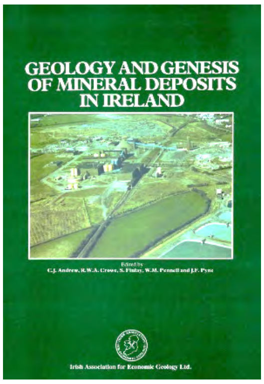

A review of the geological setting of the Tynagh orebody, County Galway.

J.A. Clifford, P. Ryan & H. Kucha.

To cite this article: Clifford, J.A., Ryan, P. & Kucha, H. (1986) A review of the geological setting of the Tynagh orebody, County Galway. *In:* Andrew, C.J., Crowe, R.W.A., Finlay, S., Pennell, W.M., and Pyne, J.F. '*Geology and Genesis of Mineral Deposits in Ireland*', Irish Association for Economic Geology, Dublin. 419-439. DOI:

To link to this article: https://

A review of the geological setting of the Tynagh orebody, Co. Galway.

J. A. Clifford,[1] P. Ryan[1] and H. Kucha[2]

1 Ennex International PLC, 162 Clontarf Road, Dublin 3.

2 Institute of Geology and Mineral Deposits, University of Mining and Metallurgy, 30-059 Krakow, Poland.

Abstract

Regionally the Tynagh Pb-Zn-Cu-Ag deposit was located to the NE of a major Lower Palaeozoic and Old Red Sandstone inlier. The mineralization was concentrated within a generally diachronous Lower Carboniferous carbonate sedimentary sequence in the hanging wall of an E-trending normal fault.

The area lies within the gently folded Variscan foreland. The principal structural features are the roughly dome-shaped Slieve Aughty Inlier, the North and South Tynagh Basins, and their associated faults. Gentle open folds with an ENE trend and E-trending faults dominate. The principal fault is the North Tynagh Fault. This is a complex structure and is essentially composed of an *en echelon* series of normal faults with each branch terminating in a splay zone. Adjacent to the Fault a series of northerly striking folds have been identified. These folds are thought to be related to points of maximum vertical dip slip movement of the fault branches and are considered to have a spatial relation both with areas of reef growth and with dolomite formation. In addition the Tynagh Iron Formation is located within one of the folds.

The local stratigraphy and structure of the area are described. Particular attention is given to the Waulsortian Bank Limestone and its facies distribution. The paragenesis of the sulphide mineralization is outlined. Four stages of sulphide mineralization were distinguished: (i) Early diagenetic sulphides as rim cements and infills (linings) of stromatactis cavities; (ii) Sulphide infills and geopetal sediments in the dilatant fracture/breccia system of the main stage of mineralization.; (iii) Vein infills and replacements, epigenetic Cu-Pb-Ba mineralization; (iv) Post-ore carbonate infills and replacements.

The sulphide mineralization is pre-dated, accompanied and post-dated by Fe-calcite, Fe-dolomite, baroque dolomite cements, geopetal sediments and replacements. Trace mineralization of similar style to that at Tynagh is found hosted within fractured Waulsortian Bank Limestone over 5km of strike in the hanging wall of the North Tynagh Fault. Widespread mineralization has also been noted within Lower Bioclastic (L4) limestones. Increase in grade is noted in the vicinity of faults. With the exception, however, of the Old Tynagh Mine area nowhere does it make ore grade over mineable widths.

The various genetic theories proposed over the years are reviewed and discussed.

Introduction

Mineralization in the Tynagh area is first mentioned in the Annals of the Four Masters (Ó Cleirigh et al.,1632). They refer to the "Old Tynagh Mine", generally accepted as being located to the east of the present mine site, as a source of silver. This mine is again referred to in a memoir of the Geological Survey of Ireland (Kinahan, 1863). In 1955 a group of Irish men who had gained experience of mining and mineral exploration in Canada considered the possibility that large mineral deposits remained undiscovered in Ireland. The initial approach of the group was to examine old mining properties and areas of general interest in Ireland. In 1957 the Tynagh area, among others in Counties Clare, Galway and Kerry, was briefly examined and further work was recommended.

At the instigation of Pat Hughes, the Old Tynagh Mine was included in a reconnaissance shallow soil geochemical survey conducted in September 1960, and anomalous values for lead and zinc were obtained. Additional surveys were carried out a year later about 1.5km to the west of the reported site of the Old Tynagh Mine. Soil samples were analysed in the field and showed very anomalous values for lead and zinc - in excess of 1,000ppm Pb and 8,000ppm Zn. It was later shown that the area sampled coincided with the central portion of what proved to be Zone I of the Tynagh Orebody.

After the initial results had been received, the soil sampling was extended to the east and to the west. Before long a strong geochemical anomaly approximately 750m in length and 125m wide had been outlined. The importance of the anomaly was enhanced by the discovery of galena-bearing float boulders (Donovan, 1966).

Very little geophysical work was undertaken before drilling of the geochemical anomaly took place. Nonetheless, the surveys were extremely important in directing the drilling programme. It should be noted at this point that the Induced Polarization geophysical data outlined some 50 anomalous areas, 14 of which were stronger than the anomaly associated with the Tynagh Orebody. Furthermore, the geochemical soil survey, when completed, produced 45 anomalous areas in addition to that associated with the Tynagh Orebody.

However the size and general coherence of the Tynagh anomaly made it the priority target. This was fortunate because it was found subsequently that none of the other anomalous areas had any mineralization associated with them.

Diamond drilling in the Tynagh area commenced on November 14, 1961. The first hole encountered 12m of

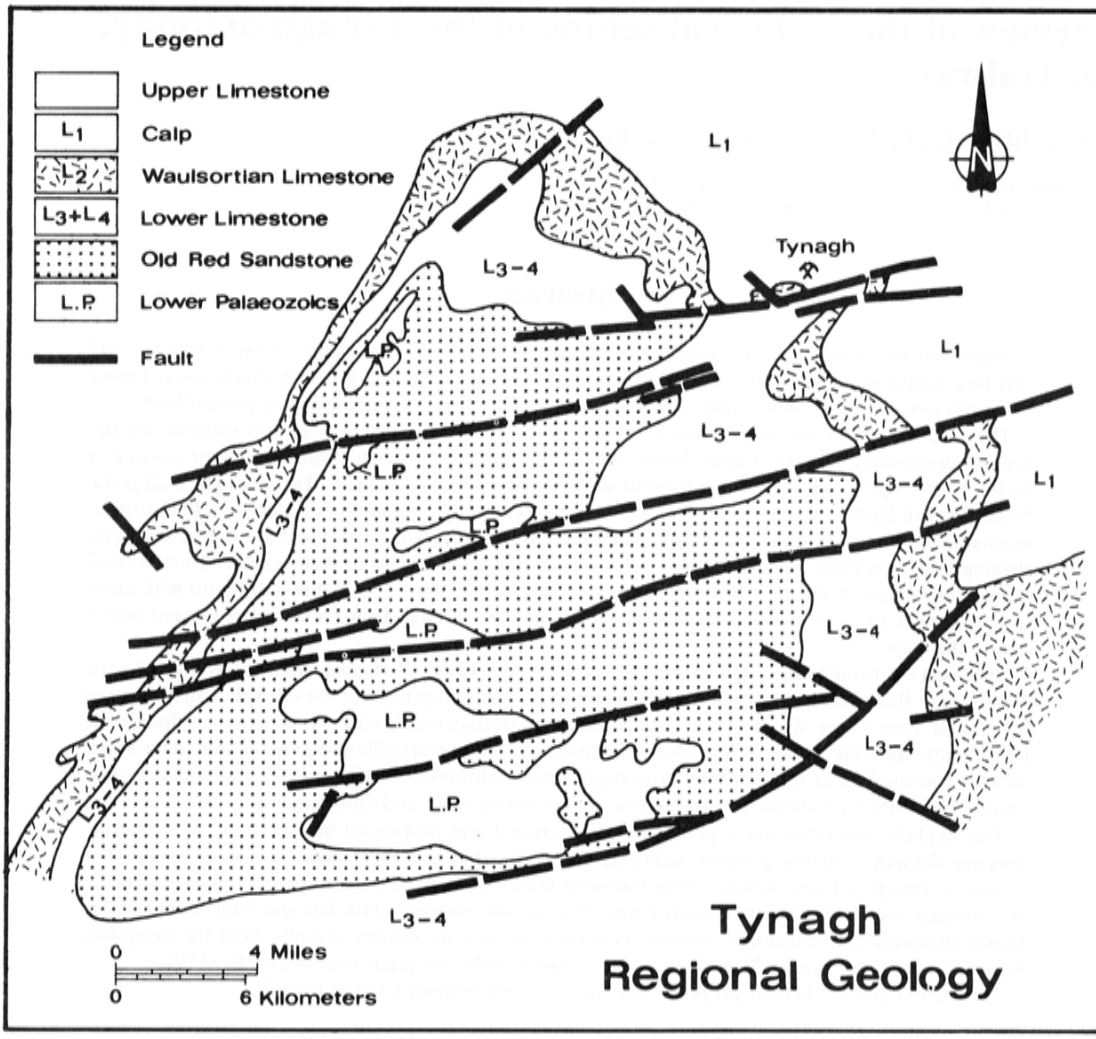

Figure 1. Regional geological map of the Tynagh area of south Co. Galway.

overburden, and then a curious black mud down to 53m. From 53m the hole encountered 3m of solid limestone with scattered cubes of galena. Without very much evidence of mineralization, the first hole had in fact intersected one of the richest deposits of base-metal ever discovered in Ireland.

Luckily, the sludge from this hole had collected in a small depression on the surface. Panning of this sludge indicated the presence of sulphide mineralization. Assaying confirmed this, giving a very significant result of 2.5% Pb and 3.5% Zn. At the same time a pit sunk some 180m to the NW encountered boulders which assayed 52.4% Pb., 7.2% Zn and 450 g/t Ag. This encouraged further examination of the area.

In an attempt to improve sampling of the unconsolidated black mud, a locally available water-well drill was employed. The first two holes drilled by this method confirmed the presence of mineralization and suggested the possibility that a major discovery had been made. The average assays in these two holes are given in Table 1.

Forty seven holes were drilled with this method; all encountered high grade mineralization, and all stopped in ore grade material lying on solid rock. Conventional drilling techniques proceeded, a substantial body of lead-zinc

Table 1.

Tynagh — discovery holes

Hole No.	Interval (m)	Pb%	Zn%	Cu%	Ag g/t
1	30	13.2	1.5	0.26	54
2	36	20.1	1.4	0.37	94

mineralization in the solid rock was also indicated, and the hybrid nature of the Tynagh Orebody began to emerge.

Between November 1961 and March 1963, 160 holes (a total of 21,300m of diamond drilling) had been completed. By the time this drilling programme was finished, it had been shown that the Tynagh Orebody consisted of two parts. The upper portion of the Orebody (later termed the Residual Orebody — Zone I) consisted of unconsolidated material occupying a karstic sinkhole approximately 600m long, 50m wide and morphologically resembling the keel of a boat. It was extremely rich in oxide and sulphide minerals of lead, zinc, copper, iron and silver. Beneath the Residual Orebody lay the Primary Sulphide Orebody of similar dimensions and predominantly composed of galena and sphalerite with some copper sulphides. The Primary

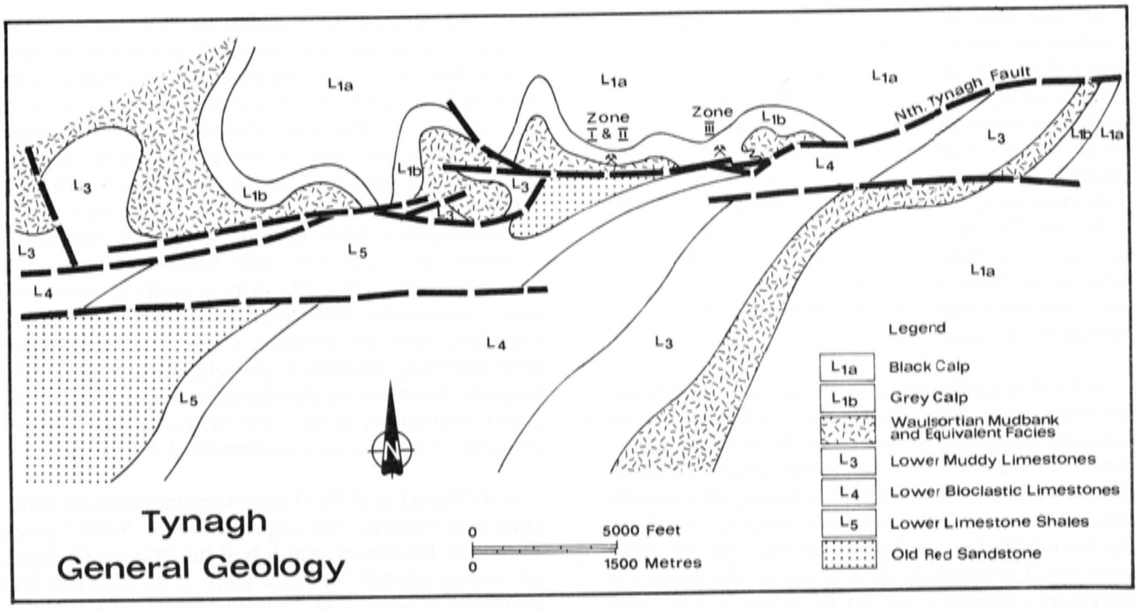

Figure 2. Simplified geological map of Tynagh Mine.

Orebody had a much lower grade than the overlying Residual Orebody.

The following preliminary ore reserves were estimated from surface drilling:

Table 2.

Initial ore reserves, Tynagh (Hutchings, 1979).

	Tonnage (Mt)	Pb%	Zn%	Cu%	Ag g/t
Residual orebody					
Sulphide ore	2.80	8.55	7.36	0.23	83
Oxide ore	1.20	9.92	4.66	1.32	104
Primary orebody					
Sulphide ore	3.76	4.76	4.27	0.60	58

Additional drilling between 1963 and 1965 added to the ore reserve, and when Tynagh Mine went into production on October 22, 1965, there were indications that the final ore reserve would be close to 9.90Mt of economic grade mineralization.

Between February 1967 and March 1968 diamond drilling along the extension of the North Tynagh Fault outlined an additional 1.90Mt of ore grade mineralization. This mineralization had no evident geochemical or geophysical surface expression, and was found only as a result of a decision to drill test the area to the east and west of the mine area (Schultz, 1971). The difficulty in locating and defining this extension to the Tynagh Orebody foreshadowed the problems to come, as, notwithstanding extensive drilling between March 1968 and 1980, no further economic concentrations of mineralization were located and as a result the Tynagh Orebody was worked out by August 1980.

The importance of the Tynagh discovery goes beyond the benefits it gave to the company or to the local area. Essentially it established Ireland as a mining centre of world-wide importance, and provided the impetus and confidence necessary for the development of mining activities in the widest sense.

Geology

Introduction

The Tynagh Orebody was located on the northerly hanging wall of an approximately easterly trending normal fault, the North Tynagh Fault, and was hosted in Waulsortian facies limestones of Courceyan age (Figs. 1 and 2). This Fault, which has a throw of approximately 600m, has juxtaposed Calp (Chadian-Holkerian) limestones and Old Red Sandstone (Sevastopulo, 1979). Tertiary weathering and karstification resulted in the decalcification and collapse of the Calp and part of the Waulsortian adjacent to the Fault, and led to the development of the Residual Orebody.

The North Tynagh Fault forms the northern boundary of an inlier of Old Red Sandstone which is isolated from the main Lower Palaeozoic/ORS inlier of the Slieve Aughty Mountains to the SW. This large inlier contains a faulted core of Silurian sediments and Ordovician volcanics and sediments with an envelope of sandstones, shales and conglomerates (Emo, 1978).

The Carboniferous sediments in the area represent the onset and development of the Carboniferous marine transgression. Initial transitional marine sediments become progressively more calcareous and of marine aspect (the Lower Limestone Shale) passing gradationally into shelf limestones of the Lower Limestone followed by the Waulsortian facies and culminating in the basinal Calp Limestones (Philcox, 1983).

Stratigraphy

The stratigraphic succession of the Tynagh area is summarized in Figure 3 and generally follows the classification of Schultz (1968).

Lower Palaeozoic basement in the Tynagh area consists predominantly of greenish-grey to dark green greywackes and shales with occasional greywacke conglomerates, containing feldspathic minerals in a ground mass of chlorite and clay minerals. Coarser fragments are often of a volcaniclastic origin.

The **Old Red Sandstone** facies rocks encountered in drilling are similar to those which outcrop in the Slieve Aughty Mountains and consist of sandstones (often conglomeratic), siltstones, shales and calichiferous mudstones. Sandstones consist predominantly of subrounded to subangular coarse to medium sized quartz grains and 10-30% feldspars.

The mineralogy suggests a granitic provenance for the sand grains. The textural maturity of the sediments suggests deposition in a shallow water moderate to high energy environment. Some specimens have a weakly calcareous cement and one sample had a marine fauna of bryozoa and brachiopods (Longacre, 1983).

The **Lower Limestone Shale (L5)** is a transitional unit between the siliciclastics of the Old Red Sandstone facies and the marine carbonates of the overlying Lower Limestone. The lowest beds dominantly consist of a mixed succession of sandstones and shales becoming progressively more calcareous upwards. Limestone bands become dominant towards the top, grading into the overlying unit. In its upper part it is essentially an argillaceous silty biomicrite with frequent laminae rich in clay and organic material with microstylolites.

Faunal content is suggestive of an open marine depositional environment, and the presence of micrite suggests a quiet, possibly shallow water setting. About 15m above the base of the unit,a finely laminated non-calcareous silty micaceous shale occurs. This 3-5m thick marker horizon, the Ballyvergin Shale, is persistent throughout western and southwestern Ireland (Philcox, 1983; Hudson et al., 1966) Although the Lower Limestone Shale differs from the overlying Lower Bioclastic Limestone (L4) only in its higher argillaceous content, the contact between the two units is marked by a sudden influx of sand, represented by the Tynagh Sandy Band, a calcareous sandstone often having a high bioclastic content. This member is 2.5-3.5m thick in the Tynagh area, although drilling evidence indicates that it increases in thickness to the north and northwest.

The Lower Bioclastic Limestone (L4) is predominantly a silty nodular bioclastic crinoidal calcarenite with thin interbeds of black calcareous shales and silts. Petrographically the unit consists predominantly of silty fossiliferous biosparudites and biomicrites. The fauna suggests open marine conditions for the most part. Almost all the micrite has been winnowed out leaving a grain-supported fabric indicating a shallow water high energy environment. In other areas the interparticle space may be infilled by carbon-stained argillaceous matter and micrite. The silt content indicates that siliciclastics continued to be available, being transported either through subaqueous or subaerial processes. The fine grain size and excellent sorting suggest a subaerial mechanism. The unit has been sub-divided by Schultz (1968) into the following two subunits:

Bioclastic Limestone: Calcarenite bands with grain-supported brachiopod shells and lesser amounts of crinoids and isolated zaphrentid corals.The bioclastic debris has been reworked and abraded.

Crinoidal Bioclastic Limestone: This subunit differs from the Bioclastic Limestone in that the biota consists almost exclusively of crinoid detritus with a minor shelly component. There is also an increased shale content. The boundary with the overlying Lower Muddy Limestone is marked by a series of shales and siltstones the first of which is termed the "1045 Marker".

The **Lower Muddy Limestone (L3)** unit is characterized by increased mud content. It consists of medium grey argillaceous crinoidal biomicarenites interbedded with black skeletal shales. There is abundant crinoid debris in fossil-rich layers. The fauna also consists of brachiopods and bryozoans with minor corals and calcareous spicules, and occasional intraclasts. Micrite with some argillaceous carbonaceous matter make up the fine-grained matrix material (Schultz, 1968). Coarser bioclasts are often partly or wholly mud-supported. Thin laminae of terrigenous material, ranging from silty shale to sandy siltstone, also occur. Limestones and shales are closely interbedded. Limestone beds are generally 5-8cm thick with thinner shale interbeds. Bedding is generally wavy, nodular with lenticular limestone clots having shales draped about them. Minor silicification occurs. The increased shale content indicates a lower energy environment of deposition.

In the Tynagh area the Waulsortian limestones are developed in an elongate belt subparallel to the North Tynagh Fault. The limestones, which host the Primary Orebody, are limited to a belt 75m wide north of the fault and over an interval of up to 150m. They interdigitate with, and pass laterally into, the Grey Calp.

The **Waulsortian Bank (L2)** complex consists of well-developed massive, pale to medium grey, coalesced, reefoid stromatactid biomicrite mounds which are enveloped and overlain by crinoidal biomicrites and by off-bank slump breccias containing grey micrite clasts set in a dark calcareous shaley matrix. The flank reef biomicrites and biomicrudites thin basinwards to the north and grade into reef-equivalent beds, — nodular coarse crinoidal biomicrites with greenish grey silty wispy partings and interbeds. In Zone III the biomicrite mound bifurcates into stacked lower and upper tongues separated in the inner part of the mound by bioclastic shales and laterally in the outer northern part by reddened laminated limestone and/or reddened crinoidal conglomerates, breccias and cherts (Gallery, 1979). Clasts consist of large massive micritic or laminated limestone set in a chloritic matrix. The upper tongue contains a well-developed cavity system at its base. These cavities are infilled by reddened geopetal mudstones, pelsparites and pelmicrites (Gallery, 1979). It is covered by thick, coarse, reef-derived breccias formed probably by massive off-reef slumping which developed on steep slopes. Often the Upper Waulsortian Mudbank is so thin and covered by reef-derived breccias of such thickness, that a larger original reef mass growing further to the south of the North Tynagh Fault should be considered (Gallery, 1979).

A comparison of the surviving Waulsortian at Tynagh with a postulated complete and tectonically undisturbed mound would suggest that at the mine area only 30-40% of the original mound is preserved. The remaining 60-70% being faulted, uplifted and eroded away. This eroded part of the mound, which presumably was also mineralized, can be considered as a source of the Residual Orebody redeposited into karstified Grey Calp and Upper Waulsortian (Zone I). The Bank Complex can be subdivided into a number of distinct facies (Fig. 4) as follows:

Reef Core (L2c): The reef core consists of stromatactid biomicrite and minor patches of biolithite with fenestrate bryozoans, crinoids, bivalves, molluscs, brachiopods, fine spicular debris, algae and a few corals (Morrissey, 1965; Gallery, 1979). Sometimes the reef core contains a

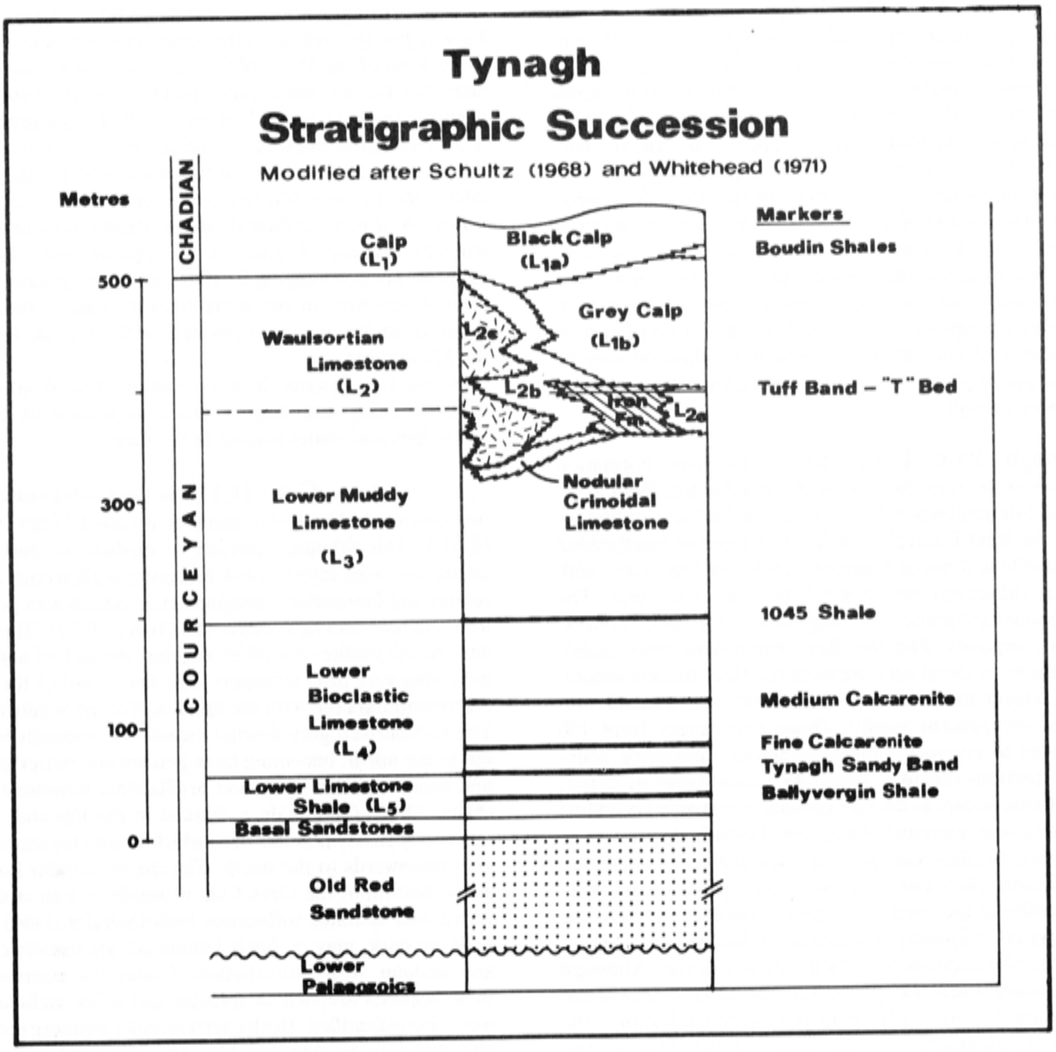

Figure 3. Stratigraphic succession at Tynagh.

remarkable quantity of intraclasts. The primary void spaces consist of:

—Stromatactis varying in size between 1 and 100cm in lateral extent (Boast et al., 1981) and constituting as much as 50-60% of the mudbank. Stromatactis infilled with RFMC (Radial Fibrous Mosaic Calcite) cement, geopetal micritic sediment, bladed Fe-free calcite, Fe-calcite and minor dolomite, and with pyrite or sphalerite spar linings (Plate 1).

—Shelter spaces beneath, and inside, fossils cemented by RFMC, bladed calcite and Fe-calcite.

—Interparticle porosity infilled as above (Plate 2).

The secondary porosity includes:

—Dilatant fractures and breccias (Boast et al., 1981); this is the main type of secondary porosity. Infills include, at the first stage, RFMC, followed by Fe-calcite and then by massive banded sphalerite, minor barite, galena, pyrite, dolomite cements and geopetal sediments.

—Moldic Porosity: This type of secondary porosity is less common and is best developed in biolithite interfingerings. Infill includes Fe-calcite, barite and sphalerite (Plate 2).

Reef Breccia (L2b): On the slopes of the individual knolls forming the mounds, Schultz (1966) distinguished small scale slump structures. They consist of biomicrite and micrite boulders with laminated micrite as an infill sediment between the clasts and in crevices of dilation/fracture spaces. There is a variable content of shale, from a few wisps to thick intervals of haematite-stained shale. The biota in the clasts reflect their reef origin.

Intraclasts are irregular with fragile margins indicating that there was very little abrasion during transport. The amount of calcite cement is small and includes bladed submarine cements. Many of the bioclasts, as well as some of the limestones, are replaced by sphalerite. Pyrite specks may be abundant in places. Occasionally the L2b is haematite-stained, either syndepositionally or through later replacement. Sometimes replacement by haematite and magnetite is complete, and only pseudomorphs of the original particles can be seen.

Reef Equivalent (L2e): This lithology consists of nodular calcilutite and shale, enveloped in micritic and argillaceous non-carbonate material which is draped across the nodules. Shales become less skeletal and more abundant towards the top of the unit (Morrissey, 1970). First cements include bladed Fe-free calcite rim cements succeeded by Fe-calcite cements and replacements. Locally Fe-calcite is followed and replaced by sphalerite. Sphalerite also replaces bioclasts which are often seen as pseudomorphs in otherwise massive sphalerite. Replacement of bioclasts by sphalerite is always preceded by replacement of Fe-calcite and is followed by irregular zones of non-staining amorphous calcite which in turn are replaced by sphalerite. Although this sulphide mineralization may be pervasive in places, it does not form economic concentrations at Tynagh.

Tynagh Iron Formation: The Iron Formation occurs in the same horizon as the Waulsortian Bank (Fig. 5). It interdigitates with the main knoll(s) and continues into the Reef Equivalent facies. It consists of interbedded haematite and minor magnetite, chert and limestone, with minor tuffaceous beds towards the top of the unit. The limestones are graded and suggestive of turbidite deposits. These deposits, like the Reef Equivalent beds (L2e), appear to be distal equivalents of the Reef Breccia lithofacies. Haematite is the most abundant iron mineral with magnetite present locally. Grain size ranges from 150 microns to cryptocrystalline, commonly displaying colloform textures (Schultz, 1966). As a constituent of jasper, haematite occurs as discrete crystals or coarsely crystalline clusters or in extremely fine-grained cloudy dispersions in chalcedonic silica. Quartz occurs in whitish grey and greenish chloritic chert and in light to deep red jasper. Approximately 60% of the overall thickness of the Iron Formation is comprised of limestones which are coloured shades of red or green by dispersions of haematite or chlorite. Although such tinted limestones persist into the outcrop area of the Residual Deposit overlying the primary mineralization, the main development is to the north of the deposit. The limestone beds tend to wedge out in a northerly direction while ironstone beds tend to become more numerous and thicken to attain individual thicknesses of several metres. At its northern end the Iron Formation interdigitates and passes into Reef Equivalent limestones. Towards the top of the Iron Formation a distinctive marker horizon of considerable lateral extent occurs. It consists of reworked fine-grained pyroclastic debris and is designated the "T" Bed (Schultz, 1968). This horizon extends laterally into the carbonates, is generally less than 1m in thickness, is often graded, and comprises several units. Tuffaceous layers constitute less than 10% of the thickness of the Iron Formation, and Schultz (1966) regarded these pyroclastics as windborne from a distant source of early Chadian volcanic activity having no genetic connection with the host ironstones. Schultz (1966) suggested that the iron and silica were derived by chemical weathering of Lower Carboniferous sediments, while Derry et al. (1965) considered that iron and silica were derived from spent mineralizing solutions of hydrothermal origin emanating from fissures associated with an active fault during Waulsortian development.

Centred on the Waulsortian sedimentary package, an extensive aureole of Mn enrichment has been established. The extent of this anomaly, which has a radius of 7km, precludes epigenetic dispersion (Russell, 1975). Russell suggests that the Fe- and Mn-rich brines were discharged from hot springs associated with the North Tynagh Fault. Fe was precipitated as ferric oxide closer to the source, while some of the Mn, which reaches its limits of solubility later than Fe, was precipitated further from the Fault. The concept was later refined (Russell, 1983) suggesting that, in an area where subsidence and sedimentation are occurring at the same rate, and in the absence of any damming effect, the Fe- and Mn-rich solutions would move basinwards. A double diffusion plume theory was proposed whereby the Iron Formation was precipitated from the oxidized bottom-hugging Fe-rich part of the plume, while most of the Mn, in the more buoyant plume, remained reduced, to become incorporated in the $CaCO_3$ forming the Mn aureole.

Above the Tynagh Iron Formation, the Waulsortian off-bank facies inter-fingers with a succession of basinal limestones and shales known as the Calp.

At Tynagh the Calp (L1) has been subdivided into two members. The lower member is called Grey Calp (L1b). This lithology consists of medium to dark grey calcilutites with interbedded bioclastic argillaceous calcarenites and biomicrite - conglomeratic calcirudites grading into fossiliferous black shales (Morrissey, 1970). The reef-derived calcirudites are often angular, the lack of abrasion indicating very little transport. The lower part of the Calp is contemporaneous with the upper half of the Waulsortian. The reef-derived grey detrital limestones gradually wedge out to the north, becoming finer-grained and better graded and being replaced by darker argillaceous limestones and shales. Distal Grey Calp is flanked at the top and at the bottom by cherty nodular beds which extend for more than 4km basinwards to the north. The cherty nodular horizon at the bottom of the Grey Calp is usually rich in crinoidal debris and contains tuffaceous beds (Schultz, 1966). The beds are dark, may be finely laminated, are usually cherty and nodular with bioturbation. Under the microscope, some sections are rich in spicules and a few radiolarians were also indentified. Both cherty nodular beds are remarkably richer in Sr, Mg and Mn. The increased content of these metals is often twice as high as in the directly flanking sediments. All these features from the two cherty horizons flanking the distal Grey Calp are characteristic of suspension sediments adjacent to reef mounds (Bosselini and Rossi, 1974; Schlager and James, 1978; Enos and Moore, 1983). Mn contents in the cherty nodular horizons at the bottom of the Grey Calp exceed 8,000ppm in the areas overlying the Iron Formation (Russell, 1975; Gibson, 1979). In the cherty horizon at the top of the Grey Calp the Mn content exceeds 13,000ppm (Russell, 1972). Mn is centered on the mineralized Waulsortian mound (ibidem) and is much higher than in typical suspension deposits of ancient — (up to 3560ppm Mn) and modern oozes — (up to 2,000ppm) (Shanmugam and Benedict, 1983). Only when suspension deposits overlap with tuff deposits does the Mn concentration increase up to 8,794ppm (Shanmugam and Benedict, 1983). This suggests that, despite the sedimentary factors which increase Mn concentration in the two Mn anomalies at Tynagh, hydrothermal activity was the main factor controlling abundance of Mn (Russell, 1972 and 1975). Closer to the mound, both cherty horizons, but especially the upper one, include reef-derived bioclasts and algal structures. Reef clasts are more difficult to recognise in drill core but a few are observed. Despite a strong cherty and nodular fabric a partial Bouma sequence flanked by dark cherty beds is suggested proximal to the mound. These features are considered as diagnostic for turbidity current

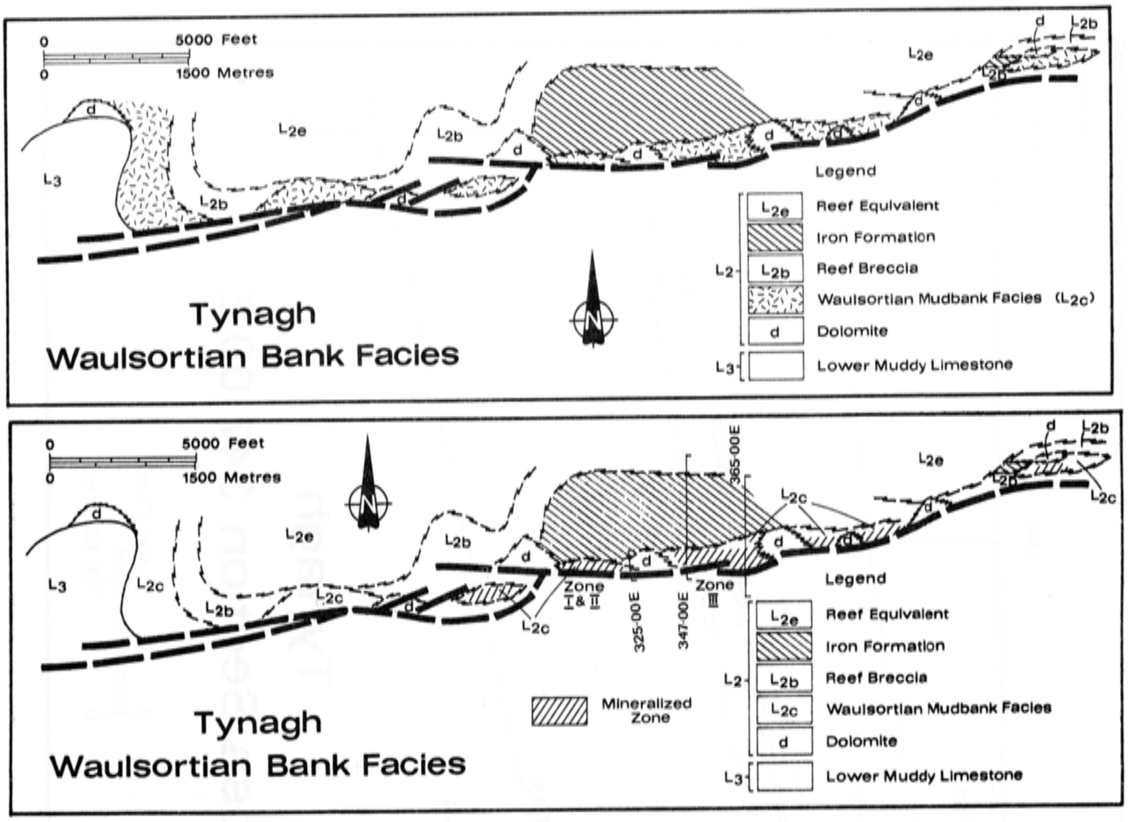

Figure 4. (a) Distribution of the Waulsortian facies and extent of dolomitization.
(b) Relation of the Waulsortian facies distribution to mineralization.

deposits (Enos and Moore, 1983). The nodular subunit at the base, included with the Lower Muddy Limestones in the vicinity of the mound, contains sulphides, mainly sphalerite, as conformable bands 10-20cm in thickness and disseminations and replacements of the Fe-calcite spar (Boast, 1979; Riedel, 1980). Bladed calcites are the first cement, followed by extensive Fe-calcite cements and replacements which are partly associated with Fe-dolomite. Sulphides, mainly sphalerite and minor pyrite, extensively replace Fe-calcite spar (Boast, 1979). The Lower Muddy Limestone directly underlying the Waulsortian is very rich in Fe (2.2-6.5 wt.%) (Russell, 1972). This is reflected in the presence of high Fe-calcite, siderite and abundant pyrite.

The Black Calp (L1a) member consists of black carbonaceous and argillaceous fine-grained limestones and black shales of basinal facies. The black shales are often pyritiferous. Morrissey (1970) recorded lenses and stratiform bands of pyrite and marcasite up to 8cm thick approaching the Waulsortian/Calp contact in the open pit.

Schultz (1966) noted the presence of fossiliferous interbeds approaching the diachronous contact with the Waulsortian where occasional calcarenite and subordinate calcirudite horizons are also encountered. A decrease in reef-derived material with a corresponding increase in shales and argillaceous limestones is noted northwards away from the reef development.

Schultz (1966) concluded that restricted reef growth was still in progress during early Black Calp deposition, with less frequent off-bank sliding. The high proportion of carbonaceous material and pyrite suggests strongly anaerobic conditions.

Structure

The Tynagh Orebody was located on the hanging wall of an easterly trending normal fault, the North Tynagh Fault, which has a northerly dip of 60-65° in the mine area (Fig. 5). Regionally the area of Carboniferous suboutcrop is divided into the North and South Tynagh Basins by the small sandstone inlier which is located in the footwall of the North Tynagh Fault (Figs. 1, 2 and 6).

At the end of the Silurian, tight folds on a NE to E trend with associated reverse and strike slip faults were developed. Weir (1962) noted E- to ENE-trending systems of normal faulting which displace all Caledonian structures, but generally have not affected the ORS.

The Hercynian deformation gave rise to more gentle folding along axes which strike mainly ENE and plunge at shallow angles to the east and west. Towards the north of the Slieve Aughty inlier, the fold axes swing to a more northeasterly trend. Associated faults are generally normal and strike ENE, possibly representing reactivated Caledonian structures. The throw of these faults is often in excess of 300m.

Faulting

The North Tynagh Fault, which dips at 60-65°N, attains a maximum dip-slip displacement of 600m in the neighbourhood of the deposit. It splays to the east and west of the mine area and the dip decreases to 45°. In detail, the Tynagh Fault, which can be traced along strike for at least 10km, consists of a series of *en echelon* structures. Each structure terminates in a splay, with the next along strike developing from the margins of the splay zone. The posi-

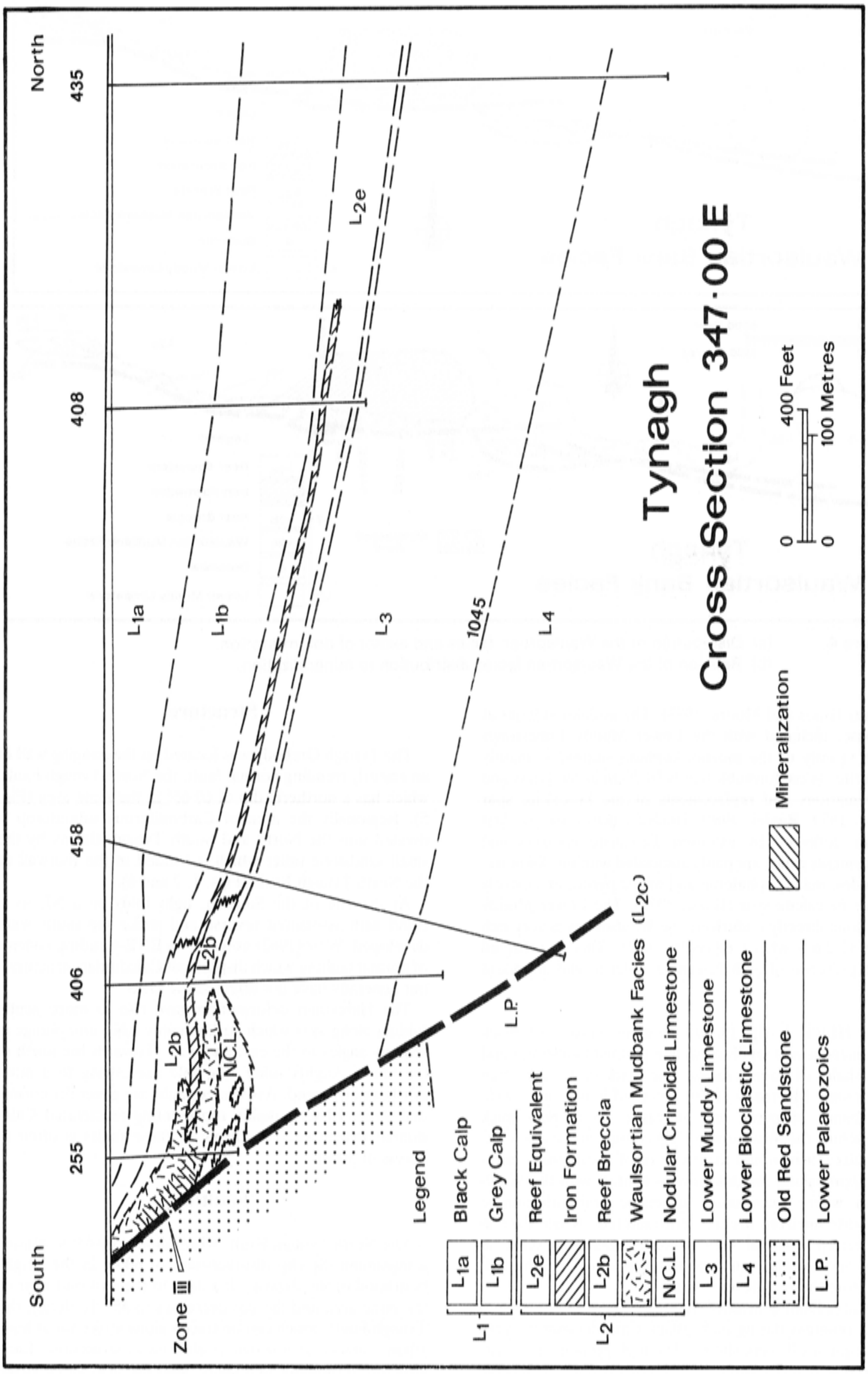

Figure 5. N-S cross-section 347.00 E; Zone III mineralization and Iron Formation.

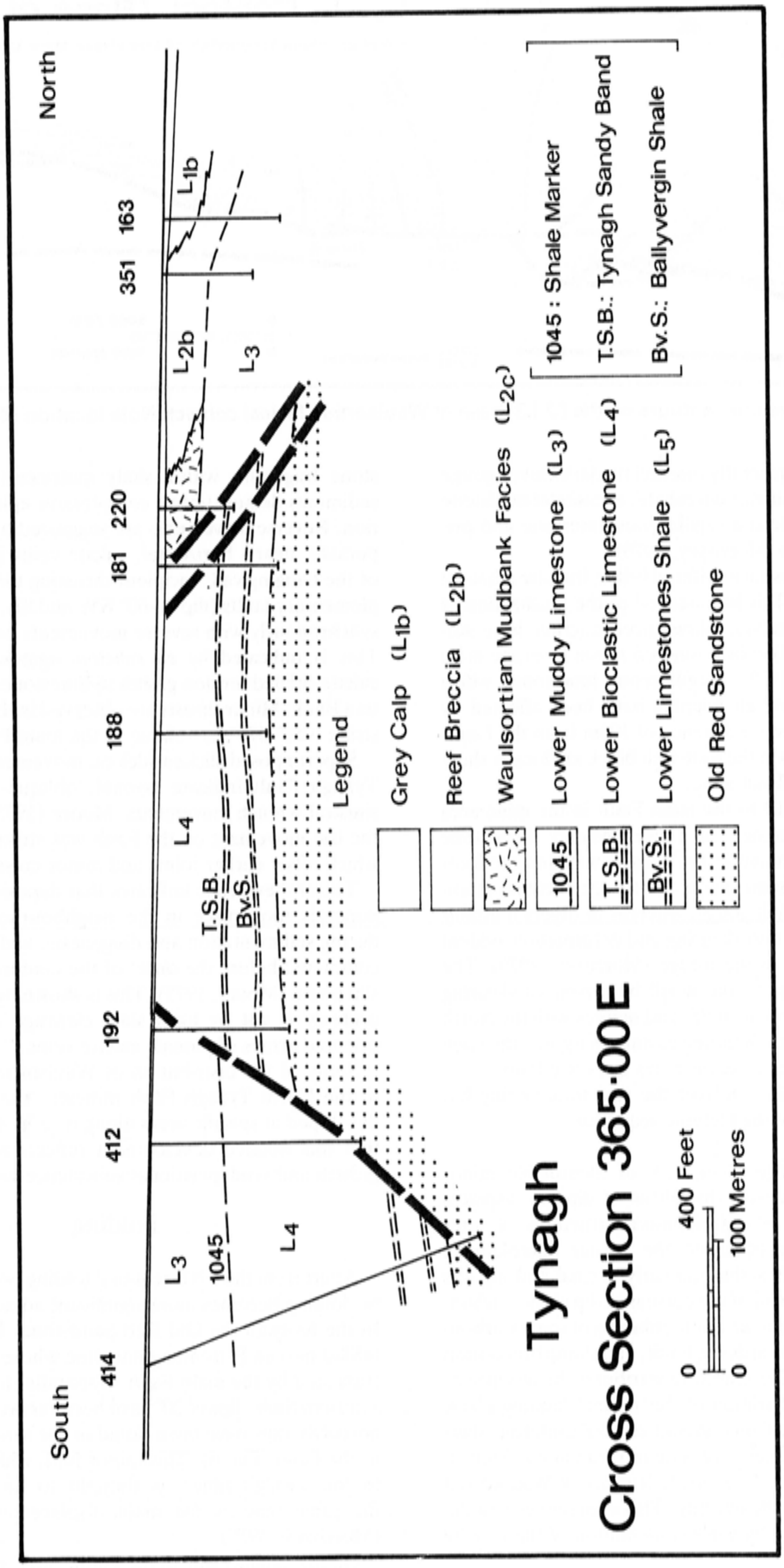

Figure 6. N-S cross-section 365.00 E; Tynagh inlier.

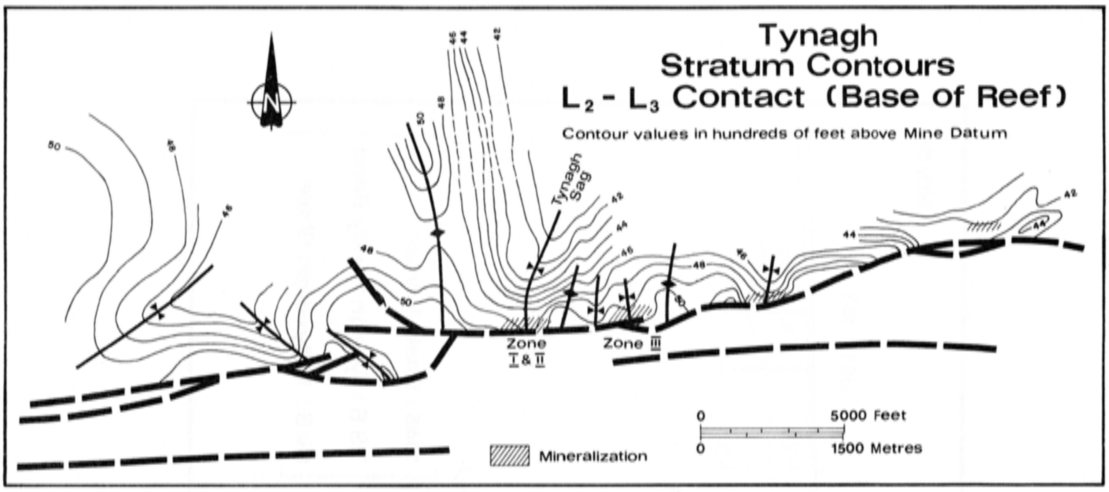

Figure 7. Stratum contours on the L2-L3 (base of Waulsortian facies) contact. Note location of mineralization.

tion of the Fault is generally marked by dark clayey gouge up to 3m thick containing vein calcite, occasional sandstone fragments, bioclastic and argillaceous limestone and primary mineralization (Morrissey, 1970).

Micritic limestones have suffered brittle fracture adjacent to the main Fault. This has assisted in the localization of epigenetic mineralization. Mineralized micrites have suffered later deformation in a zone up to 6m from the main Fault (Morrissey, 1970). Argillaceous limestones which underlie the Waulsortian micrites have been affected by shearing and drag over a distance of 100m from the Fault. Devonian sediments in the foot-wall block are locally sheared adjacent to the Fault zone.

Faulting subparallel to the main Fault in the mine area has interposed a wedge of Lower Muddy Limestone between the Waulsortian in the hangingwall and the footwall sandstones. In some places this wedge becomes attenuated to a narrow fault gouge, whereas in others it attains widths of up to 45m with shearing and deformation evident only at the margins of the wedge (Morrissey, 1970). The fault slice is bounded to the north by a zone of shearing which dips northwards at 70-85° and merges with the North Tynagh Fault at depth. Near the eastern margin of the open pit the northern shear zone becomes a reverse fault.

Moore (1975) in his study of the structural setting has established the following tectonic sequence:—

Normal Faulting: The lack of identifiable minor structures associated with this phase of dip-slip displacement is attributed to superimposed structures of later displacement having obscured the earlier microfabrics. Moore (1975) considers that the early normal faulting was synsedimentary because of the decreased dip of the Carboniferous beds away from the Fault, thinning of some Carboniferous formations towards the Fault, and slump brecciation in the Waulsortian. He therefore attributes the absence of a micro-fabric manifestation of this normal faulting phase to movement between unconsolidated Carboniferous sediments and the Devonian sandstone footwall block. Morrissey (1970) however records brittle fracture in Waulsortian beds associated with the faulting. This apparent contradiction can be explained by early cementation of the reef by RFMC cement.

Compressional Structures (Reverse and oblique slip movements): The presence of a slaty cleavage in limestone fragments within shaly matrices in Carboniferous sediments demonstrate a compressive episode of deformation. Reverse movements are suggested by the presence of pinnate, near - horizontal, calcite veins in the limestones of the hangingwall. Incipient thrusting took place on complementary faults (dip 40-60° NW and SE, strike 050°-070°) synchronously with reverse movements on the main Fault. This is indicated by *en echelon* sigmoidal or lenticular calcite-infilled tension gashes in limestones of the Waulsortian Bank. Minor thrusts are observed in the open pit whose strike (050°-070°) is oblique to the main Fault.

Superimposed slickensides on movement surfaces of the Tynagh Fault indicate normal, oblique-slip reverse and sinistral wrench movements. Moore (1975) concludes that the last movement on the Fault was strike-slip wrenching, which offset earlier joints and minor cross-faults.

Textural evidence indicates that deposition of economic minerals took place in the neighbourhood of the Fault during sedimentation and diagenesis, and that it had been completed before the onset of the compressional oblique-slip phase (Moore, 1975). This is shown by the fact that the orebody is cut by local slaty cleavage and horizontally oriented arrays of pinnate calcite veins.

Study of the distribution of Waulsortian facies relative to the North Tynagh Fault indicates the reef core facies developed at specific areas along it (Fig. 4). It is suggested that this isolated development reflects zones where reef growth and syndepositional subsidence were balanced.

Folding

Apart from the ENE regional folding previously referred to, folding becomes more significant adjacent to the mine. In the footwall the Old Red Sandstones have been gently folded into an E-trending anticline whose northern limb is truncated by the main Fault subparallel to its axis. On the southern limb, dips of 20° have been recorded while shallow northerly dips have been noted in the sandstones adjacent to the Fault (Fig. 6). This minor fold, which has given rise to the Tynagh Inlier, is thought to have developed at the same time as the main displacement on the Fault (Morrissey, 1970).

On the hanging wall of the Fault, the Carboniferous beds have been folded into upright flexural folds (axial trend to the north) which plunge gently northwards. Moore (1975) has ascribed these folds to the compressional phase of the tectonic sequence stating that they are coeval with his oblique-slip reverse movements. Schultz (1966) on the other hand suggests that these folds developed in the hanging wall at its point of maximum displacement and are a response in the hanging wall to the greater movement of the Fault at that point relative to its extremities.

Structure contour plots, using all of the available drill hole and underground data, define a number of these folds or sags (Fig. 7). The most prominent of these, termed the Tynagh Sag by Schultz, impinges on the North Tynagh Fault in the area of Zones I and II. A similar setting is recognized in Zone III and in other areas along the Fault where mineralization has been detected. These were also the loci of reef core facies development. In addition it can be demonstrated in the case of the Tynagh Sag, and inferred in the others, that each of these settings is coincident with the point of maximum throw on individual fault segments. All of which suggests, at the very least, a geometric relation, and possibly a genetic link, with the mineralizing process.

Mineralization

Residual Orebody (Zone I)

In the hanging wall of the main Fault a deep post-karstification trench was infilled with 5Mt of rubble and mud — the Residual Orebody. The sub-till dimensions were 700m from east to west, and a maximum of 150m from north to south. The base of the deposit sloped irregularly from both east and west towards the centre where the unconsolidated material of the residual deposit was up to 75m thick. The deposit was elongated parallel to the strike of the North Tynagh Fault which formed its southern boundary (Fig. 8), otherwise it was bounded by Waulsortian facies limestones often containing strong sulphide - barite mineralization of the Primary Orebody (Zone II).

Morrissey and Whitehead (1971) described the Residual Orebody in detail. It contained oxidized and unoxidized portions. The former constituted about 30% of the Orebody and consisted of carbonates, sulphates, oxides and silicates of base metals. The unoxidized portion had the same mineral composition as the Primary Orebody.

The main constituents of the Residual Orebody were fragments of primary ore ranging from microscopic size to over 2m across, dark grey and black decalcified muds which resulted from the decomposition of Calp, as well as brown, yellow and orange oxidized products of the decomposition of limestones and primary ore (Morrissey and Whitehead, 1971). Development of the trough at the western end of the deposit commenced in the Tertiary. The exposure of pyritiferous primary ore in the Waulsortian or diagenetic pyrite in the Black Calp initiated oxidation and decalcification through the production of acidified groundwater and an elongate cavity formed in the limestones below the water table. This trough became progressively deepened and the side walls became steeper resulting in fragments and boulders of well-jointed primary ore collapsing into the black mud carbonate residuum. Continued weathering of the limestone host and the development of depressions resulted in gravity sliding and a chaotic distribution of limestone residue and primary and supergene sulpides. Sedimentary structures in the finer-grained transported materials suggest that they settled in bodies of still water and locally suffered post-depositional subsidence (Morrissey and Whitehead, 1971).

Continued exposure to percolating solutions caused progressive decomposition of residual sulphides with the migration of metals in solution towards the periphery of the deposit. The main directions of movement were downwards and northwards. Metals precipitated within the residuum resulted in the formation of supergene sulphides of zinc, lead, copper, cadmium and silver. Subsequent decomposition of secondary sulphides resulted in the development of cerussite, smithsonite, azurite and malachite within the residuum. These minerals were also precipitated at the margins of the deposit where migrating metals in solution caused large scale replacement of the limestone wallrocks by smithsonite at the zinc-rich western end of the deposit, and by cerrusite and malachite at the Pb- and Cu-rich eastern end. Where the limestone wall rock was impure, some hemimorphite and dundasite were also precipitated.

In areas where primary ore protruded above the water table or in areas of strong groundwater flow, a gossan developed as lead, zinc and copper were leached out leaving silver-enriched limonite/goethite (Morrissey and Whitehead, 1971).

Subsequent movements within the deposit led to mixing of oxide and sulphide ore types and waste material.

Primary Orebodies (Zones II and III)

The primary mineralization occurred in two elongate zones in the hanging wall of the North Tynagh Fault separated by a plug of dolomitized reef. The ore zones were designated the Main Orebody (Zone II) and the East Extension Orebody (Zone III). Zone II had an 850m strike length along the Fault zone. The horizontal width north of the Fault was variable, with a maximum of 120m; vertically the Zone attained a maximum of 200m. The East Extension, Zone III, extended eastwards for 600m and lay within 60m north of the main Fault.

In the western and north central parts of the Main Orebody, the ore zone was a subhorizontal wedge which thickened southwards to about 60m. In the north central part of the area the ore zone changed attitude as it neared the Fault zone, and it extended up dip of the fault as a lenticular steeply dipping body of massive mineralization in places over 60m wide (Fig. 9). This steepening of the Orebody was accompanied by an upwards displacement of the base of reef contact.

Mineralization was mainly concentrated in Waulsortian micrites, with an estimated 10% in other reef lithologies and in Lower Muddy Limestones and Calp. It occurred in a series of ramifying lenticular bodies whose shape and extent were largely determined by the distribution of the micrite bank facies. This association has given rise to a pseudo-stratiform geometry to the ore zones (Whitehead, 1971). The principal ore minerals present were galena, sphalerite, chalcopyrite, pyrite, tennantite — tetrahedrite, bornite and arsenopyrite. The main gangue minerals were barite and calcite. Minor fluorite has also been observed. Silver occurred associated with galena, and with copper sulphides and sulphosalts. Some mercury was also associated with the copper sulphosalts. Sphalerite contained minor associated cadmium in a Cd : Zn ratio of approximately 1:200 (Whitehead, 1971).

Mineralization in the Black Calp occurred in:—

(1) Narrow cross-cutting veinlets containing colloform pyrite and sphalerite lining, and infilled with calcite and/or barite.
(2) Disseminated sphalerite, barite and galena found mainly in fossiliferous limestone beds.

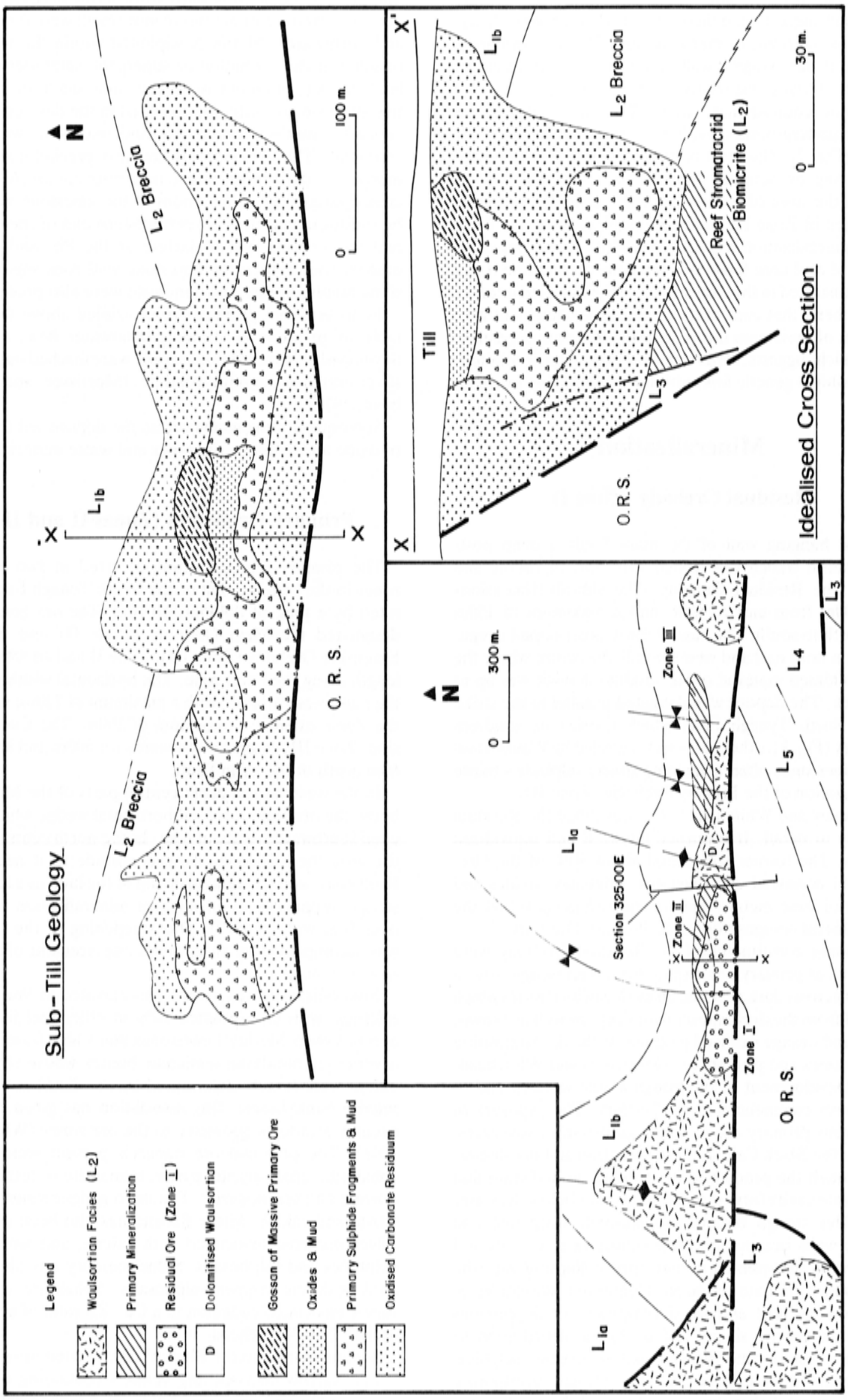

Figure 8. Zone I — the Residual Orebody; location and internal relations (after Morrissey and Whitehead, 1971).

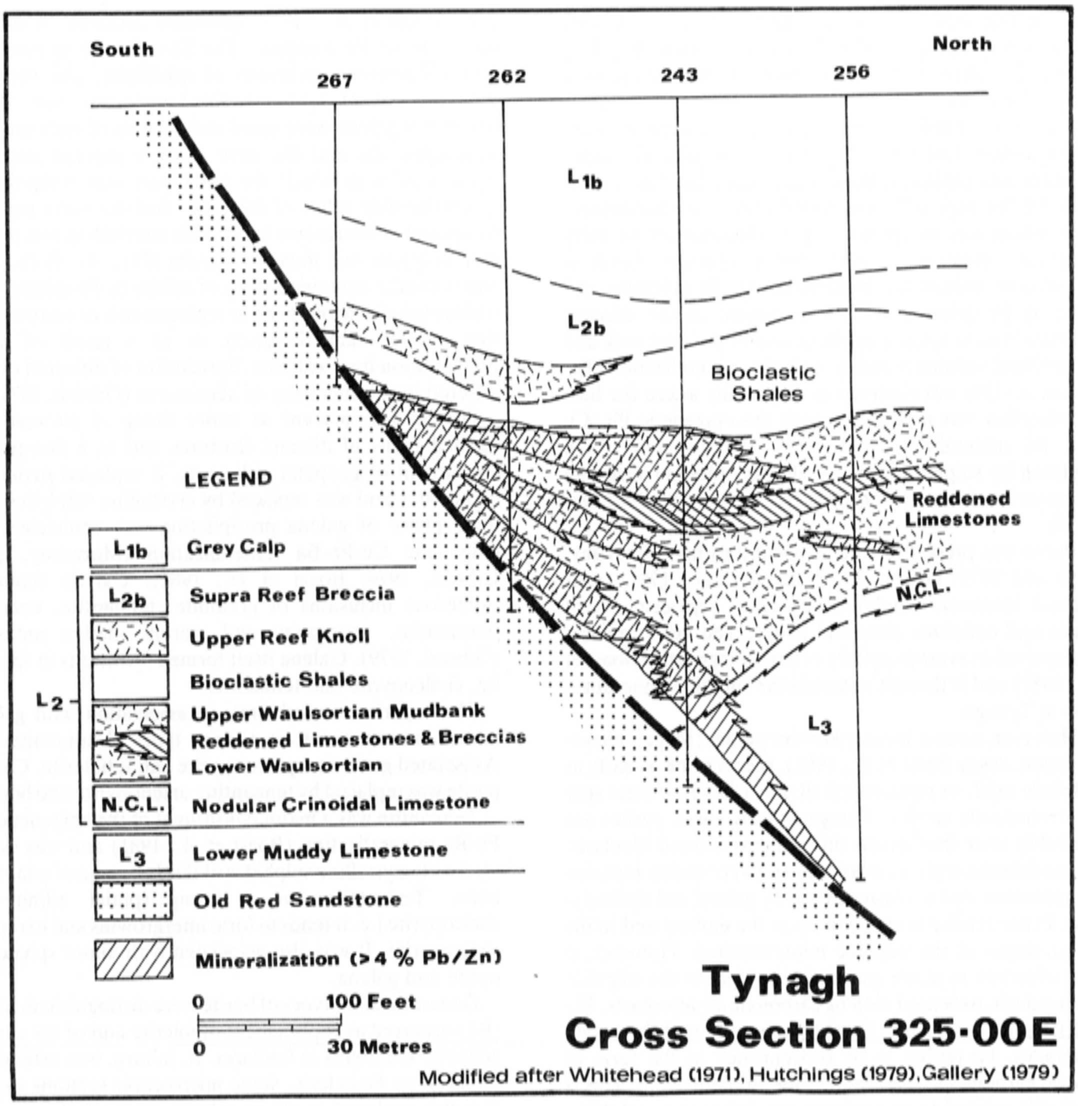

Figure 9. N-S cross-section 325.00 E; Relation of mineralization to Waulsortian facies, Zone II.

(3) Massive replacement aggregates of barite, galena and lesser sphalerite, some containing central cores of corroded cavity-infilling colloform pyrite or sphalerite. This indicates that replacement spread out from fissures or solution cavities.

In the order of deposition of ore minerals, and in silver/lead ratios, the Black Calp mineralization was similar to other lithologies at equivalent relative positions to the fault zone (Schultz, 1966).

Metal distribution

There was pronounced metal zoning of the orebodies (Morrissey, 1970). Copper and barite were concentrated in the eastern half of Zone II and tended to be concentrated in close proximity to the main Fault and to the lower facies contact of the Waulsortian. In the western part of Zone II, grades in excess of 0.50% Cu occurred at a few places more than 15m north of the Fault, usually in the upper part of the Lower Muddy Limestone. However the main Cu concentrations were in the immediate hanging wall of the main Fault. Copper concentration was similarly positioned in Zone III. Chalcopyrite tended to be the dominant copper mineral with grey coppers common in the higher grade areas. A vertical zonation of copper minerals was also apparent with bornite/chalcopyrite occurring beneath chalcopyrite/tennantite (Whitehead, 1971). Lead and zinc were concentrated in the central and western parts of the orebody. Since high grade zinc mineralization was only patchily distributed where Cu concentration was relatively high, there may be an antipathetic relation between Cu and Zn. In both zones, Zn was more widely distributed than Pb and was dominant on the northern and western fringes.

Mineralogy

Calcite was the dominant carbonate mineral at Tynagh, and non-cathode-luminescent low Mg-calcite formed the main mass of micrite, RFMC, blocky calcite spar and calcite rims around bioclasts. Fe-calcite infilled porosity which remained after cementation by RFMC and dog-tooth spar. It pre-dated, accompanied and post-dated the introduction of sulphide mineralization into the secondary porosity. Fe-calcite was banded due to variable content of Fe^{2+} and

Mn^{2+} and up to 50-60 bands have been detected by cathode luminescence (Gallery, 1979). Discontinuous interfingering of high Fe-calcite with banded sphalerite was observed in dilatant fractures.

Four types of dolomite related to the mineralization were distinguished. Dolomite (D1) was coeval with Fe-calcite cements and replacements and pre-dated the mineralization. Fe-dolomite (D2) was coeval with pyrite mineralization, which was interpretated as synsedimentary or early diagenetic (Boast et al., 1981), and was present mainly as an aureole around the mineralization. Fe-dolomite and baroque Fe-dolomite (D3) was present in the dilatant fracture/breccia systems as alterations of the host rock and as geopetal sediments coeval with the mineralization. Fe-dolomite (D4) was observed as alterations where the host Waulsortian was mineralized with the epigenetic Pb, Cu and Ba mineralization. Dolomite rhombs were often replaced by sulphides. Chemically the dolomite varied in composition from Fe-free dolomite to ankerite (Gibson, 1979).

Pyrite was present in several textural forms (Morrissey, 1965 and 1970; Gibson, 1979; Boast et al., 1981); rims around bioclasts, framboids, euhedra, replacements of clasts and colloform clots and bands. The last form was interpreted as synsedimentary or early diagenetic (Boast et al., 1981) and is thought to herald the sulphide mineralization at Tynagh.

However, none of these colloform pyrites (Stage 1 mineralization, *sensu* Boast et al., 1981), seems to be as early as sulphide infill, or replacement of an earlier Fe-calcite spar in stromatactis cavities. Paragenetically these pyrites are probably later than pyrite rim cements around bioclasts. Pyrite euhedra replace carbonates and were widely replaced by sphalerite and to a lesser extent by galena and chalcopyrite. Pyrite tended to concentrate in the earliest and in the latest stages of the sulphide mineralization. However, it was observed in minor quantities throughout the sulphide paragenesis associated with its carbonate counterparts, Fe-calcite and Fe-dolomite. During precipitation of Zn and Pb sulphides, Fe tended to be concentrated in the form of coeval carbonates rather than in the sulphide form. This is probably related to an environment deficient in sulphidic sulphur which would favour precipitation of monosulphides (ZnS, PbS) rather than bisulphides (FeS_2). In such an environment, pyrite might be expected to be replaced by monosulphides. This is indeed widely observed (Morrissey, 1970; Gibson, 1979). Some pyrites are Ni- and Co-bearing (Rowe, 1970; Gibson, 1979).

Sphalerite was the main sulphide mineral at Tynagh. Several paragenetic types of ZnS were distinguished: the earliest documented sphalerite at Tynagh ocurred as rims, often with pyrite, around bioclasts (Morrissey, 1965).

Microcrystalline ZnS conformable with pyritic horizons in argillaceous interdigitations may be synsedimentary or early diagenetic (Boast et al., 1981). Banded sphalerite was often the first infill of dilatant fractures. Individual sphalerite bands were often separated by relics of carbonate bands. Such relics consisted of non-staining amorphous Zn-calcite which was extensively replaced by sphalerite during the process of sulphidization. Such sphalerite contained numerous voids, possibly due to reduction in volume during replacement of carbonate precursor by ZnS (Kucha and Czajka, 1984). Precipitation of Zn-bearing carbonates suggests an initial sulphidic sulphur-deficient environment. Banded sphalerite also extensively replaced pyrite (Gibson, 1979). Banded ZnS also occurred in geopetal sediments where it was intermixed with fine-grained (10-15μm) dolomite (Boast et al., 1981). Sphalerite contained numerous inclusions of Fe-dolomite. The Fe-dolomite in turn contained numerous inclusions of sphalerite, and both the dolomite and sphalerite contained numerous voids. Barite and minor galena were usual components of such geopetal sediments. Zn and Ba were often reconcentrated into micronodules in which the outer part was composed of sphalerite with relics of dolomite, and the inner part was composed of overgrown barite with interlath spaces infilled with dolomite and minor sphalerite (Plate 4). Both barite and dolomite contained relics of calcite or Fe-calcite. Crystalline sphalerite occurred as replacements or recrystallization of the banded variety or as a result of direct precipitation from solution. Sphalerites of different origins differed in the chemistry of admixtures (Gibson, 1979).

Galena was present as minor lining of stromatactis, banded infills of dilatant fractures and as a fine-grained constituent of geopetal sediments. It replaced pyrite and carbonates and was replaced by crystalline sulphides. The main phase of galena precipitation was connected with epigenetic Cu-Pb-Ba mineralization (Morrissey, 1970; Gibson, 1979; Boast et al., 1981). Galena contained numerous inclusions of gratonite, tennantite, enargite, bournonite, geocronite and, rarely, native antimony (Gibson, 1979). Galena itself formed inclusions in sphalerite, chalcopyrite and tennantite.

Chalcopyrite formed rims, in association with galena, barite and tennantite, in massive types of mineralization. As isolated grains it replaced pyrite and sphalerite. Chalcopyrite was replaced by tennantite, arsenopyrite and bornite.

Tennantite was a major constituent of the epigenetic Cu-Pb-Ba mineralization (Boast et al., 1981) and was associated with crystalline sulphides of this last stage of mineralization. Tennantite has a strong spatial affinity for chalcopyrite i.e. it tends to form intergrowths and to replace chalcopyrite. It was also associated with minor sphalerite, pyrite and galena.

Generally three types of barite were distinguished. Barite (B1) occurred as replacement of micrite and of the earliest geopetal sediments in fractures. It, in turn, was extensively replaced by Fe-calcite. Some microscopic sections suggest that this replaced barite may have originally been partly baritocalcite. Later barite (B2) was coeval with banded sulphides. Barite (B3), more abundant than the other types, was coeval with epigenetic crystalline Cu-Pb-Ba sulphide mineralization (Boast et al., 1981).

Authigenic Na and K feldspars have been recognized in alteration aureoles around epigenetic Pb, Cu and Ba mineralization (Boast et al., 1981) and as cements infilling moldic porosity voids (Gibson, 1979).

Muscovite and chlorite were present as inclusions in sphalerite, pyrite and siegenite in flow-solution microtextures within the dilatant breccia close to the North Tynagh Fault (Boast et al., 1981).

Arsenopyrite, bornite, chalcocite, covellite were minor sulphides connected with epigenetic Pb, Cu, Ba mineralization (Gibson, 1979; Boast et al., 1981). Fluorite and gypsum associated with epigenetic mineralization were also noted (Gibson, 1979). Occasional grains of millerite, polybasite — pearceite, pyrargyrite — proustite, myargyrite, and stephanite were proved by microprobe (Rowe, 1970).

Textures

Ore textures observed in the mineralized Waulsortian (Morrissey, 1970; Boast et al., 1981) were:

1. Lining of stromatactis cavities: Linings of

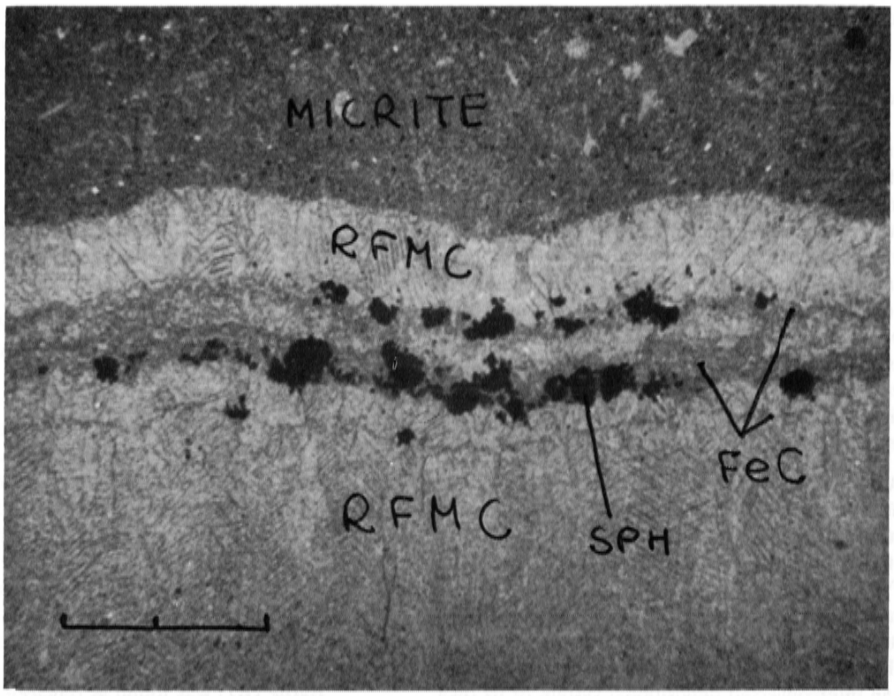

Plate 1. Microphotograph of stromatactis cavity filled with RFMC containing linings of sphalerite (SPH) inside linings of Fe-calcite (FEC). The order of cementation suggests that prior to the introduction of sphalerite into stromatactis cavities, a reducing environment, indicated by the Fe-calcite, was established inside the cavity. Scale bar: 800µm.

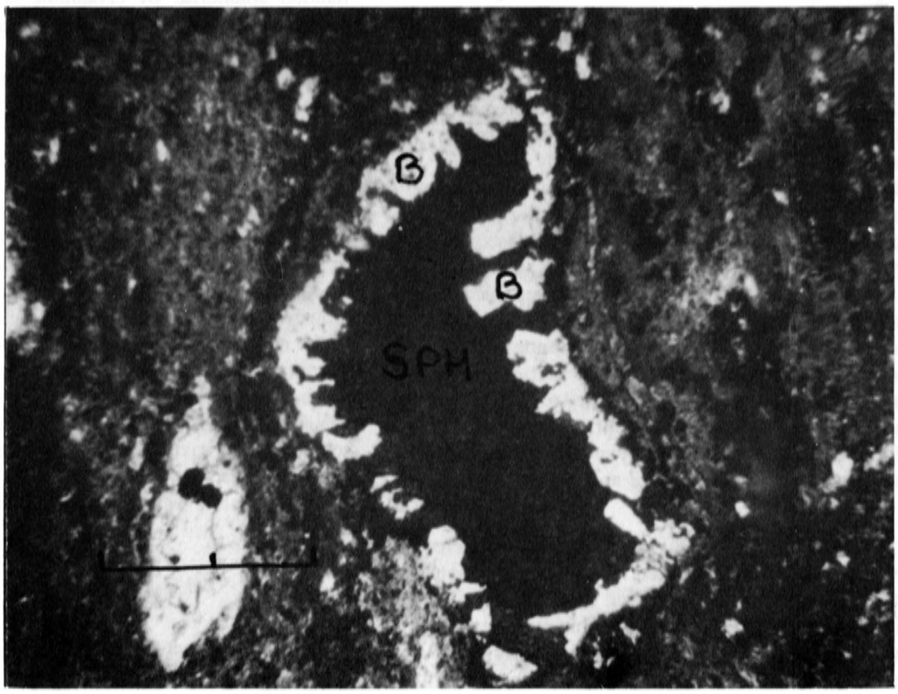

Plate 2. Microphotograph of moldic porosity infilled by barite (B) and later by sphalerite (SPH). Scale bar: 800µm.

crustified sulphides occurred in zones (Plate 1). The order and the mineralogy of the sulphides in individual cavities varied.

The general order of these linings of stromatactis were as follows: RFMC, Fe-calcite, sulphides, dolomite (if present) barite and blocky calcite. This mineral assemblage may also include high Fe-calcite linings. Sulphides probably form a symmetric paragenetic sequence viz. pyrite — galena — sphalerite — galena — pyrite, but such a complete sequence was never observed. At least one of the sulphides was usually missing; this was generally pyrite, which may be missing due to replacement by later Pb and Zn sulphides.

The presence of initial RFMC cement of marine origin (Bathurst, 1980), suggests that this mineralization was early since Fe-calcite always separated RFMC and sulphides. It also indicated that reducing conditions were established in the pore environment prior to sulphide emplacement.

2. Sulphide infills of a dilatant fracture — breccia system: Randomly oriented fractures which varied in width from a few millimetres to several tens of centimetres passed transitionally into breccias close to the North Tynagh Fault. These breccias, composed of angular clasts and blocks of Waulsortian, had a fine-grained geopetal matrix of Fe-dolomite, sphalerite, minor galena and barite (Boast et al., 1981). The dilatant fracture-breccia formed an interconnected depositional system of its own, displaying a series of microtextures:

Microbreccia infill: This included small micritic clasts, crinoidal debris and clasts of carbonate/sulphide intergrowths set in a matrix of fine-grained Fe-dolomite, minor galena and barite.

Geopetal sediments: Sediments of fine-grained sulphides and Fe-dolomite as described above, which displayed grading, load cast structures and microslumping.

Banded spar: Banded infills were composed mainly of sphalerite lining fracture surfaces. RFMC typically was separated from the banded sphalerite by a lining of Fe-calcite. The first sphalerite band usually contained numerous carbonate relics and may have formed by replacement of precursor carbonate bands. Subsequent sphalerite bands also contained numerous carbonate relics and voids. Banded sphalerite was accompanied by minor galena, pyrite, barite and high Fe-calcite. Replacement of pyrite by monosulphides was a common feature. The sequence of minerals was similar to that described for linings of stromatactis cavities. Banded textures were displaced by microfaults, disrupted and folded (Boast et al., 1981). Banded spars may be symmetrical and may also contain Fe-dolomite, ankerite and authigenic feldspars (Gibson, 1979).

Flow-solution: Flow-solution microtextures were observed within the dilatant breccia close to the Fault (Boast et al., 1981). It was composed of fine sphalerite, chlorite, minor pyrite and siegenite. This microtexture typically flanked solution surfaces and was only a few tens of micrometres in width.

3. Veinlets: Vertical to subvertical veinlets up to 10cm in width were characteristic of the epigenetic Pb, Cu and Ba mineralization. Sulphides and sulphosalts formed allotriomorphic mutual intergrowths. Veinlets, controlled by stylolites, contained, in order of crystallization, barite, sphalerite and galena.

4. Sulphide rims around bioclasts: In bioclastic interbeds pyrite and sphalerite formed rims around bioclasts (which they may partly replace) or precipitated as rim cements together with Fe-calcite spar in shelter voids of bivalves. These rims are considered to have been originally introduced as sphalerite spar (Morrissey, 1970).

5. Replacements: Replacement, together with dilatant breccia infills, formed the dominant texture type and was always associated with other textures and microtextures. Various types of replacement were recognized.

Fe-calcite spar replacement always pre-dated and accompanied sulphide, but was not always followed by sulphides.

Alteration aureoles up to a few centimetres wide around mineralization were controlled by the mineralogy and the chemistry of the mineralization and consisted of fine-grained dispersions and inter-growths. Fe-dolomite, Fe-calcite and pyrite occurred around pyrite mineralization (Boast et al., 1981). These carbonates together with baroque Fe-dolomite, sphalerite, galena and barite occurred around sphalerite. While baroque Fe-dolomite, Fe-calcite, barite, quartz, Na- and K-feldspars occurred around epigenetic Cu-Ba-Pb mineralization (Boast et al., 1981).

Barite (B1) was found as replacement of Fe-dolomite and baroque dolomite geopetal sediments. This was in turn replaced by Fe-calcite, galena and sphalerite. This style of replacement was abundant in places.

Older sulphides have been observed to have been replaced by younger mineralization and by carbonates. The most common examples were replacements of pyrite by sphalerite, or older impure and nonstoichiometric banded sphalerite by crystalline sphalerite (Gibson, 1979). Replacement of both pyrite and sphalerite was also locally observed.

Replacement of carbonate spar by barite and sulphides was also noted. These intimate fine-grained intergrowths of sulphides and dolomite in banded fracture infillings, numerous relics of sulphides in dolomite, and numerous relics of carbonates in sulphides suggest replacement of original metal-bearing carbonates by a mixture of Fe-dolomite, sphalerite, minor galena and barite.

This texture was interpreted by Boast et al., (1981) as coeval precipitation of ore minerals and dolomite. However, relics of Fe-calcite and calcite in sulphides, barite and dolomite, and sulphide nodules cross-cutting geopetal banding, all suggest a replacive origin.

Disseminated sulphides, mainly pyrite but also minor sphalerite and galena, were observed in silty geopetal sediments in cavities, and argillaceous interbeds in micrite (Morrissey, 1970; Gibson, 1979). The source of reduced sulphur was probably the clay-bearing organic matrix itself.

Paragenesis

Calcitic and dolomitic mineralized Waulsortian Reefs have been distinguished. The former was rich in Pb, Mn and Ba, and richer in Zn compared to dolomitic reefs, but was significantly impoverished in Cu.

Synsedimentary sulphides constituted less than 1% of the total mineralization. The main cements of this stage were RFMC and dog-tooth acicular calcite. RFMC cement was present in stromatactis and in other primary void spaces including the first lining of dilatant fractures. Some

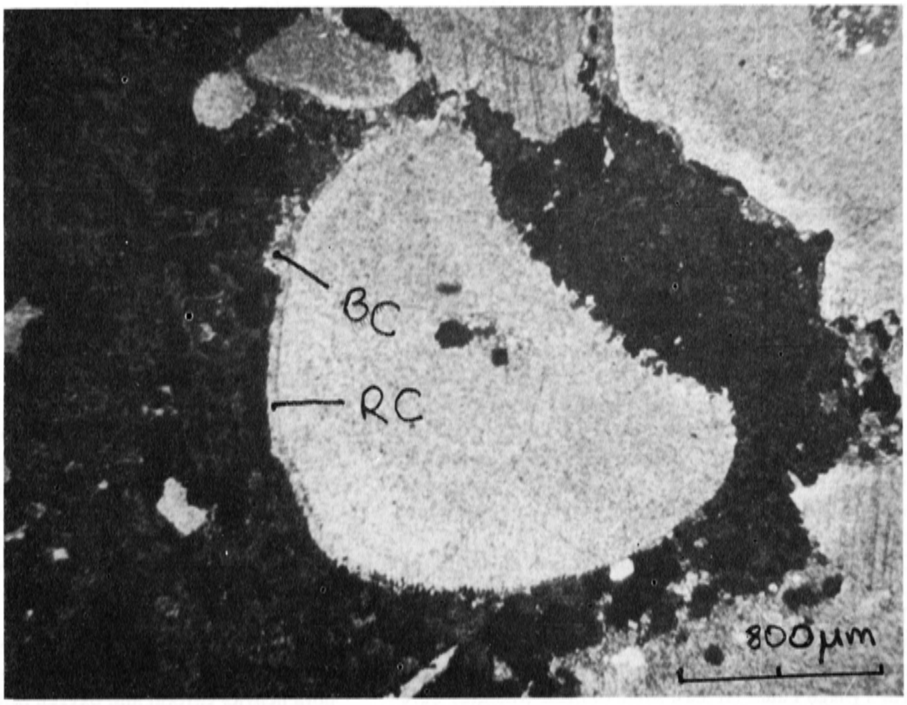

Plate 3. Microphotograph of interparticle porosity in bioclastic sections infilled initially by calcite rims around the bioclasts (RC), and subsequently by blocky calcite (BC); sphalerite occurs as infill and replacement of RC and BC. This indicates that sulphide mineralization was introduced after an initial period of marine cementation (RC + BC) in a subsurface environment. Prior to replacement by sphalerite, RC and BC are converted to Fe-Calcite.

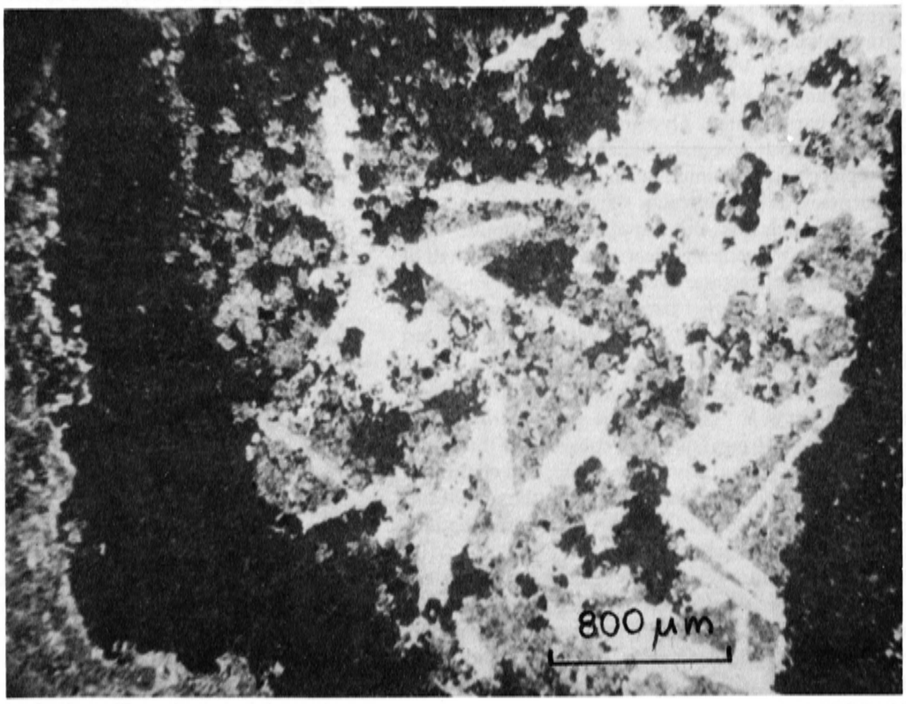

Plate 4. Micronodule in geopetal sediment within a dilatant fracture. The inner part of the nodule consists of barite laths (white). Interlath spaces are infilled by a mixture of Fe-dolomite (grey) and minor sphalerite. The outer part of the nodule is composed of sphalerite.

stromatactis cavities were entirely infilled by RFMC containing thin interlinings of Fe-calcite with grains of pyrite and minor sphalerite or galena. The RFMC, which is considered to be submarine synsedimentary cement (Bathurst, 1980), is optically continuous and unfractured, suggesting that Fe-calcite linings with sulphides were introduced as a cement rather than as replacement. In bioclastic interbeds the first cements were bladed Fe-free calcite rims which were overgrown by Fe-calcite. In places, however, bioclasts were surrounded directly by rims of sphalerite and pyrite. This suggests that sulphides coated the bioclasts before remnant porosity was sealed with Fe-calcite spar (Morrissey, 1965).

The early diagenetic stage includes colloform aggregates of pyrite in darkened Waulsortian micrites (Boast et al., 1981). These pyrites were enveloped by an aureole of micrite recrystallized into a mixture of Fe-dolomite and Fe-calcite. Shale beds interdigitated with micrites contained pyritic horizons with minor microcrystalline sphalerite (Boast et al., 1981) and may be an early diagenetic product of recrystallization.

During the sedimentary and early diagenetic stage, the Waulsortian micrites were converted into a rigid mass by RFMC cements. Probably in response to early tectonic movements (Moore, 1975) rigid micrites developed extensive systems of dilatant fractures and breccia close to the North Tynagh Fault. At least some of these fractures were very early and contained RFMC as the first infill followed by Fe-calcite spar and later sulphides. The main mineral of this stage was Fe-calcite as cements and replacements associated with slightly ferroan dolomite (D1), Fe-calcite infilled remnant porosity left by RFMC or bladed calcite and was often a major infill of moldic porosity. At the end of this stage barite (B1) was introduced as replacements and overgrowths.

In the dilatant fracture/breccia dolomite system the major components were banded sphalerite linings and geopetal sediments. Sphalerite was associated with minor galena and barite linings. Overgrowth and replacements developed mainly in geopetal sediments (Boast et al., 1981) and as replacements and infills guided by developing stylolites (Morrissey, 1965). Sulphides were persistently accompanied by Fe-dolomite and baroque Fe-dolomite. Two episodes of minor fracturing occurred at the second half of this stage. These fractures were infilled with Fe-calcite (which also replaced earlier barite) and later barite which in turn replaced Fe-calcite. These fractures also guided replacive sphalerite, Fe-dolomite and minor pyrite.

The epigenetic Pb, Cu and Ba mineralization was interpreted by Boast et al., (1981) as one event. More recent work (Kucha, 1984) suggests that it consisted of three substages viz. barite-galena, tennantite-pyrite, and chalcopyrite-dolomite. Silicification can be placed at the end of this stage (Gibson, 1979; Boast et al., 1981) and may be spatially related to the dolomitization.

Post-ore carbonates were mainly related to pinnate calcite veins and *en echelon* arrays of sigmoidal or lenticular tension gashes (Moore, 1975). They were filled by Fe-calcite with Fe content decreasing towards the end of the cementation. Some pyrite may also occur at the beginning of this stage.

Boast et al., (1981) place the dolomitization in the last stage, after the latest calcite cement. However, dolomite cements and replacements accompanied the mineralization. The earliest dolomite is seen to be coeval with Fe-calcite cements and replacements pre-dating the mineralization. The mineralization itself was pervasively accompanied by Fe-dolomite and baroque Fe-dolomite cements, replacements, geopetal sediments and alteration aureoles. The last-named were best developed around epigenetic Cu mineralization (Gibson, 1979; Boast et al., 1981).

Dolomite bodies separated individual ore zones and surrounded the northern perimeter of the mineralization as interbeds with the Iron Formation. It is noted that the dolomitized plugs along the Fault are coincident with the intersection of the northerly trending "anticlinal axes" and the Fault (Fig. 4). This distribution suggests an origin as an extensive aureole around the mineralization.

Isotopic composition

The isotopic composition of the Tynagh mineralization (Table 3) indicates that the Lower Carboniferous seawater was a source of reduced sulphur for the earlier sulphides and the source of sulphate for the precipitation of barite. The epigenetic Cu-Pb-Ba mineralization is enriched in isotopically heavier sulphur. The interpretation of Boast et al. (1981) was that these minerals were precipitated by reduced sulphur derived from the mixing of two solutions — a deep-seated solution with heavier sulphur and seawater with lighter sulphur.

Mineralized limestone, carbonates coeval with sulphide mineralization and post-ore carbonates are all depleted in both heavier carbon and oxygen isotopes in comparison to unmineralized limestone (Table 3). The depletion in δ^{13} C is ascribed to the mixing of the host-derived and bacterially oxidized carbon during the early mineralizing event, and by the mixing of the host-derived and hydrothermal (deep-seated) carbon during the epigenetic stage.

The depletion of the mineralized host in the heavier oxygen isotope is interpreted as isotopic exchange between the host- and ore-bearing fluids (Boast et at., 1981).

An oxygen isotope fractionation temperature, based on a single determination of epigenetic quartz — albite pair, is 200° C (Boast et al., 1981).

Genesis and concluding remarks

The mechanism of Waulsortian mud mound growth has recently been ascribed entirely to locally derived lime mud bound by blue-green algal mats (Pratt, 1982; James, 1983). The Waulsortian formed some distance from contemporary shore lines in moderately deep water, 150-300m below the wave base which prevented both a winnowing of lime mud and deposition of increased amounts of terrigenous material (Lees 1964, 1982; Sevastopulo, 1982). On the other hand Boyce et al. (1983) ascribed the formation of Waulsortian mudbank to a local, sudden development of a "trapdoor" fault. This local depression, controlled by the Tynagh Fault, was to be infilled by lime mud, the host to the syngenetic and epigenetic sulphides. As evidence of a rapid subsidence in the area, the existence of debris-flow breccias which underlie the Waulsortian was quoted. The rock underlying the mudbank is a nodular cherty limestone, and strongly resembles a conglomerate. It is considered however that this fabric was produced by uneven rates of cementation, and at Tynagh there is no evidence that the Nodular Cherty Limestone underlying mudbank and equivalent facies suffered any gravity-induced movements.

Gibson (1979) considered that the Tynagh Fault was a basement structure which influenced the development of the sandstone inlier as an elevated island. This Fault was reactivated during the formation of the Waulsortian, and

Table 3.

Isotopic composition of the Tynagh orebody carbonates and sulphides (from Boast et al., 1981). All values expressed as parts per mille.

Mineral or rock	$\delta^{34}S$	$\delta^{13}C$	$\delta^{18}O$
Early diagenetic sulphides (colloform and granular pyrite)	−15.5 to − 3.1	—	—
Infills and geopetal sediments in dilatant fracture/breccias	−26.0 to − 4.1	—	—
Epigenetic and geopetal veins and replacements	−26.0 to +11.1	—	—
Barite	+17.4 to +21.1	—	—
Unmineralized limestone	—	+3.1 to +4.1	+22.2 to +28.1
Mineralized limestone	—	+2.1 to +4.0	+17.6 to +27.1
Ore-stage carbonates	—	−2.8 to +3.4	+17.1 to +26.9
Post-ore carbonates	—	−4.0 to +2.6	+15.9 to +25.8

kept pace with the subsidence of the basin. He considered the presence of small amounts of argillaceous silty material containing sub-angular quartz as evidence that an elevated island of the Old Red Sandstone was a source of this terrigenous admixture. However, Waulsortian mounds across Ireland typically contain such argillaceous silty interbeds whether or not they are intersected by any fault.

The Waulsortian at Tynagh is predominantly a very clean carbonate, and contains no sandstone-derived clasts. Clasts of this type are only described from the Residual Orebody, and are probably a result of Tertiary weathering of mineralized limestone (Morrissey, 1970). Therefore, juxtaposition of the ORS sandstone and the Waulsortian, as observed today, is probably a late structure, and this final fault movement probably uplifted the southern part of the mineralized Waulsortian at Tynagh. Intensive weathering produced the ore-residuum which gravitated into a steep, fault-controlled trench created by karstification and collapse of the Grey Calp and Upper Waulsortian limestones of the hangingwall. The footwall was eroded with resultant exhumation of the Old Red Sandstone. The fault was a long-lived structure, sporadically active during the Carboniferous. Assuming that gravity-induced flow deposits were triggered by the fault movement, two main episodes of fault activity may be suggested, the first betweeen the Lower and Upper Waulsortian, equivalent to the time line separating the Reef Equivalent and the Grey Calp, and the second between the Grey and Black Calp, where massive and large scale development of debris-flow breccias and turbidites developed on the slope of the Upper Waulsortian. These two horizons of gravity-induced flow deposits, and especially turbidites, are the host to extensive geochemical anomalies centered on the fault and on the orebodies (Clifford et al., 1985). This suggests a genetic link between faulting, gravity-induced deposits and the mineralizing process (Derry et al., 1965; Russell, 1975).

Hutchings (1979) proposed that mineralizing fluids had been introduced along a reactivated basement structure, the North Tynagh Fault, into previously fractured Waulsortian micrites. Fracturing in the micrite had occurred due to squeezing of the rigid micritic mass between the enveloping Calp and Lower Muddy Limestone, towards the footwall clastic mass. While the rigid micrite responded by fracturing, movement in the enveloping well-bedded carbonates was accommodated by bedding slip and dewatering. The micrite fractured into a honeycomb network through which metal-bearing fluids periodically flowed and interacted with sulphur-bearing fluids. This resulted in the building of a layered sedimentary Zn-Pb mud. Host rock replacement only became significant in the final Pb-Cu-Ba acidic phase. Finally Mg-rich fluids were introduced into the carbonates on the structural highs along the fault zone, resulting in the late dolomite plugs.

The Tynagh Orebody was associated with the synsedimentary Iron Formation which at least in part is of turbidite origin (Schultz, 1966). This association led Derry et al. (1965) to the conclusion that the sulphide mineralization at Tynagh was synsedimentary. The dispersion aureole study provided evidence for a spatial and therefore an assumed genetic link between the Orebody and metals dispersed in the host carbonates. A study of major and trace elements (Russell, 1972, 1974, 1975; Gibson, 1979) showed that the geochemical anomaly is centered to the north of the Tynagh Fault and Orebodies. This led these authors to the conclusion that the mineralization was related to submarine exhalations along the Tynagh Fault. The detailed stratigraphic distribution of elements such as Cu, Pb, Zn, Mn, Fe, Mg, As, Hg, Ba, Sr, Ni and Co suggests however, that there are two stratigraphically distinct geochemical anomalies located at the base and at the top of Grey Calp (Clifford et al., 1985). For the first anomaly, Fe and Mn anomalous values are centered on the Iron Formation. Cu, Pb and Ba anomalies are centred on the Orebodies and the Fault, while Zn and Hg are centred only on the Orebodies. In the case of the second anomaly, at the top of the Grey Calp, Cu, Pb, Zn and Hg anomalies are centred on the Fault and the Orebodies, while Fe and Mn are centred on the Fault and the Iron Formation (Russell, 1972, 1974, 1975). The second anomaly has a lateral extent in excess of 4km.

A comparison of the stratigraphic position of the mineralization in the Waulsortian and the stratigraphic position of the anomalies indicates that the anomalies are located at a slightly higher stratigraphic level than the mineralization. The first geochemical anomaly, which is rich in Fe, spatially overlaps with the extent of the Iron Formation, and may be related to the main stage of the mineralization in a dilatant fracture-breccia system infilled mainly by sphalerite. The second geochemical anomaly, which is very rich in Mn (up to 2wt.% Mn average), is related to epigenetic Cu (Pb-Ba) mineralization.

Schultz (1966) considered the Tynagh mineralization as hydrothermal, epigenetic, cavity infillings and replacements and regarded the association between the mineralization and ironstones as accidental. According to this hypothesis the Fe and Si for the Iron Formation were supplied by weathering of exposed Old Red Sandstone and uplifted Lower Carboniferous sediments; the mineralization was derived from a deep magmatic source with a contribution of connate and meteoric waters. Russell (1978) expands on this concept emphasizing the importance of an underlying thick Caledonian prism as a source for the metals.

Boast et al., (1981) distinguished four major stages of mineralization, (a) colloform and granular pyrite of early diagenetic origin, (b) sphalerite, Fe-dolomite, minor galena and barite infills in a dilatant fracture/breccia system of the main stage of the mineralization, (c) vein infills and replacements of the epigenetic Cu-Pb-Ba mineralization, and (d) precipitation of calcite in veinlets and cavities and dolomitization of the Waulsortian adjacent to the Orebodies.

The dilatant fracture system is believed to have been opened by a forceful injection of the metal-bearing fluid into a rigid mudbank adjacent to the fault (Boast et al., 1981). Excessive fluid pressure is suggested as the mechanism keeping these fractures open. However, in many of the fractures the first lining is composed of RFMC, which suggests that marine water penetrated the dilatant cavity system before sulphide emplacement. This seems to be contradictory to the idea of Boast et al. (1981).

The sulphur isotope composition indicates that contemporaneous seawater was a source of sulphur for barite and sulphides of the first and the second stages of the mineralization. The solutions carrying the reduced sulphur probably migrated from off-bank facies and particularly from the off-bank trough now filled with ironstones (Schultz, 1966; Boast et al., 1981). The third stage sulphides were formed by the mixing of sulphur derived from a deep seated source and from seawater (Boast et al., 1981).

Acknowledgements

We thank Ennex International PLC for permission to publish this paper. Helpful discussions with our colleagues in Ennex have greatly aided in the preparation. Throughout this review we have liberally drawn on previous studies by numerous researchers, both academic and in-house. We are indebted to them and to all those who have worked on the Tynagh Orebody. Special thanks go to R. Schultz, C. Morrissey, D. Whitehead and J. Hutchings whose high standard of geological observation and reporting made this paper possible.

References

BATHURST, R. G. C. 1980. Stromatactis—origin related to submarine cemented crusts in Palaeozoic mud mounds. *Geology* 8. 131-134.

BOAST, A. M. 1979. A textural and isotopic study of Irish base metal mineralization of Lower Carboniferous age, with specific reference to the Tynagh deposit. Unpub. Ph.D. Thesis, London University.

BOAST, A. M., COLEMAN, M. L. and HALLS, C. 1981. Textural and stable isotopic evidence for the genesis of the Tynagh base metal deposit, Ireland. *Econ. Geol.* 76. 27-55.

BOSSELINI, A. and ROSSI, D. 1974. Triassic carbonate buildups of the Dolomites, Northern Italy. *In:* Laporte, L. F.(ed) *Reefs in Time and Space,* 209-233. Soc. Econ. Palaeo. Min. Spec. Pub.

BOYCE, A. J., ANDERTON, R. and RUSSELL, M. J. 1983. Rapid subsidence and early Carboniferous base metal mineralization in Ireland. *Trans. Inst. Min. Metall. (Sect. B. Appl. Earth Sci.)* 92. B55-66.

CLIFFORD, J. A., KUCHA, H. and MELDRUM, A. H. 1985. Lithogeochemistry, its applicability to base metal exploration in a carbonate environment. (Abstract) *In: Fortschritte der Mineralogie.* Band 63, Beiheft 1, 1985 44. Stuttgart.

COOK, H. E. and MULLINS, H. T. 1983. Basin margin environment. *In:* P. A. Scholle, D. G. Belbout and C. H. Moore (Eds.) *Carbonate Depositional Environments.* Amer. Assoc. Petrol. Geol. Tulsa, 708pp.

DERRY, D. R., CLARKE, G. R. and GILLATT, N. 1965. The Northgate base metal deposit at Tynagh, Co. Galway, Ireland. *Econ. Geol.* 60. 1218-1237.

DONOVAN, P. R. and JAMES, C. H. 1966. Geochemical dispersion in glacial overburden over the Tynagh (Northgate) base metal deposit, West Central Eire. *Sym. Geochem. Prospecting.* Geol. Surv. Canada. 66-54 89-110.

EMO, G. T. 1978. The Lower Palaeozoic and Old Red Sandstone of Slieve Aughty, Counties Clare and Galway. Unpub. Ph.D. Thesis, University of Dublin.

ENOS, P. and SAWATSKY, L. H. 1981. Pore networks in carbonate sediments. *Jour. Sed. Petrology,* 57. 961-985.

ENOS, P. and MOORE, C. H. 1983. Forereef slope environment. *In:* P. A. Scholle, D. G. Belbout and C. H. Moore (Eds.) *Carbonate Depositional Environments.* 508-537. Amer. Assoc. Petrol. Geol. Tulsa. 708pp.

GALLERY, D. 1979. Tynagh Mine Project Progress Report No. 5. Unpub. Internal Report to Irish Base Metals Limited.

GIBSON, C. 1979. Primary dispersion patterns for selected elements in the sulphide ores, host rocks and iron formation at Tynagh, Co. Galway, Ireland. Unpub. Ph.D. Thesis, Cardiff Univ. 251pp.

GOLDSCHMIDT, V. M. 1958. *Geochemistry.* Oxford University Press. 730pp.

HUDSON, R. G. S. and SEVASTOPULO, G. D. 1966. A borehole section through the Lower Tournaisian and Upper Old Red Sandstone, Ballyvergin, Co. Clare. Sci. *Proc. R. Dub. Soc. Series A.* Vol. 2.

HUTCHINGS, J. 1979. The Tynagh deposit. *In:* Brown, A. G. (ed) *Prospecting in areas of Glaciated Terrain, Ireland 1979, Excursion Handbook* 34-46. Irish Association for Economic Geology, Dublin.

JAMES, N. P. 1983. Reef Environments. *In:* P. A. Scholle, D. G. Bebout and C. H. Moore (Eds.). *Carbonate Depositional Environments* 346-440. Amer. Assoc. Petrol Geol. Tulsa, 1983. 708pp.

KINAHAN, G. H. 1863. *Explanatory memoir to accompany sheets 115 and 116 of the maps of the Geological Survey of Ireland, in the county of Galway.* Mem. Geol. Surv. Ireland, Dublin.

KUCHA, H. and CZAJKA, K. 1983. Sulphide-carbonate relationships in Upper Silesian Zn-Pb deposits (Mississippi Valley type) Poland, and their genesis. *Trans. Inst. Min. Metall. (Sect. B. Appl. Earth Sci.).* 93. B12-22.

LEES, A. 1964. The structure and origin of the Waulsortian (Lower Carboniferous) reefs of west central Ireland. *Phil. Trans. Roy. Soc. London.* B 247. 493-531.

LEES, A. 1982. The palaeoenvironmental setting and distribution of the Waulsortian facies of Belgium and Southern Britain. *In:* K. Bolton, H. R. Lane and D. V. LeMone (Eds.) *Symposium on the palaeoenvironmental setting and distribution of the Waulsortian Facies.* 1-16. El Paso, Texas. 202pp.

LONGACRE, S. 1983. Summary report on the deposition, diagenesis, and mineralization in the Tynagh area, Co. Galway. Unpub. Internal Report to Irish Base Metals from Getty Research Centre, Houston.

MOORE, J. McM. 1975. Fault tectonics at Tynagh mine, Ireland. *Trans. Inst. Min. Metall. (Sect. B Appl. Earth Sci.)* 84. B141-145.

MORRISSEY, C. J. 1965. The Tynagh lead-zinc deposit, Co. Galway, Ireland. Unpub. B.Sc. Thesis, London Univ.

MORRISSEY, C. J. 1970. The mineralogy, structure and origin of the lead-zinc-copper residual orebody at Tynagh Co. Galway, Ireland. Unpub. Ph.D. Thesis, London Univ.

MORRISSEY, C. J. and WHITEHEAD, D. 1971. Origin of the Tynagh residual orebody. *Proc. 9th. Commonwealth Mining and Metallurgical congress 1969.* Inst. Min. Metall.

MORRISSEY, C. J., DAVIS G. S. and STEED, G. M. 1971. Mineralization in the Lower Carboniferous of central Ireland. *Trans. Inst. Min. Metall. (Sect. B Applied Earth Sci.)* 80. B174-185.

O'CLEIRIGH, M., O'CLEIRIGH, P., O'DUIGENAN, P. and O'MULCONRY, F. 1632. *Annals of the Four Masters.*

PHILCOX, M. E. 1971. A Waulsortian bryozoan reef ("cumulative biostrome") and its off-reef equivalents, Ballybeg, Ireland. *C.R. 6me Cong. Int. Strat. Geol. Carb.* (Sheffield, 1967) Vol. 4 1359-1372.

PHILCOX, M. E. 1984. *Lower Carboniferous Lithostratigraphy of the Irish Midlands.* Irish Association for Economic Geology, Dublin. 89pp.

PRATT, B. R. 1982. Stromatolitic framework of carbonate mud mounds. *Jour. Sediment Petrol.* 52 1203-1277.

RIEDEL, D. 1980. Ore structures and genesis of the Lead-Zinc deposit, Tynagh Ireland. *Geol. Rdsch.* 69, 363-383.

ROWE, J. 1970. The Eastern Extension Orebody, Tynagh mine, Co. Galway, Ireland. Unpub. B.Sc. Thesis, London Univ.

RUSSELL, M. J. 1972. The geological environment of post Caledonian base metal mineralization in Ireland. Unpub. Ph.D. Thesis, Univ. of Durham.

RUSSELL, M. J. 1974. Manganese halo surrounding the Tynagh ore deposits; a preliminary note. *Inst. Mining Metallurgy Trans. (Sect. B Appl. Earth Sci.).* 83, B65-66.

RUSSELL, M. J. 1975. Lithogeochemical environment of the Tynagh base metal deposit, Ireland, and its bearing on ore deposition. *Trans. Inst. Min. Metall, (Sect. B: Appl. Earth Sci.)* 84, B128-133.

RUSSELL, M. J. 1978. Downward excavating hydrothermal cells and Irish type ore deposits: Importance of an underlying thick Caledonian prism. *Trans. Inst. Min. Metall. (Sect. B: Appl. Earth Sci.)* 87. 168-171.

RUSSELL, M. J. 1983. Major sediment hosted exhalative zinc-lead deposits: Formation from hydrothermal convection cells that deepen during crustal extension. *G.A.C.-M.A.C.* Vol. 8, 257-282.

SCHLAGER, W. and JAMES, P. 1978. Low magnesium calcite limestone forming at the deep sea floor, Tongue of the Ocean, Bahamas. *Sedimentology.* 25. 675-702.

SCHULTZ, R. W. 1966. Lower Carboniferous cherty ironstones at Tynagh, Ireland. *Econ. Geol.* 61. 311-342.

SCHULTZ, R. W. 1968. The geology of the Primary Sulphide — Barite deposits at Tynagh, Ireland. Unpub. Ph.D. Thesis, Dublin University.

SCHULTZ, R. W. 1971. Mineral exploration practice in Ireland. *Trans. Inst. Min. Metall. (Sect. B. Appl. Earth Sci.)* 80. 238-258.

SEVASTOPULO, G. D. 1979. The stratigraphic setting of base metal deposits in Ireland. *In: Prospecting in areas of glaciated terrain, 1979.* Inst. Min. Metall. London, 8-15.

SEVASTOPULO, G. D. 1982. The age and depositional setting of Waulsortian limestones in Ireland. *In:* K. Bolton, H. R. Lane and D. V. LeMone, (Eds.) *Symposium on the palaeoenvironmental setting and distribution of the Waulsortian facies.* El Paso. 65-70.

SHANMUGAM, G. and BENEDICT, G. L. 1983. Manganese distribution in the carbonate fraction of shallow and deep marine lithofacies, Middle Ordovician, Eastern Tennessee. *Sediment. Geol.* 35. 159-175.

TAYLOR, S. 1984. Structural and palaeotopographic controls of Lead-Zinc mineralization in the Silvermines orebodies, Republic of Ireland. *Econ. Geol.* 79. 529-548.

WHITEHEAD, D. 1971. Base metal sulphides at Tynagh. *In:* D. Skevington (Ed.). *The Genesis of Base Metal Deposits in Ireland.* Irish Geol. Assoc. Galway Symposium Proc. 30pp.

WEIR, J. A. 1962. Geology of the Lower Palaeozoic inliers of Slieve Bernagh and Cratloe Hills, Co. Clare. *Sci. Proc. R. Dublin Soc. 1.* 233-263.