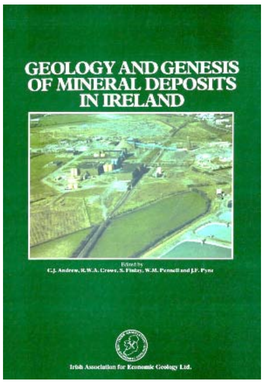

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The tectono-stratigraphic controls to mineralization in the Silvermines area, County Tipperary, Ireland

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The tectono-stratigraphic controls to mineralization in the Silvermines area, County Tipperary, Ireland.

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Abstract

In the Silvermines area Zn-Pb-Ba mineralization occurs within basal Carboniferous (Courceyan) transgressive siliciclastics and in the overlying carbonate sediments. Regionally the ore district lies on the NE flank of the Slieve Phelim — Slieve Aughty palaeohigh, a positive massif of attenuated sedimentation during the Courceyan to Brigantian Stages, which forms the SW limit of the NE-trending and pitching 'Iapetus' or Central Midlands Syncline.

Locally the geology of the Silvermines area is dominated by a complex of structures grossly trending ENE and known collectively as the Silvermines Fault Zone. This zone comprises an array of dip-slip listric and oblique-slip transfer faults which were active during sedimentation and mineralization.

Mineralization occurs in hydraulic fracture zones and as epigenetic replacements within the Lower Palaeozoic greywackes, basal Carboniferous clastics and as stratabound zones within secondary dolomites. All of these epigenetic zones are within, or spatially proximal to, WNW-trending components of the Silvermines Fault Zone. To date some 4.74Mt grading 2.44% Pb, 5.49% Zn is known to have occurred in these lower ore zones, all of which lie stratigraphically below the upper ore lenses developed at the base of the Waulsortian carbonates. The upper orebody is a tabular, stratiform, irregular lens of massive barite, siderite and marcasite-pyrite with variable amounts of base-metal sulphides. The orebody is developed down dip of WNW normal dip-slip faults and their associated slump zones. The thickness and distribution of the upper orebody is related to the palaeotopographic control of the irregular development of knolls of rapidly lithifying Waulsortian micrites. As a result of periodic tectonism of the fault complex, the ore sediments were subject to variable degrees of slumping and to pervasive *in situ* brecciation. In the main, Pb-Zn mineralization postdated the Fe-Ba sediments and largely occurs within intraclast void spaces, although fine-grained laminated particulate sphalerite — galena sediments are also present. Metal-zoning plots show the cross-cutting nature of the Pb-Zn mineralization with regard to the host facies, and Pb is enriched adjacent to the feeder zones along WNW faults. To date, the upper ore zones are known to have contained 12.94Mt grading 2.55% Pb, 6.78% Zn with an additional 5.0Mt of 85% $BaSO_4$.

Debris-flow breccias of dolomitized clasts of Reef Limestone set in a primary dolomite matrix occur in the hangingwall of the upper ore zones. Clasts of earlier formed, and often re-brecciated mineralized sediments are also found in these breccias. The hangingwall sequence shows distal and upward diminishment of the amount of breccia sediments and passes into typical Waulsortian facies away from the vicinity of the Silvermines Fault Zone.

Genetically, the Silvermines orebodies are a classic example of the so-called sedimentary exhalative group of deposits. It is thought that metalliferous brines at temperatures of approximately 220°C and salinities of 10-15 wt% NaCl equivalent were derived from the Lower Palaeozoic basement and from the Old Red Sandstone Munster Basin clastics by convective mechanisms. These solutions rose up the basal root zone of the Silvermines Fault Zone, initially flushing green shaley fault-gouge material from the fracture system to be deposited on the sea floor as the footwall Green Shale to the upper orebodies. At high levels within the dilatant fracture system the ascending brines encountered formational waters (c. 20°C, 25 wt% NaCl equivalent) derived from Carboniferous seawater wherein mixing occured with rapid and, possibly, locally explosive boiling, leading to the precipitation of the epigenetic lower ore zones. These lower zones are considered to be feeder zones to the upper ore body which is considered to be a sedimentary exhalative deposit. Brines debouched from WNW faults onto the sea floor and migrated gravitationally to palaeotopographic lows between the Waulsortian mudbanks. Within these dense brine accumulations, beneath a halocline, the Fe-Ba sediments were precipitated, the distribution of the sulphate, carbonate and sulphide facies depending on the redox potential and activities of reduced sulphur and CO_2 in the local environments. Subsequent tectonism and brecciation created void spaces which were infilled by later solutions depositing galena and sphalerite. Examination of host-rock, cement, and sulphide mineralogical parageneses indicates a temporal evolution of the hydrothermal fluids migrating through and debouching from the fracture system.

Introduction

The base metal and barite deposits of the Silvermines district occur on the northern flank of the Silvermines Mountains, some 8km south of the market town of Nenagh in northern County Tipperary. The earliest records of mining in the area date back to the early 9th century when argentiferous galena was mined by the Danes. From the 16th to the 19th century subsequent operations along the Silvermines Fault raised copper, silver, lead, zinc and sulphur ores. In this century, mining of 'calamine' (smithsonite) at Ballygowan South and of lead at Shallee continued sporadically until 1958. The major base metal and barite deposits worked, repectively, until July 1982 by Mogul of Ireland Ltd., and currently by Magcobar Ltd. (Dresser Industries), were discovered in 1962 by geologically directed diamond drilling. The Mogul mine produced some 10 783 859 t of ore grading 2.70% Pb, 7.36% Zn from 1968 until closure, from underground workings on the Upper G, Lower G, B and K Zones. (Table 1). To date the Magcobar operation has produced approximately 4 000 000 t of 85% $BaSO_4$ lump barite. Currently the Silvermines area is being extensively explored by Ennex International PLC who hope to add to the known remaining base metal ore reserves of 6 894 929 t grading 2.26% Pb and 4.98% Zn.

The earliest description of the deposits dates back to 1861 with the first series sheet memoirs of the Geological Survey of Ireland (Wynne and Kane, 1861), while Griffith (1956), Rhoden (1958), Taylor and Andrew (1978) and Taylor (1984) have described the contemporary knowledge of the mineralization in detail. Additional data on the deposits has been contributed by Greig et al. (1971), Coomer and Robinson (1976), Larter et al. (1981), Brück (1982) and Samson and Russell (1983). Recent work has led to a major revision of the structural setting of the Silvermines deposits and is published here for the first time.

The Silvermines deposits together form a classic example illustrating the relations between epigenetic ore zones (interpreted as feeders) and exhalative stratiform sediment-hosted ore bodies. This paper reviews all available data on the Silvermines district and is designed to supercede the previous description by Taylor and Andrew (1978).

Regional setting

The Silvermines area is situated on the fault-bounded northern flank of the Slieve Phelim — Keeper Hill inlier, cored by Silurian sandy turbidites and argillites (Doran, 1974; Edwards and Feehan, 1980; Archer, 1981) To the NW, the Arra Mountains, comprised of upper Llandovery greywackes with local transported shelly faunas, constitute an E-trending periclinal dome. These Lower Palaeozoic inliers form part of the larger Slieve Phelim-Slieve Aughty massif (Fig. 1) which was an active palaeohigh during the early Carboniferous, defining an area of attenuated sedimentation from the Courceyan to Brigantian Stages. The Silvermines area lies on the southern limb of the gentle post-Lower Carboniferous Kilmastulla Syncline which trends easterly to the west of Silvermines, turning to trend to the NE towards Nenagh and Birr (Fig. 1). This syncline is thought to constitute the southernmost extremity of the major 'Iapetus' or Central Midlands Syncline running SW from Navan via Tullamore to Nenagh, which is thought to coincide with the course of the Caledonian Iapetus plate suture (Phillips et al., 1976; Phillips and Sevastopulo, this vol.). To the NE of Silvermines, the Lower Carboniferous succession gradually thickens, with Courceyan carbonates being superceded by Chadian to Holkerian shelf limestones (Brück, 1982) (Fig. 1).

Stratigraphy and petrology

The stratigraphy in the Silvermines area has been summarized by Taylor and Andrew (1978) and on a more regional basis by Brück (1982) and Philcox (1984). This paper comprises a detailed account of the local mine stratigraphy and includes new data on the petrology of the host rocks to the mineralization (Catlin, 1983; Locklin, 1983). The stratigraphy is summarized diagrammatically in Figure 2.

The basement exposed locally in the Silvermines Mountains and in the foot-wall of the Silvermines Fault Zone, consists of grey-green sandy turbidites and argillites, which occur as thinning and fining-up sequences. Archer (1981) considered that the presence of repetitive sequences of

Table 1.

Ore reserve figures for the Silvermines orebodies. Figures based on Mogul of Ireland production records and detailed ore-reserve calculations (cf. previously published figures based on surface drill-indicated reserves in Taylor and Andrew (1978) and Taylor (1984)).

Nature and host of ore zone	Name of Zone	Tonnage (t)	% Pb	% Zn	g/t Ag
Exhalative ore zones at the base of the Waulsortian facies.	Upper G Zone	7,977,148	2.10	8. 18	22
	B Zone	4,639,233	3.38	4.53	30
	Magcobar South Zone*	326,807	1.70	4.72	26
	Magcobar Barite Zone	5,000,000 @ 85% $BaSO_4$			
	B Zone Barite	500,000 @ 75% $BaSO_4$			
Epigenetic ore zones hosted in the Lower Dolomite.	Lower G Zone	1,964,505	3.98	6.58	34
	K Zone*	1,434,188	1.38	4.40	15
	P Zone*	561,877	1.23	4.01	17
Epigenetic ore zones hosted in the Basal Clastics and Silurian.	C Zone	433,007	1.19	6.06	32
	K Devonian Zone	342,014	1.88	5.68	64
	Total	17,678,779	2.53	6.43	23
		5,500,000 @ 84% $BaSO_4$			

* = Excludes ore added during 1983-1985 drilling.

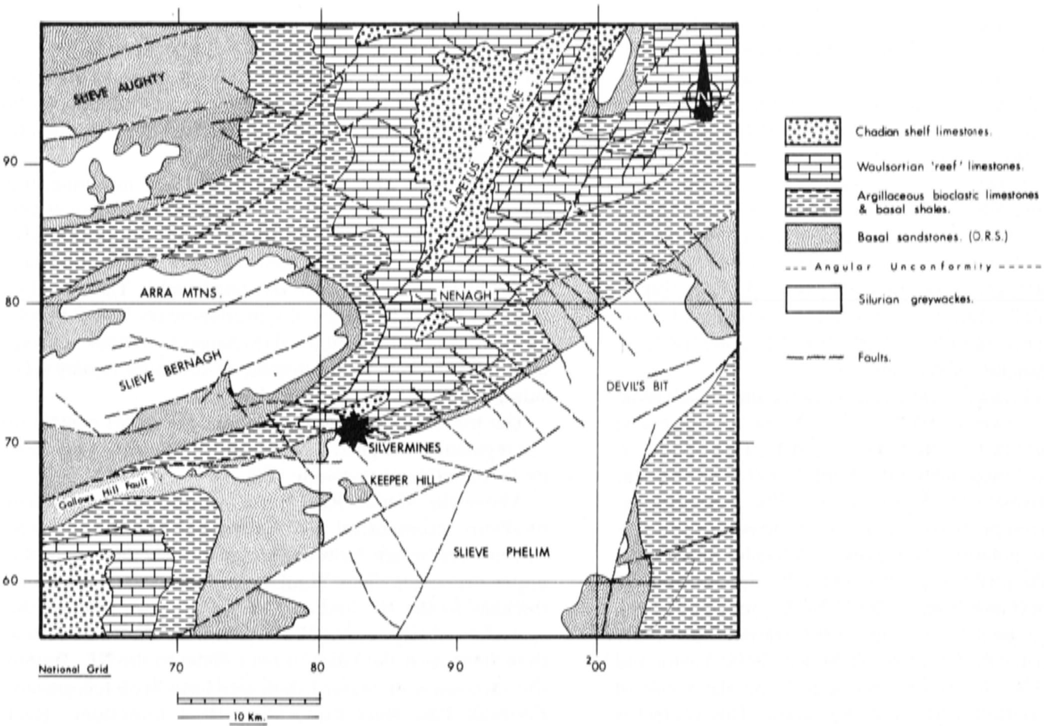

Figure 1. Regional geology of the Silvermines area.

sand-dominant bodies enclosed in argillites indicated sedimentation by migrating channel systems within an outer fan palaeoenvironment. During the Caledonian Orogeny low grade metamorphism of prehnite —pumpellyite grade was attained.

The Silurian in the Silvermines area is equated with the Hollyford Formation (Doran, 1974; Archer, 1981) of the *C. lundgreni* — *M. ludensis* graptolite zones of the Upper Wenlock. Petrologically, these turbidites comprise angular, mostly volcanic, quartz (<30%) and highly altered labile components (>70%, dominantly of volcanic detritus and feldspars altered to carbonates), originally of basaltic, andesitic and rhyolitic affinity (Archer, 1981).

The Silurian is overlain by an irregular angular unconformity below which minor haematization has occurred. The superceding Basal Clastics (Fig. 2), have in previous literature (Taylor and Andrew, 1978; Taylor, 1984) been referred to as Devonian. However, miospore assemblages obtained by Higgs (cited in Brück, 1982) indicate an early Courceyan *VI* biozonal age. The Basal Clastics in the Silvermines area are exposed as remnant veneers on the northern flank of the inlier and are seen in drilling throughout the region. Although lithologies of pebble conglomerate, grit, sandstone and siltstone are persistently developed in the area, the colouration changes from red, purple and beige east of Silvermines village (Fig. 3) to green and white over the rest of the area. Oxic colours also begin to appear in drilling in the basin 600-700m north of the inlier boundary faults. In the mine area, Rhoden (1958), and later Provencher (1971), sub-divided the 120m-thick clastic succession into six units defined by colour and siltstone — sandstone — conglomerate proportions (Fig. 2). In general, the sequence, which contains sedimentary fabrics indicative of deposition in an alluvial plain and fluvial palaeoenvironment (Gardiner and MacCarthy, 1981), passes upwards from gritty quartzites with lensoidal interbeds of vein-quartz pebble conglomerates, through finer gritty sandstones with thin mudstones and siltstones, to fine-grained clean sandstones with occasional pebble lenses. The uppermost 5-7m comprises thinly bedded, fine-grained, ripple-bedded sandstones indicating a provenance from the NE, which pass up into sandy siltstones and thin, bioturbated, calcareous mudstones with sparse winnowed bioclasts. This mixed, uppermost unit of the Basal Clastics is known locally as the Transition Beds. Petrologically, the Basal Clastics show minor quartz overgrowth and major ferroan calcite cements with later ferroan dolomite infilling primary or leached void spaces and fractures. Post-diagenetic euhedral pyrite pyritohedra (0.02-0.20mm) are pervasively scattered throughout both red-purple and green-white lithotypes.

The superceding Basal Shales (Fig. 2) comprise 10-12m of thinly bedded, dark-grey to black, calcareous shales with minor thin, dark-grey biomicarenites up to 5cm thick, and occasionally grey-green phosphatic siltstones. These siltstones become more prevalent in the eastern part of the district. A *PC* miospore zonal assemblage has been obtained for the Basal Shales (Higgs, in Brück, 1982). The uppermost 1-3m of this unit consists of a distinctive greenish-grey siltstone with a sparse shelly fauna known as the Ballyvergin Shale (Fig. 2). This sub-unit forms a distinctive chronostratigraphic marker horizon throughout much of SW Ireland (Philcox, 1984; Carter and Wilbur; Clifford et al.; Romer; Steed; Brown and Romer; Grennan; all this vol.).

Above the Basal Shales lies some 85-235m of the Argillaceous Bioclastic Calcarenite, the Ballysteen Limestone of Shepherd-Thorne (1963) and Philcox (1984). At Silvermines a complex local stratigraphy has been used by mine staff which several regional workers (e.g. Brück, 1982; Philcox, 1984) have related to other stratigraphic nomenclatural systems for this part of the succession. These are summarized in Figure 2.

The Basal Fragmental immediately overlies the Ballyvergin Shale and comprises 10-40m of medium-grey, thinnly bedded (with a pronounced nodular fabric) bioclastic calcarenites and shales. The unit becomes siltier upwards, with mica and quartz silt scattered throughout the shale. The lower beds also contain sporadic relict ooids, and brachiopod and sponge detritus. Bioturbation increases upsection. In the Silvermines area, the Basal Fragmental is dominantly a replacement dolomite and is locally recrystallized, with ferroan dolomite zoned with iron-free dolomite, and most fossil detritus is replaced by silica (Locklin, 1983). Recently, small cauliflower-like displacive nodules of anhydrite have been identified in the Basal Fragmental from east of Silvermines village (Fig. 3).

The Basal Fragmental is overlain in the immediate mine area by the Lower Dolomite which hosts the epigenetic mineralization of the Lower G, K and P Zones (Table 1, Fig. 3). The Lower Dolomite comprises 0-35m of thick-bedded, massive, medium pale-grey oolitic biosparrenite, which has been pervasively altered to a massive equigranular low-iron dolomite. The Lower Dolomite thins to the northeast and north away from the Fault Zone, as does the apparent effect of dolomitization. This has previously been interpreted to be a direct result of the effects of proximity to hydrothermal fluid conduits (Rhoden, 1958; Taylor and Andrew, 1978), but is now thought to be the result of lithological control of the dolomitization. This control is lithology-selective, with the oolitic beds preferentially affected. The oolites thin away from the inlier and suggest a shallowing palaeoenvironment in this direction. Similar lithological variation is seen regionally on the eastern flank of the Slieve Phelim inlier (Fig. 1).

Overlying, or laterally equivalent to the Lower Dolomite, lies the Bioclastic Limestone (Fig. 2) which consists of 30-55m of medium-grey, highly fossiliferous biosparrenite with thin wispy shale partings. Fossils include crinoids, echinoids and brachiopods, with less abundant bryozoa, corals, sponge spicules and worm tubes. Most bioclasts are bored and partially silicified. Cements are typically ferroan calcite and ferroan dolomite, but overall dolomite content is less than 10%. The Bioclastic Limestone is much siltier than the Lower Dolomite, and is considered to represent its deeper water offshore equivalent.

The overlying Muddy Limestone consists of 20-60m of medium dark-grey, planar-bedded skeletal shales with subordinate bioclastic calcisiltites. Fossils include crinoids, echinoids, bryozoans, spiny brachiopods and sponge spicules. Bioturbation is locally well developed. Cements were dominantly iron-free initially, but later ferroan calcites infilled remaining pore space to cement the rock tightly. Highly ferroan calcite infilled fractures and solution seams and silicification of bioclasts occurred. Dolomite is sparse or absent.

The Muddy Limestone is superceded by the Muddy Reef, 15-45m in thickness. The unit comprises medium to dark-grey nodular biomicarenites with wispy shale partings and occasional thin lenses of crinoid biosparrudites. The upper part of the unit (5-20m) typically contains many nodular horizons of silicified biomicrite whereas the lower beds are devoid of silicification. The silica may have been derived from abundant sponge spicules which are now replaced by ferroan calcite. The dominant cement in the Muddy Reef is ferroan calcite, although some recrystallization of original carbonate mud matrix to microcrystalline calcite has taken place. Commonly an increase in crinoid ossicle size occurs towards the top of the Muddy Reef (Barrett, 1975). In areas of well-developed mineralization proximal to feeder zones to the immediately overlying upper stratiform ore zones (Upper G, B and Magcobar Barite Zone — Fig. 3), the Muddy Reef shows significant lateral facies variations which are thought to be influenced by early exhalations of silica-rich dense brines. These local facies are described in the sections on the upper ore zones.

Isopach plots of all the units below, and including, the Muddy Reef show a general thickening to the NE (with the exception of the Lower Dolomite which thickens to the southwest and thins antipathetically with Bioclastic Limestone thickness to the east and northeast.). There is also evidence that early stages of synsedimentary WNW-trending tectonism influenced local thickness variations in these units with thickening developing on the more rapidly subsiding northern side of the faults.

The top of the Muddy Reef marks the upper contact of the regionally recognized Argillaceous Bioclastic Calcarenite or Ballysteen Limestone (Fig. 2).

Above the Muddy Reef lies a complex of Waulsortian mudbank stromatactid biomicrites and Waulsortian-derived breccias which form the hangingwall sediments to the upper ore zones. This Waulsortian 'equivalent' sequence thickens to the NE and on the downthrown sides of the synsedimentarily active WNW-trending faults from less than 100m near the inlier to over 400m to the NE. Within the succession six major lithologies have been recognized; Footwall Pale Reef Limestone, Reef Limestone, Reef Limestone Breccia, Dolomitized Reef Limestone Breccia, Dolomite Breccia and Chert. Many of these breccias have been interpreted as debris-flows (Boyce et al., 1983), however flank mudbank-knoll breccias are also present.

In the vicinity of the upper ore zones, the Muddy Reef passes directly into ore sediments and then up into the breccia sequence (Fig. 2). However at the fringes of the ore zones, stromatactid Waulsortian biomicrites form knolls below the ore sediments and eventually attain sufficient relief against which the ore lenses are wedged-off. This provides clear evidence for a palaeotopographic control to synsedimentary mineralization (Taylor and Andrew, 1978; Taylor, 1984) and is discussed more fully below. This palaeotopographic surface is contoured in Figure 10 and, apart from gentle tilting to the north it closely resembles the Lower Carboniferous sea-floor. The surface is marked by a thin (0-30cm) unit of fissile green silty shale which has previously been described as a tuff and as a ". . . . . sluggish influx of mud from a terrestrial source." (Barrett, 1975). The mineralogy of this shale consists of sub-rounded to angular grains of quartz, chert, plagioclase, biotite, pyrite and less than 5% carbonates, set in a matrix of illite-sericite, mixed-layer illite-smectites and kandites; it is broadly similar to the composition of the Silurian greywackes. The presence of reworked and abraded Silurian acritarchs confirms this supposition. This Green Shale overlies both Muddy Reef and Footwall Pale Reef Limestone knolls but thins and eventually dissappears to the north.

The Green Shale is overlain by a complex of interdigitating lenses of variable breccias and knolls of Waulsortian Reef Limestone (which become increasingly prevalent away from the fault complex to the north). Typically the Waulsortian Reef Limestones comprise pale-grey stromatactid biomicrites with knoll-flanking veneers of crinoid biosparrudites and flank-reef breccias. As stated above, both flank-reef and debris-flow breccias are present in the Waulsortian equivalent succession, and it is important to recognize the difference between these breccia types. Flank-reef breccias comprise clast-supported, poorly sorted, angular clasts of Waulsortian micrite (typically 5-

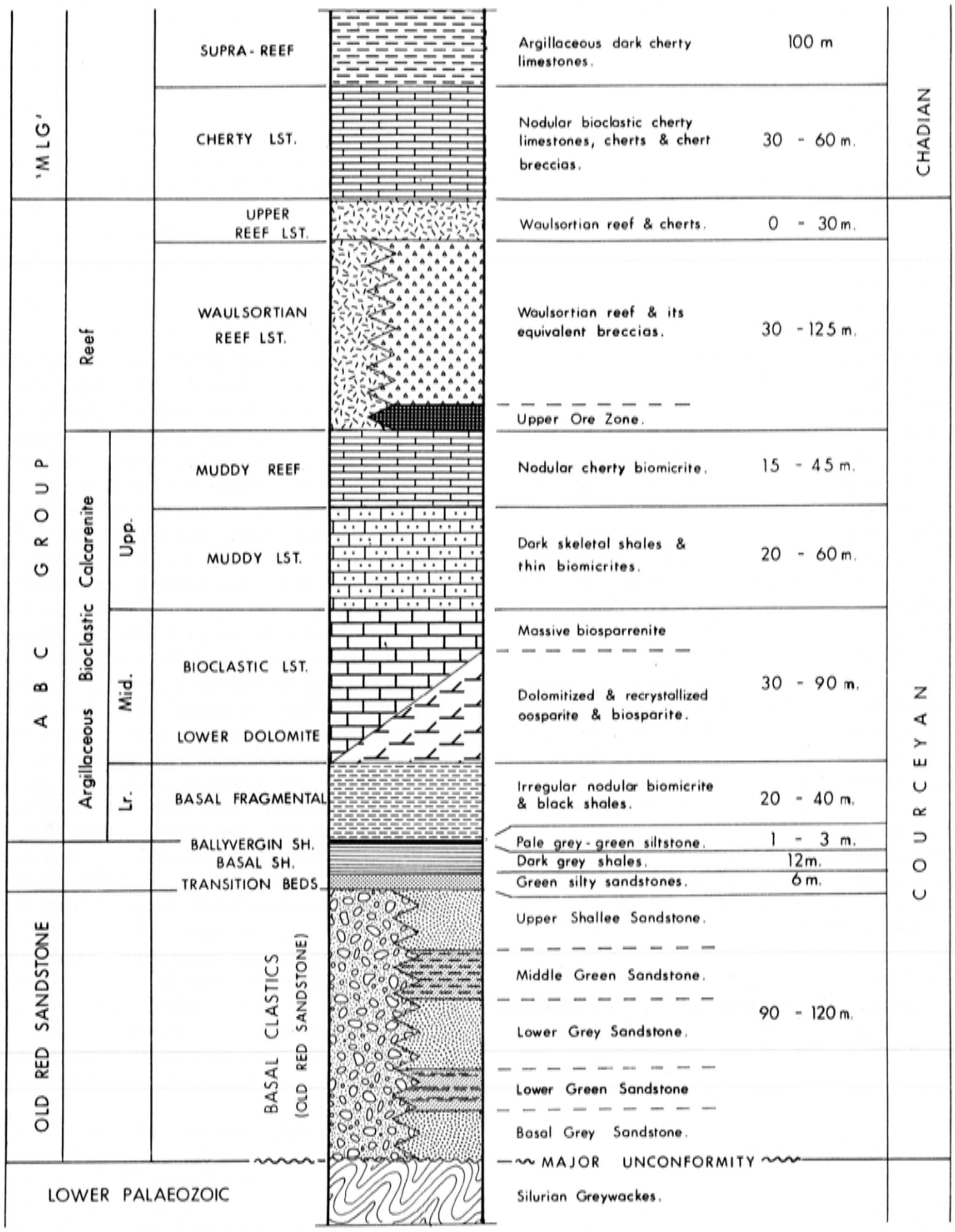

Figure 2. Summary stratigraphic column for the Silvermines area. Based on Taylor and Andrew (1978) and Brück (1982).

15cm in diameter, but occasionally up to 5m), set in a matrix of black argillaceous mud with abundant skeletal detritus. Primary cements in both Waulsortian Reef Limestone and Reef clasts are iron-free calcites including several layers of radiaxial calcite shelter-space cements which preceded ferroan calcite along fractures. In Reef and flank-reef breccias, ferroan dolomite is restricted to late-stage fractures, whilst in debris-flow breccias it was present early in the diagenetic history. The debris-flow breccias have been classified as Dolomitized Reef Limestone Breccia and Dolomite Breccia, but these terms are in fact two end members of a full range of variable sediments. Dolomitized Reef Limestone Breccias comprise both those which have been dolomitized *in situ* and breccias of mixed clast affinity, some dolomitized, others undolomitized, set in a matrix of fine rock debris. These breccias are dominantly matrix-supported and contain textural evidence that both lithic and semi-lithic clasts were incorporated in the debris flows. Typically the matrix is dark grey with rounded pale dolomite rhombs in a finer groundmass of dolomitized clay or organic-rich dolomitized carbonate mud. Minor quartz and mica silt is also present. The sediments show numerous solution/compaction surfaces formed during lithification, and abundant marcasite occurs along these surfaces, which appear to be a late diagenetic event. Clast size and percentage of dolomitization appear to be related, with the finest breccias being virtually totally dolomite. These are interpreted as distal zones of the debris-flows, where exhalative brines precipitating dolomite were commonplace. In these distal zones, fine-grained vermicular Dolomite Breccias dominate, these being formed by alignment and recrystallization or growth of dolomite crystals in the muddy organic matrix to form crusts, with subsequent compaction causing deformation and disruption. Re-brecciation is a common phenomenon and clasts of cemented breccias occur within the debris-flow sequence.

To the NE, the breccia-dominated sequence passes laterally through interdigitating lenses of flank-reef breccias with thin lenses and knolls of Waulsortian micrites into massive Waulsortian Reef Limestone. In general, the zoning of proximal, medial and distal debris-flow breccias appears to be from SE to NW respectively. In the mine area, the breccia sequence passes up into a variable thickness (0-35m) of typical Waulsortian stromatactid micrites with lenses of blue-grey banded cherts and cherty dolomitized flank-reef bioclastic calcarenites. This mixed part of the succession is locally termed the Upper Reef Limestone (Fig. 2). These in turn pass up into 30-60m of nodular pelletal and bioclastic siliceous calcarenites with black chert nodules, collectively known as the Cherty Limestone (Figs. 3 and 4). Primary cements are iron-free calcite, but later fracturing permitted the passage of solutions which deposited zoned ferroan calcites in void and fracture porosity. Silicification post-dates the ferroan calcite.

Conodont assemblages obtained from the Waulsortian equivalent succession and superceding units indicate that the Courceyan — Chadian Stage boundary lies near to, or at, the base of the Cherty Limestone (Brück, 1982). Assemblages obtained from the Footwall Pale Reef Limestone knolls in the immediate footwall of the upper orezone have indicated a *P. communis carina* biozone, chronologically equivalent to the ore host rocks at Navan (Brück, 1982; Andrew and Ashton, 1985; Phillips and Sevastopulo, this vol.).

Structure

The Silvermines area lies on the fault-bounded southern limb of the broad asymmetric Kilmastulla Syncline (Figs. 1 and 3) which trends and plunges gently to the ENE. Dips on the northern limb are generally less than 10°, whereas the southern limb is generally steeper at 15° , increasing to 60° in the drag attenuation zone of the Silvermines Fault Zone (Figs. 3 and 4).).

Previous accounts of the structure of the Silvermines area (Taylor and Andrew, 1978; Taylor, 1984) have included a structural plan based on company information dating from 1966. Recent reappraisal work using information from 548 surface drillholes, over 2,500 underground drillholes and some 68km of underground mapping has led to a major revision of this interpretation by the present author (Fig. 3).

The Silvermines Fault has been traced from the Shannon Estuary, north of the Courtbrown prospect (Grennan, this vol.) via Gallows Hill in County Limerick (Fig. 1) to the west of the Silvermines district near Shallee White (Fig. 3), a distance of almost 50km. Coller and Phillips (1981) defined the Fault as a narrow shear zone of high strain and large displacement, dominantly accommodated along a single major fault plane, which they inferred as a dextral transcurrent simple shear active during the Lower Carboniferous. Coller and Phillips (1981) interpreted the pattern of faults as shown in previous publications (Rhoden, 1958; Taylor and Andrew, 1978) to show the major fault rotating clockwise and terminating in a splay of faults indicative of a broad zone of low finite strain. However, recent drilling has resulted in a significant re-interpretation of the fault pattern.

In the Silvermines area several trends of faulting have been recognized (Rhoden, 1958; Taylor and Andrew, 1978). This complex fault pattern suggests that many of these trends are synchronous and interrelated. The dominant fault trend is WNW and northerly dipping (Fig. 3). These faults are always associated with slumping, drag attenuation zones and monoclinal flexures, and are coincident with sediment thickness variations; in addition they always have a close spatial association with mineralization. The most important of these faults, the Shallee — G Zone — K Zone — C Zone Fault (Fig. 3) colloquially termed the Silvermines Fault, was formerly interpreted as the eastern extension of the Gallows Hill Fault, an interpretation now known to be incorrect. The Silvermines Fault *sensu lato* has a normal downthrow which varies from 100 to 350m and typically exhibits a curved profile flattening with depth, and thus is consistent with a listric style. This fault trends westerly for part of its known extent, where its dip steepens from 60° to near vertical. At points of maximum throw the fault attains its steepest dip, and a component of rotational movement is suggested. The Silvermines Fault *sensu lato* exhibits a strike change from westerly to WNW in at least two areas. At these points (at the positions of the C and K Devonian Zones; see Fig. 3) branch faults, trending WNW, bifurcate from the main fault, initiating as a monocline and increasing in throw to the WNW to become slump-faults. These faults are obviously coeval with the main fault, and similarly affect sedimentational thickness variations and control the distribution of mineralization. The combination of the main fault and these branch faults combine to form the horsetail structural pattern which dominates the Silvermines area (Fig. 3).

In detail, the main faults are tight, shaly, gouge-filled structures rarely exceeding 1m in width. Within a gouge zone in the K Zone Coller & Phillips (1981) determined two components of displacement (from crystal growth history in carbonate-quartz fibre veins) indicative of early extensional (dip-slip) and later (post-ore) transcurrent movement. A broad zone up to 100m in width of poorly developed post-ore cleavage shows a clockwise rotation to parallel the faults proximally, thus indicating at least some post-ore dextral shear.

Minor faulting within the footwall block of the main fault structure trends both parallel to, and *en echelon* to the main fault. Within this block the WNW faults define several structural zones. The *en echelon* structures to the main fault often contain simple fracture-vein or more complex hydraulic-fracture breccia zones which are often mineralized (as at Shallee, Shallee White, Gortnadiha and Garryard). At Shallee (Fig. 3), normal dip-slip slickensides occur on most veins, although later, post-mineralization, superimposed oblique-slip is indicated by striae in steel-ore galena selvedges.

Post-ore faulting is seen in the Upper G and B Zones

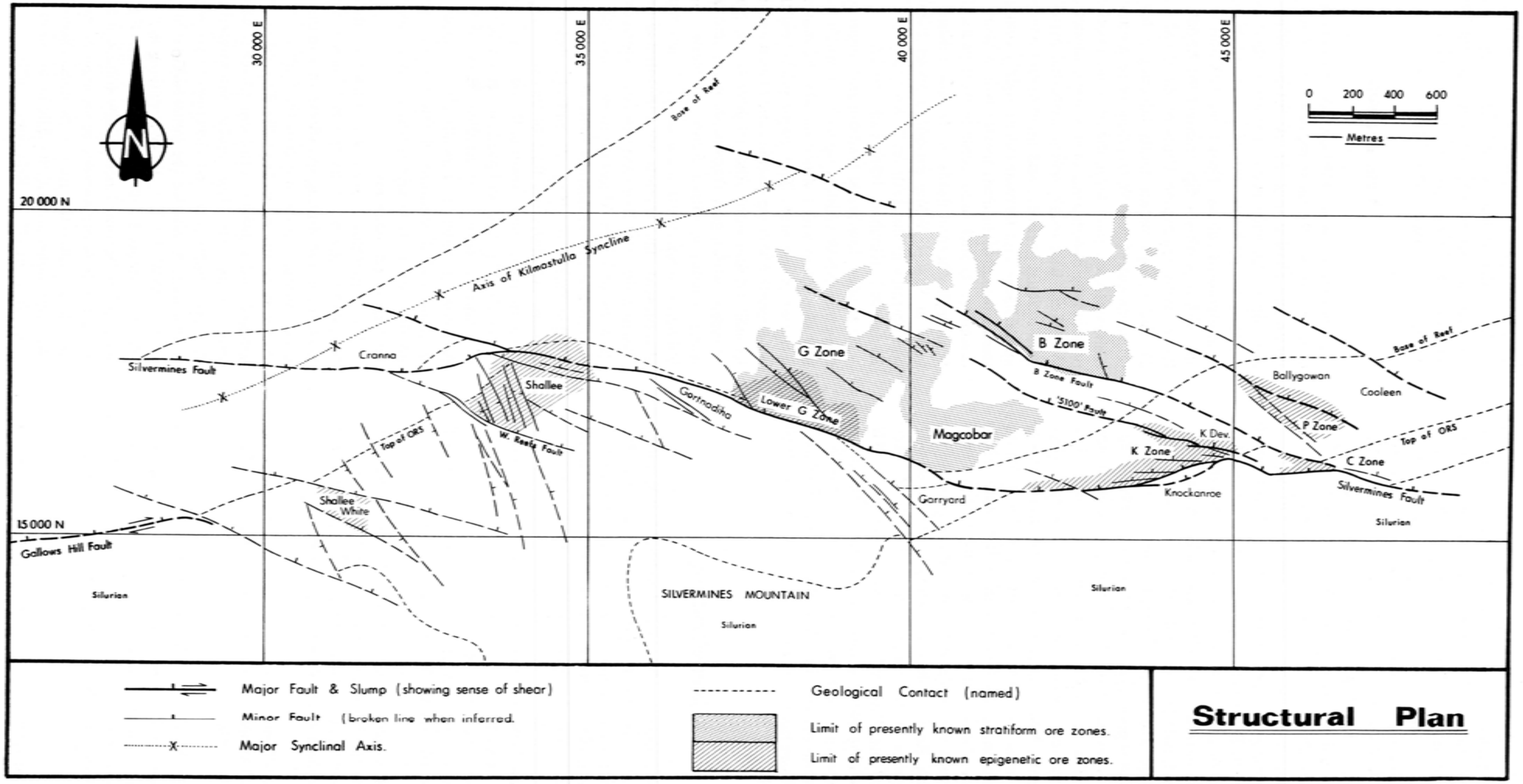

Figure 3. Structural plan of the Silvermines area showing the location of the main ore zones and outline geology.

(Fig. 3) and trends NW, that is, *en echelon* to the major WNW slump-faults. Slickensides on these faults are dominantly normal but, rarely, oblique-slip components have been demonstrated by detailed underground mapping. These faults are very tight and generally contain little or no gouge or breccia. Vertical displacements range from 0-10m. In the K Zone (Fig. 3), bedding-plane slip thrusting has been seen striking approximately easterly. This thrusting is associated with quartz — carbonate veining and jointing which cuts pre-existing sulphide mineralization and thus is obviously a post-ore event. Similar jointing and carbonate veining is seen elsewhere in the area, notably in the Upper G and B Zones and is spatially and systematically associated with easterly striking monoclinal flexural-slip folding. This period of tectonism appears to be a synchronous and related event to the development of the Kilmastulla Syncline and its NE extension into the Central Midlands, and is generally regarded as a main-phase Hercynian event (Sevastopulo, 1981; Sevastopulo and Phillips, this vol.). The main WNW-trending faults, with their evidence of synsedimentary tectonism, are spatially associated with gentle NNE-plunging folding. The major synclinorial fold belts are coincident with, and run down-dip from, points of maximum throw on the WNW faults. These fold belts are considered by Taylor (1984) to have been formed coevally with sedimentation at the immediate top of the Muddy Reef, as they are spatially coincident with facies variations in the upper beds of the Muddy Reef and the overlying Waulsortian Equivalent succession. The pattern of folding and its geometric relations to the faults, with their known curving profile, is closely analagous to similar relations of listric faulting produced in extensional basins and basin margins (Crans et al., 1980; Beach, 1984; Gibbs, 1984).

Mineralization

In the Silvermines area base metal and barite mineralization occurs at every stratigraphic level up to and including the Waulsortian Equivalent succession, and in numerous tectonic and geologic settings. These can be divided into four specific groups of varying economic significance:

1. Simple vein deposits in joints and minor fractures with minor disseminations in the Basal Clastics and the Silurian rocks. Examples occur at Shallee White, Shallee and, in many smaller developments, throughout the Silvermines Mountains (Fig. 3).

2. Complex breccia zones within dilational tectonic settings in the Basal Clastics and Silurian rocks, as at Knockanroe, Gortnadiha, Shallee, Cranna, and in the K Devonian and C Zones (Fig. 3, Table 1).

3. Cavity-fill and fracture-fill zones in the secondary Lower Dolomite as in the Lower G, K and P Zones (Fig. 3, Table 1).

4. Tabular bedding-parallel zones at the base of the Waulsortian Equivalent succession exhibiting sedimentary characteristics. These typically contain debris-flows of mineralized clasts in the hanging-wall as in the Upper G, B and Magcobar Zones (Fig. 3, Table 1).

It has been generally recognized and accepted that the first three styles of deposits were formed epigenetically in the feeder system to the major upper exhalative to syndiagenetic stratiform orebodies (Barrett, 1975; Taylor and Andrew, 1978; Larter et al., 1981; Boyce et al., 1983; Samson and Russell, 1983; Taylor, 1984).

Vein deposits

In the extreme west of the district a number of lead/barite veins are known, the most important areas being at Shallee White and Shallee (Fig. 3). At Shallee White, numerous veins up to 2m wide occur and are infilled with white to grey translucent barite, minor quartz and sporadic patches of fine-grained galena. They trend NW and WNW, generally with a northerly dip, transect the Middle Green and Lower Grey Sandstone Units of the Basal Clastics (Fig. 2), and occupy minor faults affecting a few metres of displacement. The NW-trending veins parallel the dominant systematic joint set in the area, members of which are occasionally mineralized over a few centimetres of width. Within the host rocks, minor subhedral pyrite and galena infill residual porosity, and quartz-grain overgrowths with minor barite and ferroan calcite tightly cement the sandstones instead of the more usual low-iron calcite and ferroan dolomite. As such these cements were probably deposited from hydrothermal fluids of the mineralizing event. The veins at Shallee White produced about 1,000t of galena concentrates in the 18th and 19th centuries (Wynne and Kane, 1861; Kinahan, 1889; Cole, 1922).

At Shallee, low-grade lead mineralization occurs within numerous NNW veinlets up to 2m in width (but most are less than 20cm wide) which occupy the major systematic joint set in the area. The major joints/veinlets are often connected by bedding-parallel and diagonal stringers. Veinlet infill is dominantly either medium-to fine-grained galena or galena within grey translucent barite and quartz in the wider structures. Minor pyrite, sphalerite, arsenopyrite, lollingite, boulangerite, chalcopyrite and tennantite are also present. The veinlets are concentrated in swarms 10-70m in width, 100-200m long and developed over a vertical thickness of 5-25m. Mineralization is concentrated immediately below the Transition Beds at the top of the Upper Shallee Sandstone (Fig. 2) and also below a 1m thick siltstone 3m above the base of this sub-unit. Only minor mineralization occurs lower in the clastic succession. Minor disseminated galena and pyrite occur within the sandstones in residual porosity as at Shallee White, although there is petrological evidence of locally more intense pre-sulphide leaching and dissolution of feldspar and quartz grains, notably below shale and siltstone bands, providing space for high galena contents.

The mineralized area was formerly thought to be bounded to the north by the main WNW fault (Fig. 3), however recent drilling has shown that similar mineralization continues to the north of the fault for at least 100m. Adjacent to the main fault the mineralization is coarser grained and exhibits colloform textures where it infills irregular anastomosing veinlets interpreted as hydraulic fractures. Sphalerite and chalcopyrite are more common in this area. At Shallee the mineralized area is terminated to the SSW by the WNW-trending northerly-dipping 'Western Reefs Fault' (Rhoden, 1958) (Fig. 3). To the west, barite becomes increasingly dominant at the expense of galena. Post-ore movement on some of the NNW joints has block faulted the area of the mineralization and led to the recrystallization of the galena as 'Steel-ore' selvages (the "*Bleischweif*" of Ramdohr, 1969).

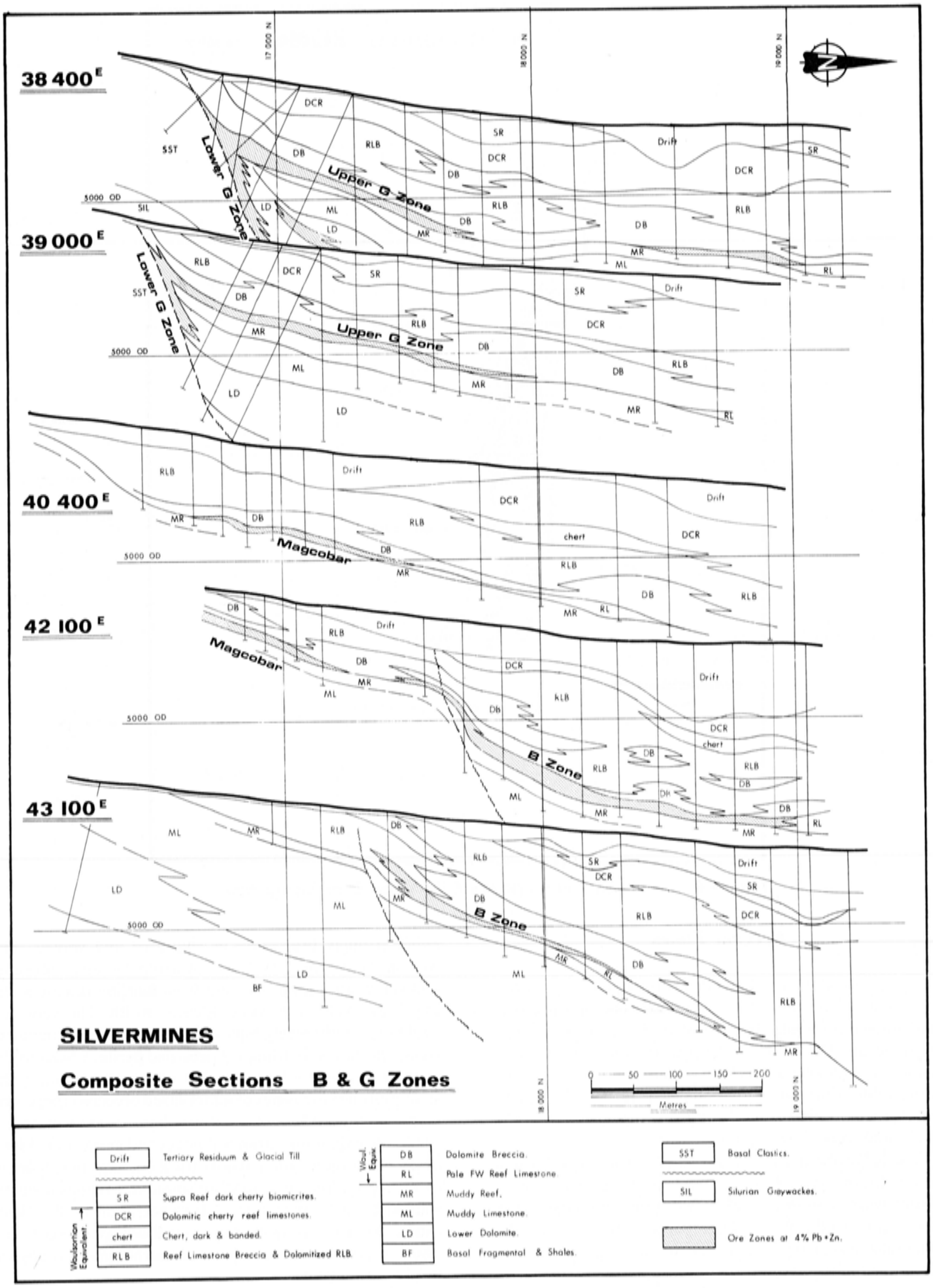

Figure 4. Serial sections facing west through the central part of the mine area.

Rhoden (1958) calculated that the Shallee ore zone, which was exploited until 1958, contained 1.3Mt grading 1.95% Pb, 0.10% Zn and 18g/t Ag. From 1951 to 1958 some 355,000t of ore was mined yielding 6,586t of lead concentrates.

Minor barite, quartz and galena veins and veinlets have been recorded at numerous localities within the Silurian of the Keeper Hill and Silvermines Mountain areas (Figs. 1 and 3), mostly in veins trending WNW and NW. Veins of other trends, most notably easterly and ENE, are earlier, are often folded, are devoid of sulphides and are infilled with white milky quartz and chlorite.

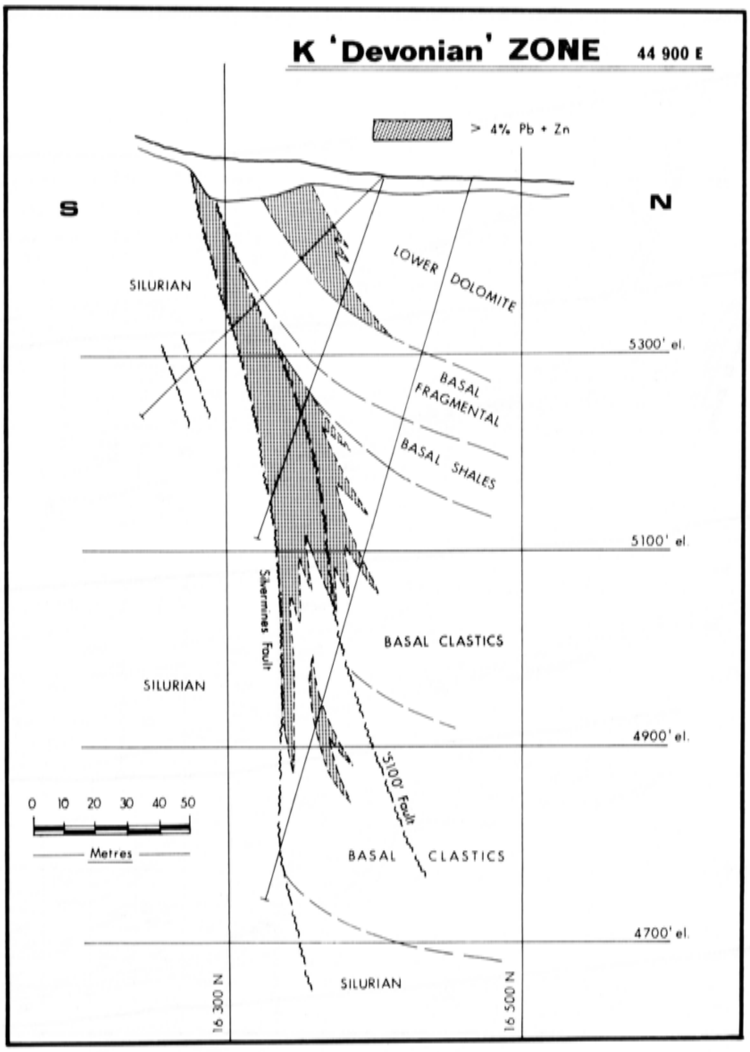

Figure 5. Section through the K Devonian Zone facing west.

Breccia Zones

Throughout the area there are many examples of breccia zones comprised of anastomosing veinlets of quartz, barite and sulphides cutting Basal Clastics. The most important of these are the C and K Devonian Zones (Fig. 3 and Table 1), with smaller occurences known at Knockanroe, Gortnadiha, Garryard and at Shallee (Fig. 3). All of these examples are either located within, or bounded by, WNW faults and show close tectonic control.

The K Devonian Zone (Figs. 3 and 5, Table 1) is located at a point of strike change of the main Fault (Silvermines Fault) where a branch or splay fault (the '5100 Fault') was propagated to the WNW (Figs. 3 and 5). In plan view the mineralized zone occurs between the two faults and is best developed in the apex of the bifurcation. At this point, in section (Fig. 6), the mineralized zone attains its maximum thickness of 45m at 100m below surface, tapering upwards to less than 5m. At increased depths, mineralization dies out as the faults diverge, apart from thin zones immediately abutting the fault planes. To the WNW, as the faults separate, and to the ESE where the northern branch fault (the '5100 Fault') passes into a monocline, mineralization dies out. This mineralization is contained within quartzites, sandstones and grits of the Basal Clastics, which are locally either strongly brecciated or shattered and veined. The shattered beds are fractured by irregular anastomosing, non-systematic, joints ranging from hairline fractures less than 1mm wide up to veins 10cm in width. The veins are infilled by rhythmically banded brown and beige colloform sphalerite with subordinate galena and pyrite. Closer to the main bounding faults, and also interspersed within the shattered units are zones of mineralized breccias comprising clasts of silicified Basal Clastic lithologies set in a matrix of sphalerite exhibiting variable colours and grain sizes. Many of the clasts show either symmetrical coatings of sphalerite or ragged outlines due to dissolution and replacement by sulphides. Little evidence of transportation of the clasts can be discerned as no mixing of the lithologies is seen, and also it is possible to trace heavy-mineral laminae between neighbouring clasts.

Paragenetically, silicification and growth of small, well shaped pyrite crystals (<5mm) occurred prior to fracturing and mineralization. This effectively sealed all primary porosity. The sulphide sequence begins with pale-brown to cream fine-grained sphalerite with interlayered pyrite-marcasite. This was followed by coarser grained translucent brown sphalerite, then pyrite and finally galena. Rebrecciation of earlier phases is commonplace in the breccia zones. The later sphalerite has a higher iron content than earlier varieties, averaging 4% in comparison to less than 1.5%.

The K Devonian Zone contains 0.3Mt grading 1.88% Pb, 5.68% Zn and 64g/t Ag indicated by surface diamond drilling (Ennex International PLC, company report; 1984).

The C Zone is the most easterly of the presently known orebodies and is located within the middle and upper beds of the Basal Clastics. The orebody is similarly tetonically situated to the K Devonian Zone, occurring at a strike change in the main Fault (Silvermines Fault) where a branch or splay, here the main B Zone Fault (Fig. 3) forks to the WNW. Mineralization occurs in the zone between the faults to a depth of 125m, attaining a maximum width of 25m, and as a narrow zone on the immediate hangingwall of the main Fault for a strike length of 250m.

Mineralization occurs in similar styles to those in the K Devonian Zone. However, veinlet style mineralization, including barite, is more widespread and extends along the B Zone Fault and several minor sub-parallel structures. In the main part of the ore zone the footwall Silurian slates are locally derived and included in the mineralized breccia. In the vicinity of the orebody there are several thin horizons of disseminated galena and pyrite assaying up to 4% Pb over a metre or so. These horizons are always within clean white sandstones immediately underlying a shale or siltstone band, and may extend for up to 200m north of the main Fault.

The C Zone contains 0.4Mt grading 1.19% Pb, 6.06% Zn and 32 g/t Ag as indicated by surface drilling (Ennex International PLC, company report; 1984).

At Knockanroe, in the footwall of the main Fault bounding the K Zone, the so-called 'Great Sulphur Ramp' (Wynne and Kane, 1861; Cole, 1922) occupies a breccia body trending WNW in a zone between the main Fault and an ESE minor branch-fault. The mineralized zone attains a maximum width of 20m and is dominantly composed of marcasite — pyrite cementing brecciated Basal Clastics. Minor crystalline sphalerite, galena and chalcopyrite are present, all paragenetically post-dating the pyrite. Grades at Knockanroe average 0.6% Pb, 2.5% Zn and approximately 25% FeS_2. No tonnage figures are available.

At Gortnadiha, two parallel ESE faults displace the Basal Clastics by about 30m, downthrowing to the north on the footwall side of the main Silvermines Fault. These faults splay away from the main Fault in a clockwise direction, and bound a breccia zone 5-15m in width. Within this zone the sandstones are silicified and strongly fractured by veinlets of chalcedonic silica, barite and pyrite, with lesser amounts of chalcopyrite, galena and sphalerite. Rhoden (1958) observed that the early pyrite was followed by sulphidization of siltstone clasts by spherulitic granular marcasite, later fractured and veined by the silica, barite and sulphides. The deposit was worked in the 18th and 19th centuries and mineralization is reported to have extended for 500m along strike and to a depth of 40m below surface.

Minor occurrences of similar breccia-hosted mineralization are also known at Shallee and east of Cranna (Fig. 3). Deep drilling in the syncline north of the Upper G Zone has encountered analagous cupriferous breccias in the Basal Clastics along strike of the '5100 Fault' (Fig. 3).

All of these breccia bodies lie in similar tectonic positions, which can broadly be defined as tectonically dilatant. It is proposed that these zones, with their resultantly low lithostatic pressures, facilitated the uprise of pressurized hydrothermal fluids from depth, which subsequently hydraulically and chemically brecciated Basal Clastic lithologies and deposited barite and sulphides in the resultant spaces. The variety of the mineralogy in these zones reflects that of the overlying, or formerly overlying, exhalative mineralization at the base of the Waulsortian Equivalent succession (see below).

Lower Dolomite zones

The Lower Dolomite throughout the Silvermines area contains trace mineralization which attains economic concentrations in three zones, the Lower G, K and P Zones (Fig. 3, Table 1).

The Lower G Zone (Figs. 4, 6 and 7) is confined to the Lower Dolomite immediately underlying the Upper G Zone (Fig. 7) in the drag-attenuated zone abutting the main Silvermines Fault. The host Lower Dolomite thickens away from the Fault as dips moderate to the north. Mineralization diminishes away from the drag zone, becoming restricted to three or four horizons and eventually to a single thin zone immediately at the base of the Lower Dolomite. The orebody, which is defined by assay parameters, has a strike length of approximately 500m, extends down dip for about 150m, and attains a maximum thickness of 30m. It is situated in the locus of maximum throw of the Fault (Fig. 6). East and west of the orebody the dip of the Fault flattens from 65° to 50° and drag accomodates much of the displacement.

In the uppermost parts of the Lower G Zone, for up to 30m immediately below the contact with the Upper G Zone (Fig. 7), the rocks are intensely brecciated, silicified and replaced by fine-grained colloform pyrite with coarse sphalerite and galena. Below this is a zone of intense veining and brecciation with the fractures infilled with dolomite, quartz, crystalline and colloform sphalerite, galena and pyrite. At increasing depth, the mineralization assumes its more usual aspect as open-space fillings to dolomitization voids, to fracture and brecciation zones and as disseminations. Infillings may be mono- or polymineralic which show rhythmic banding and multiple, superimposed textures which provide evidence of fracturing synchronous with mineralization. Mineralogically sulphides average about 20% of the ore zone with galena and sphalerite dominant; pyrite — marcasite is generally present in minor amounts, although it increases to be a major component in the uppermost parts where replacement is dominant. Chalcopyrite and arsenopyrite are important accessories and their distribution is shown in Figure 6; tennantite, lollingite, boulangerite and numerous Pb, Cu, and Ag sulphosalts occur in minor amounts. Mineralogically complex exsolution and myrmekitic intergrowths are commonplace on a microscopic scale. Dolomite, calcite, quartz and barite are the common gangue minerals and occur in variable amounts.

Mineral zoning in the Lower G Zone (Fig. 6) shows the orebody to consist of an upper central zone of relatively zinc-rich mineralization which passes down and out into a lead-rich fringe and eventually into a zone where low-grade chalcopyrite mineralization accompanies the galena. Cadmium (averaging 0.03%) and arsenic (0.10%) are irregularly distributed. Graham (1970) established a direct antipathetic relationship between lead and zinc and between zinc and silver. To the east and west of the orebody, surface and underground diamond drilling has shown that the Lower Dolomite contains not only minor base metal sulphide mineralization, but also significant quantities of barite and silica. These minerals occur as cements to fracture and breccia zones and as replacements which locally totally replace the host rock precursor. At Garryard (Fig. 3) drilled sections of Lower Dolomite assaying up to

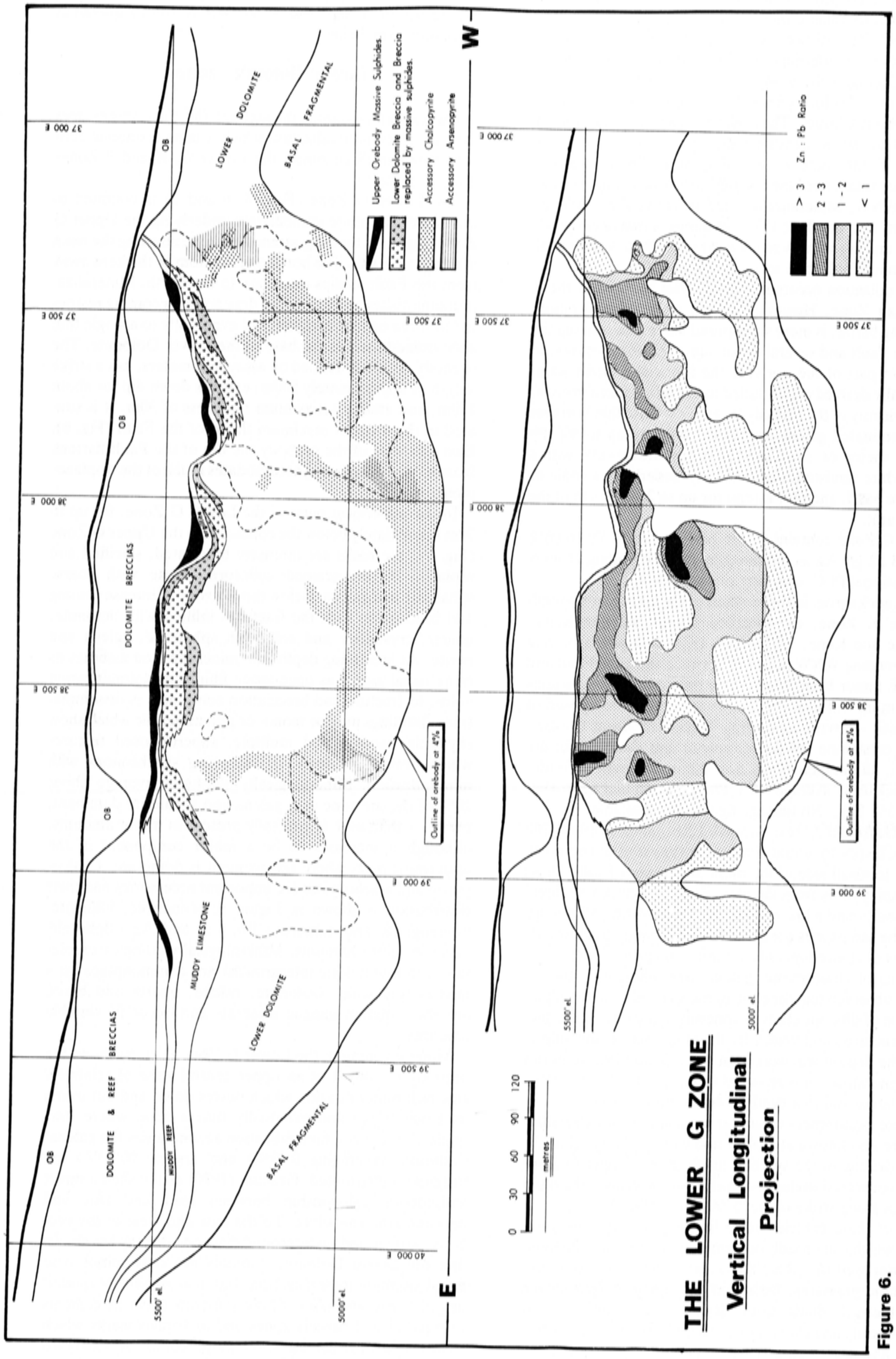

Figure 6.
Vertical longitudinal projections of the Lower G Zone facing south. The upper diagram shows the outline of the orebody at a 4% Pb+Zn cutoff and the distribution of accessory sulphide minerals. The lower diagram shows metal zoning trends based on Zn:Pb ratios.

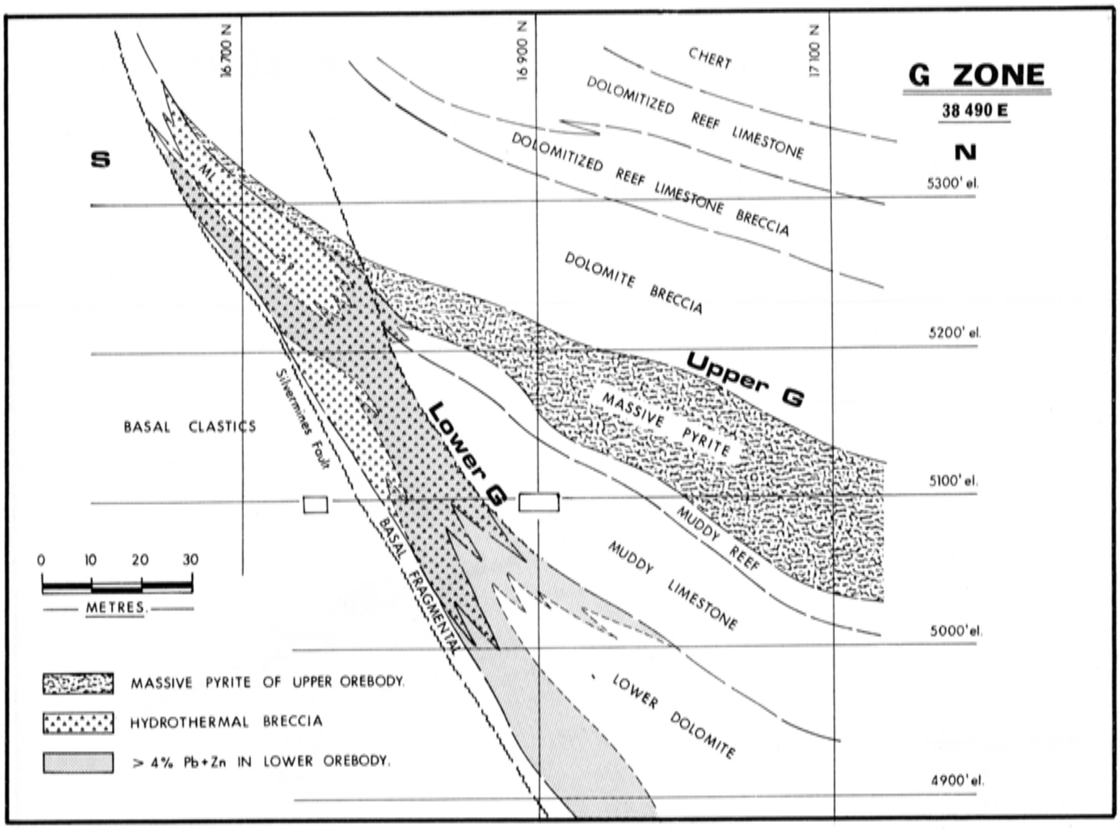

Figure 7. Section through the southernmost part of the Lower G Zone and part of the Upper G Zone. Section facing west.

15% $BaSO_4$ over 15m have been intersected. The proximity of this epigenetic barite mineralization to the overlying Magcobar Barite Zone (Fig. 3) suggests a close genetic relationship.

Studies on the petrology of the Lower G Zone (Graham, 1970; Catlin, 1983) have shown that the original limestone and cements were totally replaced by iron-free dolomite with minor accompanying masses of fine-grained pyrite. This was followed by fracturing and subsequently by ferroan baroque dolomite and pyrite which infilled fractures and void spaces created during the dolomitization process. Silicification of the host rocks and precipitation of chalcedonic silica followed, and bulk analyses of the Lower G Zone ores indicate an average of 17% SiO_2, although values or up to 40% have been recorded in the brecciated upper parts of the orebody which indicate the importance and pervasive nature of this alteration (Mogul of Ireland Ltd., company records). This stage was followed by sulphides (locally replacing earlier pyrite), barite and sericite with contemporaneous fracturing.

The Lower G Zone contained 2.0Mt grading 3.98% Pb, 6.58% Zn and 34 g/t Ag: 90% of the orebody was extracted between 1966 and 1982 (Ennex International PLC, company report; 1984).

In the K Zone (Figs. 3 and 8, Table 1), mineralization attains its maximum thickness in the steeply dipping drag-attenuated zone adjacent to the main Silvermines Fault. To the north, away from the Fault, the Lower Dolomite thickens as dips moderate and mineralization splits into two distinct lenses. (These are subjectively defined by assay, as traces of sulphides occur throughout the unit.) The upper lens, in the middle of the Lower Dolomite, is typically about 3m thick, locally swelling to 10m, and persists laterally to 75m north of the Fault. The lower lens is more extensive, reaching 275m to the north. The latter lens has a base which generally coincides with that of the Lower Dolomite, averages 4-7m in thickness, but thickens towards the main Fault to 20m and also in the vicinity of the '5100 Fault' trending WNW across the eastern part of the orebody (Figs. 3 and 8).

Mineralization is present as two styles, but transitional areas of hybrid and mixed types occur locally. In the western part of the K Zone, apart from areas immediately abutting the main Fault, fine-grained dark brown sphalerite with subordinate pyrite — marcasite occurs as geopetally laminated sediments in, and as linings to, voids and cavities formed during dolomitization, as thin anastomosing veinlets in diagenetic fractures, and as irregular disseminated replacements and interstitial fillings of bioclasts. Minor crystalline 'honeyblende' and sparse galena occur sporadically in the central portions of veins and cavities which were ultimately filled by barite and ferroan calcite. In contrast, adjacent to the '5100 Fault' and the main Fault, the mineralization is typically coarser grained and exhibits textural features indicative of repetitive fracturing and sulphide deposition. Mineralization occurs within fracture breccias, in symmetrically banded veins paralleling the faults and in irregular nebulous replacements. Paragenetically, dark-brown fine-grained sphalerite with pyrite — marcasite was followed by pale-brown to beige, rhythmically banded, fine-grained sphalerite with minor pyrite ("schallenblende"). Later galena and crystalline sphalerite infilled fractures which were finally filled by ferroan calcite and barite. Adjacent to the '5100 Fault' and in the upper parts of the

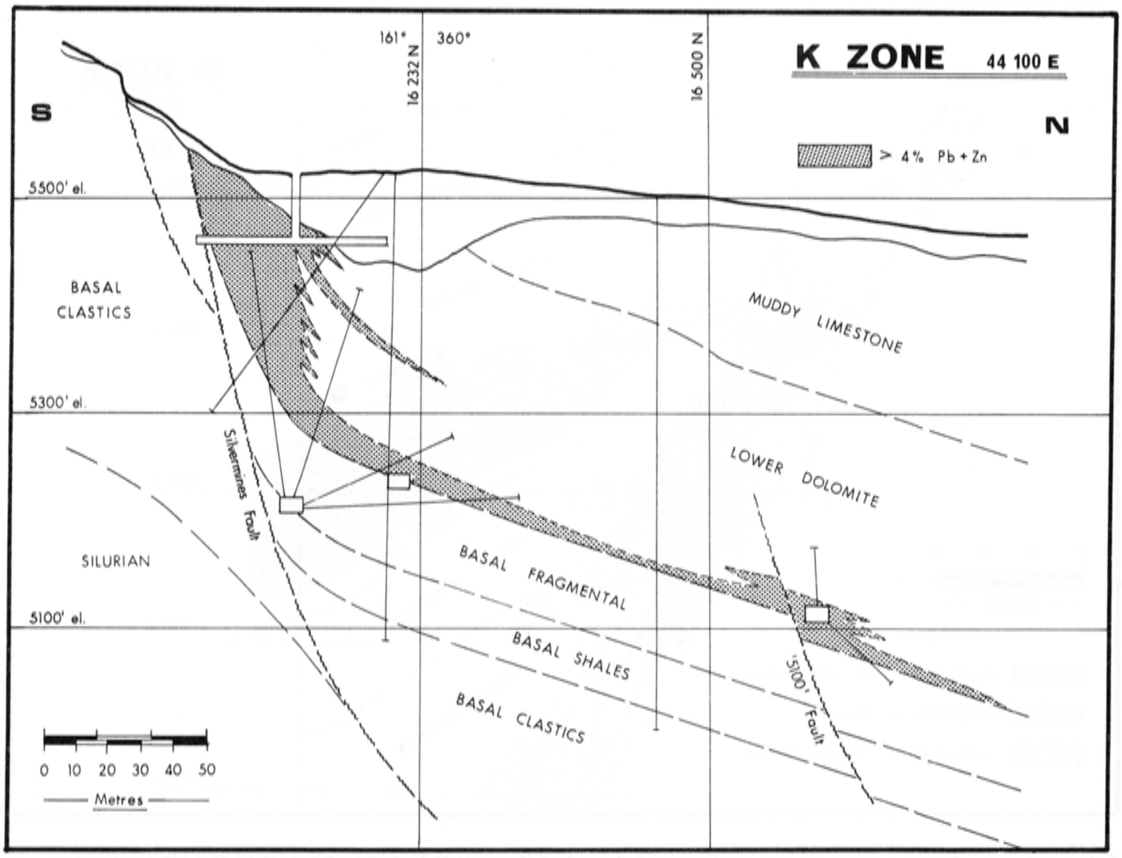

Figure 8. Section through the K Zone facing west.

drag-attenuated main zone, pyrite-marcasite accounts for up to 40% of the rock mass. Elsewhere sulphides only average 15-20%. Minor chalcopyrite (mainly as exsolved microscopic grains in sphalerite), boulangerite, arsenopyrite and guitermanite ($3PbS.As_2S_3$) also occur.

Petrological studies (Catlin, 1983; Locklin, 1983) reveal that the original sediments were totally replaced by iron-free dolomite with minor disseminated euhedral pyrite crystals. Subsequent fracturing was followed by ferroan dolomite with minor marcasite and then renewed fracturing, contemporaneous to the precipitation of the sulphides with sericite and barite. Minor fractures which post-dated the sulphides were infilled by ferroan calcite. Later ferroan baroque dolomite infilled tensional veins associated with post-mineralization tectonism.

The K Zone, which is still undergoing evaluation and exploration, has an ore reserve of at least 1.4Mt grading 1.38% Pb, 4.40% Zn and 15 g/t Ag (Ennex International PLC, company report; 1984).

The P Zone, adjacent to the K Zone, is located in an area of several WNW-trending faults, all of which downthrow to the north. Ore, economically defined by assay of >4% Pb+Zn, occurs at the base of the Lower Dolomite over 3-5m, but is thicker and richer immediately adjacent to the faults. The nature of the mineralization and paragenetic sequence is identical to the K Zone.

The P Zone is currently being explored and is still open to both the east and west. A minimum ore reserve shows the zone to contain at least 0.5Mt grading 1.23% Pb, 4.01% Zn and 17 g/t Ag (Ennex International PLC, company reports; 1984).

Upper stratiform Zones

The upper orebodies of the Silvermines district include the Upper G, B and Magcobar Zones (Figs. 3 and 4, Table 1). Previously (Taylor and Andrew, 1978; Taylor, 1984), these have been described as separate and discrete zones. However, due to the similarities of mineralization and setting, they are here regarded as parts of a single system.

The upper orebody system is located at, or near to, the base of the Waulsortian Equivalent succession (Figs. 2 and 4). In general the orebodies immediately overlie the Muddy Reef, although locally, and to the fringes of their development, knolls of Footwall Pale Reef Limestone occur below or wedge-off the ore-hosting sediments. Throughout the area the surface above which the main ore-hosting sediments occur is defined by the Green Shale Marker. This marker either lies directly at the top of the Muddy Reef or above the knolls of Footwall Pale Reef Limestone. The morphology of this surface is shown as a stratum contour plot in Figure 10. As little post-ore tectonism has affected the Silvermines area, this contoured surface may be regarded as a close approximation of the seafloor palaeotopography at the time of deposition of the ore-hosting sediments.

The upper orebody system is presently known to extend easterly for 2km of strike and down dip for 1.25km. Typically the orebody is 5-10m thick, but maximum thicknesses of up to 35m are attained immediately down dip of the main Silvermines Fault in the Upper G Zone and the B Zone Fault (Figs. 4, 7 and 9).

The Upper G Zone occurs as massive pyrite at the base

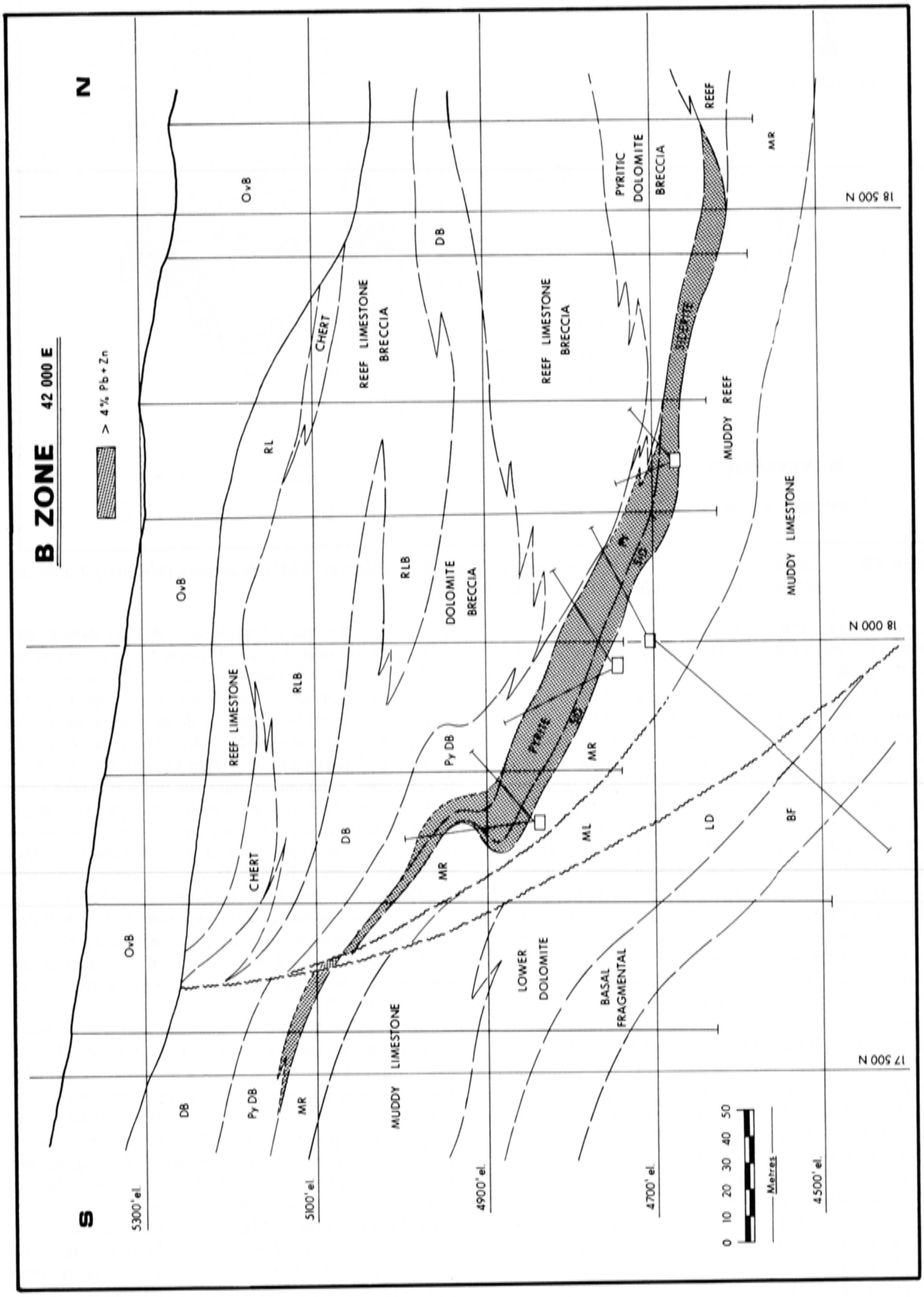

Figure 9. Section through the B Zone facing west.

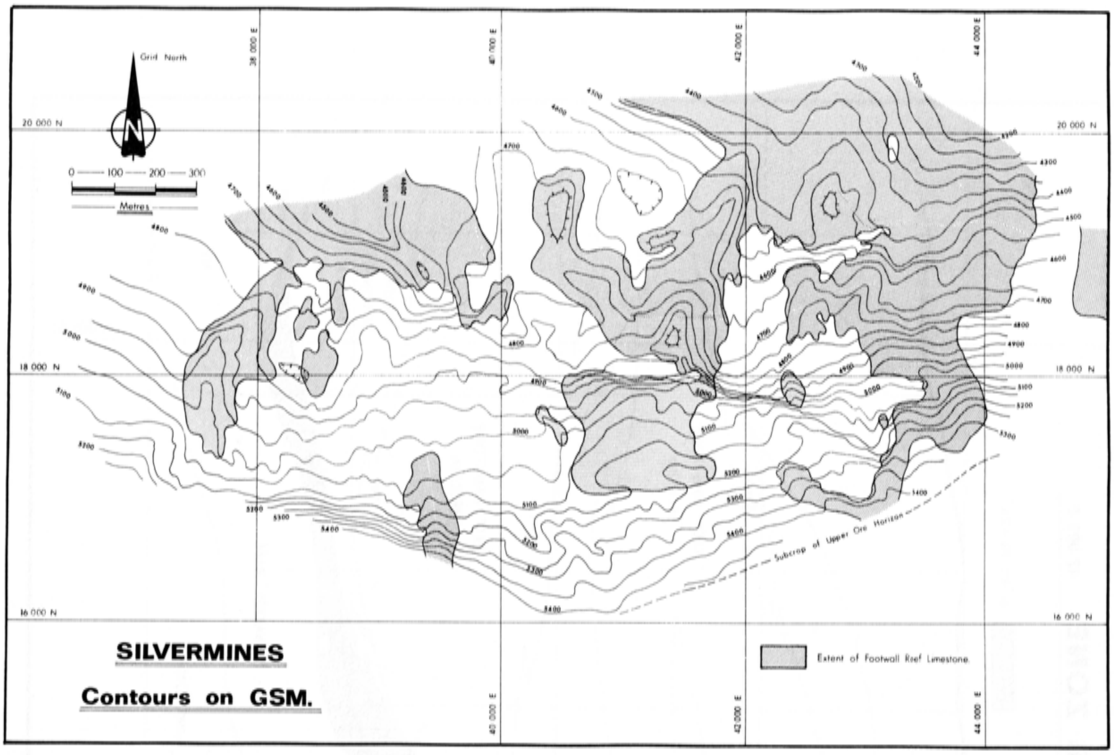

Figure 10. Contour plot on the chronostratigraphic Green Shale Marker (GSM). Numbers refer to mine datum elevations based on 5000 feet equal to sea level.

of a sequence of vermicular fine-grained dolomite breccias of medial and distal affinity (Fig. 11) and dips gently at 10-15° to the north. The southern margin of the orebody occurs on the downthrow side of the main Silvermines Fault where the massive pyrite thickens to over 30m. To the other margins of the zone, the massive pyrite thins into discrete lenses within a pyritic dolomite debris-flow breccia sequence, and pinches out against the irregular development of the Footwall Pale Reef Limestone knolls (Fig. 12). The B Zone (Figs. 9 and 11) occurs at the base of a complex, interdigitating sequence of Reef Limestone breccias, Dolomitized Reef Limestone breccias and thin lenses of Waulsortian Reef. The ore sediments include massive pyrite, barite and siderite host facies, but mineralization also occurs in overlying debris-flow breccias (Fig. 11). The southern margin of the ore zone is formed by a locally overturned slump-structure developed on the hangingwall of the WNW-trending B Zone Fault (Figs. 9 and 11). The remaining margins of the ore zone are controlled by knolls of Footwall Pale Reef Limestone against which the ore-bearing sediments wedge out (Figs. 9, 12 and 13). Similar controls define the location of the Magcobar Barite Zone (Figs. 4 and 11) with the exception of the southern margin which is developed against a slump structure on the hangingwall of the Main Silvermines Fault.

In the part of the stratigraphy hosting the upper orebody system, the earliest indications of the mineralizing event are seen in the Muddy Reef. In general, this unit comprises a crinoidal, nodular, cherty biomicrite with thin wispy shales. However, in the vicinity of the thickest parts of the orebody and adjacent to the WNW faults, this lithology passes laterally and interdigitationally into a silicified, sparsely fossiliferous, fissile shale with well developed lamination, and locally into massive blue-black cherts devoid of fossil detritus (Figs. 11 and 14). Within these modified lithologies fine-grained, laminated, pale-yellow to cream sphalerite with minor galena occurs, typically showing well developed soft-sediment deformation textures. Economic grades (>4% Pb+Zn) are attained over thicknesses of up to 8m, notably in the '2 East Panel' area of the Upper G Zone (Figs. 11 and 14). Spatially these areas of anomalous Muddy Reef form several NNE-trending zones (Fig. 14), being best developed in the Upper G Zone but also in the B Zone over a thinner stratigraphic interval. These zones correlate with NNE-trending gentle synclines (palaeotopographic lows) which pitch down-dip of points of maximum throw of the main Silvermines Fault and B Zone Fault, thus implying a genetic relation with synsedimentary tectonism. Gentle anticlinal fold belts paralleling this NNE trend are the sites of development of the Waulsortian Footwall Pale Reef Limestone knolls, whose rapid growth and lithification (Lees, 1964 *et seq.*) led to the accentuated palaeotopography prior to the major exhalative phase of mineralization (Figs. 10 and 12).

The Green Shale Marker overlies the Muddy Reef mineralization and Footwall Pale Reef Limestone knolls, and appears to define the change from quiescent to hydrodynamic sedimentary regimes. In the ore zones the Green Shale is immediately superceded by the massive barite, siderite and pyrite ore facies within the troughs between the knolls. The inter-relations between the various ore facies are complex, particularly in the B Zone, which is shown semi-diagrammatically in Figures 11 and 13.

The barite facies in the Magcobar and B Zones is variable and shows complex local variations. In Magcobar the barite occurs in a roughly triangular basin approximately 650m along strike and 250m down dip, opening away from the Silvermines Fault and associated slump zones. The barite is bounded down dip to the north by a shallow Footwall Pale Reef Limestone knoll (Fig. 12). The barite, averaging 85% $BaSO_4$, attains its maximum thickness of 25m in the centre of this basin (Fig. 14), so defining a relation between

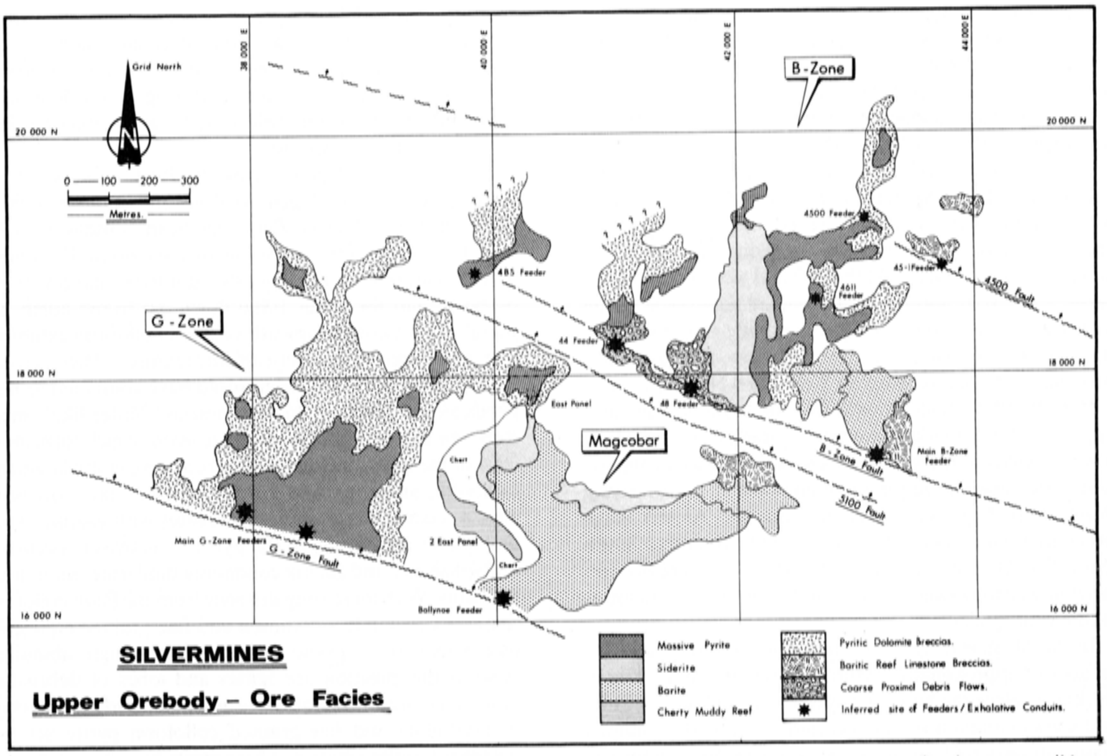

Figure 11. Plan showing the distribution of the various ore facies comprising the upper orebody system (Upper G, B and Magcobar Zones).

the palaeotopography and the geometry of the barite body (Barrett, 1975). In the main part of the barite body the Green Shale Marker, here containing diffuse lenses of siliceous allothigenic barite up to 1cm in thickness, is overlain by up to a metre of laminated, red, siliceous haematite (jasperoid). This passes up into a layered haematite to red haematitic barite succession 1-5m thick with slumping, *in situ* brecciation and penecontemporaneous faulting. Syneresis cracks of jasperoid lenses and nodules are infilled with chalcedonic silica and barite. The haematitic barite, which wedges out northwards, is superceded by massive 'pseudo-augen' textured crystalline pale pink, white and

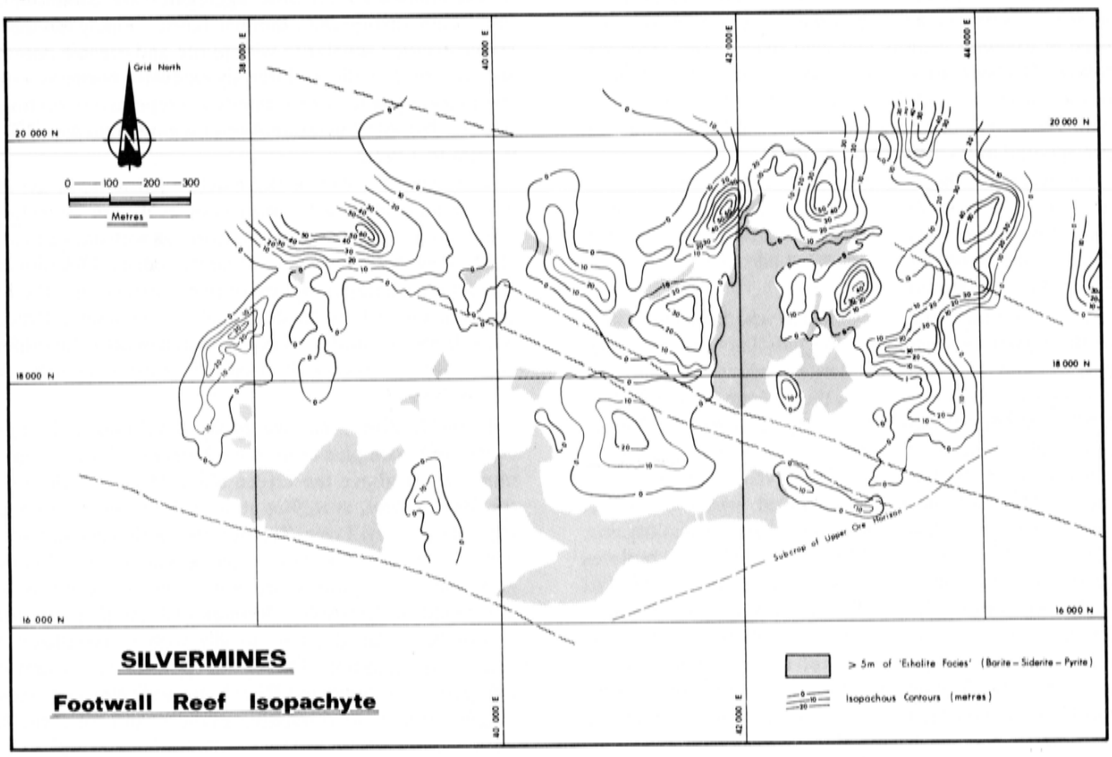

Figure 12. Isopachous plot of the Waulsortian Footwall Pale Reef Limestone knolls.

grey barite exhibiting local brecciation and well developed stylolites. The superceding massive, dark-grey, finely crystalline barite comprises the bulk of the barite orebody which, over the uppermost metre or so, is extensively recrystallized and contains much pyrite — marcasite. The hangingwall contact is sharp with the overlying pyritic Dolomite and Dolomitized Reef Limestone Breccias of medial debris-flow affinity. Sparse rip-up clasts of barite and scours on the upper surface of the orebody suggest that high-energy dynamic sedimentation immediately superceded deposition of the barite. At the east and west fringes of the barite zone, thin horizons of brecciated haematitic barite with Reef Limestone clasts pass laterally into Dolomite Breccias with sparse pyrite. To the north, interdigitation with pale-buff siderite breccias is common (Fig. 11).

Barrett (1975) demonstrated that the barite was precipitated as a microspherulitic cryptocrystalline 'mud', which was remobilized, recrystallized and stylolitized by compaction under loading during sedimentation of the overlying Waulsortian Equivalent breccia sequence. At this stage pyrite-marcasite, and in the extreme east (Magcobar South Zone; Fig. 11, Table 1) galena and sphalerite were precipitated in anastomosing fractures and in *in situ* breccia intraclastic void spaces.

In the SE part of the B Zone, barite is developed over an area of approximately 300m by 150m and up to 15m in thickness. Here the barite is typically mottled buff or grey, and shows common *in situ* brecciation. Sporadic rounded clasts of jasperoid up to 15cm in diameter, commonly showing marginal bleaching and alteration, occur in the lower parts of the barite, and are thought to have been derived by down-palaeoslope migration from the haematitic basal part of the Magcobar Zone. Catlin (1983) observed that early syneresis cracking in these jasperoid nodules was infilled by barite, chalcedonic silica and clay minerals. Petrological studies on the barite from this part of the B Zone have shown that the barite was initially precipitated with minor silica and illite — sericite, and later pyrite — marcasite; subsequently sphalerite and galena were deposited in irregular veinlets and void spaces. This stage was followed by fracturing of the sulphides and recrystallization of the barite into nodular clumps. Finally, iron-free calcite with minor galena, arsenopyrite and a little barite was precipitated in fractures (Catlin, 1983).

Elsewhere in the B Zone, the barite facies occurs as the matrix to a megaclastic debris-flow or olistostrome, comprising large boulders of Reef Limestone up to 10m in diameter set in pale-brown mottled barite. This area (45-1; Fig. 11) is still poorly understood.

The barite facies in the Magcobar and East Panel area of the Upper G Zone (Fig. 11) pass laterally into pale-buff to cream siderite and siderite breccias. This facies is developed more extensively in the B Zone, where it fills a NNE - trending trough 500m long, 125m wide and up to 20m thick. Typically the siderite facies is characterized by a fine-grained, buff to grey, polymodal, angular, *in situ* breccia. The siderite is interstratified with thin, fissile, undisturbed grey shales with fine sphalerite laminations. Fine-grained brown and buff sphalerite diffusively replaces siderite clasts locally, and commonly occurs in intraclast voids with minor galena. Small, steep-sided local basins a few tens of metres across and a few metres deep in the footwall palaeotopography allowed thickening of the siderite. Within these basins, the basal parts are almost totally replaced by dark-brown, fine-grained massive sphalerite with subordinate galena in colloform aggregates.

Catlin (1983) demonstrated that the original carbonate rock was dominantly comprised of siderite with subordinate ferroan calcite. This was brecciated and subsequently cemented by early pyrite and later by ferroan dolomite with sphalerite and galena; later fracturing was followed by precipitation of ferroan calcite with barite, minor galena and euhedral arsenopyrite.

Massive pyrite facies forms the host to most of the mineralization in the Upper G Zone and in much of the B Zone. In the Upper G Zone significant variations in the style and nature of the pyrite can be recognized. Proximally to the Silvermines Fault at the southern margin of the orebody, and for about 100m down dip to the north, the pyrite — marcasite is typically coarsely colloform exhibiting complex superimposed crustiform textures. These growth forms during mineralization would have combined to have produced initially a highly porous 'sinter-like' mass. Between these colloform pyrite growths, which form about 70% of the mass, sphalerite occurs as geopetally laminated cavity-fill, superimposed rhythmic crusts, and, occasionally, as coarsely crystalline aggregates with galena, barite and quartz. Fracturing of the pyrite — marcasite occurred, and sphalerite and galena commonly infill irregular hairline fractures. With increasing distance from the Fault colloform textures become less common and fine-grained equi-granular marcasite — pyrite becomes increasingly abundant. Also in this position are lenses and lobes of debris-flow type pyrite breccias comprising angular, poorly sorted clasts of crystalline and fine-grained colloform pyrite set in a dolomitic argillite matrix. These pyrite breccias are thought to have been derived from upstanding masses of sinter-type sulphides adjacent to the Main Fault. Within the pyrite breccias sphalerite and galena occur in intraclastic voids and in later crosscutting fractures. Distally to the pyrite breccias and towards the fringes of the Upper G Zone, the massive pyrite is typically very fine-grained and may represent either detrital particulate sulphide sediments or chemically precipitated pyrite. Sub-surface growth textures as exemplified by plumose aggregates are commonplace and locally disrupt fine, laminar fabrics. Finely laminated, colour-banded sphalerite with pyrite and organic dolomite silt form thin (<10cm), laterally extensive horizons within the massive pyrite. These bands are repetitively rhythmically banded with the laminations ranging in thickness from 0.5mm to 1.0mm.

The upper contact of the massive pyrite is, in general, well defined and sharp, and passes by way of an irregular scoured surface into Dolomite Breccias with angular rip-up clasts of pyrite, sphalerite and rarely, galena. Occasionally, upward-projecting 'tongues' of pyrite extend into the hangingwall breccias suggesting that the Dolomite Breccias were deposited onto semi-consolidated pyrite. The sulphide content of the breccias diminishes upwards over about 30m to less than 1%.

In the B Zone, massive pyrite development is significantly more complex than in the Upper G Zone, occurring immediately above the Green Shale Marker at the top of the Muddy Reef, as well as above siderite and barite facies (Figs. 11 and 13). Typically, the latter facies pass up through pyritic transitions to massive fine-grained pyrite. Plumose and colloform textures are not as pervasive or as well developed as elsewhere, although mesoclastic pyrite breccias of fine-grained clasts, locally with recrystallized selvedges, are common. The pyrite typically passes upwards into pyritic, Dolomitized Reef Limestone Breccias, (colloquially termed 'semi-massive pyrite'), and, in turn, into weakly pyritic mixed breccias of the hangingwall succession.

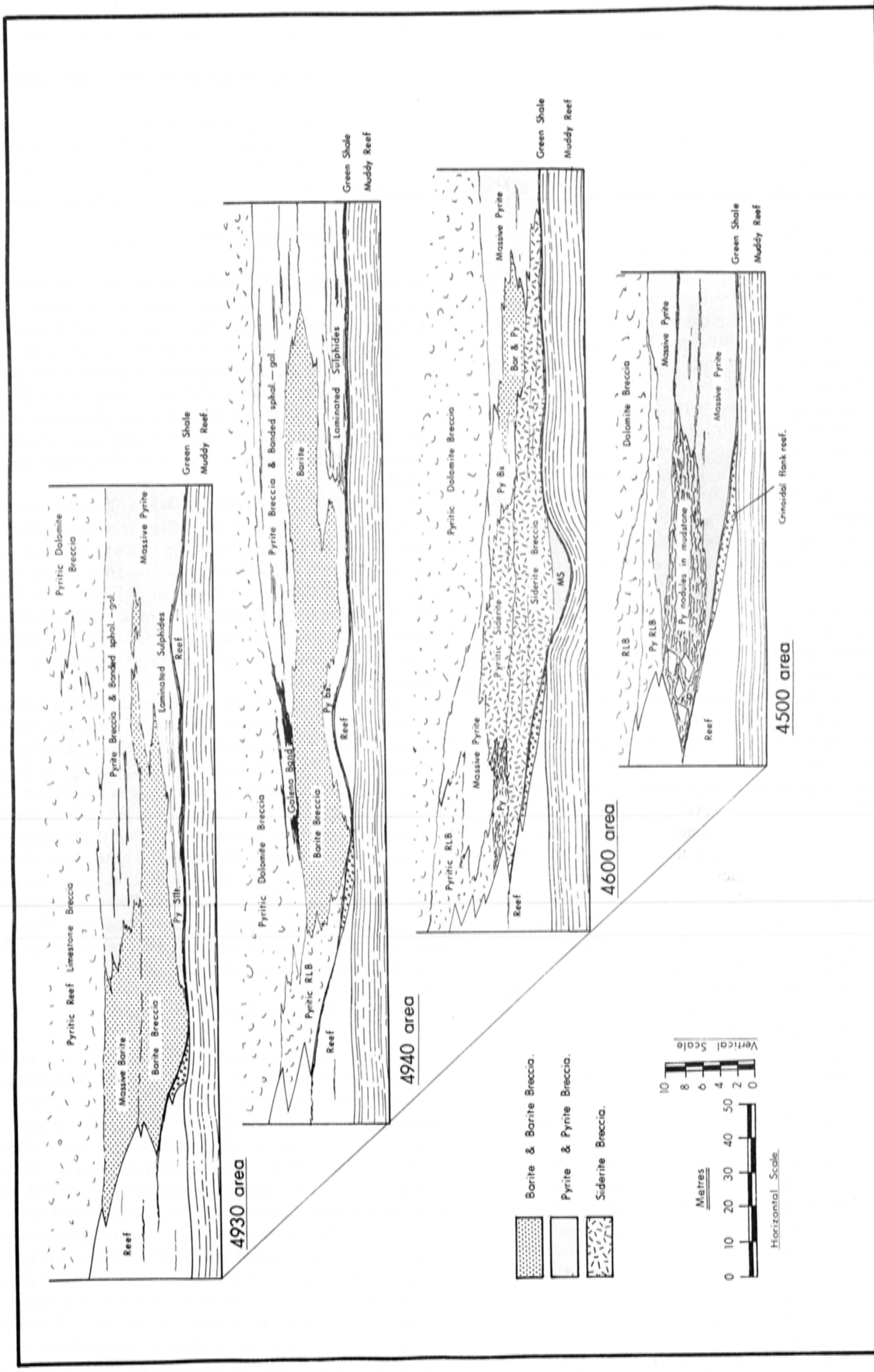

Figure 13.
Semi-diagrammatic serial sections facing south drawn through the eastern side of the B Zone to show the complex relations of the various ore host facies. Based on underground mapping.

In addition to the pyrite, siderite and barite ore-host facies, economic (>4% Pb+Zn) mineralization occurs within the overlying breccia succession. In the Upper G Zone, the vermicular Dolomite Breccias contain small, angular and rounded clasts (generally <1cm in diameter) of pink to buff fine-grained sphalerite with minor fine-grained galena. However, in the East Panel area (Fig. 11), Dolomitized Reef Limestone Breccias occur with lead-rich mineralization dominated by clasts of galena set in a muddy dolomitic matrix with occasional pyritic muds. The B Zone lead-rich breccias are considered to be of debris-flow affinity (Boyce et al., 1983; Taylor, 1984) and comprise angular clasts of pale-grey Waulsortian Reef Limestone up to 50cm in diameter, set in a matrix-supportive sulphide mud dominantly composed of very fine-grained galena with subordinate pyrite, ferroan calcite, barite and boulangerite. These lead-rich mineralized breccias are systematically arranged in lobes running down dip to the NNE, away from the B Zone Fault and slump, notably in the 44 and 48 Areas (Fig. 11). Isopach plots of these debris-flow lithologies show no sympathetic relation with the palaeotopography which controls the distribution of the underlying pyrite, siderite and barite facies. However, they thicken towards a zone parallel to the B Zone Fault. Lead-rich mineralization within Dolomitized Reef Limestone Breccias, analagous to the East Panel area of the Upper G Zone, is also known to occur down dip of the '4500 Fault' (Fig. 11) overlying the northward-extending lobe at the extreme NE of the B Zone.

Metal-zoning plots of the economic section (>4% Pb+Zn over 3m) of the various ore facies in the upper orebody system, composed from some 500 surface and 2500 underground drill-hole intersections, are shown in Figure 15. These plots show several important trends. The Silvermines Fault in the Upper G Zone is clearly paralleled by Zn:Pb ratios of less than 3, with NNE-trending areas of ratios of 5 to 7 in a background of 9. These NNE trends closely follow isopachs of thinner massive pyrite development, whereas thick pyrite development coincides with higher Zn:Pb ratios (cf. Figs. 14 and 15). The eastern part of the Upper G Zone, notably in the East Panel area, has greatly enhanced lead values, dominantly comprised of galena-bearing breccias, and in this area Zn:Pb ratios fall to below 0.1. In the B Zone, the slump - fault is, like the Silvermines Fault in the Upper G Zone, closely defined by an area of high lead values falling to a Zn:Pb ratio of below 0.1. These values result not only from galena-bearing hangingwall debris-flow breccias, but also from galena-rich pyrite, siderite and barite host facies. The northwards-trending zone of Zn:Pb values greater than 3 almost exactly defines the limits of siderite development (cf.Figs. 11, 14 and 15), and like the G Zone, demonstrates a close relation between Zn-rich mineralization and the development of thick host facies.

More generally it can be clearly seen that the B Zone represents a more lead-rich area of the upper orebody system than the Upper G Zone. This is confirmed by the ore-reserve grades for the two zones (Table 1), with the B Zone having a Zn:Pb ratio of 1.34 and the Upper G Zone a ratio of 3.90. The broad lead-rich areas in the middle of the B Zone reflect distal hanging-wall debris flows as well as mineralization associated with minor feeder centres. In the Magcobar South area (Figs. 11 and 15) the lead values increase northwards towards the B and '5100' Faults.

Trace-element zoning within the upper orebody system is not well documented but in general it appears that cadmium and arsenic are enriched sympathetically to zinc (average 0.025% Cd, 0.030% As). However silver is irregularly sympathetic to lead which is not unsurprising because of its intimate mineralogical association with galena. Statistically lead and zinc have an antipathetic relationship.

Summary of the controls to mineralization

Before discussing the genetic models interpreted for the orebodies, it is worthwhile summarizing the salient structural and stratigraphic controls of mineralization observed in the Silvermines area.

Lower epigenetic ore zones

Veins at Shallee and Shallee White occur as swarms trending NNW and occupying small normal faults and systematic regional joints. The veins are preferentially mineralized over a narrow stratigraphic interval in the upper Basal Clastics. Mineralization is enriched immediately below siltstone bands and below the superceding Basal Shales. Laterally, lead-rich mineralization passes out into barite and quartz-rich zones; minor copper mineralization occurs immediately adjacent to the main Silvermines Fault at Shallee.

The Gortnadiha, K Devonian and C Zones occur in brecciated middle and upper Basal Clastics and are typically 'ponded' below the Basal Shales in dilation zones at the point of divergence of a WNW fault zone from a clockwise strike change in the main Silvermines Fault. Zinc:lead ratios average 3, but no systematic zoning can be recognized within the orebodies. Irregular vein sets occur peripherally to the breccia bodies, containing pyrite proximally and barite distally to them.

Lower G, K and P Zone mineralization in the Lower Dolomite all occurs adjacent to points of maximum throw and steepening of the associated faults. This steepening of the faults appears coincident with a lessening of drag-effects so that the Lower Dolomite lies immediately on the hangingwall plane of the faults. Mineralization occurs in lithologically selective dolomitization voids and fracture systems, and is preferentially developed at the base of the Lower Dolomite. In the drag-attenuation zones of the faults, mineralization is thickened and enriched over a greater stratigraphic interval. Laterally these zones have a fringe of barite and silica mineralization, whilst at depth, lead and copper are increasingly abundant.

Upper stratiform zones

The upper orebody system, including the Upper G, B and Magcobar Zones, occurs at the base of the Waulsortian Equivalent carbonates, and immediately overlies a chronostratigaphic Green Shale Marker. This marker defines a palaeotopographic surface above which the orebody host facies of massive pyrite, siderite and barite occur. These sediments show close palaeotopographic control and are selectively developed in troughs between knolls of Waulsortian Footwall Pale Reef Limestone. The troughs coincide with gentle NNW-trending synclinal fold belts developed at right angles to points of maximum throw on the B Zone and Silvermines Faults. Coeval tectonism is indicated by slumping, *in situ* and debris-flow breccias and differential subsidence. Base metal mineralization occurs within fracture and void porosity and as laminated particulate sulphide sediments. Well-developed metal-zonation patterns crosscut host-facies boundaries. Zn:Pb ratios are lowest adjacent to the WNW faults. Enhanced zinc values closely

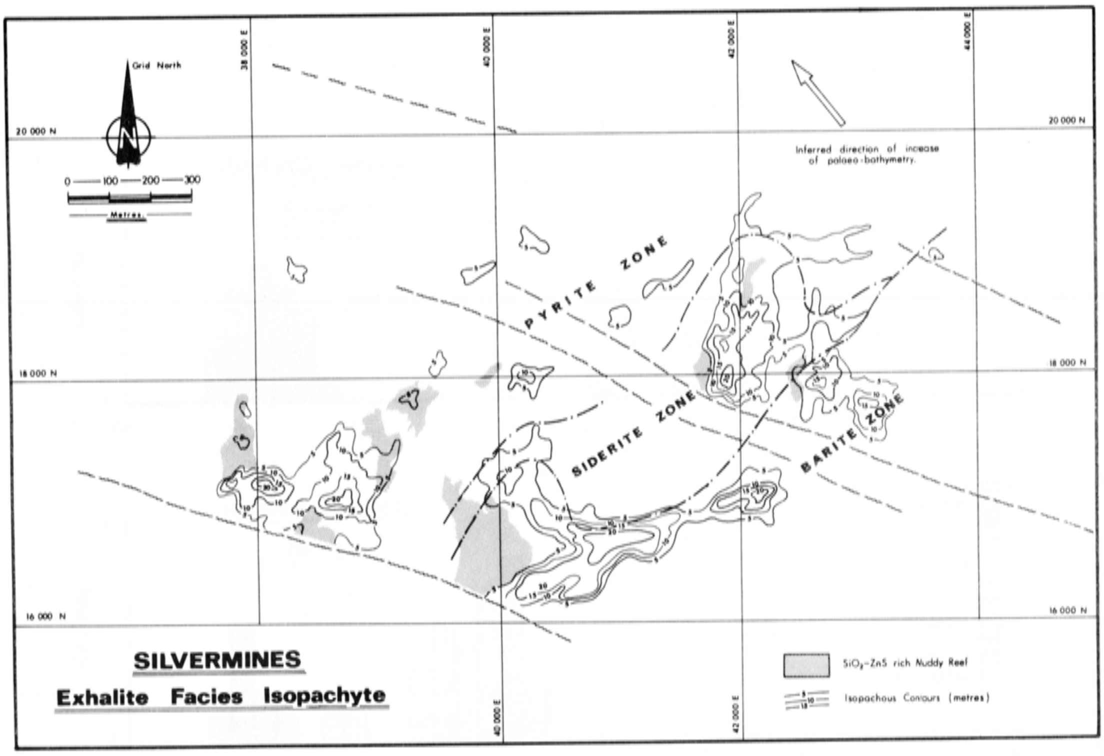

Figure 14. Isopachous plot of the major "exhalite" ore facies (barite, siderite and pyrite), also showing the distribution of the mineralized modified Muddy Reef lithologies.

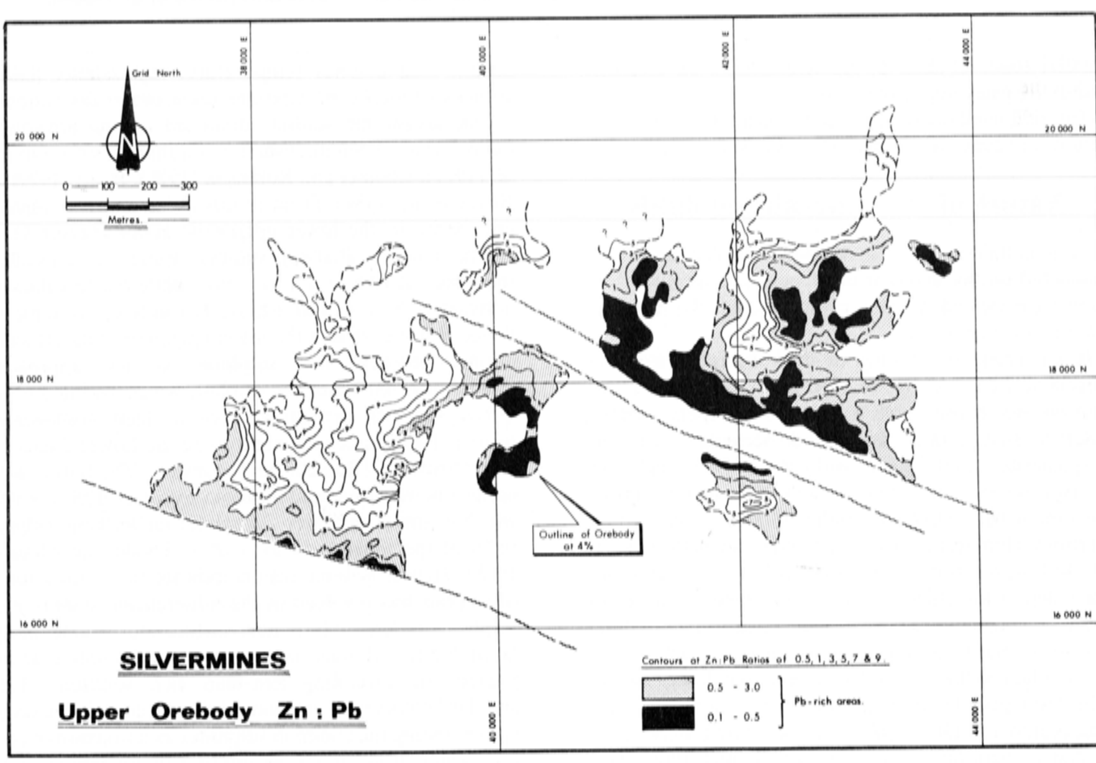

Figure 15. Metal zoning (Zn:Pb ratios) in the upper orebody system. Based on Taylor and Andrew (1978), Taylor (1984) and additional Mogul or Ireland Ltd. data.

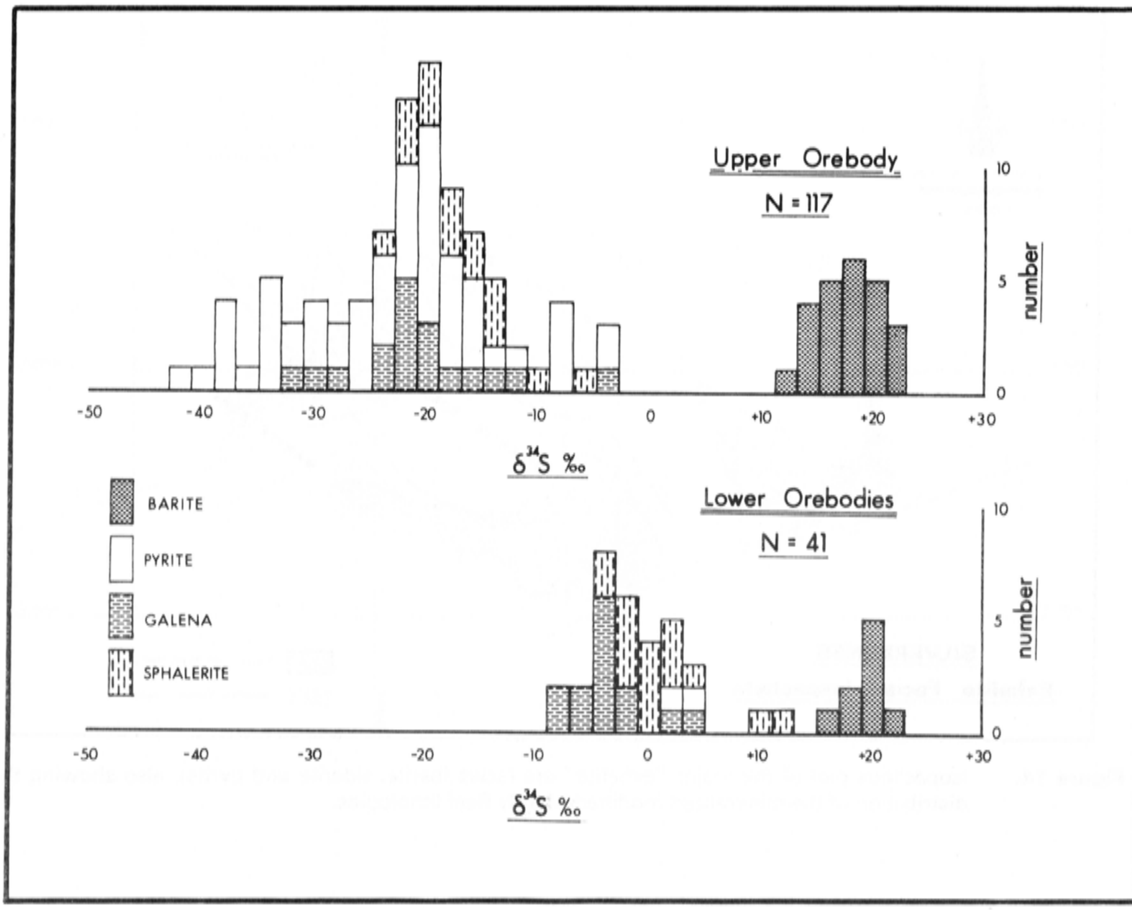

Figure 16. Sulphur-isotope results obtained from the Silvermines orebodies. Compiled from data presented by Graham (1970), Greig et al. (1971), Coomer and Robinson (1976) and Boyce et al. (1984).

parallel zones of thick pyrite and siderite development within the palaeotopographic troughs.

The simplified diagenetic and paragenetic history of the various ore zones is summarized in Table 2.

Nature of the mineralizing fluids

Various fluid-inclusion and isotopic studies have been conducted on the different ore types at Silvermines, and these have yielded valuable evidence as to the nature of the mineralizing fluids.

In comprehensive studies of fluid inclusions from the epigenetic Lower G, K, Shallee and Gortnahida zones, Samson and Russell (1983) and Probert (pers. comm.) observed many primary and pseudo-secondary inclusions in sphalerite, quartz, barite and calcite. These inclusions are typically two-phase liquid plus vapour and a very few are vapour-rich, which may indicate minor boiling of the solutions. Homogenization temperatures are in the range of 80-240°C with a modal value of about 190-200°C. Freezing-point depression studies show a wide range of indicated salinities ranging from 0 to 25 equivalent weight % NaCl (eq. wt. % NaCl), but mostly in the range 12-22 eq. wt. % NaCl. Fluid inclusions of barite and sphalerite samples from the Upper G and Magcobar Zones indicate a lower temperature (50-120°C) and higher salinities (20-24 eq. wt. % NaCl). Samson and Russell (1983) interpreted these fluid-inclusion studies as indicating the mixing of a high-temperature, low-salinity fluid, presumably of deep-seated origin, with a lower temperature, high-salinity fluid of connate or local contemporaneous seawater derivation.

Sulphur-isotope studies conducted on the Silvermines deposits have been published by Graham (1970), Greig et al. (1971), Coomer and Robinson (1976), Boast (1979) and Boyce et al. (1984). From results obtained from sulphides and barite in the lower epigenetic zones (Lower G, K, Gortnadiha and Shallee), sulphide values are typically in the range of $\delta^{34}S$ = +4 to −5‰, while barite values are between $\delta^{34}S$ = +18 to +23‰. Textural and isotopic evidence indicates that in the lower epigenetic zones fractionations between the sulphide species approached equilibrium and hence the sulphur, which averages $\delta^{34}S$ = +3‰, suggests derivation from a deep homogenized source. This source is thought to be the Lower Palaeozoic metasediments (Russell, pers. comm.). The barite in the epigenetic vein and void-fill zones averages $\delta^{34}S$ = +19‰, which is similar to Lower Carboniferous seawater sulphate ($\delta^{34}S$ in the range +14 to +22‰, Thode and Monster, 1965). Hence, isotopic results indicate that a dual source of sulphur was involved in the mineralizing system; early sulphur was derived from near-surface sources and precipitated barite, whereas later deep-seated sulphur accompanied the ascending zinc-lead rich solutions. From standard plots of equilibrium sulphur-isotope fractionation values among the common sulphides as a function of absolute temperature, it can be inferred that sulphides in the lower epigenetic zones were precipitated at temperatures in the range 150°-280°C. These temperatures indicate a

Table 2.

Summary of the diagenesis and paragenesis observed within the various ore zones. Based on the work of Rhoden (1958, 1960), Barrett (1975), Catlin (1983) and Locklin (1983).

LOWER ORE ZONES	Basal Clastics	Shallee and Shallee White.	ORIGINAL SEDIMENTS	Early Fe-free dolomite cements and minor pyrite euhedra.		Fracturing and silicification.	Barite, galena±pyrite. Rare Sphalerite.	—
		C Zone, K Devonian Zone and Gortnadiha.		Early Fe-free dolomite cements ± minor pyrite-marcasite.		Fracturing and silicification with minor pyrite.	Fracturing, sulphides; (pale sphalerite to dark sphalerite and minor galena.)	—
	Lower Dolomite	Lower G Zone		Replacement by Fe-free dolomite and minor pyrite-marcasite.		Fracturing, Fe-dolomite, silica and minor pyrite-marcasite	Fracturing, sulphides, barite and minor sericite.	Ferroan calcite.
		K Zone and P Zone.		Replacement by Fe-free dolomite and minor pyrite-marcasite		Fracturing, Fe-dolomite, minor pyrite-marcasite sporadic silicification.	Fracturing, sulphides, barite and minor sericite.	Ferroan calcite.
UPPER ORE ZONES	Base of Waulsortian Equivalent	Magcobar Barite Zone.		—	SEDIMENTATION	Silica, hematite, barite and ferroan dolomite.	Fracturing, recrystallization, later pyrite-marcasite followed by sulphides.	Fracturing, ferroan calcite.
		Siderite (B & Upper G).		—		Siderite and ferroan calcite.	Fracturing, Fe dolomite, sulphides, later galena and arsenopyrite.	Fracturing, ferroan calcite.
		Pyrite (B & Upper G).		—		Pyrite-marcasite.	Fracturing, Fe dolomite, sphalerite, galena and barite.	Fracturing, ferroan calcite.
		Waulsortian Reef Lst.		—		Fe-free calcite as cements	Fracturing and Fe calcite, minor pyrite.	
			TIME ——→					

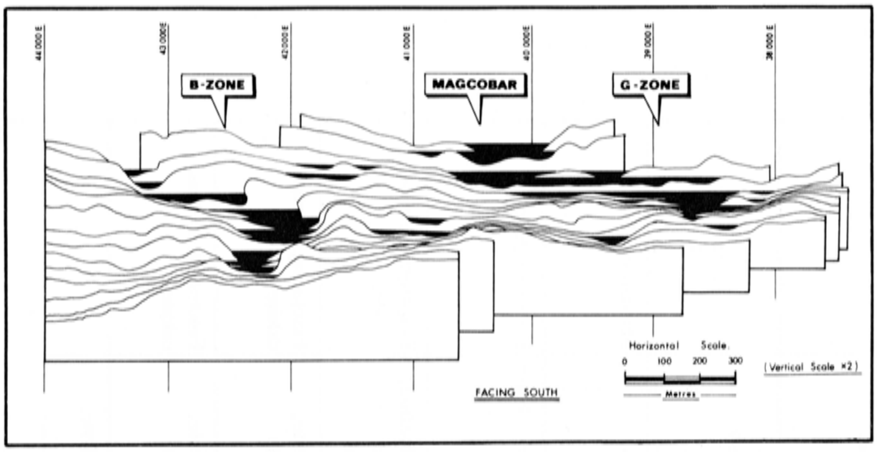

Figure 17. Stacked serial profiles up to the Green Shale Marker facing south. The upper orebody system is shown semi-diagrammatically in black, and demonstrates the close palaeotopographic control of ore distribution.

similar range to those inferred from fluid-inclusion studies.

Sulphur-isotope results in the upper orebody system show a wide range for sulphides spread from $\delta^{34}S = -4$ to $-43‰$, with most in the range -13 to $-24‰$. Barite falls in the range of $\delta^{34}S$ values from $+12$ to $+23‰$, similar to that of the barite in the lower epigenetic zones. Textural and isotopic evidence suggests that disequilibria existed between all sulphide phases and barite in the upper orebody system. It appears that solutions carrying barium and iron precipitated barite (± haematite) on encountering contemporaneous Lower Carboniferous seawater in an oxic environment. Pyrite was precipitated where the sulphur was derived from low-temperature bacteriogenic reduction of sea-water sulphate in areas where reducing conditions were dominant. Paragenetically later base-metal sulphides and pyrite derived some of their sulphur from deep-seated sulphur, but dominantly from seawater sulphate.

Diagenetic and paragenetic evidence (Table 2) and isotopic information suggest that the ore-forming fluids not only mixed to precipitate the upper orebody system, but may have evolved temporally. Initially these brines were iron-, barium and silica-rich, later they became lead-zinc rich, and finally, in the waning stages of the mineralizing event, carried only magnesium and manganese. Some sulphur travelled with the base-metal-bearing hydrothermal fluids which mixed with seawater sulphate in the uppermost parts of the epigenetic zones and in areas of the upper orebody system proximal to these epigenetic zones (feeder sites). Intense brecciation seen in the uppermost parts of the Lower G Zone may represent phreatic explosive hydrothermal activity caused by rapid pressure-release and local boiling at the site of exhalation onto the sea-floor.

Summary

Regionally, the Silvermines district lies on the flank of an Upper Devonian to Lower Carboniferous palaeohigh. This palaeohigh stikes NW, cutting across the Caledonian grain and the postulated course of the Caledonian Iapetus Suture at right-angles (Phillips and Sevastopulo, this vol.). Hiatic fault reactivation along the course of this suture has been demonstrated to have occurred in the Middle and Upper Devonian in the Devil's Bit Mountains (Fig. 1) 10km E of Silvermines (Feehan, 1980; Gardiner and McCarthy, 1981), and during the Courceyan in the mine area. Hercynian tectonism similarly followed this line of crustal weakness. The course of this basement suture is coincident with a NE-trending zone of enhanced sedimentary thickness of strata ranging in age from the *PL* miospore zone of the Upper Devonian through to, at least, the Asbian stage of the Dinantian. This basin or trough, colloquially termed the Iapetus Syncline (the Kilmastulla Syncline of the mine area), is terminated by the Silvermines palaeohigh. Thus the Silvermines deposits may be said to lie at the intersection of a NW-trending palaeohigh with Caledonoid ENE basement faulting, and at the edge of a contemporaneously tectonically active sedimentary basin.

The ore-hosting sediments at Silvermines pass up from alluvial plain and marginal marine clastics, through transgressive muddy lagoonal and estuarine carbonates, to shallow-water shelf bioclastic limestones. The superceding Waulsortian Reef Limestone stromatactid biomicrites are generally considered to have been deposited on a carbonate shelf at the base of the photic zone (Sevastopulo, 1982; Lees, 1982), that is, in water depths in the range 100-300m. In the mine area the Waulsortian Equivalent breccias are sandwiched between the Footwall Pale Reef Limestone knolls and the Upper Reef Limestone, both of Waulsortian affinity, and thus the breccias must have been deposited in similar water depths. The Supra Reef lithologies generally imply deeper water conditions after Reef deposition, thus basin subsidence must have kept pace with sedimentation at this time.

The dramatic change in depositional palaeo-environment from quiescent shelf to hydrodynamic debris-flow sedimentation at the top of the Muddy Reef appears to coincide with the onset of contemporaneous tectonism. Isopach plots of the superceding Waulsortian Equivalent show enhanced thicknesses on the northern downthrown sides of the WNW-trending faults. Debris flows are lobate and run downdip of these faults. These faults, essentially normal dip-slip structures exhibiting a curving profile flattening with depth, appear to be of a listric style. Gentle folding, trending at right-angles to these faults, developed a palaeorelief on the seafloor. The relations of synclinal troughs to points of maximum throw on the faults would appear to be similar to the development of 'roll-overs' associated with listric faults (Gibbs, 1984). Sedimentation of Footwall Pale Reef Limestone knolls occurred along crests between the troughs and in the areas away from active tectonism, while

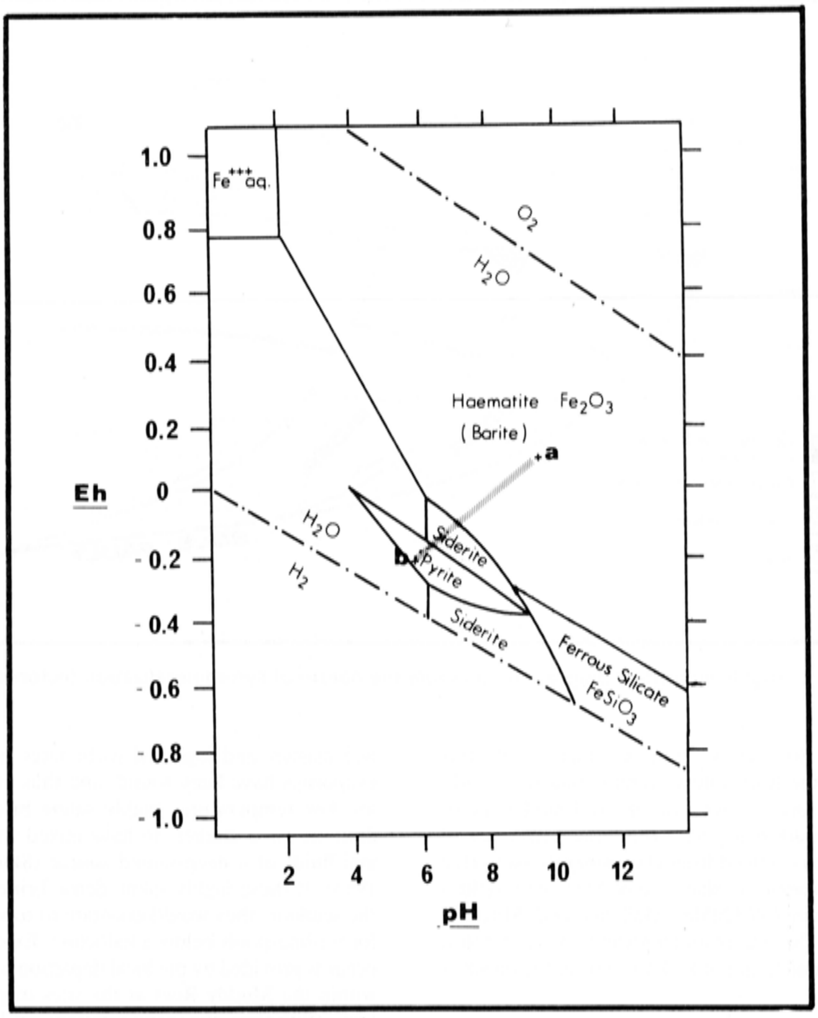

Figure 18. Eh-pH stability relations among iron oxides, pyrite and siderite at 25°C, 1 atm total pressure, total dissolved carbonate = 10°m, total dissolved sulphur = 10^{-6}m and in the presence of amorphous silica. (Redrawn from Garrels, 1960). The line a-b approximates to the range of depositional conditions of the host facies in the upper orebody system.

silica-rich modified Muddy Reef lithologies were deposited in the troughs.

Above this palaeotopographic surface, the Green Shale Marker was deposited. The mineralogy and presence of derived Silurian micro-fauna indicates a Lower Palaeozoic source for this chronostratigraphic marker. As there is no evidence to suggest submarine (or subaerial) exposure of Silurian lithologies in the immediate vicinity at that time, it is proposed that the material was flushed out of the developing fault systems from depth by the onset of the main mineralizing event, and was deposited on the sea-floor.

Mineralization occurs in numerous host environments. The lower ore zones typically show epigenetic characteristics. However, the presence of finely laminated base metal sulphides in the silica-rich modified Muddy Reef lithologies suggests a significantly different depositional environment for the stratigraphically earliest manifestations of the upper orebody system. This environment is thought to be synsedimentary, and further evidence for this origin is afforded by numerous sedimentary fabrics. These include finely laminated bedding-parallel sulphides, soft-sediment deformation and disruption textures, sedimentary breccias of pyrite clasts and particulate sulphide sediments, scoured upper surfaces to the barite and pyrite ore facies with rip-up clasts and flasers included in the hangingwall breccias, and the close palaeotopographic control of the distribution of the ore facies by the relief of the Footwall Pale Reef Limestone knolls.

Without exception, all the epigenetic lower ore zones are closely related to WNW or westerly faults, being either within, bounded by, or developed against and proximally to, such faults. Similarly the upper orebody system is developed in troughs down-dip of these same faults. Hence an obvious spatial and temporal relationship between mineralization and faulting is indicated.

Isotopic evidence from both types of ore zones supports this interpretation. Sulphur-isotope results from barite in the epigenetic Shallee, Lower G and K Zones has an analagous range of $\delta^{34}S$ values (+18 to +23‰) to those obtained from barite in the upper orebody system (Fig. 16). Lead-isotope values obtained from galenas from the Lower G Zone, Shallee and from Basal Clastics intersected in deep drillholes N of the Upper G Zone, have isotopically indistinguishable values from those obtained from the B, Upper G and Magcobar Zones of the upper orebody system

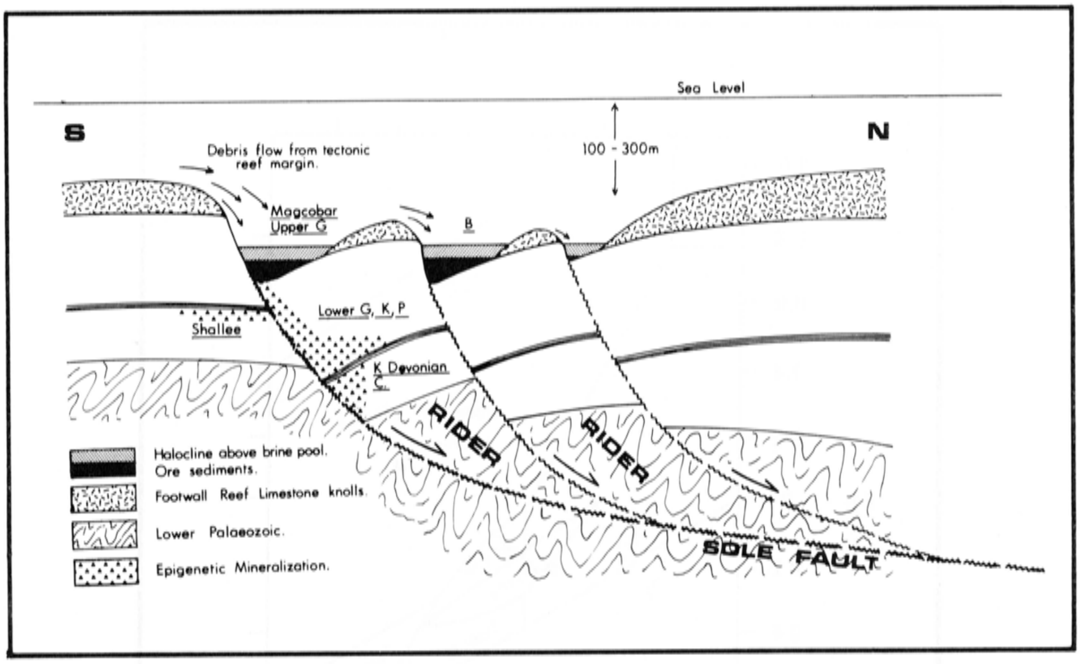

Figure 19. Highly simplified diagram to illustrate the nature of syn-mineralization tectonism.

(Lambert, 1980; Boast et al., 1981; Caulfield et al., this vol.). Typically the lead-isotope values indicate a radiogenic character and, as such, the inferred model age of 271±24Ma is at discrepancy with the sedimentary age of 350Ma. K-Ar ages obtained from clay minerals associated with the mineralization at Shallee and Magcobar yield a similar range from 295-320Ma (Halliday and Mitchell, 1983). These pre-date the main Hercynian event and thus some 'resetting' due to argon leakage during tectonism is suggested.

Genetic model

The localization of the orebodies within, and adjacent to, the WNW and locally westerly faults suggests that these fractures, or enhanced porosity and permeability zones adjacent to them, acted as fluid conduits. The fracture zones occur either in bulk tectonic dilation zones or at the points of maximum throw of the listric fault complex. These points of maximum throw correspond to the position of the mineralized zones of the upper orebody system, and consequently the faults and associated mineralized fracture zones may be regarded as 'feeder' conduits to the upper exhalative orebody system.

The earliest mineralizing solutions probably rose passively through the incipient fracture system during deposition of the upper Muddy Reef. This fracture system initiated above a major tectonic zone at the basin margin. These early solutions produced iron-free dolomite cements in the Basal Clastics and replacement dolomitization of the Lower Dolomite oolitic protolith. It is not obvious if these brines migrated up the fracture system to the seafloor, as little effect of exhalation can be seen on the sediments at this point in the stratigraphy. The brines may have been derived from dewatering of the sedimentary basin to the NE, where approximately three times the thickness of Lower Carboniferous sediments were developed than at the basin edge at Silvermines. These sediments contain calichiferous red-bed clastics and lagoonal carbonates in which traces of evaporites have been found, and thus may have provided the low temperature, highly saline brine inferred, from fluid-inclusion studies, to have mixed with the hydrothermal fluids of a deep-seated source (Samson and Russell, 1983). If these highly saline dense brines did exhale onto the seafloor, they would gravitate to topographic lows and form brine-pools below a halocline. Evidence that this did occur is provided by the local depletion or absence of fauna within the Muddy Reef at the sites of palaeotopographic lows. With time, the rising solutions gradually changed and became enriched in silica. This was possibly derived from biogenic silica (sponge spicules) remobilized from the dewatering sediments to the NE and transported as a hydrophilic sol. The silica was deposited in fractures and replacements within the epigenetic zones and eventually sealed the system. At the seafloor, these silica-rich brines precipitated laminated cherts in the palaeotopographic lows. At the time of sedimentation of the uppermost beds of the Muddy Reef, the fluid system appears to have encountered the first manifestations of deep-seated base-metal bearing solutions. Evidence for this is shown by the presence of finely laminated pale buff sphalerite (and very minor pyrite and galena), which become increasingly abundant upwards, in the laminated cherts of the Muddy Reef. Immediately adjacent to the WNW feeder faults in the B Zone and Upper G Zone, these Muddy Reef cherty argillites are interbedded with galena and marcasite as opposed to sphalerite.

The Green Shale Marker marks the onset of the main phase of exhalative and synsedimentary tectonic activity, and is thought to represent detritus flushed out of the fault systems by the onset of the main phase of hydrothermal fluid migration. Re-fracturing of the epigenetic orezones immediately followed the 'Green Shale' event with the development of non-systematic fracture and breccia zones. In these epigenetic zones, zoned ferroan-dolomites and minor iron sulphides were deposited in the resultant voids, while in the highly saline brine-pool environment of the

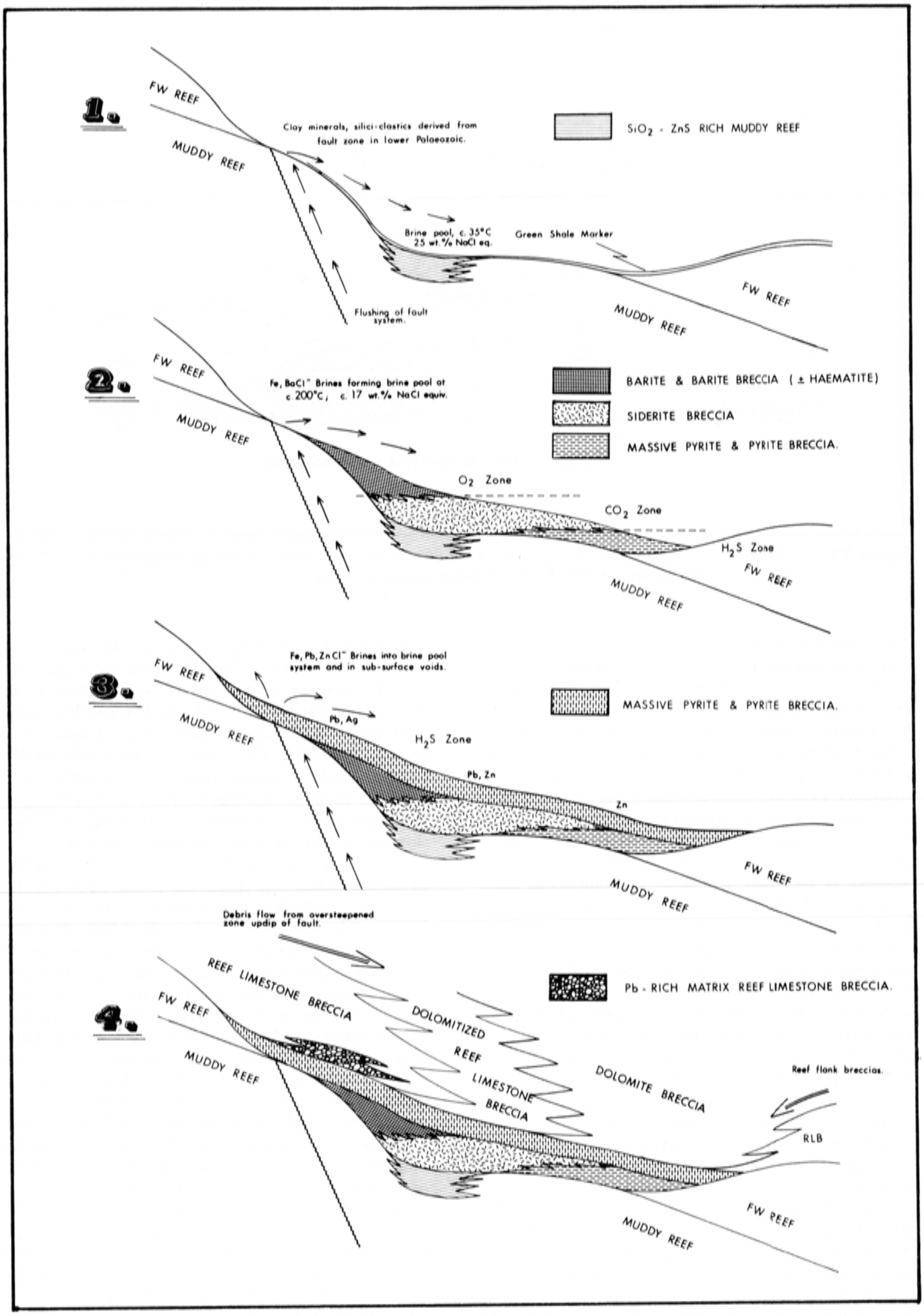

Figure 20. Sequential diagram to illustrate the development of the upper orebody system host facies and conditions of deposition.

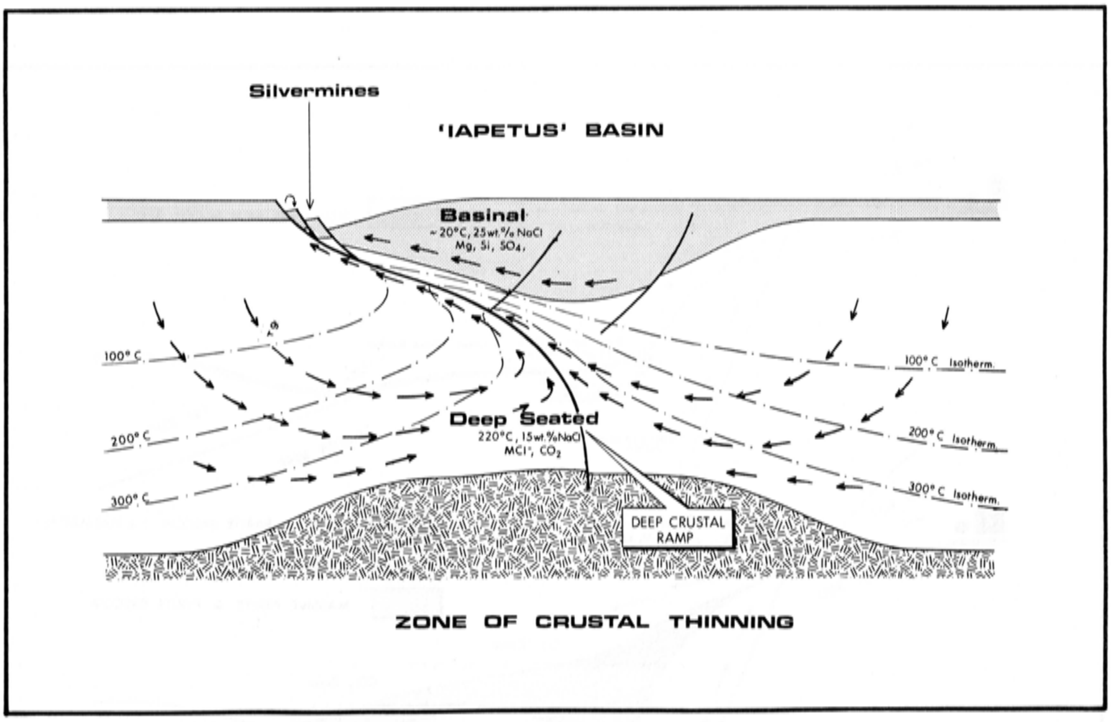

Figure 21. Schematic diagram indicating postulated fluid movement pathways and megatectonic setting of the proposed genetic model for the Silvermines orebodies.

upper orebody system, haematite - barite, siderite and pyrite were precipitated in the lows between the Footwall Pale Reef Limestone knolls (Fig. 17). Varying water depths and the redox potential of the local palaeoenvironment of exhalation, coupled with the quantity of biogenically reduced sulphur available, determined the nature of the iron species deposited (Fig. 18). The range in water depth variation is estimated at about 100m, based on a palinspastic reconstruction of the footwall palaeotopography minus the effects of post-ore tectonic tilting on the southern flank of the Kilmastulla Syncline. Overall water depth was probably in the range 100-300m, as Waulsortian Reef Limestones, which locally underlie the orebody, could only develop within the photic zone.

Where feeders debouched into the shallowest areas of the upper orebody system (such as the southern part of the B Zone and Magcobar), haematite with barite was precipitated which, with increasing depth, interdigitates with siderite, and subsequently, at deeper levels, into pyrite. Where feeders debouched in the sulphide level, as in the Upper G Zone, coarse, highly porous mounds of colloform pyrite — marcasite 'sinter' built up. At the sites of some of these feeders, tubular, concentrically zoned growth forms of marcasite — pyrite up to 5cm long and 2cm in diameter occur. These have been identified as fossil hydrothermal vent chimneys (Larter et al., 1981; Boyce et al., 1983; Banks, this vol.), and are comparable with the 'Black Smoker' chimneys of the East Pacific rise at 21°N (MacDonald et al., 1980), although the former are much smaller. After the early exhalations and deposition of the initial barite, siderite and pyrite ore facies, deepening of the entire area occurred so that later iron-bearing exhalations deposited pyrite above earlier barite and siderite. This later pyrite was deposited over a broader area, locally covering small Reef Limestone knolls which had previously bounded the development of ore facies.

Active tectonism along the feeder faults subjected the semi-lithified ore-host facies to slumping and *in situ* brecciation. This form of brecciation, with little movement of the clasts, is thought to have been formed by forceful pressured fluid migration through the semi-lithic sediments (Taylor and Andrew, 1978). These, and later, fluids deposited base metal sulphides in void porosity in the lower epigenetic zones as rhythmic coatings to clasts and as free-grown crystalline masses in open spaces. As they migrated laterally through the brecciated ore sediments of the upper orebody system, they precipitated fine-grained base metal sulphides in the intraclastic void spaces and primary porosity. Lead was preferentially deposited proximally to the feeder faults. Base metal zoning cuts across ore-host facies boundaries as it reflects feeder proximity rather than environmental redox conditions which controlled the deposition of the ore-host facies. In the G Zone the majority of the lead was deposited in the lower epigenetic zone within the feeder system, whereas in the B Zone the absence of an underlying depositional environment enabled the lead-bearing solutions to ascend and enter the upper orebody system.

Debris-flow breccias were formed by tectonically triggered gravitational flow of semi-lithic and lithic clasts of ore-host facies and Waulsortian sediments down palaeoslopes away from the faults. Immediately above the exhalative ore-host facies, adjacent to the B Zone Fault, the matrix to these debris-flows is comprised of very fine-grained galena and the minor pyrite. Similar lead-rich areas in the East Panel area (Fig. 11) have been previously referred to as a feeder location (Taylor, 1984), but are now thought to represent lobes of lead-rich debris flow generated to the NE on the B Zone Fault.

Post-sulphide hydrothermal fluids precipitated ferroan dolomite and later ferroan calcite as cements to the debris flows. Some of these solutions exhaled and precipitated crusts of dolomite on organic membranes which, with subsequent disruption produced the fine-grained vermicular Dolomite Breccias. The chert and chert breccias near the top of the Waulsortian equivalent succession have been interpreted as the waning stages of the mineralizing processes (Barrett, 1975). However, recent lithogeochemical and petrological studies on the cements within these rocks reveal a distinctive and apparently unrelated diagenetic history to ore-horizon units, and consequently no genetic relationship is now thought to exist.

Conclusions and discussion.

The Silvermines orebodies were formed by the passage of temporally evolving hydrothermal fluids through a system of synsedimentarily active, listric, normal dip-slip faults. These solutions then debouched onto the Lower Carboniferous seafloor. Epigenetic mineralization occurred within fracture and dolomitization void porosity in and adjacent to the fluid conduits, while syngenetic — syndiagenetic mineralization occurred on the seafloor within palaeotopographically located brine-pools below a halocline. Sulphide precipitation took place due to boiling, cooling and mixing of two brines of distinctly different physico-chemical character.

From this model, the Silvermines orebodies belong to the class of sediment-hosted exhalative ore deposits (SEDEX) as defined by Large (1978, 1980) and Gustafson and Williams (1981).

Elsewhere in the world, many examples of the SEDEX type of base metal deposit are found within host sediments deposited in a starved basin, and usually above a thick sedimentationally unbroken succession of greywackes (for example the Meggen, Sullivan and Red Dog deposits; Gustafson and Williams, 1981). In Ireland, deposits usually considered to be a variant of the SEDEX type (Large and Hitzman, this vol.), occur in shallow-water carbonate sediments deposited rapidly above a major unconformity.

Even between the Irish deposits there is a wide variation in the nature of the relations of the host sediments to mineralization. In general these may be divided into three:

1. Deposits deposited syngenetically on the sea floor such as Silvermines upper orebody system, the Tynagh Iron Formation (Clifford et al., this vol), and, possibly, the Garrycam barite deposit at Keel (Slowey, this vol.).
2. Deposits formed by the passage of hydrothermal solutions through sediments as they lithified and underwent diagenesis, such as Navan (Andrew and Ashton, 1982 and 1985), Tynagh, Ballinalack (Jones and Brand, this vol.), Moyvoughly (Poustie and Kucha, this vol.) and Tatestown (Andrew and Poustie, this vol.).
3. Deposits formed as epigenetic fracture and void-porosity infills, such as the lower ore zones at Silvermines and Keel.

Using the SEDEX model, the last group of deposits may be regarded as feeder systems to stratigraphically higher exhalative horizons. The first two categories, however, may relate to the rate of sedimentation during mineralization at that locality. At Silvermines, it appears that following exhalation and precipitation of the upper orebody system host facies during a period of minimal sedimentation, rapid deposition of debris-flow sediments occurred at the cessation of the mineralizing event. Whereas at Navan mineralization of an exhalative nature stayed abreast of rapid sedimentation, it was also deposited in a range of diagenetic environments in the lithifying shallow-water carbonate sediments (Andrew and Ashton, 1985). Thus it would seem that the mineralizing process at Silvermines, and by analogy the Tynagh Iron Formation, was a fairly short-lived process, whilst at Navan mineralization was ongoing throughout the period from host-sediment deposition in the Upper Courceyan through to the rejuvenation of the system in the Arundian (Ashton et al., this vol.).

The derivation and source of metals in SEDEX orebodies has been discussed at length by many authors. Russell (this vol.) argues that metals were leached from Lower Palaeozoic sequences by convective plumes of downward-excavating seawater, whereas Lydon (this vol.) suggests that dewatering of sedimentary basins adjacent to the orebodies was the source of the metals. The model proposed here for the Silvermines orebodies utilizes aspects of both of these models, with early highly saline Mg and silica-rich fluids being derived from the Iapetus Syncline or basin to the NE, and base metals from deep convected fluid systems migrating through Lower Palaeozoic and Old Red Sandstone sequences. If an average temperature gradient of 1°C per 20m is taken, it is considered that the thickness of sub-Waulsortian uppermost Devonian and Courceyan sediments within the Iapetus Syncline, at the time of mineralization, would be insufficient to generate base metal bearing hydrothermal fluids of the temperatures indicated by fluid-inclusion and isotopic fractionation studies of the orebodies.

Lead-isotope studies (Boast et al., 1981; Caulfield et al., this vol.; O'Keeffe, this vol.) suggest that the non-equivalent stratigraphic lead model age is due to selective leaching of radiogenic lead from the Lower Palaeozoic sialic greywackes below the ore-district. Similarly some of the sulphur was derived from this source, but by far the dominant source of sulphur was from biogenic reduction of seawater sulphate. The mechanism of fluid flow and leaching is thought to be along the lines of the model proposed by Russell (this vol.).

The close association of mineralization at Silvermines with synsedimentary listric faulting is of major importance in the recognition of the tectonic regime active in the Irish Midlands during the Courceyan. At Tynagh the main ore zones are located at the point of maximum throw and steepening of the Tynagh Fault, a synsedimentarily active structure (Clifford et al., this vol.). At Navan, mineralization pre-dates and is laterly contemporaneous with normal dip-slip listric faulting. Elsewhere in Ireland virtually all early mineralization is associated with normal dip-slip listric faulting which was active during the late Courceyan. This relationship points to mineralization being related to a phase of extensional basin formation. This basin formation is thought to be controlled by a series of major listric faults developed in response to crustal thinning along the line of the Caledonian Iapetus Suture (Phillips et al., 1976). Elevated heat-flows within this crustal zone generated circulatory brine systems around hot spots (residually warm Caledonian plutons), which leached metals and escaped upwards along deep-seated fractures by seismic pumping mechanisms. Cross-basin axes and structures focussed these upwelling fluids into developing local dilational listric fault systems through which the fluids escaped to the mineralizing environment. The orebodies were formed where these fluids cooled and mixed with biogenically derived sulphur either at surface or in the diagenetic subsurface environment.

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The author thanks Ennex International PLC for permission to publish this paper and to include much recently acquired data. In addition thanks are due to Stewart Taylor, with whom the author enjoyed two rewarding years at Silvermines from 1976-1978. Acknowledgement would not be complete without sincere thanks to Prof. Mike Russell and his research students at Strathclyde University, notably Adrian Boyce, Gary Gray and Iain Samson, with whom the author has enjoyed many hours of rewarding and fruitful discussion and whose interest and enthusiasm for the Silvermines orebodies has led to so much clarification of their genesis. Finally thanks are due to Rupert Crowe and Mike Russell for struggling through the initial draft of this paper and improving the author's ramblings.

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Discussion

MURRAY HITZMAN (Chevron Mineral Corporation of Ireland) asked:

1. The "vermicular breccia" in the dolomitic breccia unit at Silvermines is strikingly similar in texture to samples from the Navan Mine containing "wormy" textured barite. Do you know of any "vermicular breccia" for Silvermines which contains barite? What do you think of the possibility that the "vermicular dolomite breccia" is a dolomitized example of the same texture seen at Navan? 2. What is the evidence that the dolomite breccias overlying ore beds are primary as opposed to either (a) post-emplacement hydrothermal alteration of debris flow material, or (b) a zone of multiple hydrothermal dolomitization with *in situ* brecciation? 3. What is the evidence for boiling of mineralizing fluids at Silvermines?

REPLY:

I agree with Murray Hitzman's assertion that the vermicular dolomite breccias at Silvermines texturally closely resemble certain examples of barite from the 1-5 Lens at Navan. I think that a common genetic model may be invoked to explain this striking similarity. At Silvermines, in a moderately deep water environment, exhaled dolomite precipitative solutions nucleated on silt-organic membranes on the sediment — water interface during tectonic quiescence in the distal debris flow regime. Subsequent tectonism and slumping disturbed this crystallite dolomite horizon and plastically deformed them into the vermicular clasts. At Navan, exhalative barite precipitative solutions in a shallow water high energy regime deposited barite in algal silt — organic membranes, subsequent tidal action disturbing the laminae to form slumped horizons and intraclasts in a barite-rich sediment matrix. Hence, as a common and therefore an analagous origin can be invoked to explain the texture, and as microscopically determinable residual barite can be found in the dolomite breccias, I do not think that dolomitization of a barite precursor is a valid model.

As stated in the paper, the dolomitized debris flow and flank-reef Reef Limestone Breccias are locally altered post-depositionally by ferroan dolomite. *In situ* brecciation of non-ore horizon sediments does not appear to be an important mechanism. This may be due to the rapid lithification of the Waulsortian Reef micrites, as evidenced by angular clasts, lithification of the footwall knolls prior to exhalation etc. In comparison the pyrite, siderite and barite ore host facies show evidence of semi-lithic deformation and recrystallization; they thus retained for a longer period their semi-viscoplastic nature, and, consequently, their susceptability to *in situ* brecciation. It is also important to note that the debris flow breccias are polymicritic and thus could not be produced by *in situ* mechanisms. Post-depositional dolomitization of debris flows did occur.

Evidence for boiling is inferred from vapour-rich fluid inclusions (Samson and Russell, 1983; Probert, 1984). On a more tenuous line, superheated steam produced on boiling may be a way of producing the breccias in the epigenetic zones by phreatic explosions.

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PLATES 1-18 FOLLOW

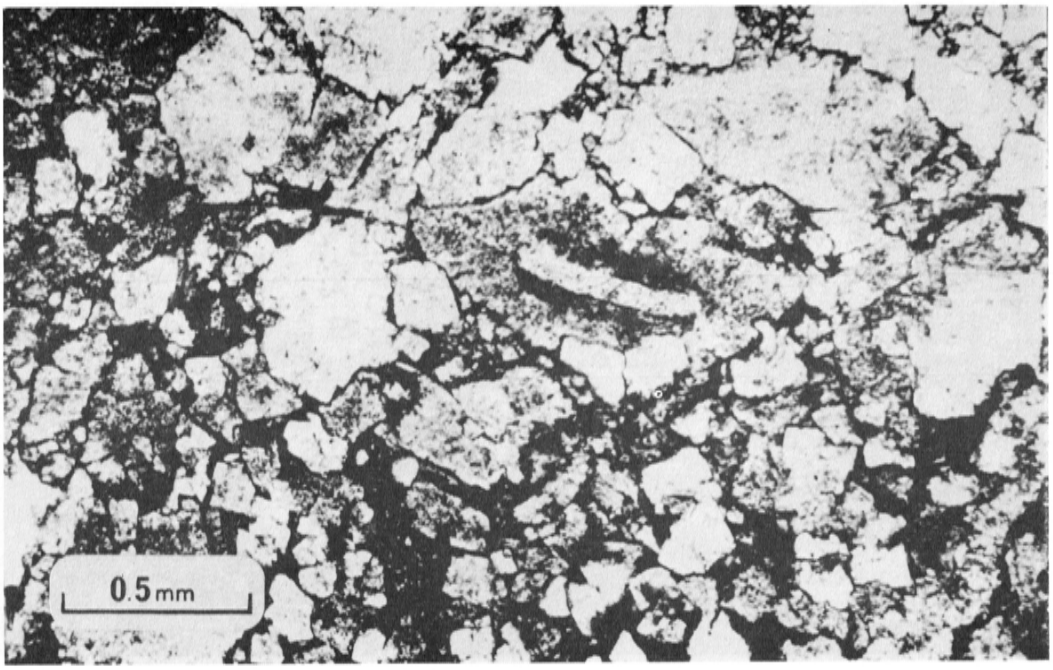

Plate 1. Basal Fragmental — dolomitized argillaceous biomicrite, well recrystallized with relict algal or oolitic texture. Dominantly iron-free dolomite. Drillhole K 64 (K Zone) 175.7m; Stained thin section.

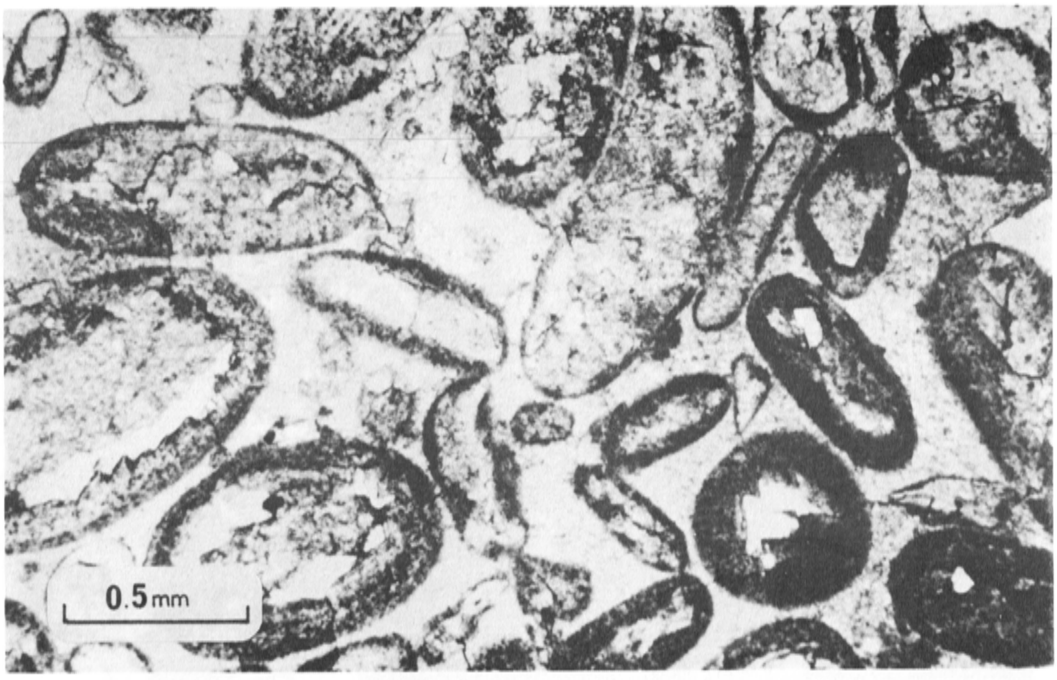

Plate 2. Lower Dolomite — dolomitized oosparite, dominantly iron-free dolomite but coarsely crystalline ferroan-dolomite replaces the cores of many of the ooliths. Drillhole K 64 (K Zone) 147.6m; Stained thin section.

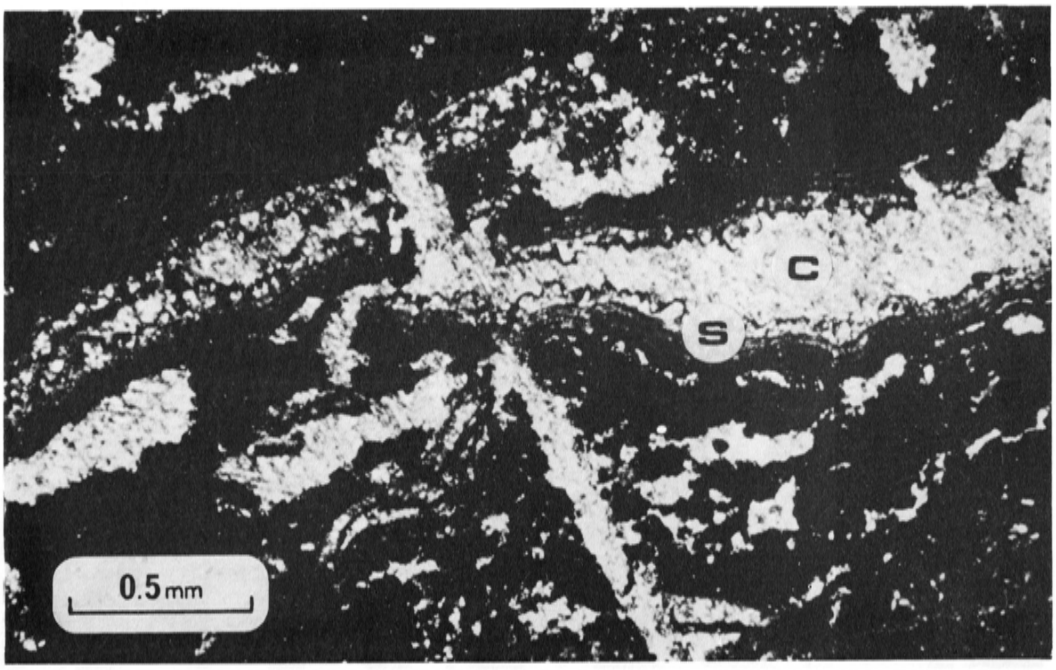

Plate 3. Lower Dolomite — ferroan calcite [C] infilling fractures cutting earlier voids lined with colloform sphalerite [S] in recrystallized dolomite (black). Drillhole K 80 (K Zone) 40.0m; Stained thin section.

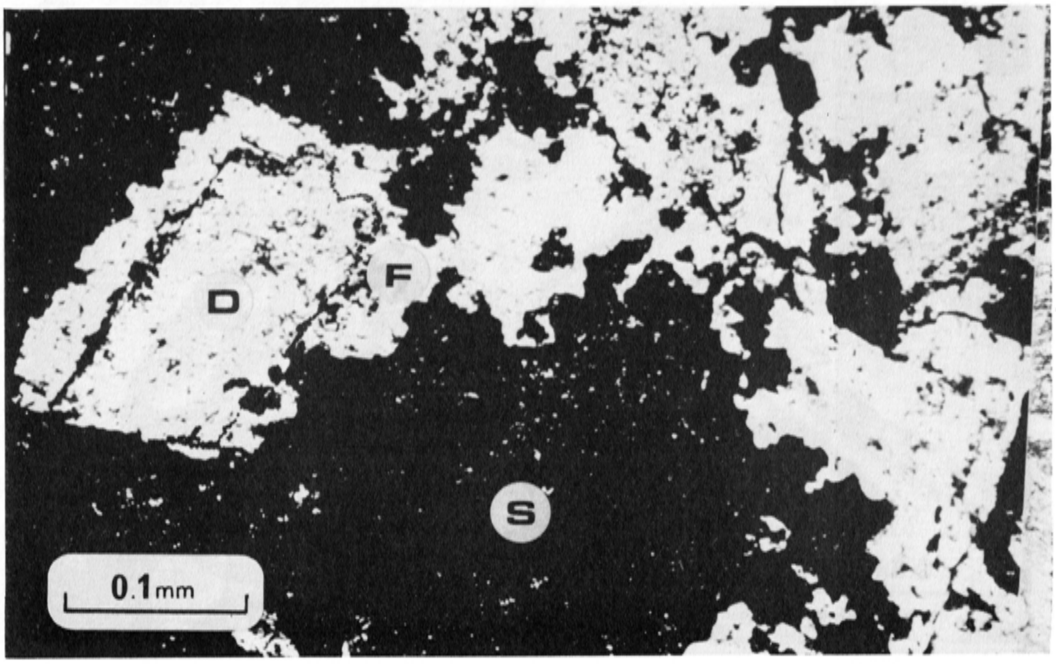

Plate 4. Lower Dolomite — sphalerite [S] replacing earlier replacement iron-free dolomite [D] and ferroan dolomite [F] which coats and cements rhombic crystals. Drillhole K 80 (K Zone) 40.0m; Stained thin section.

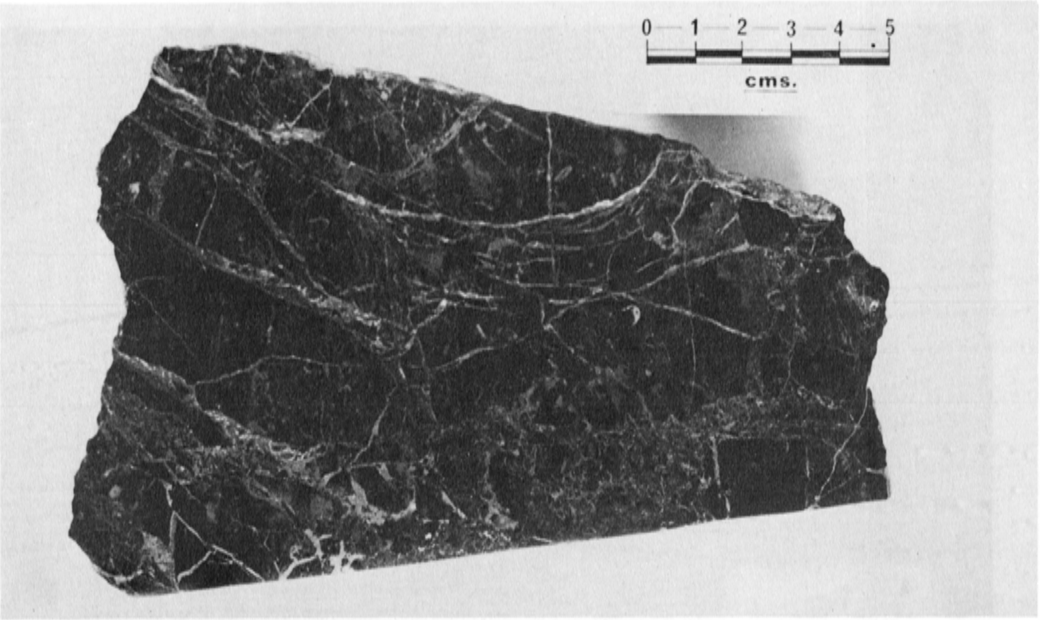

Plate 5. Lower G-Zone ore — polished slab of typical ore showing multiple generations of veins infilled by galena with minor sphalerite cutting dark grey Lower Dolomite. 2-E-2 S Stope.

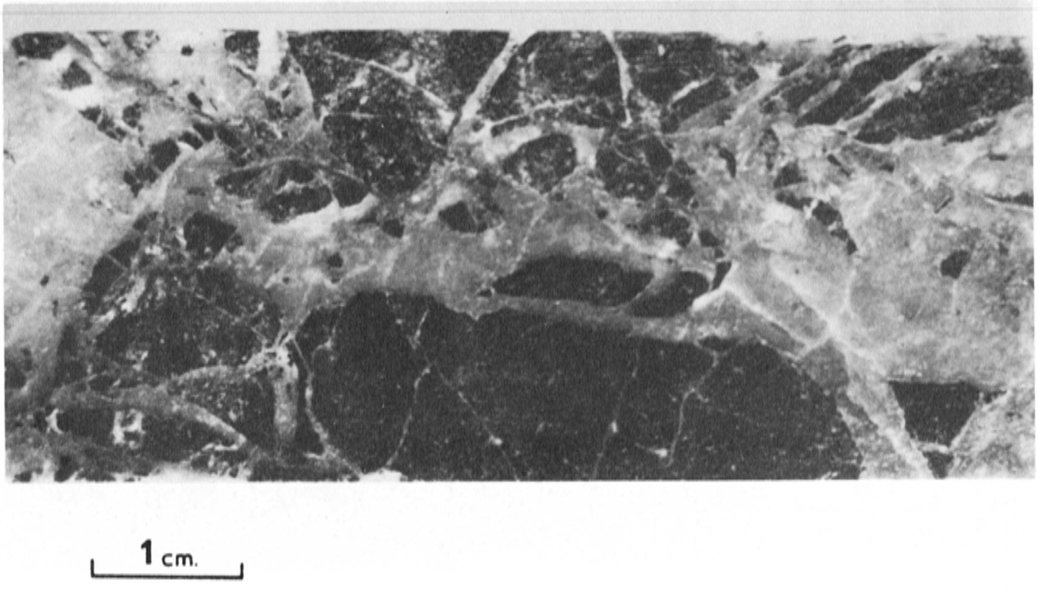

Plate 6. Lower ore, Garryard — polished drill-core of Lower Dolomite, shattered and veined by grey-white crystalline barite. Drillhole 75-84-37, 47.3m.

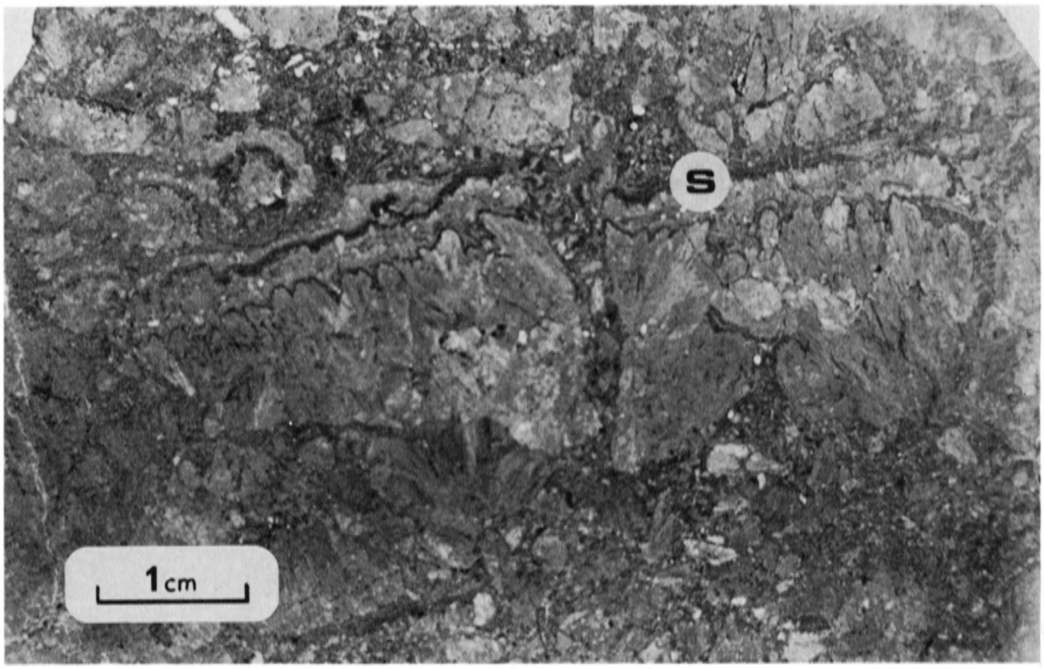

Plate 7. Massive pyrite, Upper G-Zone — polished slab of plumose textured marcasite, locally fractured, brecciated and recemented by pyrite — marcasite and sphalerite. Finally laminated sphalerite [S] along the top of the large plumose aggregate. 3-E-5 Stope.

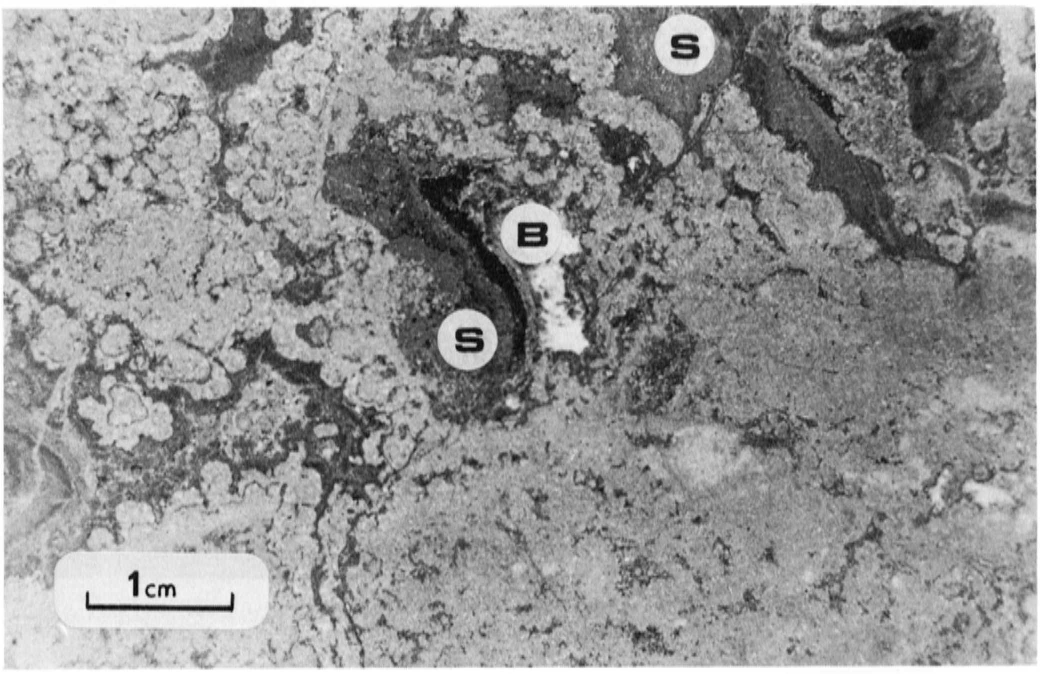

Plate 8. Massive pyrite, Upper G-Zone — polished slab of 'pyrite sinter' exhibiting well-developed colloform textures. Voids infilled with fine-grained, medium grey, sphalerite [S] and barite [B]. 2-W-5 Stope.

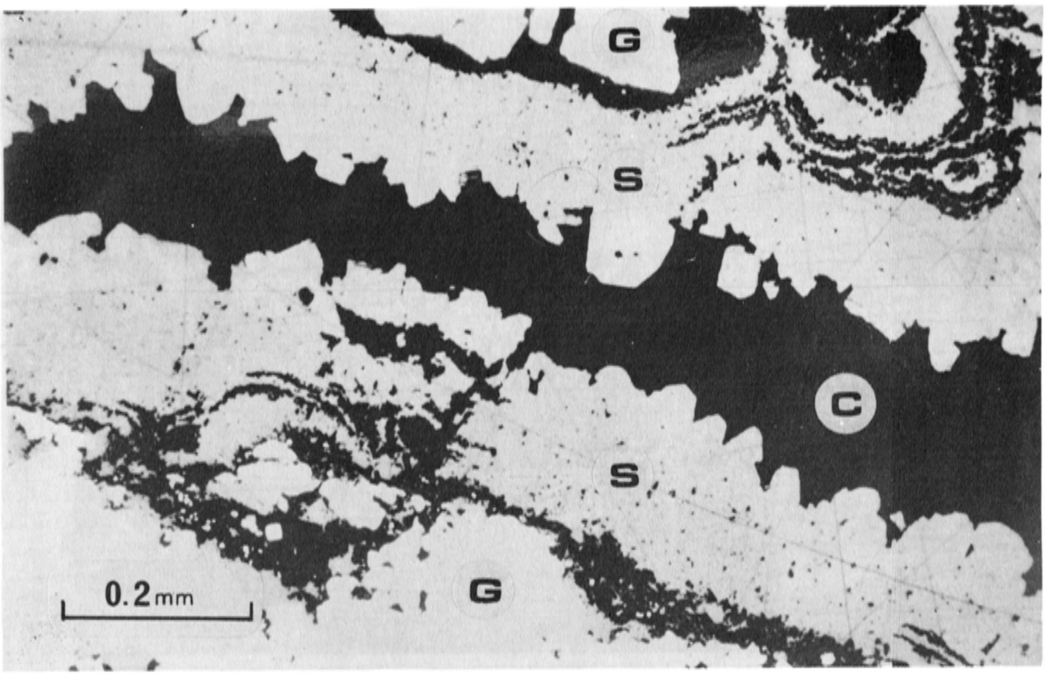

Plate 9. Siderite facies, B-Zone — sphalerite [S] showing colloform textures and galena [G] lining void in siderite breccia. Final infill of the void is by ferroan calcite [C]. 4604 Room; Polished section.

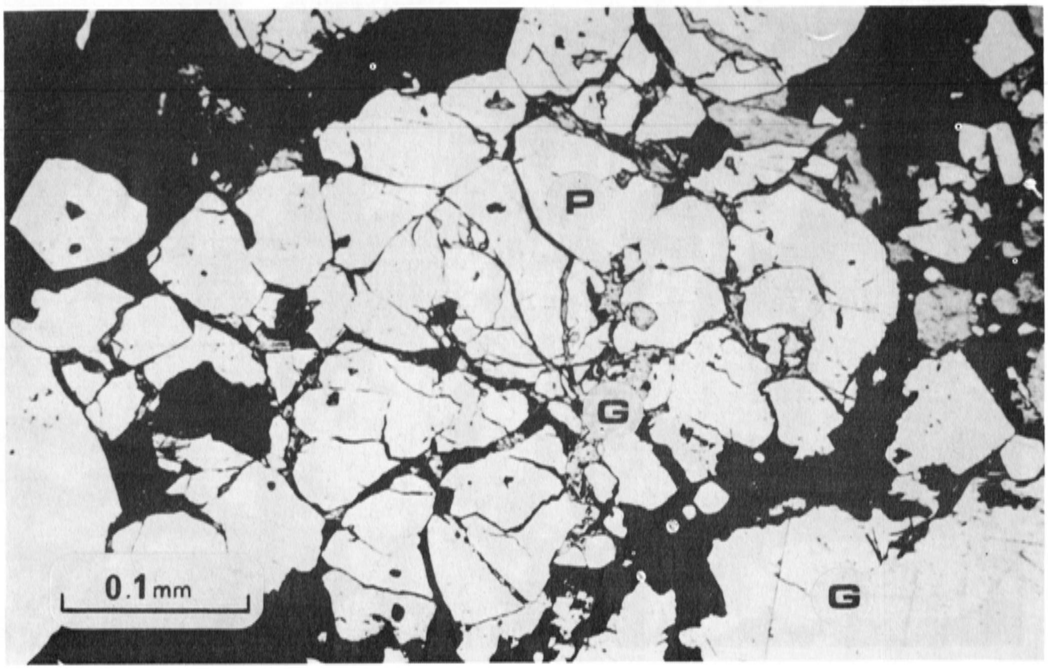

Plate 10. Massive pyrite, B-Zone — galena [G] forming veinlets in fractured pyrite [P]. 4933 Pilot Drift; polished section.

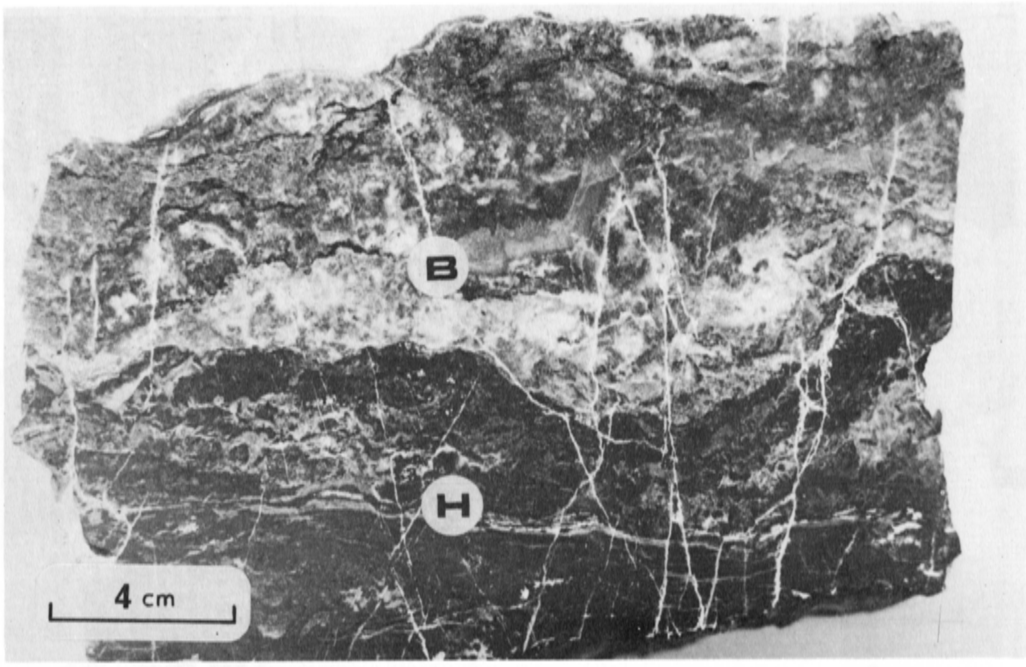

Plate 11. Barite Zone, Magcobar Pit — polished slab of the immediate base of the barite zone. Shows laminated and slumped siliceous haematite [H] overlain by paler crystalline barite [B]. Later sub-vertical minor fractures are infilled by ferroan calcite. Magcobar Pit, SW end.

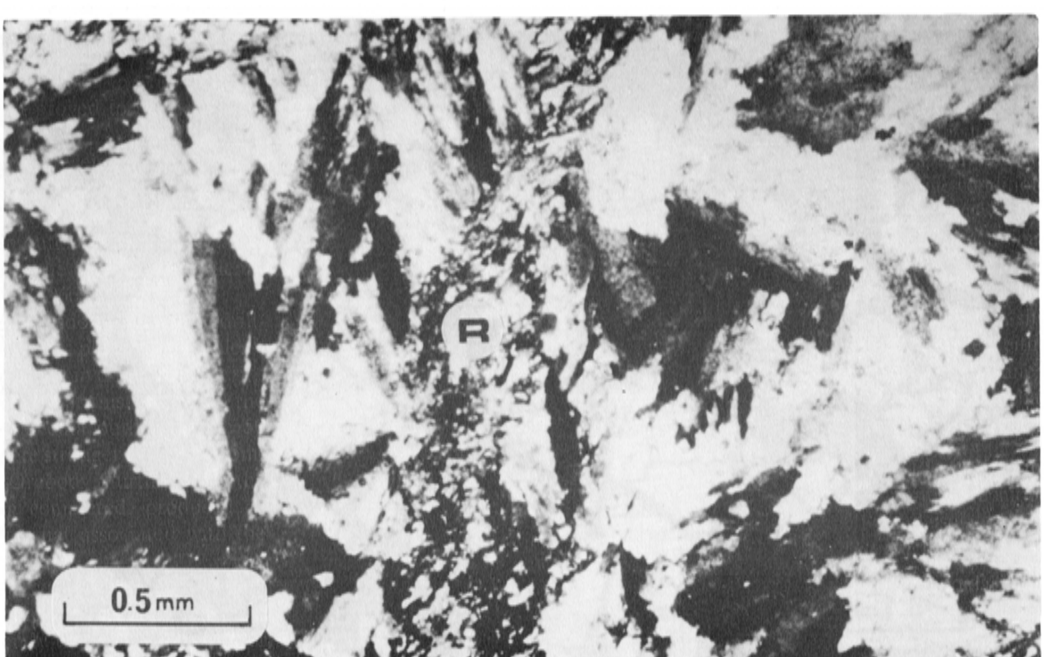

Plate 12. Massive barite, B-Zone — Note the plumose texture cut by later fracture infilled by recrystallised barite [R]. 4936 Room; thin section.

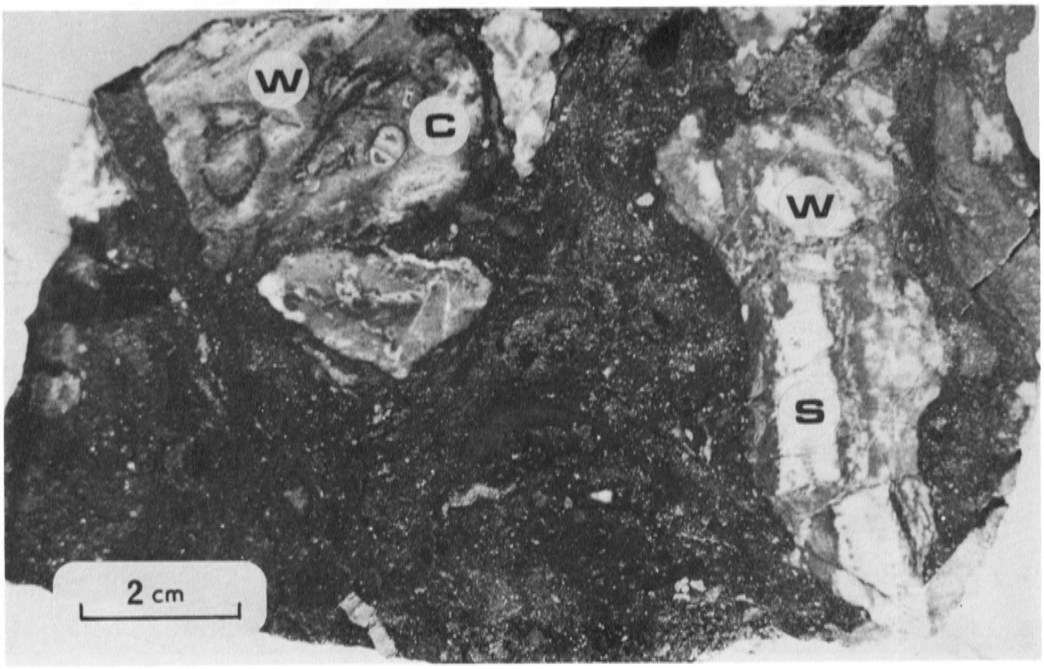

Plate 13. Galena-rich Reef Limestone Breccia, B-Zone — polished slab showing angular clasts of Waulsortian "Reef" Limestone [W] with corals [C] and stromatactis textures [S], set in a fine-grained matrix dominantly comprised of galena with minor pyrite, dolomite and fine rock debris. 4876 Stope.

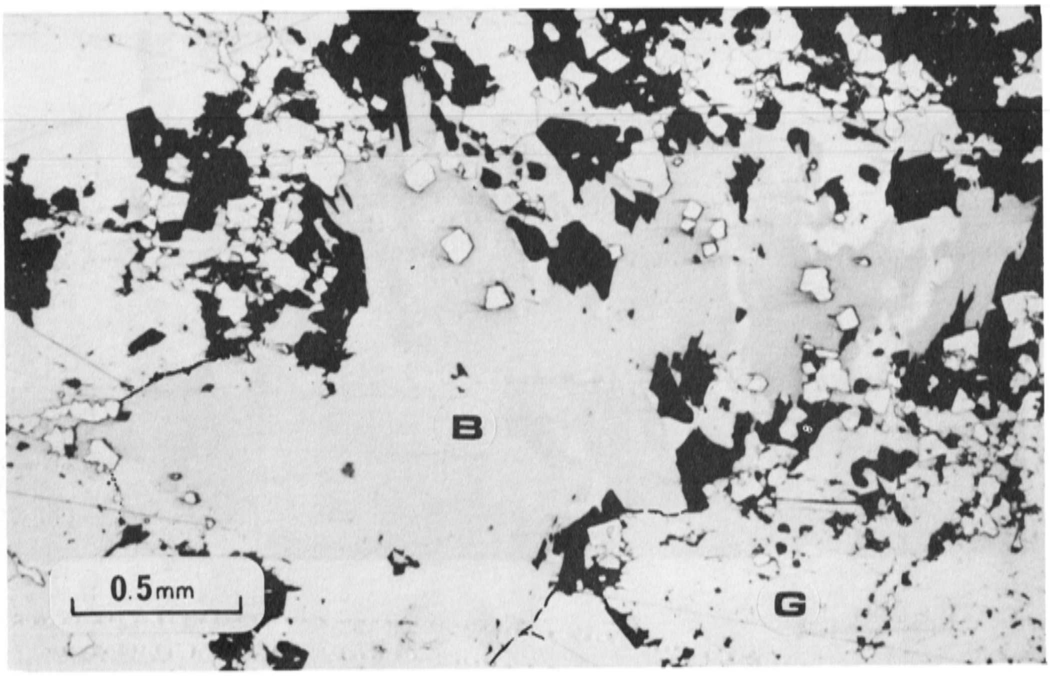

Plate 14. Massive sulphides, B-Zone — boulangerite [B] and galena [G] with minor euhedral pyrite and carbonates (black). From hangingwall galena-rich debris flow similar to Plate 13. 4876 Stope; Polished section.

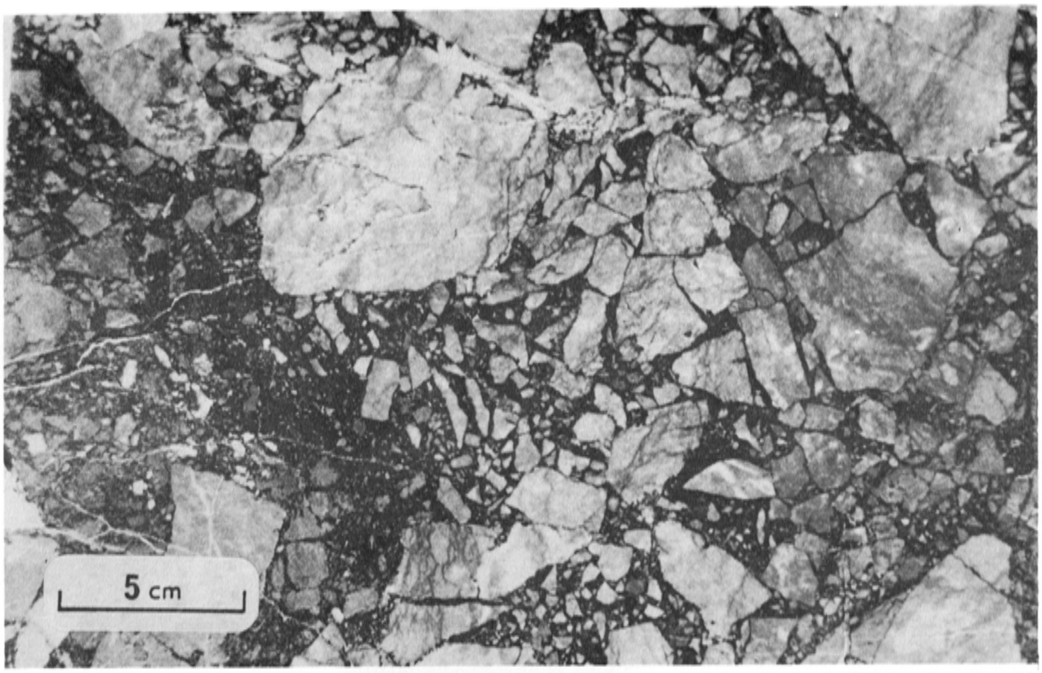

Plate 15. Reef Limestone Breccia, Magcobar Pit — polished slab showing angular clasts of Waulsortian "reef" limestone set in a matrix of argillaceous dolomite. Magcobar Pit, haul road, NE end.

Plate 16. Reef Limestone Breccia, B-Zone — polished drill-core showing polymodal angular clasts or Waulsortian "Reef" Limestone set in a matrix of very fine-grained dark argillaceous solomite. Drillhole 75-84-34, 126.8m.

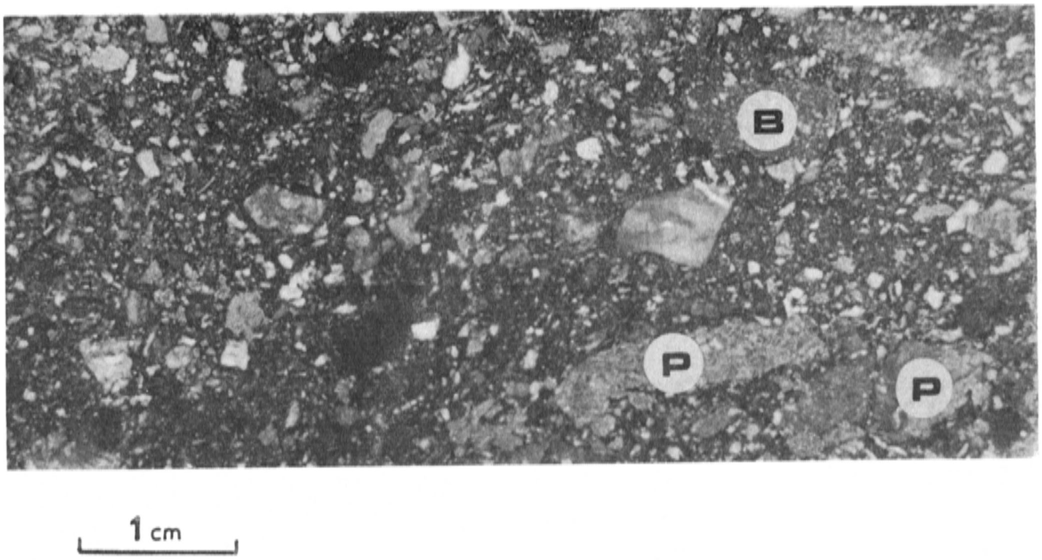

Plate 17. Dolomite Breccia, G-Zone — polished drill-core showing fine-grained polymictic Dolomite Breccia with clasts of Waulsortian "Reef" Limestone, pyrite and clasts of earlier breccias [B] set in a very fine-grained matrix of argillaceous dolomite. Drillhole 75-84-11, 10.1m.

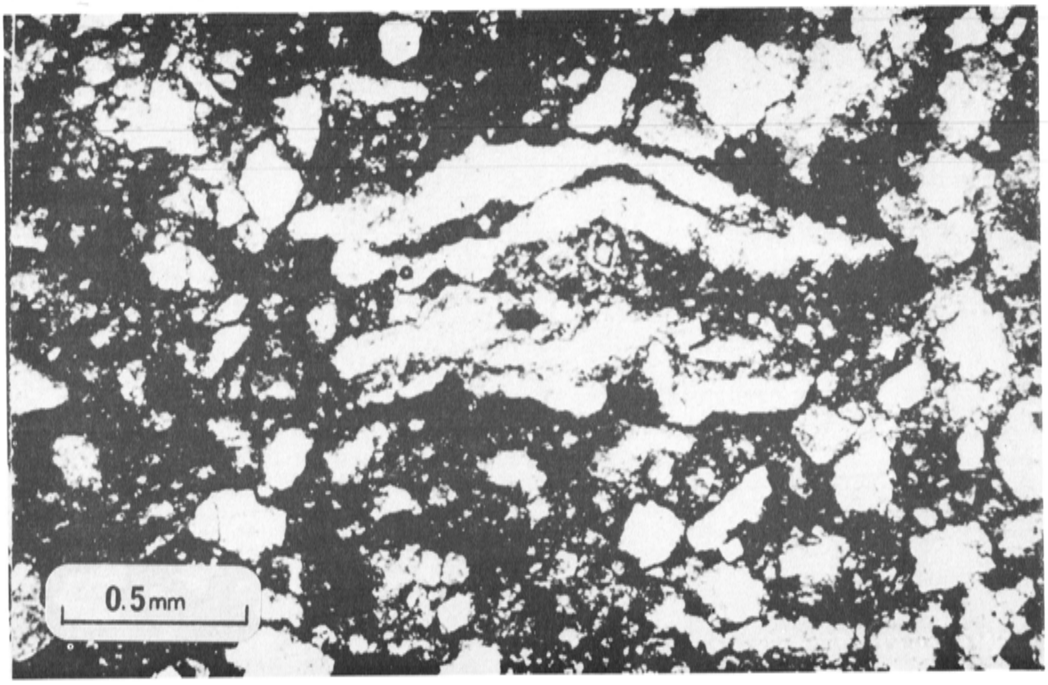

Plate 18. Dolomite Breccia, G-Zone — vermicular fabric of dolomite crystals in organic-rich mud matrix. Little clastic material. Drillhole G 112, 64.2m; Stained thin section.