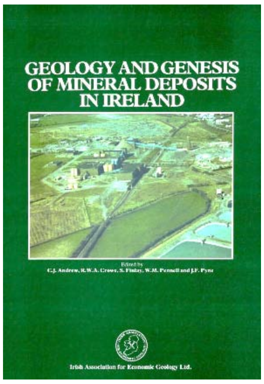




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# The setting, styles of mineralization and mode of origin of the Ballinalack Zn-Pb deposit.

**G.V. Jones & S.F. Brand**

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# The setting, styles of mineralization and mode of origin of the Ballinalack Zn-Pb deposit.

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## Abstract

At Ballinalack, sub-economic carbonate-hosted Zn-Pb mineralization occurs at two stratigraphic levels in rocks of Lower Carboniferous (Dinantian) age. The main mass of proven mineralization, generally referred to as the Ballinalack deposit, occurs as discrete pods within a series of knolls of Waulsortian Mudbank Limestone. Weaker mineralization occurs lower in the succession in a lithostratigraphic group known locally as the Mixed Beds, which are the stratigraphic equivalent of the Navan Beds. At both levels, mineralization consists of pyrite, sphalerite and galena with minor barite in a calcite gangue.

The deposit is spatially associated with the Ballinalack Fault, which trends northeastwards and has a downthrow to the NW. The mudbank facies thickens significantly across the fault in the hanging-wall block to form a series of knolls whose alignment is also parallel to the Fault Zone. A second major fault, trending northwestwards, separates high grade mineralization on its northern, downthrown side from weaker mineralization to the south.

The Waulsortian Mudbank-hosted mineralization, which is confined within the knolls, shows a progressive change in style, both vertically and horizontally. At higher levels and greater distances from the Fault, weak, and often mono-mineralic, mineralization lines cavity systems (stromatactis) within the mounds. This simple style is overlapped downwards and closer to the Fault by polyphase, cross-cutting styles of mineralization. The base of a given section consists of massive mineralization with partial or complete replacement of the carbonate host. In any vertical section the best grades of mineralization always overlie either intra-mound shale units or the base of the Mudbank, as the case may be. It is suggested that mineralization occupied space which was created during early diagenesis of the mudbanks and that it was emplaced before their final lithification.

The lower mineralization occurs principally in two separate lithological units. Towards the top of the Mixed Beds, fine-grained, disseminated sphalerite and galena are found in a calcareous sandstone, while more massive, cross-cutting sulphides occur in the Bird's Eye Micrite Member, near the base of the Lower Carboniferous succession.

## Introduction

The Ballinalack deposit takes its name from the nearby village on the Longford road, 14.5km NW of Mullingar and 60km west of Dublin. No official estimates of grade and tonnage have been published, but the deposit is generally considered to be sub-economic. Unofficial estimates have been mentioned by Finlay (1982), who quotes reserves of 4Mt, and by Williams and McArdle (1980), who describe the deposit as "containing perhaps a few million tonnes with combined Zn-Pb grades of about 8%". The average ratio of Zn to Pb for the deposit is approximately 5.5:1 (Jones and Bradfer, 1982).

The deposit was discovered following regional geochemical surveys undertaken by Syngenore Explorations Ltd. between 1965 and 1969. Geochemically anomalous stream sediment samples from the Ballinalack area were followed up and pyrite-bearing float boulders found. Later soil geochemical surveys defined two centres of anomalous Zn-Pb values, which were shown by diamond drilling to be related to weak Zn-Pb mineralization in bedrock beneath 3-5m of glacial overburden. Eventually, higher grades of mineralization were discovered to the north of the anomalous geochemical centres, beneath a cover of barren carbonates. The greater part of the deposit is therefore entirely blind (Jones and Bradfer, 1982).

Mineralization occurs at two stratigraphic levels. The upper, hosting the main mass of the deposit, is the Waulsortian Mudbank Limestone, while weaker mineralization is found in various lithologies in the Mixed Beds. The upper mineralization is comparable in its stratigraphic setting to other Irish deposits such as the B and Upper G orebodies at Silvermines, and the Tynagh deposit. The lower mineralization occurs in beds which are stratigraphically equivalent to those which host the Navan deposit.

This paper briefly summarizes the main features of the deposit, its stratigraphic, structural and lithological setting and also the mineral textures and styles. It is intended to show that an important genetic relation exists between mineralization and the environment in which it occurs, and that the causative processes of both are interlinked.

### History of previous work

Several writers have presented brief descriptions of the Ballinalack deposit, including Schultz (1971) and Williams and McArdle (1978), while Nevill (1958), MacDermot and Sevastopulo (1972) and Sevastopulo (1979) have described the regional geology and stratigraphic settings of Irish mineral deposits in general, including Ballinalack. Other authors have commented on aspects of the deposit in internal company reports. Blain (1972), in an undergraduate dissertation, mapped the geology of the Ballinalack area and of the deposit itself. Lees (1969) and Philcox (1972) described the sedimentological and stratigraphic setting, Halls (1971) examined the textures of the ore minerals and

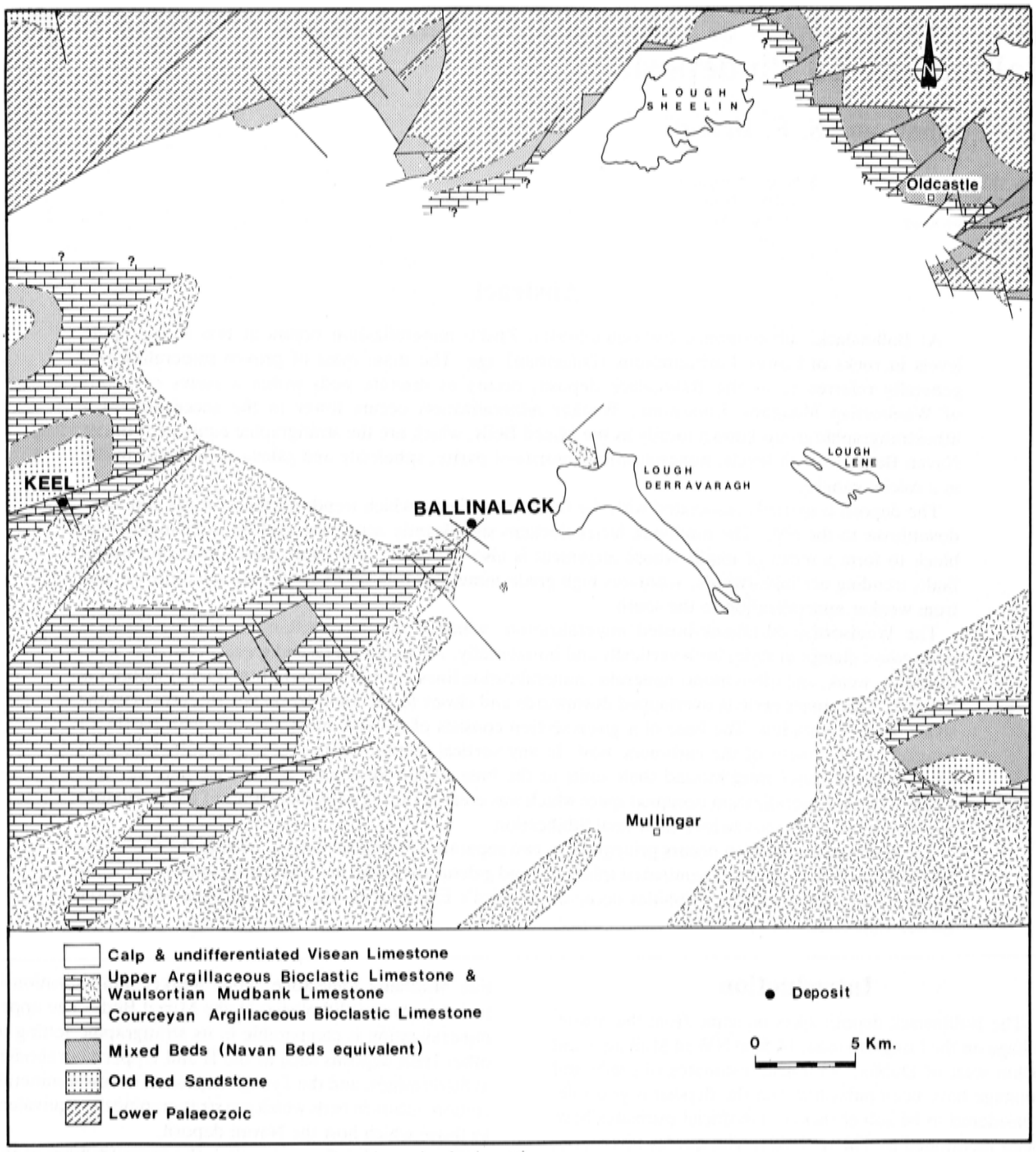


**Figure 1.** Ballinalack deposit: regional geological setting.

Beale (1976) the lithogechemical patterns, with special emphasis on Mn distribution. Bradfer (1984) studied the microfacies of the host lithologies and their relations to mineralization. A description of the discovery of the deposit and a summary of the stratigraphic and structural setting and mode of occurrence of the Waulsortian Mudbank-hosted mineralization was presented by Jones and Bradfer (1982). Last, but by no means least, many company geologists have worked on the deposit since its discovery and have contributed much to what is now known about it.

# Geological setting of the Ballinalack deposit

## Stratigraphy and structure

### Regional setting

The main elements of the regional geological framework of the NW Midlands region are shown in Figure 1. The northern boundary is defined by the Longford-Down Massif, containing shales, sandstones and mudstones, with some igneous and intrusive rocks, of Lower Palaeozoic age. Several small inliers of Lower Palaeozoic sediments with NNE - and NE - trending axes break through the Carboniferous cover, especially to the west of Ballinalack. 'Old Red Sandstone' rocks (including conglomerates) of Basal Carboniferous age outcrop on the flanks of these inliers, the trends of which reflect the underlying control exerted by Caledonian structures on subsequent events.

The basal Lower Carboniferous (Dinantian) beds, exposed along the southern margin of the Longford-Down Massif and around the flanks of the smaller inliers, are of Courceyan 3 age. They include a variety of primarily shallow-water sediments, including flaser-bedded sandstones, micrites, calcareous sandstones and bioclastic limestones (Sevastopulo, 1979). Individual units of this sequence are

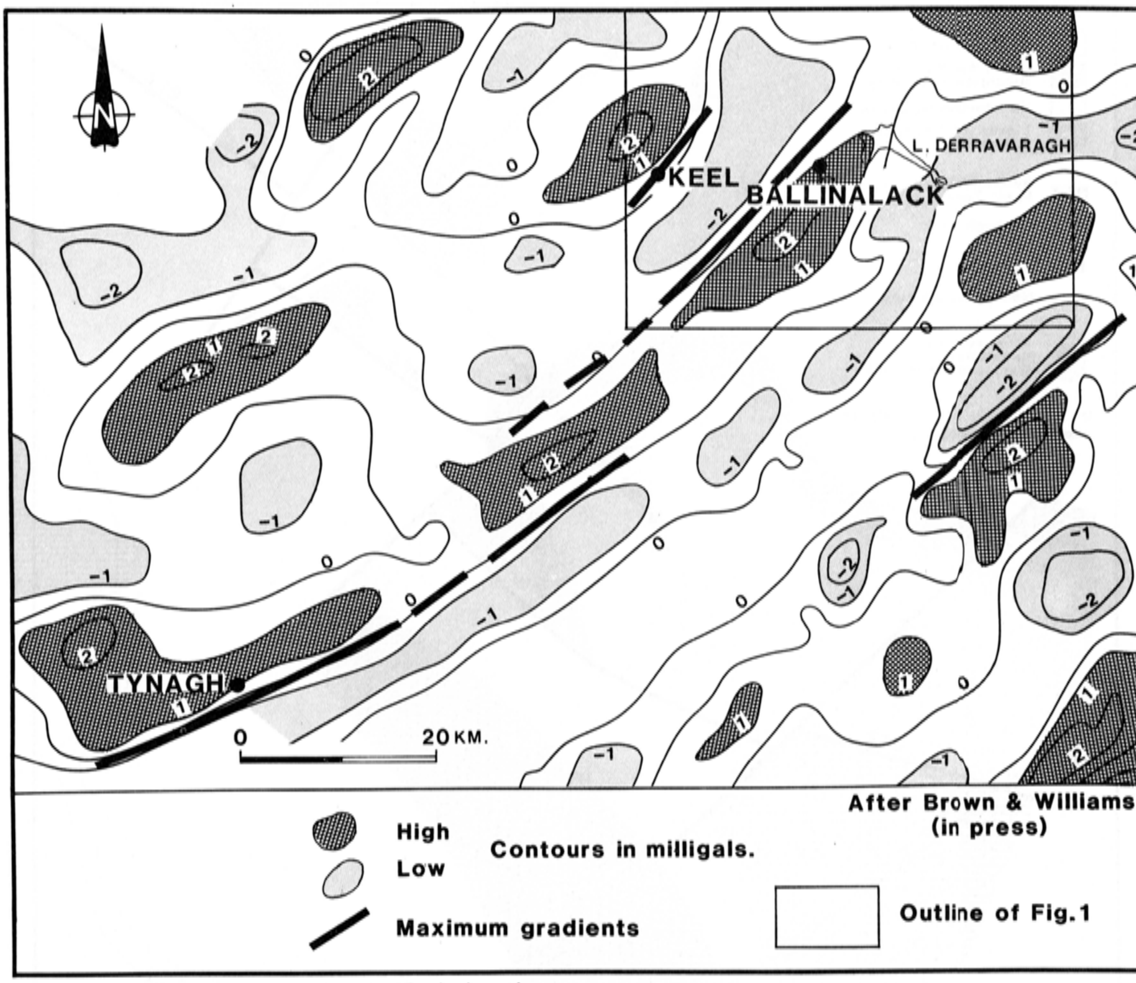


**Figure 2.** Residual gravity of the Ballinalack region.

laterally discontinuous, but the main features are recognizable throughout the region. Informally, they are known as the Navan Beds, and locally, at Ballinalack, as the Mixed Beds.

They are succeeded firstly by open marine shales, calcareous mudstones and limestones and then by the so-called Waulsortian Mudbank Limestone, generally of Courceyan 4 age (Sevastopulo, 1979); this facies is also known as "reef" but following Lees (1961) the term "Mudbank" will be used throughout this paper. The Waulsortian facies, widely developed throughout the southern part of Ireland where it reaches 300m (and exceptionally 1000m) in thickness, begins to break up into discrete mounds or isolated banks in the north Midlands and is entirely absent along the northern margin of the area shown in Figure 1 (Emo, pers. comm.). Ballinalack is within the intermediate zone of intermittent Waulsortian development. The off-bank equivalent facies include shales, argillaceous and bioclastic limestones and cherts.

The Waulsortian facies, where present, is overlain by a shale-bioclastic limestone sequence (referred to as the Upper Argillaceous Bioclastic Limestone) which, in turn, is succeeded by the basinal Calp Limestone facies of Chadian-Arundian age (Sevastopulo, 1979). The greater part of the area of Figure 1 is underlain by Calp Limestone, which, east of Ballinalack, defines a regional dip of 10-15° to the NE. Also to the east, a distinctive series of NE-trending rounded hills are composed of a festoon chert facies (The Derravaragh Festoon Cherts of Nevill, 1958).

The regional structural grain is strongly influenced by Caledonian features, as shown by the axes of the inliers referred to above and by geophysical data, particularly regional Bouguer gravity anomaly maps (Murphy, unpublished) and, to a lesser extent, magnetic intensity data (Williams, 1981). Bouguer gravity anomalies show that the Ballinalack deposit lies adjacent to the flank of a major Caledonian structure on which, to the SW, the Tynagh deposit also lies. Brown and Williams (1985) have produced an interpretation which reflects gravity sources shallower than 10km (Fig. 2). They propose that the local basement underlying the Midlands region consists of Lower-Middle Ordovician volcanic and sedimentary rocks, with perhaps a thin veneer of Silurian and Devonian sediments, which formed a series of narrow, elongate, fault-controlled blocks and basins during middle to late Courceyan times. A varied sequence of carbonate lithologies was deposited on the highs and basinal facies accumulated in the lows. Ballinalack lies towards the northeastern end of one such horst which extends southwards for several tens of kilometres. The structures which bound the high, as shown by the steepest gradients, appear to be arranged *en echelon* (Fig. 2). NE from Ballinalack the high is less pronounced and appears to terminate against a NW-trending gravity low. This suggests that the deposit lies near the termination zone of a major NE-trending structure.

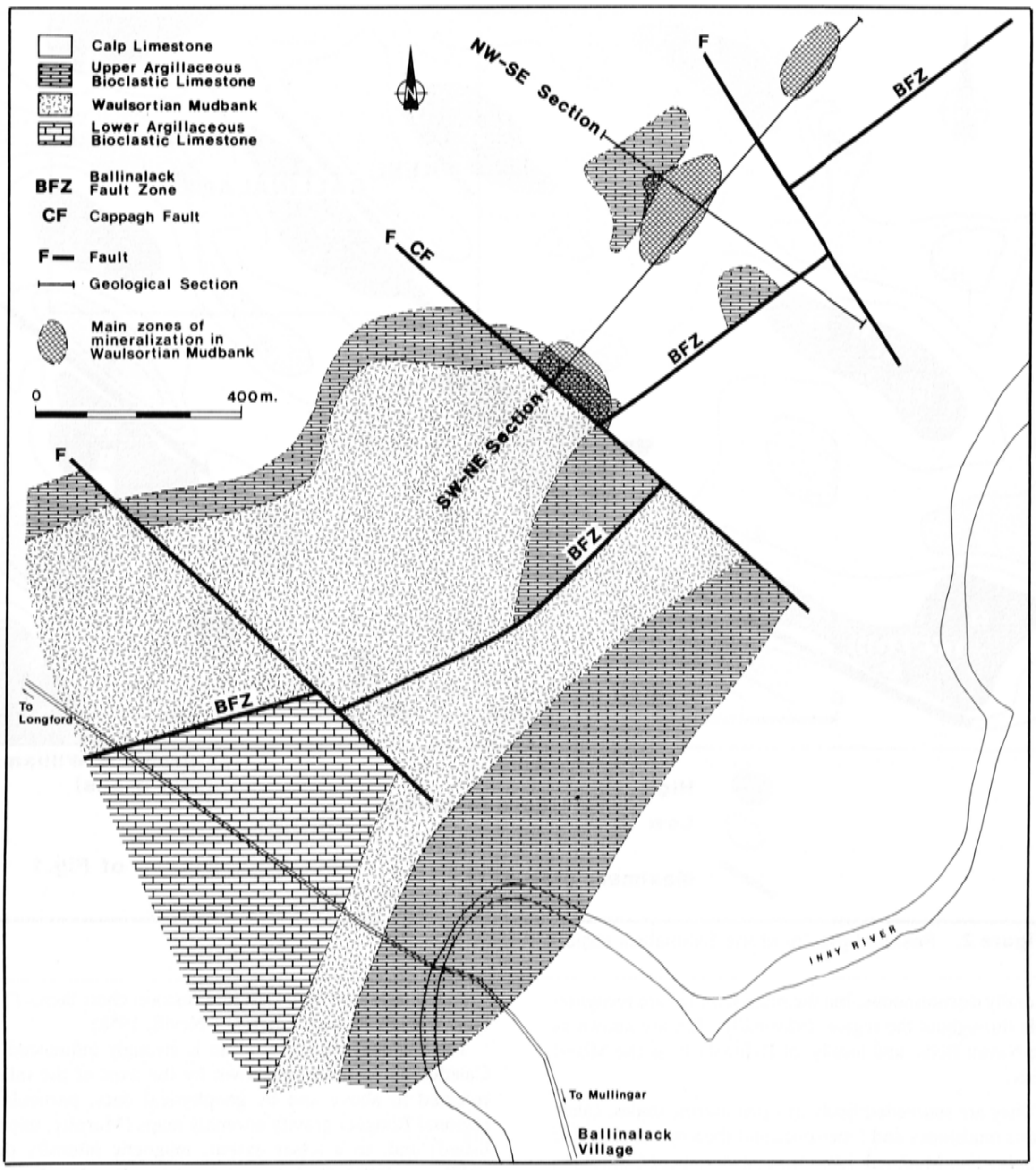


**Figure 3.** Ballinalack deposit: geological setting.

## Local setting

The geology of the area immediately surrounding the deposit is shown in Figure 3 and the detailed stratigraphic succession in Figure 4. Approximately 1000m of Lower Carboniferous and older beds have been seen in drill core at Ballinalack. The oldest beds are grey-green shales and siltstones, well cleaved, steeply dipping and presumed to be of Silurian age. Their relationship to the overlying beds is uncertain within the limited area of the deposit because the contact is usually faulted, but a major unconformity must also be present. The remainder of the section is entirely of Early Carboniferous age. (No Old Red Sandstone or other Red Bed deposits are seen at Ballinalack, but their absence may be due to the effects of faulting rather than non-deposition. These faults also affect the lowest part of the Carboniferous section, so that the detailed stratigraphy of these lowermost beds is not known.) A number of distinctive marker beds are recognizable throughout the succession. In particular, two distinctive green, silty shales, presumed to be tuffs, are found within the upper Argillaceous Bioclastic Limestone. The lower marker is persistent throughout the area of the deposit and beyond, the upper less so. When the latter is present it occurs either in the Upper Argillaceous Bioclastic Limestone or the Calp Limestone, within a metre or so of the contact. (This contact, marking the onset of a deeper water depositional environment, is especially sharp; otherwise, contacts are gradational.)

The deposit occurs in the NW, hanging-wall block of the major, NE-trending Ballinalack Fault. A zone of intense gouge marks the position of the major Fault and several smaller, parallel faults are inferred from stratigraphic relations. In the vicinity of the main part of the deposit the vertical displacement on the Fault is of the order of 200m. The NW-trending Cappagh Fault, with a downthrow to the

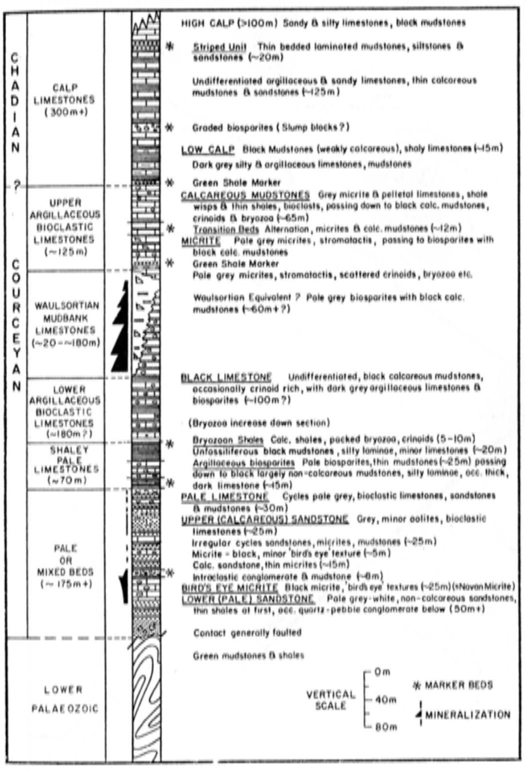


**Figure 4.** Ballinalack deposit: stratigraphic succession.

NE, divides the deposit area into roughly two halves. Other NW-trending faults, with small displacements, are probably present.

## Lithological setting

### Waulsortian Mudbank Limestone

*Lithology.* The Waulsortian Mudbank Limestone has been well described in several publications by Lees for areas in Ireland (Lees, 1961 and 1964), Belgium (Lees et al., 1977), and Britain (Lees, 1982). It forms a complex of banks or mounds of knoll- to sheet-like form. Its main lithological constituents are calcite mudstones with coarser sparry calcite mosaics. Bryozoa and other fossil debris are also present. Its diagnostic feature is the presence of stromatactis, an enigmatic texture which represents an originally interconnected system of small cavities now filled by generations of geopetal sediments and calcite cements (Bathurst, 1982, has discussed the origin of stromatactis).

The Waulsortian mounds are generally believed to have formed in water of appreciable depth ("Toe of slope carbonates" of Wilson, 1975). Lees et al. (1977) and Lees (1982) quote depths of 200-300m. Although the mounds grew much more rapidly than their laterally equivalent sediments, the general absence of shallow-water features led Lees et al. (1977) to conclude that their tops were covered by at least 100m of water.

At Ballinalack, the Waulsortian has been studied by Bradfer (1984), who identified three microfacies,

(i) Biomicrite wackestone with stromatactis,

(ii) Biomicrite wackestone with bryozoan-bounded, spar-filled cavities, and

(iii) Mottled limestones.

Shales and bioclastic limestones are also present in small quantities, with shales being more frequent in the upper parts of the mounds. Bradfer (1984) also identified three forms of stromatactis,

(i) Large size, up to 5cm in height, typically with a digitate upper surface,

(ii) Small both in height and length (1cm × 1cm), usually with a preferred orientation of 30-50°, and

(iii) Sheet spars.

The stromatactis cavities are filled by up to four generations of calcite cement. These are, in order of precipitation,

(i) Fibrous calcite, normal to the cavity wall (radiaxial calcite of Bathurst, 1982),

(ii) Inclusion-free crystals,

(iii) Large, elongate, iron-poor crystals, and

(iv) Coarse, blocky ferroan calcite.

Cements (i) and (ii) are iron-free, and cement (iv) usually seals the cavity. Bathurst (1982) considers, on isotopic grounds, that the fibrous or radiaxial calcite is early, formed from fluids that were near to equilibrium with sea water and that the blocky calcite (cement (iv) above) was formed from fluids of a different origin, either meteoric or deeper. He also believes that the development of the cavities was contemporaneous both with the deposition of sediment and submarine cementation in the mound. He calls on supporting evidence (p. 175, op. cit.) for the assertion that the mounds underwent early lithification.

*Geometry and form of the Waulsortian Mudbank.* Rapid changes in thickness and form characterize the development of the Waulsortian at Ballinalack. In the footwall block of the Ballinalack Fault Zone, the Waulsortian consists of two or three sheets of typical lithologies 4 to 7m thick, with 0.5 to 3.5m of intervening argillaceous limestones and shales. A similar section with similar thicknesses was intersected in a borehole drilled some 5km north of the deposit.

To the west, across the Ballinalack Fault into the hanging-wall block, the thickness increases markedly to a maximum of some 190m. The form of the Waulsortian also changes, and it appears as a series of knolls, strung like beads roughly parallel to the strike of the Fault Zone. The exact shape and extent of the knolls has not been defined by drilling, but there is a suggestion from the pattern of isopachs that there is a closure to the west. In the southern half of the deposit area, south of the Cappagh Fault, the mudbank sub-outcrops and the thickness and geometry of the section cannot be measured and interpreted. However, it appears that two knolls are present in the southern half of the deposit area, and two in the north. The knolls are numbered 1 to 4 on the accompanying Figure 5 and on the longitudinal section (Fig. 7).

Knolls 1 and 2, the most northerly, are some 150m in diameter and at least 190m in maximum thickness. The distance between their centres is approximately 500m. The distance between the southerly Knolls 3 and 4 is somewhat

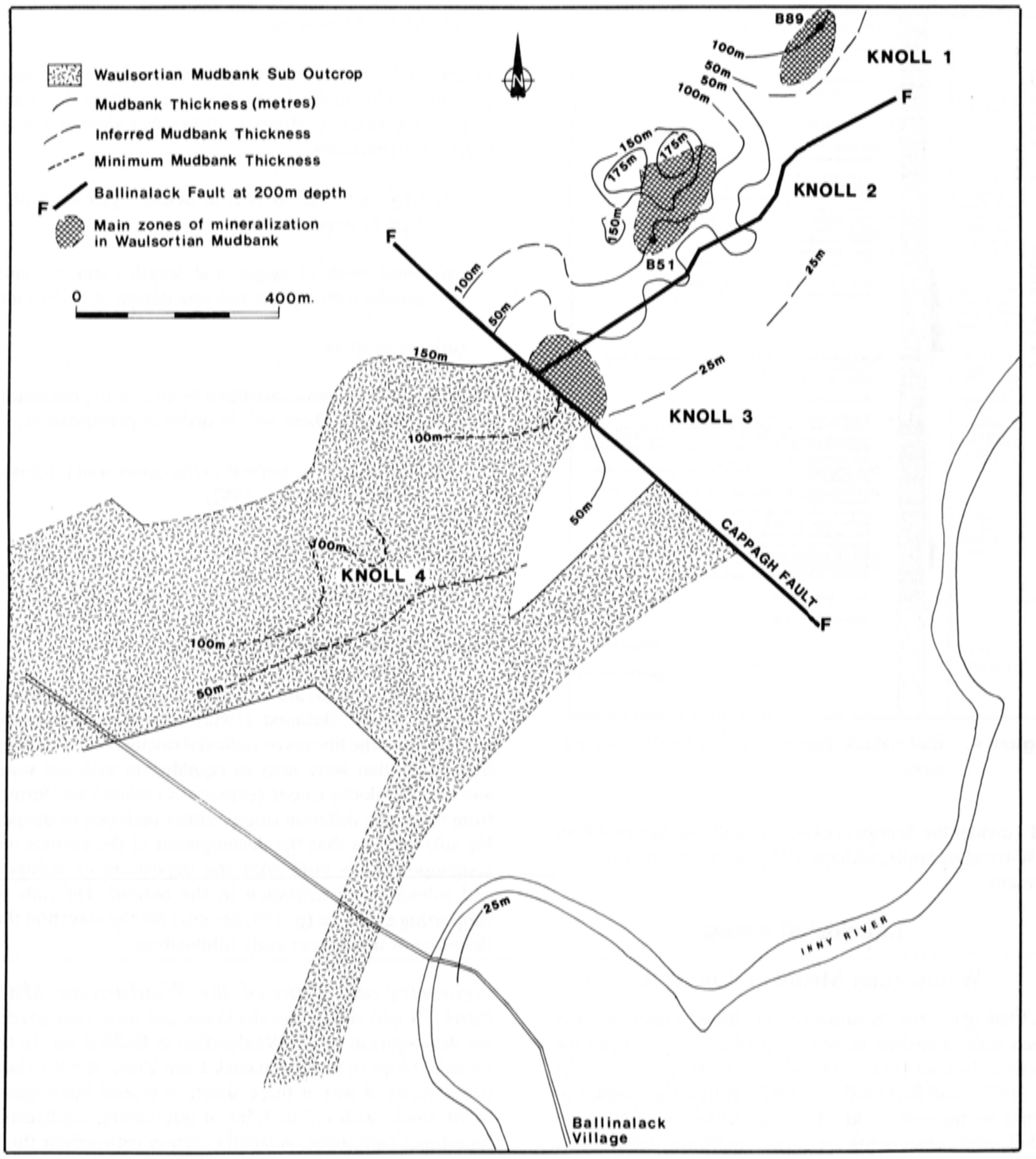


**Figure 5.** Ballinalack deposit: Mudbank isopachytes and mineralization.

greater. Between Knolls 1 and 2, the succession is reduced to some 30m of interbedded Waulsortian litho-facies, viz. shales and argillaceous limestones. The tops and bottoms of Knolls 1 and 2 appear to be at different stratigraphic levels, implying that their growth began at slightly different times at each centre, coalesced and overlapped at the time of their maximum development, and then separated in their waning stages. The tops of the mounds show little or no topographic relief and are not markedly diachronous, unlike their bases. Marker beds within the overlying sediments parallel the top of the mounds, and there is no suggestion of draping of sediment over them (Figs. 6 and 7). Although the eastern margin of the mounds is obscured by the effects of the Ballinalack Fault Zone and the critical relation with off-mound sediments is not seen, it appears that their rate of upward growth did not exceed that of the laterally equivalent sediments. This implies that subsidence was taking place along the precursor of the Ballinalack Fault during deposition of the Waulsortian and that the rate of growth of the mounds kept pace with subsidence.

Thin beds of crinoidal shales are present within each knoll. A characteristic example, having some haematitic alteration which imparts a reddish discolouration to the rock, occurs at about the middle of the complex. This, and other shale units, tend to die out westwards in the direction of increasing thickness of the knolls and cannot therefore be used as reliable marker beds.

## Mixed Beds

Mineralization in the Mixed Beds has been observed at several different stratigraphic levels, but the better developments are confined to two separate lithological units — the Bird's Eye Micrite and the Upper (Calcareous) Sandstone.

The Bird's Eye Micrite is a distinct unit some 25m thick. It is the stratigraphic equivalent of the Navan Micrite,

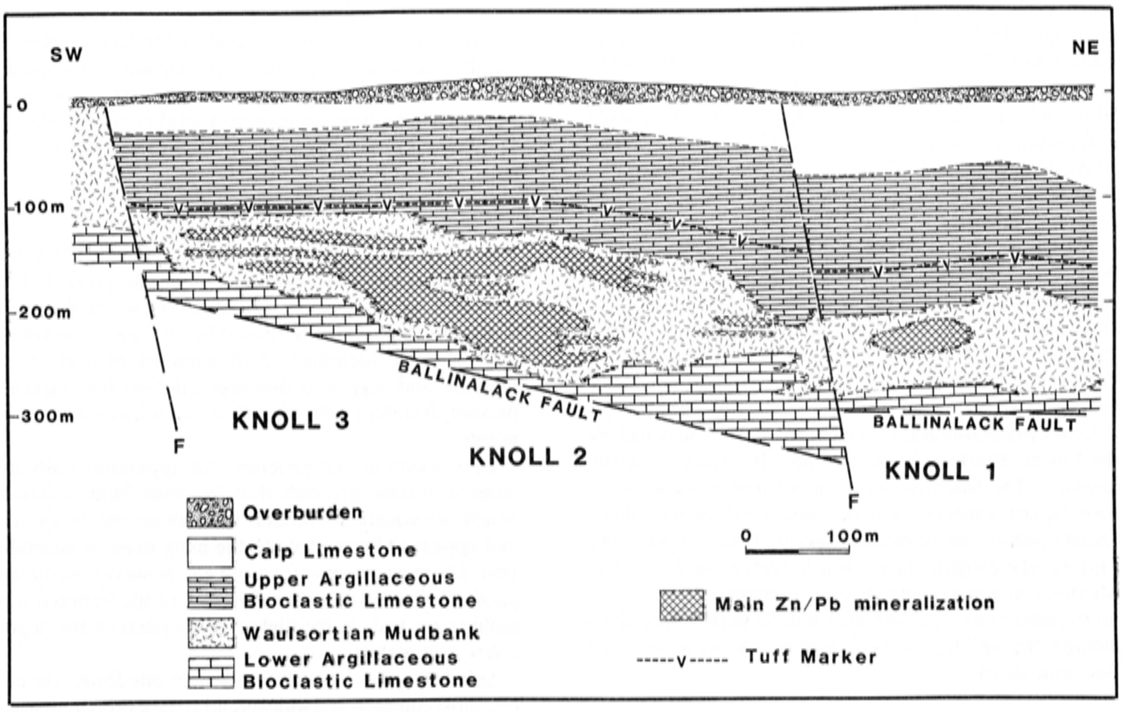


**Figure 6.** Ballinalack deposit: cross section.

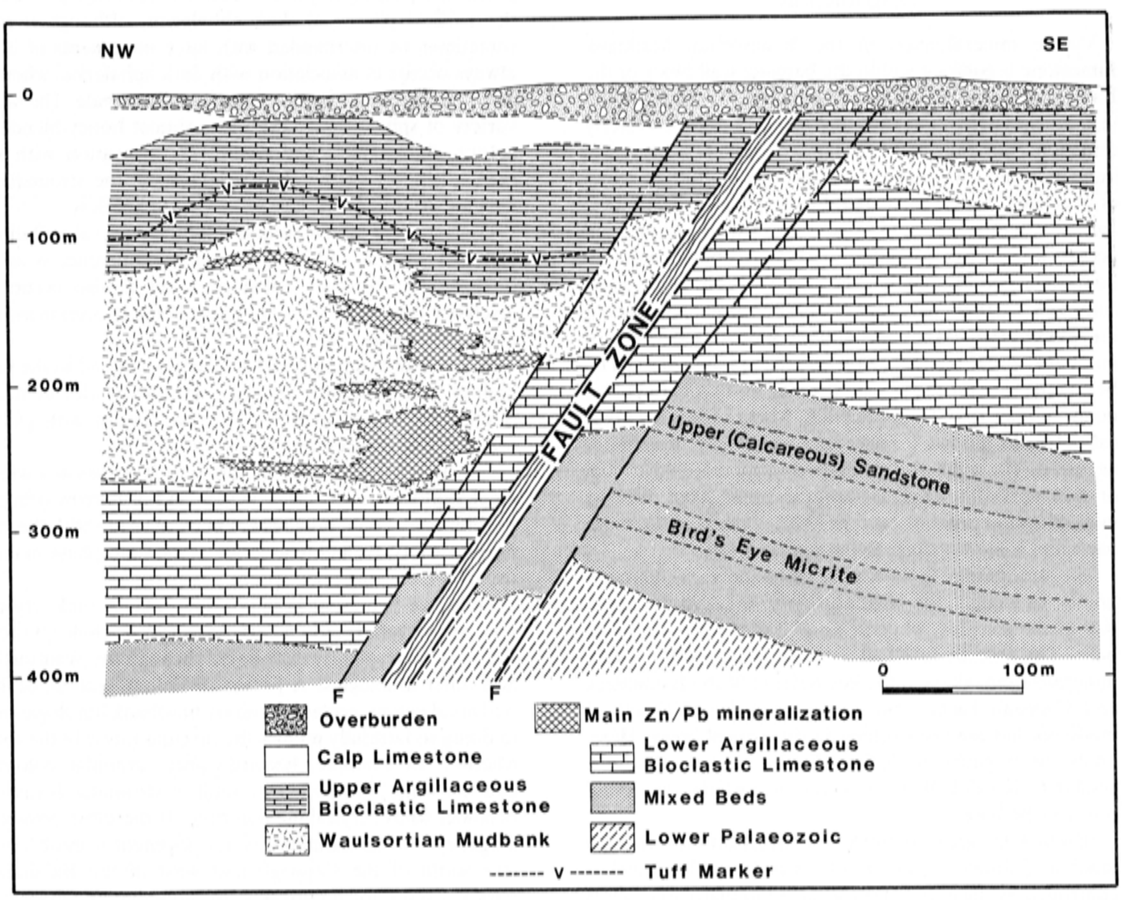


**Figure 7.** Ballinalack deposit: longitudinal section.

which is the lowest unit of the Pale Beds of the Navan succession (Philcox, 1984). Lithologically, it is a dark grey micrite with shaly laminae in the lower part. Bird's eye development is concentrated in the upper 5-10m. This fabric, which is also known as fenestral fabric, is believed to represent the remains of small gas-filled cavities (Shinn, 1968). They are usually filled by calcite, but barite may also be present. The best mineralization is confined to this upper portion of the Micrite.

The Upper (Calcareous) Sandstone is approximately 40m thick. It is a pale grey, well sorted, medium-grained sandstone with a mixed assemblage of clasts. Beds with oolites and bioclastic debris are present, but the chief constituents are quartz and microcline, in a calcium carbonate cement. Petrological evidence suggests that it had a well developed primary porosity.

Other mineral-bearing units in the Mixed Beds include the Lower (Pale) Sandstone and the "Intraclastic Conglomerate". The Sandstone in its upper part is a pale, well-sorted quartz sandstone with occasional beds of black shale. Quartz-pebble conglomerates occur lower down. The "Intraclastic conglomerate", which overlies the Bird's Eye Micrite, contains a variety of coarse carbonate components, up to pebble size, in a dark grey micrite matrix. The clasts include "rip-up" fragments of micrite, oncoliths and other bioclastic debris.

# Description of mineralization

## Waulsortian Mudbank mineralization

### Distribution

Visible mineralization in the Waulsortian Mudbank Limestone is confined within the hanging-wall block of the Ballinalack Fault. It extends over distances of at least 1.5km in a northeasterly direction, and 600m in a northwesterly direction, but the limits of mineralization are not yet known. Although it may extend through the full thickness of mudbank, high-grade mineralization is of limited extent and distribution. (Figs. 5, 6 and 7). The mineralization occurs in a series of rather narrow, elongate pod-like bodies, one to each of Knolls 1 to 3. Knoll 4, the most southerly, contains only weak mineralization. The axes of the mineralized bodies are sub-parallel to the trend of mudbank isopachs and to the Ballinalack Fault Zone. The best grades are found between the 50m and 120m isopachs, no more than 100m from the Fault. Mineralization neither extends into the Fault Zone nor, apparently, terminates against it. The width of a typical body is no more than 100m or so, and its strike length is usually less than 200m. Weaker mineralization tails out into the thicker parts of the mudbank and is more widespread at higher levels.

The stratigraphic level of mineralization varies between knolls. In Knoll 1, the most northerly, it lies in the upper half of the complex, while in Knoll 2 it occurs against the base. The relation in Knoll 3 is not clear, both because mineralization occurs at the intersection of the Ballinalack and Cappagh Faults, and because the full thickness of mudbank has not been drilled in the critical areas. High-grade intersections at shallow depths suggests that it is similar to Knoll 1. In Knoll 4 the best grades are found towards the base.

In detail, the grade and style of mineralization within the mudbanks shows a pronounced vertical zonation which is controlled by the distribution of intra-mudbank shale units or the base of the mudbank, as the case may be. The best grades are immediately above the impermeable barrier at the base of a given section, and mineralization does not usually extend into the shale units. Upwards, the quantity and complexity decreases progressively (Figs. 8 and 9). There is a similar progression to a weaker and simpler style of mineralization away from the Ballinalack Fault.

### Mineralogy

$FeS_2$ (pyrite-marcasite), sphalerite, galena and barite, in a calcite gangue, are the main minerals present. Silver is associated with galena. Halls (1971) noted that colour variations in pyrite were caused by changes in nickel content. He also identified small amounts of bravoite and millerite and suggested that argentiferous boulangerite is present. Bradfer (1984) identified minor quantities of bournonite.

$FeS_2$ occurs in two varieties. An apparently early form consists of small greenish clots less than 5mm in diameter which are widely distributed throughout the Waulsortian and appear to form a halo to the main mass of mineralization. The most common form of $FeS_2$, however, is collomorphous, in bands whose thicknesses range between a few millimetres and, in the higher grade parts of the deposit, a few centimetres.

Sphalerite also occurs in more than one form. The earliest, most common and widespread is dark brown, collomorphous, and occurs in bands of a few millimetres in thickness. A red to brown, fine-grained variety which usually occurs as inclusions within carbonate is also an apparently early form. A pale brown collomorphous variety is sometimes present, especially in parts of Knoll 2. It always post-dates the earliest phases of dark sphalerite, although it may sometimes be interbanded with later increments of it. It always occurs in association with dark sphalerite, whereas the dark variety is often independent of the pale. The latest variety of sphalerite is very pale, almost honey-blende in colour, fine-grained and occurs in association with the post-sulphide Fe-rich calcite which seals the stromatactis cavities, or in narrow, late-stage calcite veinlets.

Galena is the least common sulphide mineral at Ballinalack. Its earliest and most common occurrence is as an intergrowth with dark sphalerite, but it also occurs as discrete cubes. In Knoll 1, late-stage galena occurs in association with barite.

Barite is not common and is usually confined to the very highest grade sections, where very fine blades of it are intergrown with sulphides. The association with galena noted above is exceptional.

Calcite is the main gangue mineral. It occurs as a white, blocky infill of stomatactis cavities and as narrow veinlets. Pyrobitumen commonly occurs in association with the cavity-fill variety, probably as a late stage fluid phase making use of pre-existing open space.

Dolomite is present in minor amounts. A pink, crystalline, vuggy variety, often with fine-grained chalcopyrite in the vugs, is irregularly distributed through the Waulsortian and other lithologies. A pervasive dolomitization, of limited areal extent, replaces primary mudbank lithologies and in doing so faithfully mimics the original fabric of the rock. Micrite, for example, becomes grey, granular dolomite and the white, blocky calcite infill of stromatactis cavities becomes white, crystalline dolomite. It therefore postdates diagenesis of the mounds. Its development is more extensive south of the Cappagh and west of the Ballinalack Faults, except for a narrow strip immediately adjacent to the Ballinalack Fault Zone itself.

## Styles of mineralization

The mineralization within the Waulsortian may be subdivided, by style and mode of occurrence, into five groups,

(i) Cavity-lining,

(ii) Interconnected cavity-lining,

(iii) Massive sulphide,

(iv) Fracture-lining, and

(v) Breccia and late fracture-fill.

Groups (i) to (iii) form a continuum of increasing complexity and intensity with depth within the mounds and with proximity to the Ballinalack Fault. There is considerable overlap between groups. The amount of replacement, both of carbonate and of sulphide by sulphide, also increases in the same direction. The basic pattern is related to the development of stromatactis and other cavity systems formed during diagenesis and can be recognized throughout a mineralized section, however much modified.

*Cavity-lining mineralization.* This, the simplest style of mineralization (Plates 1a and 1b), occurs at higher levels within the mounds and at greater distances from the Fault. It is characteristic of low grade, weakly mineralized sections and is the most widespread type. It takes the form of layers, no more than 1mm or so thick, of collomorphous sulphide deposited on the floor of stromatactis cavities. Progressively, as the intensity of mineralization increases, sulphide layers (usually of dark sphalerite) completely coat the cavity walls. They overlie the various generations of fibrous calcite and other Fe-poor cements. Where geopetal sediment is present, the sulphide may either overlie or be overlain by it. It encases the blocky, Fe-rich, white calcite which sealed the cavity. Typically, the mineralization occupies the larger stromatactis as described by Bradfer (1984).

Mineralization increases in grade down section by the incremental addition of sulphide layers, either of the same mineral or of alternations of sphalerite and $FeS_2$. Layers of geopetal sediment may also alternate with sulphide bands, indicating that emplacement of mineralization was not a continuous process. The intensity of mineralization is crudely related to the size of the cavity, but the thickest accumulations of cavity-lining mineralization rarely exceed 1cm. At still lower levels, several generations and phases of sulphide overlap with geopetal sediments and with each other, as shown in Plate 1c. Where concentric layers of sulphide line the cavity, the layers show distortion by buckling of the roof and consequent partial closure of the cavity. A deposit of finely layered sulphide sometimes outlines the newly-modified cavity (Plate 1d).

This style of mineralization does not yield good grades except over short lengths.

*Interconnected cavity-lining mineralization.* This style of mineralization begins to be seen at intermediate levels within a typical section and in part overlaps with both groups (i) and (iv). It yields moderate to good grades, with values generally increasing down section.

The basic cavity-lining style is still recognized, but the cavities are much enlarged and linked by the fractures superimposed on them (Plates 2a and 2b). At its simplest, this style of mineralization consists of narrow pipe-like connections between small cavities. The "pipes" or "chimneys" have curved outlines, while the "rooms" retain the characteristic stromatactis geometry. The scale of cross-cutting is difficult to determine from drill core, but it seems that it can extend over intervals of at least several tens of centimetres.

An early-formed phase of cavity-lining mineralization was affected by the fracturing, and brecciated sulphide clasts and freshly exposed wall-rock are coated by later pulses of mineral. The later-formed sulphides cross-cut the fabric of the host sediment, although still confined within the cavity system.

Increasing intensity of fracturing produced yet more brecciation which released angular clasts of host sediment to be coated by sulphide. Partially sealed stromatactis cavities occur within these clasts, but their internal cements are not in any way affected by mineralization. The contact between mineral and the host carbonate, whether in wall-rock or breccia clast, is sharp and shows little, if any, evidence of replacement by sulphide. The reason for this appears to be that a layer of dark brown sphalerite formed a protective coating on clast and wallrock and precipitation of the later sulphide took place within this enclosed environment (Plate 2a). However, where sulphide and wall-rock are in contact, the wall-rock may be either fibrous calcite or uncoated micrite.

The increased intensity and complexity of fracturing brought about a corresponding increase in intensity and complexity of mineralization. Within enlarged cavities, there is clear evidence of sulphide replacing sulphide, usually $FeS_2$, by an intergrowth of dark sphalerite and galena. (This stage of mineral development is usually the earliest at which galena is present in any quantity.) At this intensity of mineralization the cavity system is virtually entirely filled by sulphide, with little room for the blocky calcite cement which usually seals the cavities (Plate 2c). The higher-grade sections of this class of mineralization are of the latter type.

*Massive sulphide.* In the high-grade, basal part of a vertical section of mineralization, the processes described above were taken to their extreme and the deposit at this level is best described as a complex massive sulphide. To reach this state, obviously, requires whole-scale replacement of carbonate by sulphide. Some remnants of cavity-lining mineralization are recognizable, usually in the form of sub-horizontal, banded dark sphalerite which appears to mark the position of the former cavity floor. A *mélange* of sulphide of several generations occurs above such bands. It shows repeated brecciation, recementation and replacement of sulphide by sulphide. $FeS_2$ is the dominant sulphide phase, followed by dark sphalerite. During this phase galena is much more common, either as an intergrowth with sphalerite or in isolation. Barite, coarse galena and sometimes pale sphalerite occupy any cavity space that remained.

Relict carbonate, as small clasts occluded by sulphide or as fine sediment, fills space between sulphide clasts (Plates 3a and 3b). The coarse, blocky calcite which elsewhere seals cavities is rare in this class of mineralization.

*Fracture-lining mineralization.* This class of cross-cutting mineralization is independent of cavity systems, unlike that of group (ii) (Plate 4a). The fractures or fissures, which may extend over intervals of a metre or so, are lined, usually with alternations of dark and pale brown sphalerite up to 1cm or so in thickness. $FeS_2$ is rare in this class of

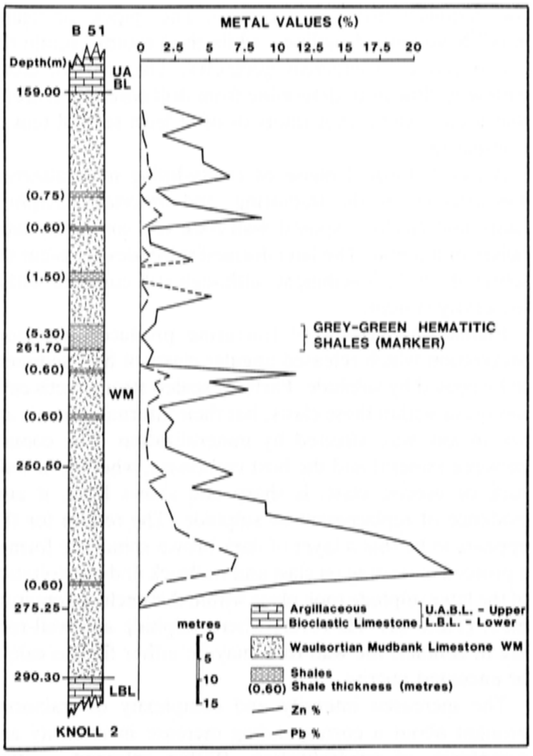


**Figure 8.** Ballinalack deposit: vertical distribution of metal values (Hole B51).

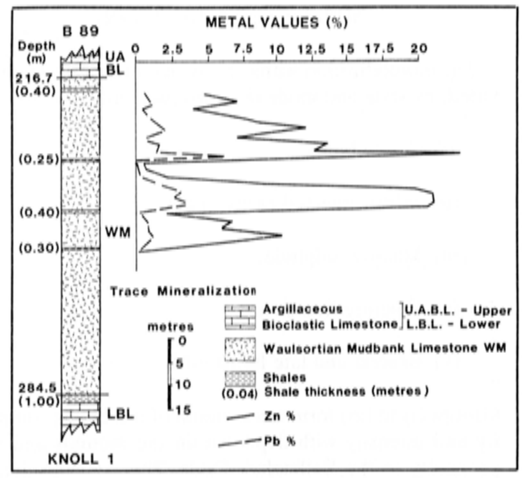


**Figure 9.** Ballinalack deposit: vertical distribution of metal values (Hole B89).

mineralization. It may be significant that pale sphalerite is much more prominent in this than in other classes, but the cause of this apparent association is not known. The sulphides are usually in direct contact with the wallrock with no intervening layer of fibrous calcite. (Sometimes, very fine-grained sphalerite is disseminated within host carbonate around the margin of a cavity or fracture; removal of carbonate by pressure-solution would leave a fine-grained sphalerite residue along the pressure-solution surface.) The contact is normally stylolitic, and the sulphide layers moulded to it by micro-folding with sharply angular axial crests. Larger-scale buckling of sulphide layers with shortening in the vertical sense has also occurred. This style of mineralization may overlap with groups (i) and (iii), but differs from (iii) in that the sulphides are simpler; usually only pale sphalerite is present. By itself it yields weak to moderate grades of mineralization.

*Breccia and late-fracture mineralization.* Mineralization falling in this category is not well developed, either in areal extent or intensity. However, some breccia-lining sphalerite mineralization is sporadically developed. The clasts are small (less than 2.5cm in diameter) and angular. The brecciation appears to be related to internal collapse within stromatactis and related cavity systems, but the mounds at Ballinalack have not, as far as can be determined, undergone extensive brecciation. Examples are shown in Plates 4b and 4c.

Weak, sub-vertical vein or fissure-lining mineralization occurs beneath the high-grade sections in Knoll 1 and peripherally to better grades of mineralization elsewhere. The sulphide is brown sphalerite and is clearly late since the veins or fissures cross-cut sealed stromatactis cavities. The fissures themselves are not lined by fibrous calcite, nor do they have stylolitic margins, but they are sealed by blocky white calcite. The example shown in Plate 4b, is cut by calcite veining. This style of mineralization does not yield good grades.

Sporadic mineralization is associated with late calcite-filled extension veins. The very palest, honey-coloured variety of sphalerite is irregularly disseminated through such veins, usually where they cross earlier-formed sulphides. Similar honey-coloured sphalerite also occurs in association with the blocky calcite which seals the cavities.

## Paragenesis

The textural evidence suggests a complex paragenesis, with episodes of mineralization overlapping in space and time. At any one level within the mounds the paragenetic sequence can be determined, but attempts to relate this to other parts of the deposit and the deposit as a whole are difficult, because there is ample evidence of replacement of early sulphide by later mineralization (typically $FeS_2$ by an intergrowth of sphalerite and galena). A tentative paragenetic sequence is presented in Figure 10. In simplified terms the following sequence is proposed:

> $FeS_2$ (early diagenetic/marine) — $FeS_2$ — dark ZnS-ZnS + PbS — pale ZnS — PbS — $BaSO_4$ — honey ZnS — blocky $CaCO_3$ + honey ZnS + pyrobitumen — fracture-fill $CaCO_3$ + ZnS.

## Mineralization in the Mixed Beds

Mineralization is present throughout the Mixed Beds sequence, over at least the same strike length as the main deposit. Its lateral extent is not known because it has been intersected only in a narrow strip along the footwall of the Ballinalack Fault Zone. The mineralogy is similar to that in the main deposit, but the proportions are different, barite being most abundant and $FeS_2$ much less. The best mineralization occurs in two units, the Bird's Eye Micrite and, to a lesser extent, the Upper (Calcareous) Sandstone. In addition, locally well-developed disseminations of sphalerite, galena and pyrite occur in the "Intraclastic Conglomerate" which immediately overlies the Bird's Eye Micrite. Occasionally, pyrite veinlets are seen in the Lower (Pale) Sandstone.

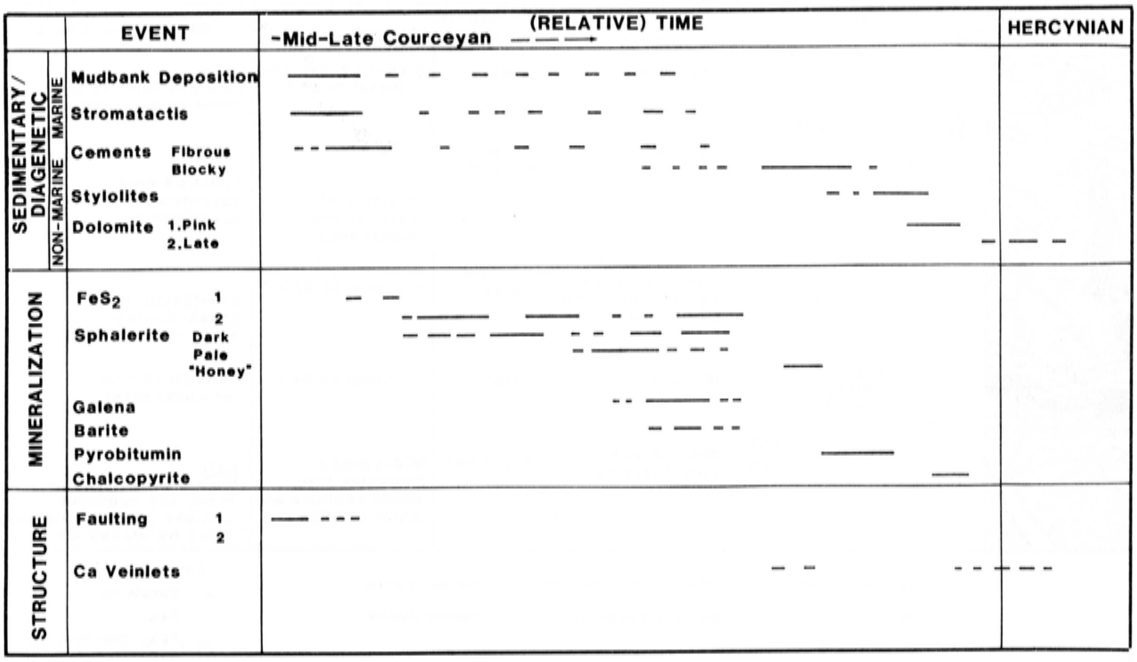


**Figure 10.** Ballinalack deposit: simplified paragenetic sequence.

## Bird's Eye Micrite

Mineralization in the Bird's Eye Micrite is predominantly cross-cutting, either as a fracture-fill or associated with dissolution along stylolites. The contact with the wallrock is generally sharp, but examples of non-selective replacement, with development of an irregular contact, have been observed.

Sphalerite is usually massive and paler in colour than that in the Waulsortian, with less well-defined banding. Galena tends to occur as large blebs, while $FeS_2$ is relatively insignificant.

Although mineralization has been demonstrated only over a narrow strip of ground, there is some suggestion of zonation. Galena, for example, locally forms very rich pockets of high-grade mineralization up to 1.5m thick.

In the "Intraclastic Conglomerate" (above the Micrite) disseminated sphalerite, galena and pyrite are present. Thin-section examination indicates that the sphalerite and galena selectively replace calcium carbonate in both cements and clasts.

## Upper (Calcareous) Sandstone

Disseminated sphalerite and galena occur throughout the sandstone, in varying quantities. Rare laths of barite several millimetres long are also present. The sulphides generally are intergranular and fine-grained. It appears that the sulphides, in part at least, replaced carbonate, although there is evidence that some of this replacement took place early in the diagenetic history of the sediment, before the rock became impermeable. Mineralization is similar to that described by Brand and Emo (this vol.) at Oldcastle, and probably has a similar history of emplacement.

# Origin of the Ballinalack deposit

Several conclusions concerning the origin of the deposit may be drawn from the foregoing description of textures and styles of mineralization, and these will be discussed in two parts. Firstly, the implications of the mode of occurrence and distribution of the different styles will be considered in relation to the genesis of the deposit, the timing of mineralization and the nature of the mineralizing fluids. Secondly, a model for the origin of the deposit will be proposed. Much of this discussion will apply only to the main mass of the deposit in the Waulsortian Mudbank Limestone, since it is better known, but attempts will be made to draw on relevant evidence from the Mixed Beds, where applicable.

## Genetic significance of styles of mineralization

(i) The basic style of mineralization is cavity-lining. It is now generally accepted that the fabric known as stromatactis is of early diagenetic origin (Bathurst, 1982). Since the cavity-lining mineralization overlies early marine cements it too is early, and follows the cessation of the phase of marine cementation. The interlayering of sulphide and geopetal sediment implies that this sulphide was very early, introduced while parts of the mound remained soft and able to supply internal sediment.

(ii) Features such as buckling of the roof of mineralized cavities and flat-lying stylolitic contacts between mineral and wall-rock probably occurred while the sediment was firm but not completely lithified, and probably in response to the effects of the weight of overlying sediment. Mineralization, in part at least, was therefore in place and was involved in the compaction processes. Relining of the newly-shaped cavity by thin layers of dark sphalerite suggests that the mineralizing processes were still active during compaction. This also supports an early origin for mineralization. (It might be argued that these coatings are the products of remobilization of early-formed mineral, but the later forms of sphalerite are usually paler in colour.)

(iii) The interconnected cavity-lining and fracture-fill mineralization (groups (ii) and (iv)) cross-cut the fabric of the mounds and clearly post-date the early, partially-sealed

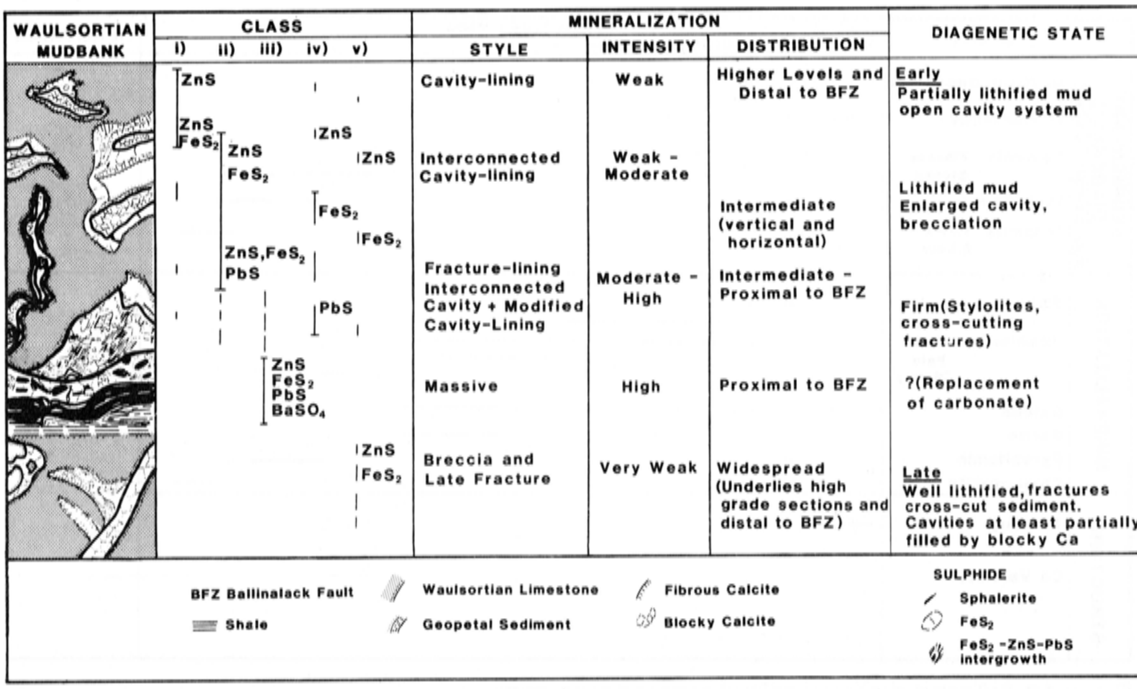


**Figure 11.** Ballinalack deposit: styles of mineralization and diagenesis.

cavities. The enlarged cavities which formed in response to this fracturing contain angular breccia clasts, which could only be produced when sediment had attained a certain state of cohesion and firmness. This style of mineralization is therefore somewhat later than the simple cavity-lining style.

(iv) The fracture-fill mineralization of group (iv) appears to be yet later. The absence of fibrous calcite cement between wall rock and mineral may be taken as evidence that this phase of fracturing post-dates the early marine cement. However, the margins are usually stylolitic and the wall rock often contains fine-grained disseminations of sphalerite, which may represent the residue left behind after removal of cement by pressure-solution. Other evidence, such as shortening in the vertical sense and micro-folding of sulphide layers, suggests that the fracturing and mineralization occurred before a great thickness of sediment was laid down, and before major tectonism took place.

(v) The evidence from the more massive sections of the deposit of repeated brecciation and recementation of sulphide by sulphide shows, again, that mineralization was not necessarily a continuous process but was active over some time, taking place in several pulses.

The conclusion, therefore, is that mineralization was contemporaneous with diagenesis of the mounds, and that the characteristic styles correspond to different states of diagenesis or firmness of the sediment. Heckel (1972) describes a series of cavity systems, which he believes evolved in response to advancing states of diagenesis, in mounds similar to those at Ballinalack. These cavity systems form a continuum, from typical stromatactis formed while the sediment was still soft to late dessication fractures formed when the sediment had become firm. According to Heckel, these textures form in response to dewatering of the mounds. The similarity in appearance between the fabric described by Heckel and that which is mineral-bearing at Ballinalack implies that they have a similar origin. Mineralization and diagenesis were therefore coeval.

The simple, cavity-lining mineralization is therefore early, relative to the diagenetic state of the sediment, and it formed at higher levels within the mounds while the sediment was soft; the cross-cutting and fracture mineralization, however, was emplaced at deeper levels at a later stage of diagenesis. (The mineralizing processes may also have assisted in keeping the fractures open.) All textural styles could have formed from a single pulse of mineralization, depending upon at which level in the mound precipitation took place. As diagenesis proceeded, styles characteristic of early stages would be overprinted by those related to more mature stages. The textural evidence bears out this conclusion. These relations are illustrated diagrammatically in Figure 11.

## Absolute age of mineralization

The criteria drawn on in the preceding section establish the age of mineralization relative to diagenesis but they cannot be used to establish the absolute age of the deposit. (Halliday and Mitchell (1983) quote ages of 222 and 239Ma, but these dates do not accord with the textural evidence.) The only conclusion to be drawn is that mineralization began after the precipitation of the Fe-poor, marine, fibrous calcite cement, but before the Fe-rich non-marine phase of cementation, the age of which cannot be established from the available evidence.

Taylor (1984) provides indirect evidence for early development of mineralization at Ballinalack from his study of the Silvermines deposit. At Silvermines, mineralization occupies depressions between the Waulsortian mounds, in sediments which are partly equivalent to, but mostly just slightly younger than, the mounds themselves. Mineralization does not penetrate the fabric of the mounds and the

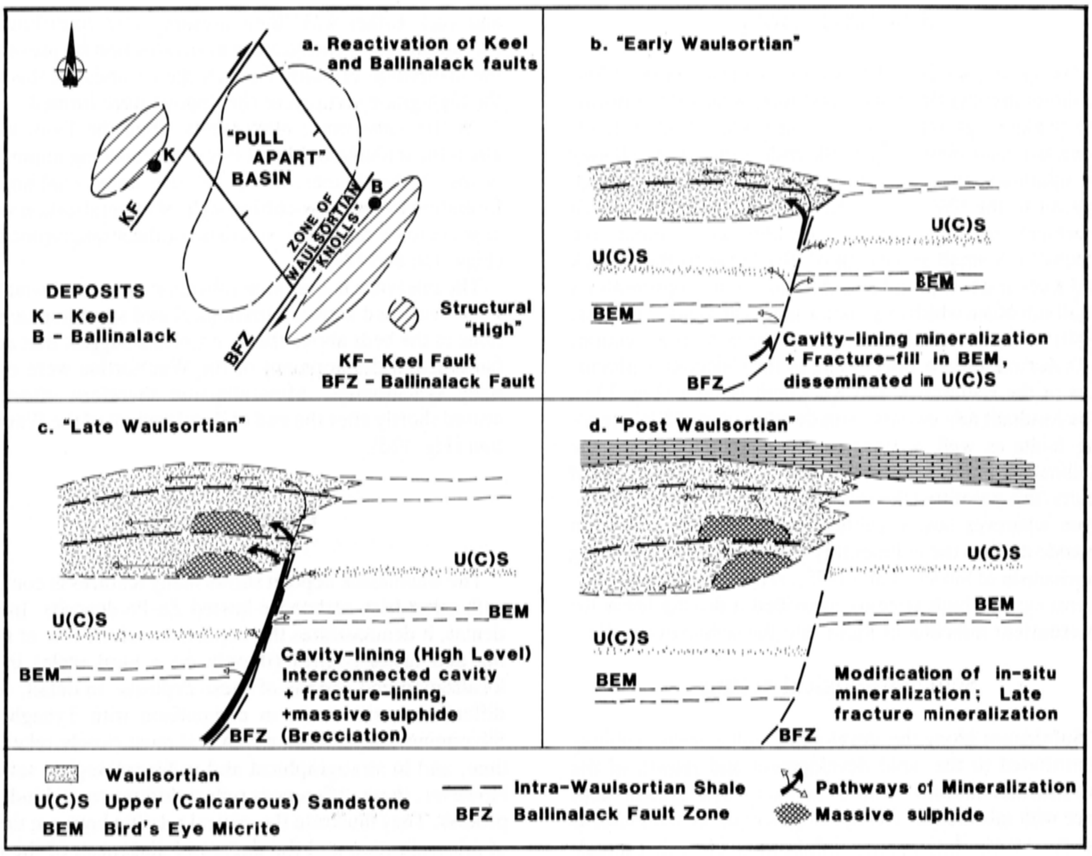


**Figure 12.** Ballinalack deposit: origin of mineralization.

implication is that the cavity system, which was indeed present, had been sealed very rapidly and before mineralizing fluids entered the system. In contrast, the mineralizing process at Ballinalack pre-dates the sealing of the cavity-system, which is itself an early diagenetic event.

Further evidence for the relative age of mineralization is provided by its relation to dolomitization, fracturing and faulting. The mineralization is cut by narrow calcite veinlets, while pervasive dolomitization (of limited areal extent) reflects the post-diagenetic fabric of the mudbanks and is therefore later than the blocky calcite cement. Incorporation of fragments of pink dolomite in the fault gouge suggest that all of these events took place before the main movement on the Ballinalack Fault, which, it is assumed, occurred during the Hercynian orogeny. The mineralization is therefore pre-Hercynian, and is most likely to be early Carboniferous (Late Courceyan to Arundian) in age.

## Nature of the mineralizing fluids

Sulphur isotope studies undertaken by Caulfield et al. (this vol.) show that $\delta^{34}S$ values for $FeS_2$, sphalerite and galena are composed of both light and heavy sulphide fractions. They conclude that the light fraction (found in early pyrite) was derived from seawater by bacteriological reduction, and the heavy fraction (found in sphalerite, galena and some $FeS_2$) from a deep-seated source. The range of observed values therefore represents the mixing of sulphur from these two sources. Textural evidence of an early $FeS_2$ phase, separate from the main mass of sulphide, supports at least part of these conclusions. However, this early phase of pyrite is not extensively developed and it would be premature to conclude that the deposit as a whole is the product of mixing of two fluids.

Lead isotope data obtained by Caulfield et al. (this vol.) show that Pb is non-radiogenic, is well homogenized and is similar to samples from Keel, Tynagh and Silvermines. They conclude that the Pb from all four deposits is derived from a similar, deep-seated, basement source.

Fluid-inclusion data are not available. However, an empirical relation, quoted by Finlow-Bates (1984), between Ag content of galena and temperature of formation, suggests that the Mudbank mineralization at Ballinalack plots at the upper end of the sedimentary-exhalative field, with a temperature of formation of approximately 150°C. This estimate is similar to results obtained by Probert (1983) who quotes modal values of 180°C and a range between 140 and 220°C for the Navan, Silvermines and Tynagh deposits.

For the deposit as a whole, replacement of calcite by sulphide is not extensive and the sharp contacts between sulphides and wall rock or breccia clasts suggest that the fluids were near to equilibrium with their environment and were not particularly aggressive.

## Genetic Model

The Ballinalack deposit, like many other mineral deposits, almost certainly owes its origin to the interrelated actions of several geological processes, and not to one single phenomenon. In this study and in this context, three factors are considered important, the structural setting, the sedimentological setting, and the entrapment mechanism (Fig. 12).

## Structural setting

The gravity study of Brown and Williams (1985) (Fig. 2) shows that the Ballinalack and Keel deposits lie towards the flanks of gravity "highs", which are probably fault-bounded, near their NW and SE ends respectively. (It may be significant that both these deposits, and the Tynagh deposit to the SW, lie towards the steep gradients which represent major basement features and bound the "highs".) A small gravity "low" lies between Ballinalack and Keel and it is postulated that this "low" representes a small sub-basin which originated as a "pull-apart" (Rogers, 1980) in early- to mid-Courceyan times by reactivation, with dextral sense of movement, of the Caledonian precursors of the Ballinalack and Keel fault systems (Fig. 12a). The resultant movements, with development of NW-trending faults as well as transcurrent displacements on the Ballinalack Fault, created dilatancy at the intersections of faults; this permitted the movement of mineralizing fluids, from whatever source (either within the basin or from outside it), into the sedimentary pile. The seismic pumping mechanism of Sibson et al. (1975), related to minor adjustments on the fault systems, provided a driving force for intermittent injection of fluids into the sedimentary pile.

## Sedimentological setting

Subsidence along the developing fault system probably contributed to the rapid development and growth of the Waulsortian mounds, and it is likely that growth kept pace with subsidence. The development of the stromatactis cavity system during early lithification of such mounds provided both a permeable and porous host for mineralizing fluids. The facies contrast between the mound and off-mound lithologies, both across the Ballinalack Fault Zone and between knolls, acted as permeability barriers which channelled and confined the ascending fluids. The knoll forms probably emphasized this effect, with the result that mineralizing fluids were concentrated within a comparatively small volume of rock.

## Entrapment of mineralization

The mechanisms invoked above would not by themselves be enough to cause a substantial mineral deposit to form, since the well-developed permeability would allow mineralizing fluids to dissipate through a large volume of rock. Alternatively, fluids would either escape to the sea-bed or seawater would penetrate and circulate freely though the mounds. In either case the effect would be the same, viz. metals would be rapidly oxidized.

The restriction of circulation needed to prevent such free movement of fluids would have been brought about by precipitation of the early, marine, fibrous calcite cement which choked up the cavity system. Seawater penetration would then be confined to the outermost few metres of the mound, while waters already trapped within the mounds would quickly become anaerobic. Mineralizing fluids introduced from sources outside the mounds would be similarly confined. There would be limited mixing of the two fluids, as indicated by the isotopic evidence. However, this is not to suggest that the deposit was formed as a result of mixing of two fluids.

The intra-mound shales, acting as impermeable barriers, served to hold up fluids and by so doing contributed to the development of porosity within the lime mud, as well as serving as channelways for movement of fluids (Figs. 12b and 12c). Either way, their presence also contributed to containing and concentrating mineralization by preventing the dissipation of fluids through the mounds. In this way, the high-grade sections of the deposit were formed.

At the same time, movements along the Fault would affect the underlying Mixed Beds by producing minor fracturing in the cleaner, more uniform units, enabling the formation of the cross-cutting style of mineralization which appears to be more characteristic of the stratigraphic level (Figs. 12b and 12c).

The inference is that mineralization continued while the Fault remained active. Lithological and stratigraphic relations of the beds above the Waulsortian suggest that active faulting and development of the Waulsortian were essentially synchronous. Mineralization therefore effectively ceased shortly after the end of development of the Waulsortian (Fig. 12d).

# Conclusions

The Ballinalack deposit shows many features in common with other Irish carbonate-hosted Zn-Pb deposits. In particular, it demonstrates the importance of the role of faulting and facies control (if only on a local scale) in the localization and genesis of these deposits. In detail, some differences exist, even in comparison with Tynagh and Silvermines, deposits to which it is most closely related in time, and in stratigraphical and sedimentological setting. However, these differences reflect differences in kind, not process. They illustrate the critical relation between timing of mineralization and the degree of diagenesis of the host sediment. At Ballinalack, the stromatactis and related cavity systems within the Waulsortian Mudbank Limestone were still open when mineralizing fluids were introduced, producing the characteristic cavity-lining style of mineralization. At Tynagh, diagenesis of the Waulsortian had reached a more advanced state and the resulting textures show a greater mix, with limited cavity-lining but extensive fracture-lining mineralization (Boast, et al., 1981). At Silvermines, however, the Waulsortian was completely sealed at the time of introduction of the mineralization and therefore is itself unmineralized.

# Acknowledgements

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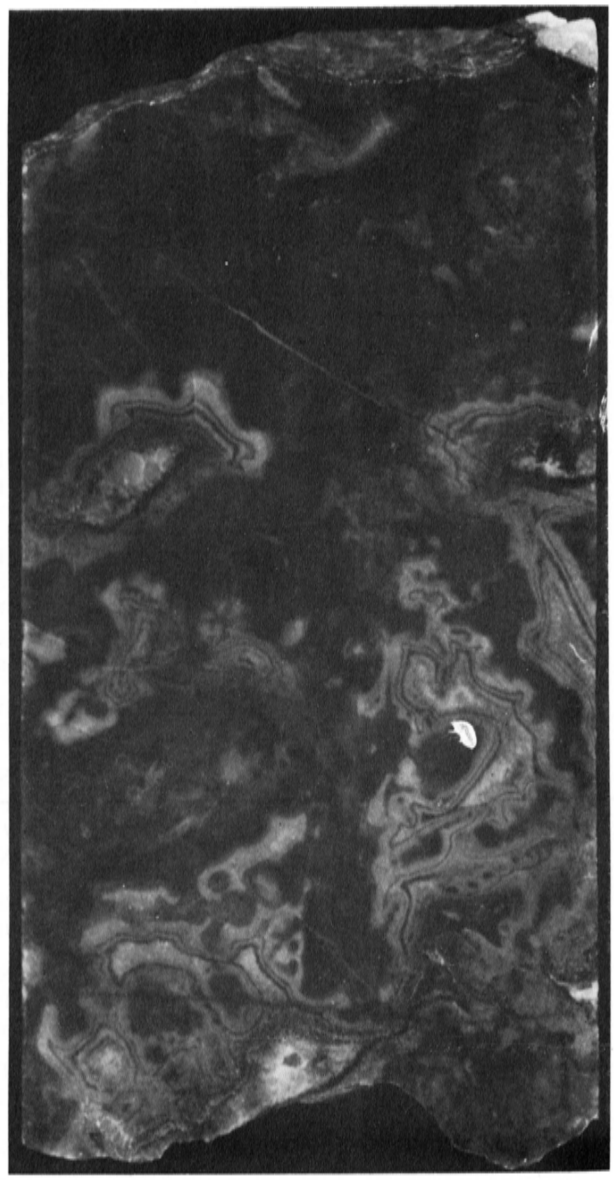
*PLATES 1-4 FOLLOW.*

**Plate 1.** Cavity-lining mineralization.

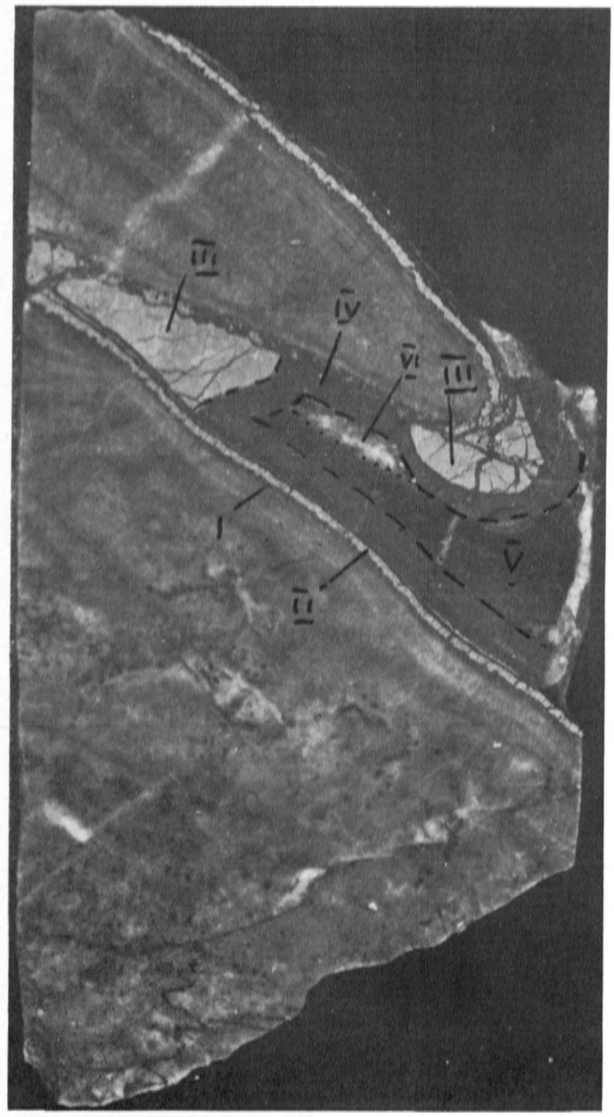
**1a.** Stromatactis cavity-lining mineralization: (light grey — fibrous calcite (Fe-poor), dark grey — sphalerite, white — blocky Fe-rich calcite)).



**1b.** Complex cavity-system with fine sphalerite (dark) coating fibrous calcite.

All samples: Width (diameter) = 3.65cm.

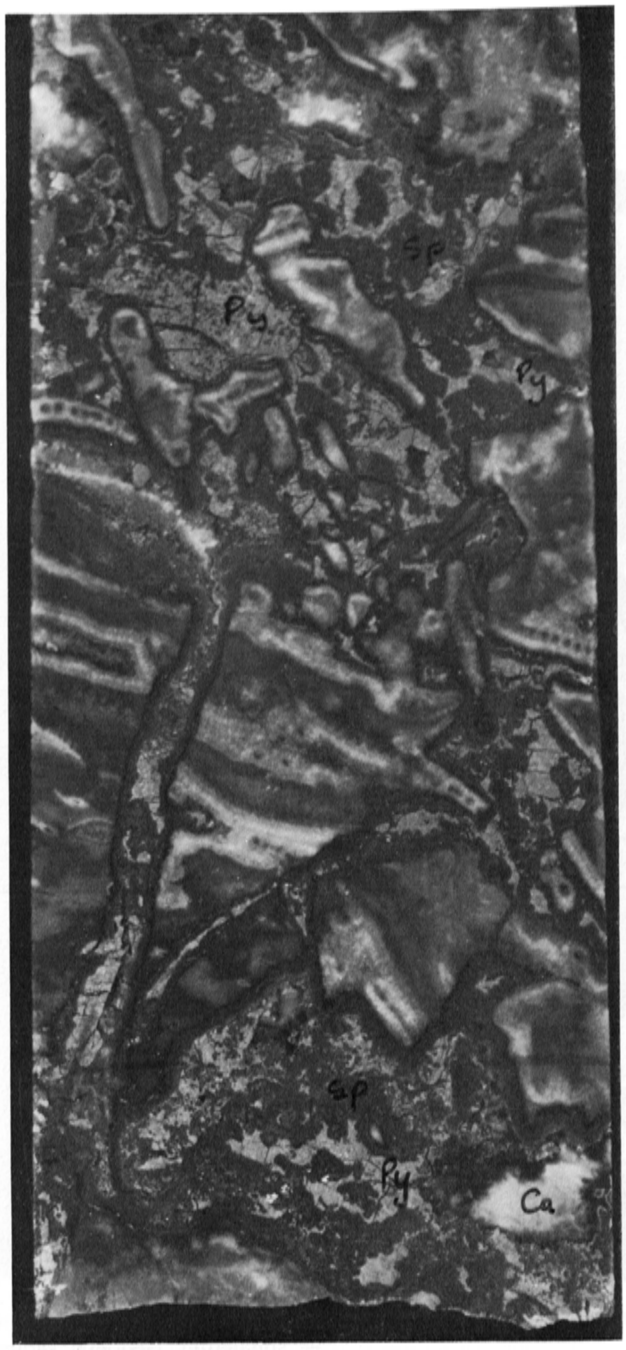
**1c.** Cavity-lining mineralization, alternating with geopetal sediment.



**1d.** Polyphase mineralization (light grey — pyrite, dark grey — sphalerite). Geopetal sediment-fill. Note discontinuous pyrite rims and sphalerite filled fractures in pyrite.

All samples: Width (diameter) = 3.65cm.

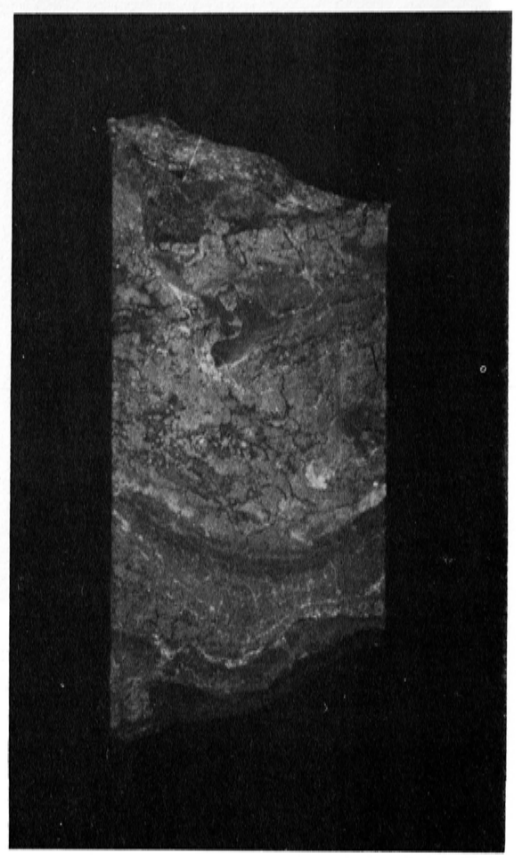
**Plate 2.** Interconnected cavity-lining mineralization.




**2a.** Complex pyrite-sphalerite intergrowth in cavity. Cross-cutting fracture is sphalerite-lined with complex sulphide-fill. Note fracture cuts partially-sealed stromatactis cavities.

All samples: Width (diameter) = 3.65cm.

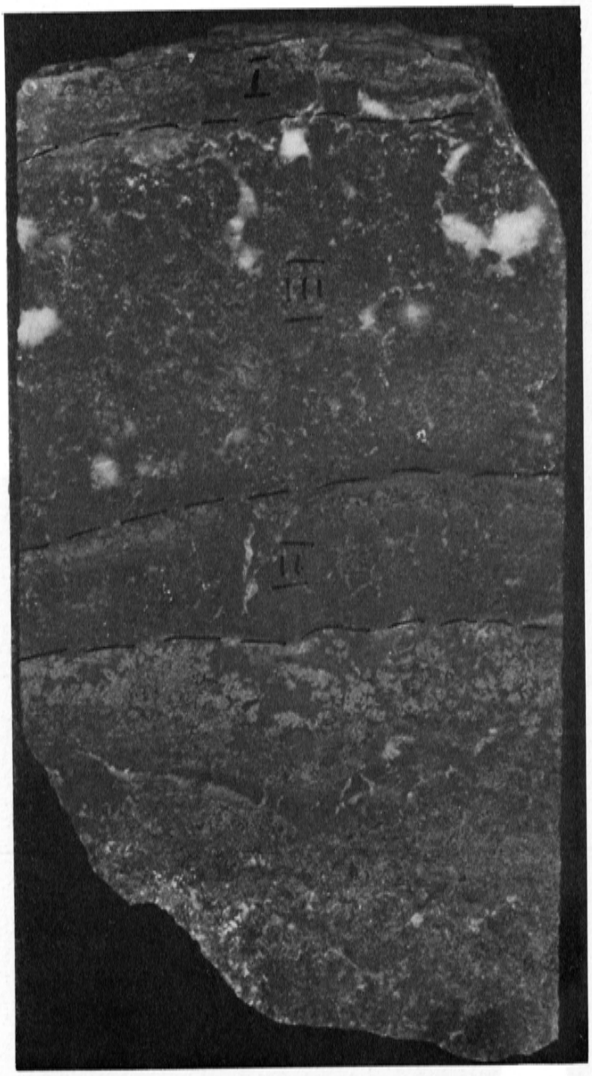
**2b.** Brecciated pyrite (light grey) with fine sphalerite coating (dark grey). Late sphalerite grains (mid-grey) in cavity fill.



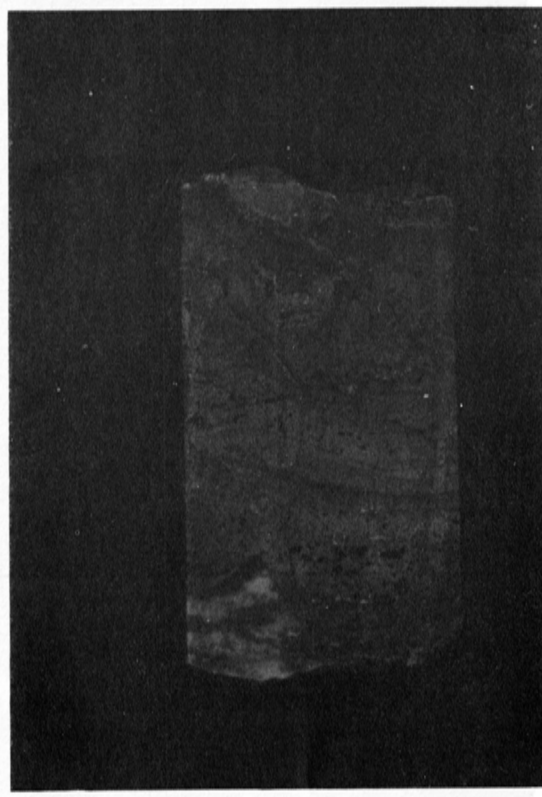
**2c.** Complex sulphide. Note finely-laminated sulphides at base (sphalerite), with amorphous pyrite cors. (White — calcite.)

All samples: Width (diameter) = 3.65cm.

**Plate 3.** Massive sulphide.




**3a.** Massive sulphides. Note zoning of sulphides, polyphase mineralization and relict carbonates [light grey]. (White — calcite.).



**3b.** Massive sulphides.

All samples: Width (diameter) = 3.65cm.

**Plate 4.** Fracture-lining, breccia and late fracture mineralization.

**4b.** Breccia mineralization. Sphalerite (dark grey) coating brecciated Waulsortian micrite.

**4c.** Late fracture with pale sphalerite, cross-cutting sealed stromatactis. Fracture may itself have re-opened with two generations of calcite-fill. Note fracture terminates against a sub-horizontal stylolite.

**4a.** Fracture or fissure lined with finely-laminated alterations of drak and light sphalerite. Note stylolitic contacts and crumpling of sphalerite laminae.

All samples: Width (diameter) = 3.65cm.