversteepened sediments collapsed.

Boron-rich fluids percolated up the zones of cross-strata permeability, soaking adjoining footwall sediments and discharging onto the sea floor. Then fluid composition and/or conditions in the sub-basin changed, and sulphides were deposited. Initial sulphide deposition over the vent area was rapid, as evidenced by lack of layering in sulphides and by lack of included clastic sedimentary rock. These features are felt to be consistent with deposition of sulphide particles which issued from the vent area.

Pyrrhotite deposition predominated during initial sulphide accumulation. Later, pyrrhotite interlayered with galena and sphalerite became dominant in the western part of the orebody. Deposition of the basal half of the Main Band may have occurred at this time, although detailed correlation of sulphide stratigraphy across the transition zone is difficult. Deposition of sulphides by chemical precipitation from a brine pool may have become the dominant mechanism during this period.

Waning stages of sulphide deposition were much less violent, and well layered sulphides intercalated with intermittent influxes of clastic sediments became the dominant depositional style. In the upper part of both the eastern and western portions of the orebody, delicate sulphide lamellae consistent with chemical precipitation are widespread.

The I, H, Little HU and HU graded sequences were laid down during filling of the sub-basin. Deposition of clastic sediments predominated but minor deposition of sulphides continued.

Composition of fluids changed again. Sodium-rich fluids percolated through the ore-bearing sequence and created albite-chlorite-pyrite alteration in the footwall, pyrite-chlorite-calcite alteration in the ore zone, and albite-chlorite-pyrite alteration in the hanging wall (Shaw and Hodgson, 1980a, 1980b).

Moyie sills (1430 ± 20 m.y.) were emplaced. Their form and contact relationships are consistent with emplacement under 2 to 4 km of overlying sediment, indicating emplacement during deposition of the overlying Creston Formation (Zartman, *et al.*, in press).

Three phases of folding are recognized (McClay, in preparation). The first two are of pre-early Cretaceous age, and since they suggest a similar stress field, may be close in time. They correlate with regional development of the Purcell Anticlinorium. The third phase is associated with east-dipping thrust faults which displace early Cretaceous lamprophyre dykes.

ACKNOWLEDGEMENTS

People who write about Sullivan geology stand on a lot of shoulders. We say thank you to the dozens of careful observers, recorders and interpreters of geological data at Sullivan who have preceded us. This manuscript was significantly improved during critical review by D. R. Shaw. K. R. McClay's comments are also appreciated.

SELECTED REFERENCES

Campbell, F.A., Ethier, V.G., Krouse, H.R. and Both, R.A., 1978. Isotopic composition of sulphur in the Sullivan orebody, British Columbia; Economic Geology, v. 73, pp. 246-268.

Campbell, F.A., Ethier, V.G. and Krouse, H.R., 1980. The massive sulphide zone: Sullivan orebody; Economic Geology, v. 75, pp. 916-926.

Edmunds, F.R., 1973. Stratigraphy and lithology of the lower Belt Series in southern Purcell Mountains, British Columbia: *in* Belt Symposium volume 1; Idaho Bureau of Mines and Geology, pp. 230-234.

______, 1977. Kimberley to Creston, stratigraphy and lithology of the lower Belt Series in the Purcell Mountains, British Columbia: *in* Lead-zinc deposits of southeastern British Columbia, edited by T. Höy; Geological Association of Canada fieldtrip guidebook 1, pp. 22-32.

Ethier, V.G., Campbell, F.A., Both, R.A. and Krouse, H.R., 1976. Geological setting of the Sullivan orebody and estimates of temperature and pressures of metamorphism; Economic Geology, v. 71, pp. 1570-1588.

Freeze, A.C., 1966. On the origin of the Sullivan orebody, Kimberley, B.C.: *in* Tectonic history and mineral deposits of the western Cordillera; Canadian Institute of Mining and Metallurgy Special Volume 8, pp. 263-294.

Hamilton, J.M., Bishop, D.T., Morris, H.C. and Owens, O.E., in press. Geology of the Sullivan orebody, Kimberley, B.C., Canada: *in* Major sulphide deposits of Canada and environs, the H. S. Robinson memorial volume, edited by R. W. Hutchinson; Geological Association of Canada.

Jardine, D.E., 1966. An investigation of brecciation associated with the Sullivan mine orebody at Kimberley, B.C.; Unpublished M.Sc. thesis, University of Manitoba, Winnipeg, 121p.

McClay, K.R., in preparation. Structural geology of the Sullivan orebody.

Ransom, P.W., 1977 . Geology of the Sullivan orebody; *in* Lead-zinc deposits of southeastern British Columbia, edited by T. Höy; Geological Association of Canada fieldtrip guidebook 1, pp. 7-21.

Shaw, D.R., in preparation. Wall-rock alteration of the Sullivan mine, Kimberley, B.C.; Ph.D. thesis, Queen's University, Kingston, Ontario.

Shaw, D.R. and Hodgson, C.J., 1980a. Wall-rock alteration at the Sullivan mine, Kimberley, British Columbia (abstract); Canadian Institute of Mining and Metallurgy Bulletin, v. 73, no. 821, p. 75.

Shaw, D.R. and Hodgson, D.J., 1980b. Wall-rock alteration at the Sullivan mine, Kimberley, British Columbia (preprint); presented at the 5th annual Canadian Institute of Mining and Metallurgy district six convention, Kimberley, October 24.

Zartman, R.E., Peterman, Z.E., Obradovich, J.D., Gallego, M.D. and Bishop, D.T., in press. K-Ar, Rb-Sr and U-Th-Pb ages of the Crossport C sill near Crossport, Idaho; Idaho Bureau of Mines and Geology.