A review and classification of the Irish carbonate-hosted base-metal deposits.

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Abstract

The Carboniferous carbonate-hosted Zn-Pb deposits of Ireland have always posed a classification problem; are they sufficiently similar to the Mississippi Valley-type (MVT) deposits or the sediment-hosted massive sulphide deposits to be classified as such, or do they represent a unique massive sulphide type? The majority of the Irish Zn-Pb deposits are stratabound and occur in the basal Carboniferous mixed sequence of carbonate and clastic rocks (informally termed the Navan Group) or within Waulsortian facies and time equivalent rocks. In County Kildare, Zn-Pb mineralization cuts rocks stratigraphically above the Waulsortian facies.

Clearly, the Zn-Pb deposits within the Navan Group and Waulsortian facies are variants of the sediment-hosted massive sulphide class. Characteristic features shared with this group include: (1) zinc, lead and iron sulphides dominate, (2) significant silver and minor copper are associated, (3) the tectonic setting of the deposits was active during mineralization, (4) structure controls mineralization, and (5) sulphide precipitation temperatures range from 100°C to nearly 300°C. Texturally however, these deposits share characteristic features of MVT deposits such as geopetal and colliform sulphide mineralization, abundant sulphide brecciation, and stratabound fracture development, all indicative of post-sedimentation mineralization.

These textures may be explained by the interaction of hydrothermal fluids with mildly argillaceous carbonate host rocks, similar to those hosting most MVT deposits, in contrast with the dominantly argillaceous host rocks found in most other sediment-hosted massive sulphide deposits. Lithification of carbonate-rich rock versus argillaceous rocks immediately proceeds at vastly different rates. Chemical interaction of hydrothermal fluids with carbonate minerals differs from that with clay minerals. Differences in host rock behavior during mineralization based on host composition and competency may lead to macroscopic textural as well as temporal differences in the style of Zn-Pb mineralization.

The Zn-Pb deposits of County Kildare are hosted, in part, by rocks above the Waulsortian facies. Unlike other Irish Zn-Pb deposits, mineralization occurs in angular breccia zones which cut lithified rocks. These deposits display many of the characteristics of MVT deposits.

The copper deposits of southern Ireland are hosted by a basal Carboniferous mixed section of clastic and carbonate rocks which are older than the lithologically similar Navan Group to the north. Mineralization in these deposits occurs in veins and as massive replacement zones. The age of copper mineralization probably post-dates that of the sediment-hosted, massive Zn-Pb sulphide deposits to the north. There is no clear genetic relation between the Irish copper deposits and either the sediment-hosted, massive sulphide or MVT Zn-Pb deposits.

Introduction

Attempts to classify the "Irish-type" Zn-Pb deposits beyond the very broad group of sediment-hosted, stratiform sulphide deposits described by Gustafson and Williams (1981), have generally collapsed into a semantic argument on whether they belong to the Mississippi Valley-type (MVT) or to the sediment-hosted, massive sulphide type.

One of the authors is among those who have previously classified the Irish Zn-Pb deposits as belonging to the sediment-hosted massive sulphide class (Large, 1980), and the purpose of this paper is to examine critically the new data pertaining to the Irish deposits with respect to this class.

Sediment-hosted, massive sulphide deposits share the following features:

1. They dominantly contain zinc, iron, and lead sulphides, with significant silver and minor copper; barite may comprise a significant amount of the mineralization; fluorite is generally absent.

2. They commonly exhibit a pronounced metal zonation within the mineralization.

3. They are generally stratiform in shape, with bedding-parallel textures indicative of a "syngenetic" to syndiagenetic age of mineralization.

4. They are commonly associated with "feeder" structures.

5. They are generally hosted by argillaceous sediments that comprise part of a thick sequence of clastics or interbedded clastics and carbonates.

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6. They occur in areas which were tectonically and thermally active during the period of sedimentation and mineralization (Large, 1980; Smith, 1983).

Mississippi Valley-type deposits share these characteristics:

1. They contain primarily lead and zinc sulphides, with minor iron sulphides, barite and fluorite, and generally lack significant silver or copper.

2. They are found in carbonate rocks, generally in "clean" shelf or platform limestones.

3. They contain a significant amount of cross-cutting mineralization commonly in the form of breccias (Beales and Onasick, 1970; Anderson and McQueen, 1982; Heyl, 1983).

Although the absolute age of mineralization is not known in most MVT deposits (Sangster, this vol.), the distribution and form of the mineralization in these deposits indicates that it was emplaced epigenetically and, in most deposits, post-dated rock lithification.

Thus, the segregation of the Irish-type Zn-Pb deposits into the MVT or sediment-hosted, massive sulphide categories is essentially a division into epigenetic and syngenetic (or syndiagenetic *sensu* Gustafson and Williams, 1981, p. 142) mineralization respectively.

Before proceeding further the reader should perhaps consider the basic necessity of these classifications: should the Irish Zn-Pb deposits be classified as anything other than what they are — Irish-type carbonate-hosted deposits? For the purpose of exploration within Ireland, it is probably more than sufficient to base the geological target on the characteristics of the Irish deposits themselves, which are well described elsewhere in this volume. With respect to convincing management and investors about the economic potential of the Irish-type, one need look no further than the Navan ore body (5th largest zinc producer in the world; +70Mt, 10% Zn, 2.6% Pb; see Table 1). However, the further classification of the Irish-type may be important in attempting to evaluate the favourability of geological environments elsewhere in the world for hosting Irish-type deposits, as well as recognizing new targets within Ireland on the basis of global comparisons.

Regional geological setting of the Irish Zn-Pb mineralization

In order to attempt to classify the Irish-type base metal deposits it is necessary to provide a brief background on the regional geological setting of Ireland, particularly the Carboniferous succession which hosts the Zn-Pb mineralization. The geological evolution of Ireland has been summarized by Sevastopulo and Phillips (this vol.), but several points considered critical to mineralizing processes are highlighted here.

The consolidation of a landmass in the area now occupied by Ireland occurred during the Caledonian orogeny along the somewhat enigmatic "Iapetus Suture" (Phillips et al., 1976). The Caledonian orogeny involved metamorphism, plutonism and widespread fracturing of the pre-Devonian basement. This basement was subsequently uplifted, and alluvial and fluvial sediments of Lower and Middle Devonian age were deposited in fault-controlled continental basins in the SW, NE and NW portions of Ireland (Sevastopulo and Phillips, this vol.).

Following a period of uplift and erosion during the late Middle to early Upper Devonian, continental sedimentation resumed in the Upper Devonian. Throughout the Munster Basin (southern Ireland) great thicknesses, locally up to 6.5km (George et al., 1976), of red, grey and green conglomerates, sandstones, siltstones and shales (Old Red Sandstone) were deposited in fault-controlled basins (Gardiner and MacCarthy, 1981).

In the latest Devonian, the Munster Basin subsided below sea level, and marine sedimentation encroached over the Upper Devonian continental clastics onto the Irish shelf to the north. During the early Carboniferous (Courceyan Stage) continuing transgression established shallow marine conditions across the Irish shelf to the central portion of Ireland. The Courceyan stratigraphic succession indicates a north to south transition from littoral and sublittoral facies, through offshore carbonate sands with intercalated argillaceous beds, to deeper water Waulsortian facies limestones (Sevastopulo and Phillips, this vol.).

In many areas the basal portion of the shelf succession contains coarse- to medium-grained clastic rocks, similar in provenance to the Old Red Sandstone, which infilled an irregular, but generally peneplanar, unconformity surface. These rocks are overlain primarily by mixed siliciclastic and carbonate rocks in the south and mixed peritidal carbonate, clastic and locally evaporitic sediments in central Ireland, here termed the Navan Group (Philcox, 1984).

This mixed section is overlain by a thick sequence of argillaceous bioclastic limestones that is in turn overlain by the Waulsortian facies, a distinctive lithology in the Lower Carboniferous of Ireland. Much of the Waulsortian facies is composed of poorly fossiliferous, micritic limestone, containing well-developed stromatactis structures, derived from a mudbank complex. Waulsortian facies rocks blanket southern and eastern Ireland, but break up into individual knolls further north and east (Lees, 1961). The onset of Waulsortian facies deposition is not chronostratigraphic in Ireland, and ranges from mid-Courceyan in the south to earliest Chadian in the NE near Navan (Andrew and Ashton, 1985).

The Waulsortian facies was succeeded in the latest Courceyan to Chadian by the deposition of shallow water shelf limestones and deeper water carbonates and argillites ("Calp"). Unlike the generally "blanket-like" distribution of facies during the Courceyan, rapid facies changes and irregular facies distributions characterize the latest Courceyan to mid Viséan. Facies distribution was apparently largely controlled by a series of fault-controlled basins, such as the Dublin Basin, in which carbonate turbidites and local conglomerates were deposited. Shallow water carbonate deposition, dominated by oolite shoals, continued on shelves between these basins.

Simultaneously with deposition of carbonates on the Irish shelf, a starved, black-shale basin (the South Munster Basin) overlying the thick sequence of late Devonian and early Carboniferous continental and marginal marine clastic sediments formed to the south. Argillaceous sedimentation, with an extremely minor influx of carbonate debris from the adjoining shelf, continued in the South Munster Basin throughout the Courceyan to the Brigantian.

Volcanic activity began on the Irish shelf in the lower Chadian, as evidenced by minor mafic dykes and several thin tuff bands recognized throughout the north central Midlands (Philcox, 1984), and continued into the earliest Arundian. A major volcanic field, composed of bimodal

Table 1.

Irish Carboniferous base metal deposits — grades and tonnages

Deposits	Host rocks	Tonnage (million tonnes)	Zn+Pb %	Zn %	Pb %	Ag g/t	Cu %	BaSO₄ %
Navan	N	>70.0	12.7	10.1	2.6	3.5*		
Tatestown/ Scallanstown	N	3.1	5.4					
Moyvoughly	N	0.12	8.0					
Abbeytown	N	1.1	5.3	3.8	1.5	40.0		
Oldcastle	N	3.0	4.9					
Keel	N	5.0	7.0					
Garrycam	W	1.0						35
Silvermines	W(+N)	17.7	8.9	6.4	2.5	23.0		
Magcobar	W	5.0						85
Tynagh	W	9.4	6.2	3.2	3.0	30.6	0.3	
Ballinalack	W	3.5	7.0					
Courtbrown	W	1.0	5.5	3.5	2.0	14.0		
Carrickittle	W	0.15	7.5	6.0	1.5			
Boston Hill	S	1.0	4.0					
Harberton Bridge	S	0.5	7.0(?)					
Aherlow	N	5.5				44.9	0.9	
Mallow	N	4.0				27.5	0.7	
Gortdrum	N	3.8				23.0	1.2	
Ballyvergin	N	0.14				17.1	1.0	

*From mining production records.

N — in the Navan Group or its equivalents, and basal clastic rocks.
W — associated with the Waulsortian facies.
S — cuts supra-Waulsortian rocks.

composition lavas, tuffs and agglomerates developed in County Limerick (Strogen, 1973a and 1973b). Smaller volcanic centres, dominantly of alkaline basaltic composition, are recognized further north into the central Midlands. Minor basaltic volcanism occurred again in southern Ireland during the Asbian.

The tectonic environment of the Irish shelf from the late Devonian until at least the Arundian appears to have been extensional. However, the degree of tectonic activity varied considerably both spatially and temporally. In general, fault activity appears to have been most pronounced during two intervals, the late Devonian and the late Courceyan to Arundian. Late Courceyan to Arundian tectonism resulted in a series of generally NE-trending fault blocks. Bounding faults may also have had a transcurrent component of motion, although little concrete evidence for such movement has been documented. Many of the major faults may have utilized pre-existing fractures in the Caledonian basement (Williams and Brown, this vol.). Hercynian deformation began to the south of Ireland during the Lower Carboniferous (Ziegler, 1982 and 1984). Hercynian deformation affected the rocks of the South Munster Basin between the late Carboniferous and the Permian (Sevastopulo, 1981a), changing the local tectonic regime from extensional to compressional or transpressional.

Regional setting of sediment-hosted massive sulphide and MVT deposits — comparison with Ireland

The overall sedimentary and tectonic environment of Ireland from the late Devonian through the Carboniferous is similar to that of both the Selwyn Basin in the northern Canadian Cordillera (Carne and Cathro, 1982), which contains the sediment-hosted massive sulphide mineralization at Macmillan Pass, and the German Hercynian Basin, which contains the Meggen and Rammelsberg deposits (Hannack, 1981; Krebs, 1981). In all three areas large prisms of clastic sediments appear to have sharply abutted against well-developed carbonate shelves. The host rocks to the sediment-hosted massive sulphide mineralization in both the Selwyn Basin and the German Hercynian Basin were deposited during periods of limited volcanism, extensional tectonics and the initiation, or continuation, of compression of one basin margin. Relatively minor carbonate-hosted sulphide mineralization, generally classified as MVT type, is also present in the carbonate shelves bordering clastic sequences in the Hercynian and Selwyn Basins.

Unlike the northern Canadian and German clastic Basins, the South Munster clastic Basin lacks evidence of

extensional tectonism and the presence of volcanic rocks is extremely limited. Furthermore, sediment-hosted massive sulphide deposits comparable to those in the Hercynian or the Selwyn Basins have not been described from the Munster Basin.

Unlike the shelves and platforms that host most MVT deposits, the Irish shelf was tectonically active during deposition of the sediments that host mineralization. The majority of the MVT deposits of eastern North America and Silesia are located within thick carbonate sequences which lack volcanism or evidence of nearby contemporaneous tectonism. Also, unlike Ireland and the basins containing sediment-hosted, massive sulphide deposits, most basins adjacent to the shelf sequences hosting the MVT deposits did not undergo compression at, or immediately following, the period of host-rock sedimentation. The Alpine belt, however, shares many features with the Irish Carboniferous including limited volcanism and an extensional setting (Bechstaedt, 1979).

The geology of the Irish Zn-Pb deposits

Although the Irish carbonate-hosted Zn-Pb deposits have commonly been grouped together, it is instructive to subdivide the deposits into those that are broadly stratabound and those that are distinctly cross-cutting. These can be further subdivided into those deposits in which mineralization penetrates supra-Waulsortian facies rocks (Fig. 1). The stratabound deposits are generally restricted to two lithostratigraphic levels, the basal Carboniferous mixed sequence of carbonate and clastic rocks informally termed the Navan Group, and the Waulsortian facies rocks. The age-range of the host-rocks to the stratabound base-metal mineralization is generally similar throughout Ireland. The variety of lithologies that host the deposits reflects the chronostratigraphic facies distributions that resulted from north to south transgression during the early Carboniferous.

Stratabound Zn-Pb deposits in the Navan Group and the Waulsortian facies

The Navan deposit occurs in the basal Carboniferous Navan Group. In addition to the Navan orebody, mineralization within similar lithologies at the same lithostratigraphic position is found at a number of locations, most of which are in the northern Midlands (Fig. 2); these include Tatestown (Andrew and Poustie, this vol.), Oldcastle (Brand and Emo, this vol.), Moyvoughly (Poustie and Kucha, this vol.), Keel (Slowey, this vol.), Newtown Cashel (Crowe, this vol.), as well as Liscarton, Clogherboy, Moyvore, Sion Hill, and Clonabreany (Browne and Reid, 1984). A minor portion of the mineralization at Ballinalack (Jones and Brand, this vol.) is also developed in Navan Group rocks. Mineralization in these deposits and prospects is hosted by rocks ranging stratigraphically from the basal red beds, sandstones and conglomerates (Keel) to the upper portion of the Navan Group (Navan mine). The Abbeytown deposit in northwestern Ireland occurs within a separate basin from that which hosts the deposits and prospects in the Midlands, but occupies a similar, although younger, stratigraphic setting (Hitzman, this vol.).

Mineralization at Tynagh and Silvermines, the first major zinc and lead mines in Ireland, is primarily restricted to the base of, and within, the Waulsortian facies. Other prospects with mineralization developed in approximately the same

lithological setting are Ballinalack (Jones and Brand, this vol.), Garrycam (Keel) (Slowey, this vol.), Courtbrown (Grennan, this vol.) and Carrickittle (Brown and Romer, this vol.). In general, deposits associated with the Waulsortian facies occur south of those associated with the Navan Beds (Fig. 1).

Morphology of, and lithological controls to, the mineralization

The Irish Zn-Pb deposits are broadly stratabound. True stratiform mineralization is present only at Silvermines in the upper sulphide orebodies and in the Magcobar barite deposit (Andrew, this vol.) and at Navan in the Boulder Conglomerate (Ashton et al., this vol.).

At Navan, and at the other deposits hosted by the clastic and carbonate rocks of the Navan Group, mineralization is consistently restricted to non-argillaceous units and is generally best developed within micritic, oolitic, pelloidal or slightly sandy carbonate beds indicative of a moderate-to high-energy, shallow water, and hence oxidizing, environment. Highest grade mineralization commonly occurs within porous and permeable (?) oolitic, pelloidal or slightly sandy packstones and wackestones adjacent to less (?) permeable argillaceous carbonates, fine-grained calcsiltites or micrites (e.g. Tatestown, see Andrew and Poustie, this vol.; Moyvoughly, see Poustie and Kucha, this vol.). The result of this lithological control is the formation of stratabound, and rarely stratiform, zones of mineralization.

The deposits associated with the Waulsortian facies characteristically display tabular, irregular to well-developed, stratiform shapes with the thickest and highest grade mineralization restricted to the contact between the Waulsortian facies micrites and adjacent argillaceous biocalcarenite. However, mineralization adjacent to "feeder" structures clearly cross-cuts stratigraphy and is hosted by sediments that range from the base of the carbonate sequence (Silvermines, see Andrew, this vol.) to near the top of the Waulsortian facies (Ballinalack, see Jones and Brand, this vol.).

Clastic sediment-hosted, massive sulphide deposits are also stratabound, and usually have a significant proportion of truly conformable, stratiform massive sulphide mineralization. There may be one or more stratiform sulphide lenses, although mineralization is generally restricted to a relatively thin (≤100m) section. An exception is the Mount Isa deposit in which stratiform lenses of Zn-Pb mineralization extend through 600m of section (Mathias and Clarke, 1975).

Structural control and tectonic activity

The majority of the Zn-Pb prospects and deposits in the Irish Carboniferous are adjacent to structures which localize high-grade zones of mineralization and are believed to have served as fluid conduits. There is evidence at many deposits and prospects that these faults were active during mineralization.

At Navan, mineralization is grossly located adjacent to the intersection of several ENE-striking, high-angle normal faults with nearly E-striking, listric normal faults. In many cases, minor ENE-oriented fractures are mineralized in the mine area. Mineralization at Tatestown, Moyvoughly and Oldcastle surrounds E- and ENE-striking, high-angle normal faults. At Keel (Slowey, this vol.) and Newtown Cashel (Crowe, this vol.) sulphides are found adjacent to the NE-trending high angle normal Keel Fault zone with the
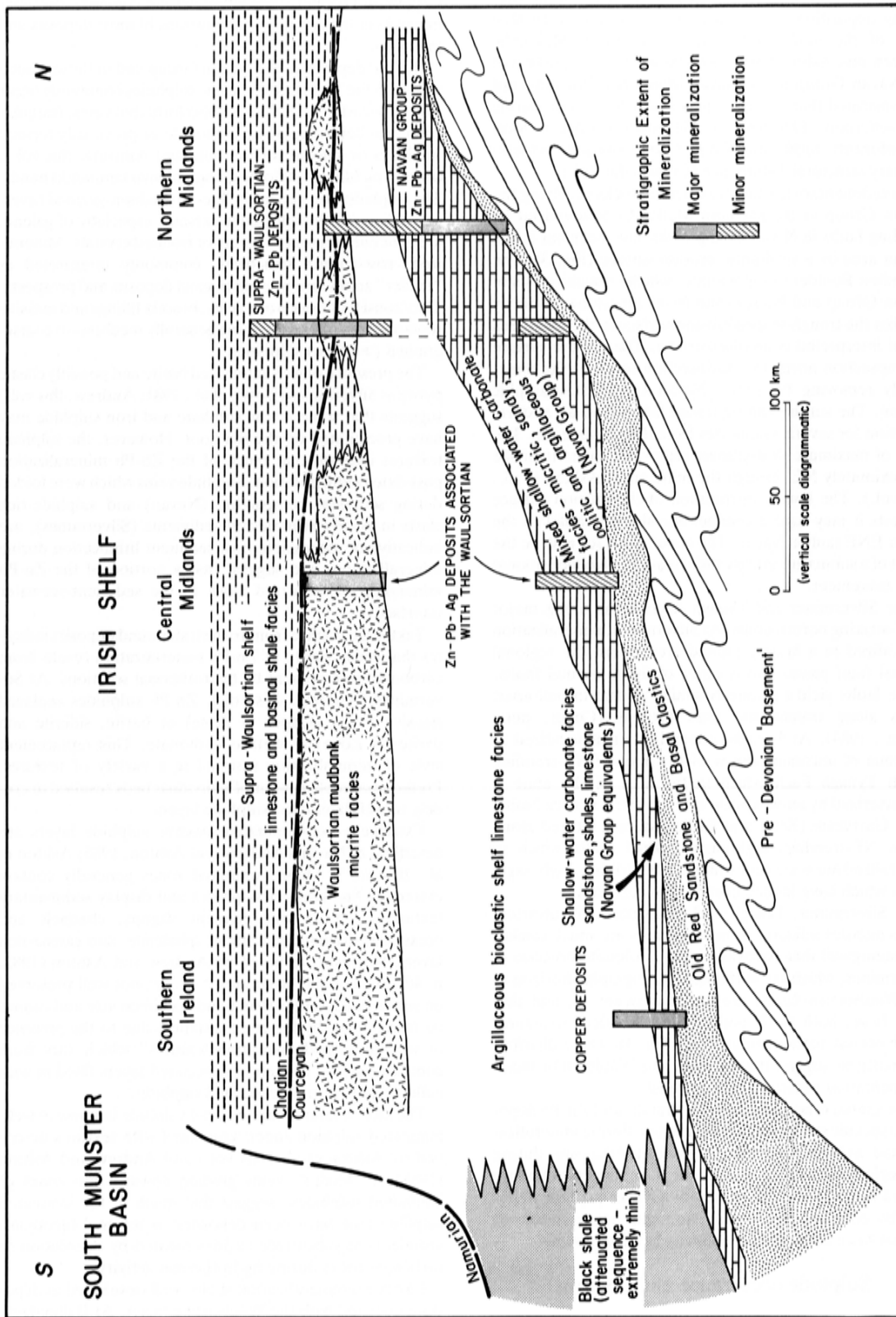
Figure 1. A generalized stratigraphy showing the stratigraphic extent of mineralization in the Lower Carboniferous of Ireland

majority of the mineralization occurring in the downthrown block.

There is little evidence of significant tectonic activity during deposition of the Navan Group rocks which host most of the mineralization in the northern Midlands. Andrew and Ashton (1985) note thickening of a portion of the Navan Group in the Navan Mine area, but have not demonstrated that this thickening is due to faulting during sedimentation. However, at Newtown Cashel a local unconformity within the Navan Group suggests synsedimentary structural disturbance (Crowe, this vol.).

Synsedimentary faulting is evident in rocks overlying the Navan Group in the northern Midlands. Mineralized E-trending faults in Navan Group rocks have been cut in the Navan area by a submarine erosion surface (Fig. 3). The Arundian Boulder Conglomerate, which contains clasts of Navan Group and Waulsortian facies limestones, directly overlies the trough-shaped erosion surface in the mine area and is interpreted as an olistostrome. The erosion surface cuts upsection north and downsection south of the mine, locally removing the entire Navan Group stratigraphic section. The surface can be traced laterally in an easterly direction for several kilometres from the Navan mine. The zone of maximum stratigraphic removal appears to strike approximately NE through the mine area (Ashton et al., this vol.). The known distribution of the erosion surface suggests it may have a channel-like shape parallel to the major ENE fault at Navan. The erosion surface may be the result of a submarine gravity slide related to syndepositional fault movement.

The Silvermines and Tynagh deposits lie along major ENE-striking normal faults. At Silvermines, mineralization is localized in a heavily faulted area where the regional normal fault passes into a series of listric normal faults. These faults yield a geometry similar to that in pull-apart zones along transcurrent fault systems (Coller, pers. comm., 1984). At Tynagh, mineralization is localized at the zone of maximum throw of the major ENE-trending North Tynagh Fault which in the area of the mine is characterized by an *en echelon* array of listric normal faults. Both Garrycam (Keel) and Ballinalack are located along major NE-trending, high-angle normal faults which in mineralized areas are cut by minor NW-striking, high-angle faults which have limited normal displacement.

At Silvermines, Tynagh and Ballinalack, Waulsortian facies micrites adjacent to normal faults are much thicker in hangingwall than footwall blocks. Dolomite breccias at Silvermines, which are at the same stratigraphic horizon as the Waulsortian facies, are found adjacent to, and thin away from, both the B and G Zone "feeder" structures which occupy listric normal faults (Fig. 4). These distribution patterns suggest that faulting and Waulsortian facies sedimentation occurred simultaneously.

The spatial relation of the Irish stratabound Zn-Pb deposits to specific structures that were active during mineralization and, at least in Waulsortian associated deposits, during the period of host rock deposition, is an important feature shared with many sediment-hosted massive sulphide deposits. By contrast, a similar relation with active structures has not been demonstrated in many MVT deposits.

Sulphide occurrence and textures

Irish stratabound deposits and prospects consist dominantly of sphalerite with lesser galena (in some cases argentiferous), pyrite and barite. Some of the deposits associated with the Waulsortian facies contain abundant pyrite and barite; the stratiform Magcobar deposit, adjacent to the Silvermines Zn-Pb deposit, contains 5Mt of 85% $BaSO_4$. Copper and copper-silver sulphides are common accessory minerals in the sulphide-rich portions of most deposits and prospects.

Both in deposits in the Navan Group and in those associated with the Waulsortian facies, sulphides commonly occur as interporosity fill. Sulphides also form thin veins, irregular colloform bands replacing carbonate or previously formed sulphides or sulphates (Fontbote and Amstutz, this vol.), coarse vug fillings, stylolites, and massive laminated bands. The sulphides are generally fine- to medium-grained (average < 1mm) although coarse crystals, especially of galena, are generally present as layers or isolated crystals. Mineralized cross-cutting structures, commonly interpreted as "feeder" zones, are present in most deposits and prospects. They consist of stockwork veins, breccia fillings and massive replacement zones containing generally medium- to coarse-grained (>0.5cm) sulphides.

The presence of well-laminated barite and possibly clastic pyrite at Silvermines (Boyce et al., 1981; Andrew, this vol.) suggests that some of the sulphate and iron sulphide may have precipitated on the sea floor. However, the sulphide textures indicate that much of the Zn-Pb mineralization post-dates sedimentation. Sulphide veins which were folded during sediment compaction (Navan) and sulphide-rich clasts in poorly mineralized sediments (Silvermines), are indicative of incomplete host sediment lithification during mineralization, and suggest that a portion of the Zn-Pb mineralization occurred close to the sediment-seawater interface.

Textural evidence from Irish stratabound deposits indicates that the majority of Zn-Pb mineralization results from carbonate replacement by hydrothermal solutions. At Silvermines (Andrew, this vol.), Zn-Pb sulphides replaced massive pyrite (Upper G Zone) or barite, siderite and pyrite (B Zone) as well as carbonate. This replacement style of mineralization resulted in a variety of textures. Preferential replacement of individual beds resulted in crudely to well-laminated sulphide layers.

Extremely well-laminated massive sulphide layers are described at Navan (Andrew and Ashton, 1985; Ashton et al., this vol.). These laminated zones generally contain extremely fine-grained sulphides and display sedimentary textures such as soft-sediment slumps, channels and occasional rhythmic grading of sphalerite- and galena-rich layers. However, as noted by Andrew and Ashton (1982, p. 40), the laminar structures ". . . are not well preserved on scales much larger than hand-specimen size and cannot be traced laterally for great distances due to the presence of well-developed disruption textures" which vary from complex folds to broken or brecciated layers filled in with collomorphic to coarse-grained sulphides.

The lack of lateral continuity of sulphide laminae in well-laminated sulphide zones, combined with textures described by Ashton et al. (this vol.) and Andrew and Ashton (1985) of "feeder" veins grading upward into zones of laminated sulphides, suggest that much of the laminated sulphide may have been deposited as internal (geopetal) sediments in subsurface cavities created by dissolution of carbonate rocks during hydrothermal activity.

Cavity-fill mineralization is also well developed in deposits associated with the Waulsortian facies. At Ballinalack, monomineralic sulphide bands are present within stromatactis cavities which are largely unaffected by hydrothermal solutions. At Tynagh, Zn and Pb sulphides occur as internal sediments in stromatactis cavities and in irregular cavities
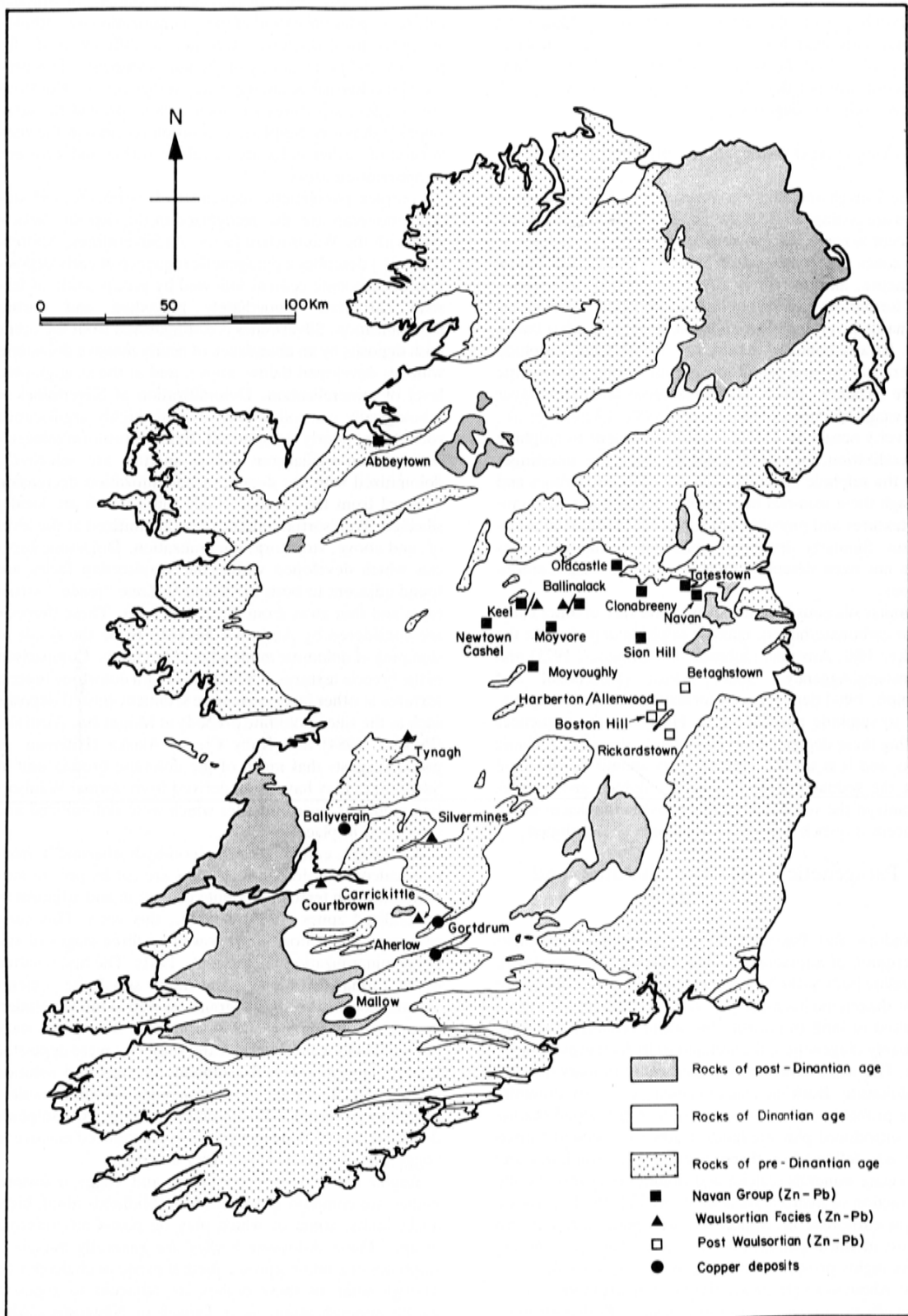
Figure 2.   Irish Carboniferous deposits and prospects.

formed in both carbonate rocks and in pre-existing sulphides (Boast et al., 1981).

These sulphide-rich sediments may be similar to the cavity-filling internal sediments in some of the Alpine and Silesian carbonate-hosted Pb-Zn deposits (Sass-Gustkiewicz et al., 1982). However, similar cavity-filling sulphide sediments are not described from other sediment-hosted, massive sulphide deposits.

Associated oxide-facies mineralization

The Tynagh and Silvermines systems in the Waulsortian facies are distinguished by the presence of haematitic zones adjacent to zones of sulphide mineralization. These haematitic zones are composed of haematite, silica and minor magnetite, and are apparently analogous to oxide-facies iron formations. At Silvermines, a laminated red siliceous haematite layer underlies a portion of the Magcobar barite lens (stratigraphically equivalent to adjacent sulphide mineralization) and passes upwards into layered haematitic barite (Andrew, this vol.). The siliceous haematitic layer at Tynagh (Schultz, 1966; Riedel, 1980; Clifford et al., this vol.) occurs as a stratigraphic equivalent to sulphide mineralization, though it generally does not interfinger with the sulphide mineralization. At both Silvermines and Tynagh these iron-rich beds display bedding-parallel laminar textures and probably formed as direct chemical precipitates. Similarly developed silica-rich, haematitic zones have not been described elsewhere in the Irish Carboniferous.

Similar siliceous haematitic layers are rare in other clastic- or carbonate-hosted, massive sulphide deposits. At the Broken Hill, Australia (Johnson and Klingner, 1975) and Gamsberg/Aggeneys, South Africa (Rozendaal and Stumpfl, 1984) deposits, iron formation is laterally equivalent to sulphide mineralization. However, the sequences hosting these deposits contain relatively abundant volcanic rocks and it is unclear whether they should be classified with the sediment-hosted, massive sulphide group or as variants of the volcanic-related massive sulphides in which adjacent iron-rich facies may commonly be developed.

Paragenetic sequence of alteration and mineralization

Andrew and Poustie (this vol.) present an excellent description of alteration and mineralization at Tatestown, a satellite body to the Navan orebody, where they recognize eight diagenetic/hydrothermal events. The earliest events resulted in infill of porosity by calcite cements and were probably diagenetic and unrelated to hydrothermal alteration. This was followed by replacement of primary micrites by dolomite. Both the calcite cement and early dolomite were probably caused by interaction of entrapped marine and introduced phreatic fluids. Carbonate cement formation was followed by the precipitation of sulphides and carbonate minerals (calcite and dolomite) formed by the interaction of hydrothermal solutions with the host rocks. Minor carbonate deposition followed mineralization. An almost identical paragenesis has been described from the Moyvoughly prospect (Poustie and Kucha, this vol.).

At Abbeytown (Hitzman, this vol.), hydrothermal alteration effects are more easily distinguished. Both early diagenetic calcite cement in sandstones, and calcite grains and cement in calcarenite, were replaced by fine-grained dolomite which generally preserved both the textures and the included material in the original calcite. This dolomite is zoned from ferroan dolomite adjacent to feeder structures, through normal, low-iron dolomite further from the structures, to a distal zone of patchy replacement of original calcite. The lateral extent of the dolomitization was lithologically controlled, presumably due to differences in the porosity and permeability of the host sediments. This pre-ore hydrothermal dolomitization extends up to 100m from the "feeder" structures and forms a halo around the later sulphide deposits. Sulphide deposition resulted in the conversion of earlier dolomite to calcite within and adjacent to mineralized areas.

Complex paragenetic sequences of carbonate and sulphide minerals are also recognized in the deposits associated with the Waulsortian facies. At Silvermines, Andrew (this vol.) describes a paragenetic sequence of early deposition of carbonate cement followed by precipitation of ferroan carbonate immediately preceding and during mineralization. Silvermines is distinguished from the other Irish deposits by an abundance of nearly massive dolostone which is developed below, above, and at the stratigraphic level of mineralization. Dolomitization at Silvermines is lithologically controlled (Fig. 5) with highly argillaceous rocks being poorly dolomitized. Below stratiform mineralization, non-argillaceous oolitic sparites are selectively dolomitized with the degree of dolomitization decreasing outward from the "feeder" fault zones which are locally silicified. Waulsortian micrites are dolomitized at the level of, and above, stratiform mineralization. Dolostone breccias which developed within the Waulsortian facies are found adjacent to both the B and G Zone "feeder" structures and thin away from these structures. These breccias are considered by Andrew (this vol.) to be the result of slumping of dolomitic muds adjacent to faults. Comparison of the breccia textures at Silvermines with dolostone breccia textures at other large carbonate sediment-hosted deposits such as the silica-dolomite orebody at Mount Isa, Australia (Perkins, 1984) and Ruby Creek, Alaska (Hitzman, in press) suggests that much of the dolomite breccia unit at Silvermines may have been derived from normal Waulsortian mudbank facies micrites which were dolomitized and brecciated in place.

At Tynagh, early diagenetic (non-hydrothermal?), iron-poor calcite and dolomite cements are cut by pre- to syn-mineralization ferroan dolomite cement in and adjacent to mineralized zones (Clifford et al., this vol.). This early carbonate deposition was followed by three stages of sulphide mineralization (Boast et al., 1981). The first resulted in the formation of pyrite and minor sphalerite cements around bioclasts and pyrite grains, as well as minor sphalerite infill of stromatactis cavities. During the second stage the host rocks were fractured and sulphides were deposited in veins and as internal sediments in vugs and solution cavities. The final stage of sulphide mineralization resulted in the formation of Cu-Pb-Ba-dolomite veins. Post-sulphide dolomitizaton of Waulsortian micrites produced massive to vuggy, sugary-textured, pale grey dolomite.

Similar late, coarsely crystalline and vuggy dolostone bodies are common throughout the Midlands along high-angle faults, some of which may be post-Carboniferous in age. These dolostone bodies are generally barren of sulphides or contain minor euhedral pyrite or chalcopyrite. Though some of these bodies are adjacent to zones of Zn-Pb mineralization, as at Tynagh or Newtown Cashel (Crowe, this vol.), many are apparently not associated with earlier sulphide mineralization.

With the exception of Abbeytown and Silvermines, the extent of dolomitization in the Irish hydrothermal systems
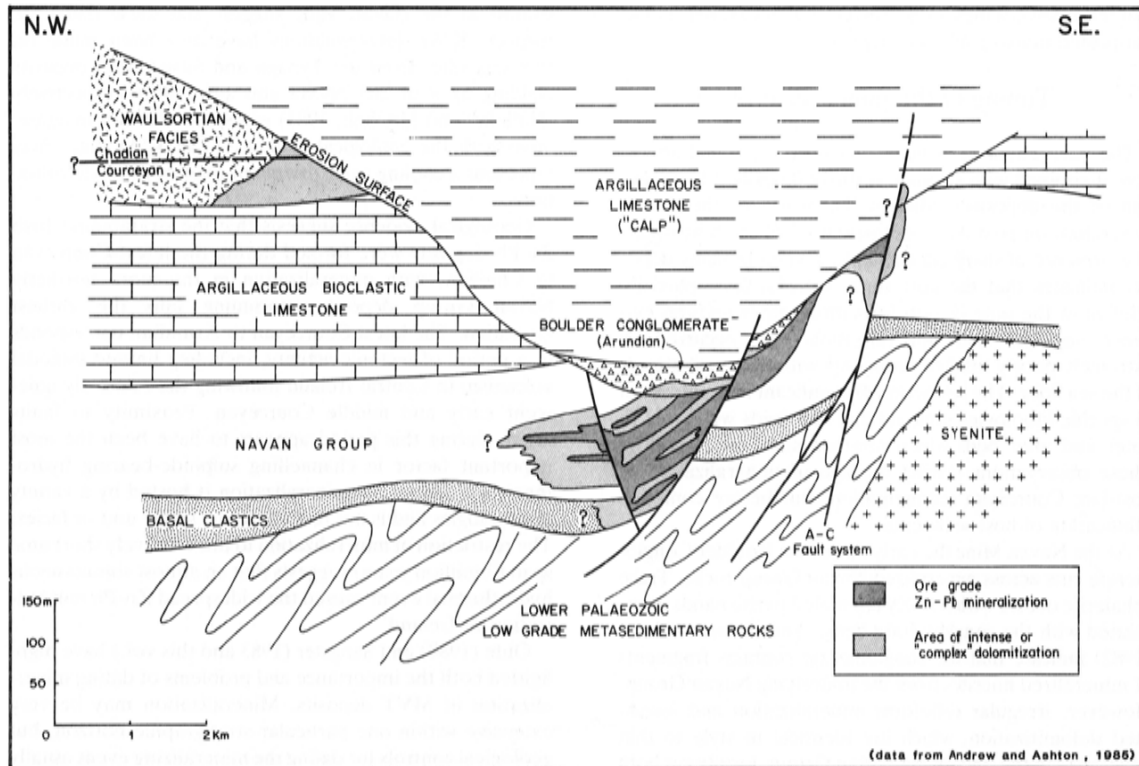
Figure 3.   Highly schematic regional cross section through the Navan area.

is generally poorly known. Minor early diagenetic (?) dolomite and calcite cement similar to that described from Tatestown and Moyvoughly occurs within non-argillaceous rocks of the Navan Group throughout the north Midlands (Philcox, 1984). However, zones of complex dolomitization involving both ferroan and non-ferroan dolomite as well as more coarsely crystalline dolomite have been recognized so far only in areas of mineralization. Unfortunately, the extent of these alteration zones has not been described.

Host rock alteration is commonly observed near massive sulphide deposits in clastic sediments, especially in the footwall adjacent to cross-cutting mineralization. However, prolonged hydrothermal activity can also result in the alteration of the hanging wall sequence, as at the Sullivan orebody, Canada (Hamilton et al., 1982). Silicification of host clastics is the dominant style of alteration although chloritization, albitization and tourmalinization are also reported in the vicinity of several deposits. Clearly the type of host-rock alteration depends on the composition of host rock and hydrothermal solution as well as the temperature, permeability and water:rock ratios. Thus, different alteration assemblages are to be expected in the carbonate-hosted Irish deposits and in the clastic-hosted massive sulphide deposits. Hydrothermal dolomitization of wall rock is commonly developed in MVT deposits, while silicification of host sediments in these deposits is rare (Heyl, 1983).

Metal zonation

One of the most significant characteristics of the better described Irish Zn-Pb deposits (e.g. Navan and Silvermines) is the iron, zinc and lead zonation. At Navan, Andrew and Ashton (1982 and 1985) describe a vertical increase in total Fe and Zn/Pb ratio from the deposit centre, and a lateral zonation of increasing Zn/Pb ratios outwards from the deposit centre. Within the No. 5 lens, the spatial distribution of equal Zn and Pb concentrations reveals NE trends parallel to a series of faults. The concentration of sulphide veins, which also strike generally NE, is greatest in the area of highest Zn+Pb concentrations. The correspondence in trend of high Zn+Pb concentrations with sulphide veins suggests that these veins may represent "feeder" systems to the mineralization (Andrew and Ashton, 1982 and 1985).

At Silvermines, well-developed metal zonation has been described by Taylor and Andrew (1978), Taylor (1984), and Andrew (this vol.). A pronounced Pb-enrichment along linear zones within the stratiform B and G Zones corresponds to the location of NW-trending listric normal faults which are interpreted to have been hydrothermal "feeder" systems. The stratiform sulphide bodies show progressively higher Zn/Pb ratios away from these feeder structures. The Magcobar barite body, and associated pyrite-rich zones, lie on the fringes of the stratiform sulphide body.

Russell (1975) has described manganese geochemical haloes within carbonates along the same stratigraphic horizon as the Tynagh deposit. Finlay et al. (1984) noted similar haloes from above and laterally around the Navan deposit. At Navan, the carbonates above the mineralization also exhibit enhanced values of Zn, As and Fe.

Lateral metal zonation is a common characteristic of both clastic and carbonate sediment-hosted massive sulphide deposits (e.g. Sullivan, see Hamilton et al., 1982; Mount Isa, see Mathias and Clarke, 1975) with Zn being more widely dispersed than Pb. The areas with high Pb/Zn ratios in these deposits correspond to zonation centres and are adjacent to faults and/or breccia zones that are interpreted as "feeder" zones. The structurally controlled zonation

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pattern at Silvermines is very similar to that of other sediment-hosted massive sulphide deposits.

Timing of the mineralization

The paragenetic sequence of mineralization and alteration, combined with sulphide textures described from several of the deposits, indicates that much of the Zn-Pb mineralization post-dates sedimentation of the host rocks. The presence of sharp-edged sulphide veins in many deposits indicates that the host rocks were at least partially lithified at the time of vein formation; other textural evidence suggests that mineralization also occurred in extremely poorly lithified sediments within several metres of the sea floor. The restriction of significant mineralization to specific lithologies suggests that ore fluids were able to enter and alter beds which retained some permeability. These observations restrict the age of mineralization to post-late Courceyan sedimentation, but before complete lithification of host sediments.

At the Navan Mine the early Arundian Boulder Conglomerate cuts across mineralized Navan Group rocks. Trace sphalerite occurs within finely laminated pyrite bands intercalated with the conglomerate beds. Andrew and Ashton (1982) indicate that the conglomerate contains fragments of mineralized micrites from the underlying Navan Group. However, irregular colloform mineralization and associated dolomitization, which are identical in style to that developed in the underlying Navan Group, locally cut both clasts and matrix of the Boulder Conglomerate. This final style of mineralization indicates that hydrothermal sulphide emplacement continued into the Arundian, although the majority of the mineralization in the underlying Navan Group may have taken place earlier during the latest Courceyan to Chadian, as demonstrated by the presence of mineralized clasts in the Boulder Conglomerate.

Dolomitization in the Silvermines and Tynagh systems was related to the hydrothermal system responsible for sulphide precipitation. Hydrothermal alteration extends to the top of the Waulsortian facies of latest Courceyan age but apparently does not affect lower Viséan rocks at Silvermines. This suggests that alteration occurred during latest Courceyan but terminated by earliest Chadian. Due to the absence of supra-Waulsortian units immediately above mineralized zones at Tynagh, it is impossible to determine whether alteration and/or mineralization affected stratigraphically higher rock units.

Tynagh and Silvermines contain laterally extensive units of iron formation and barite, which were probably precipitated on the sea floor under oxidizing conditions as a result of mixing of sea water with exhalative iron- and barium-rich hydrothermal solutions. If the solutions which formed these oxide facies are related to the fluids which caused sulphide precipitation, as seems likely, then mineralization must have occurred in the latest Courceyan, either during or very shortly after the deposition of the host rocks.

Using the sparse radiometric ages available for the lowermost Carboniferous in Britain and Ireland (George et al., 1976), the relationships at the Navan Mine suggest that mineralization took place between the late Courceyan (approximately 352Ma) and the early Arundian (approximately 345Ma), a period of approximately 7 million years. Absolute ages of 303 and 306Ma at Navan and 302 and 317Ma at Keel have been obtained from K/Ar dating of clay minerals associated with the mineralization (Halliday and Mitchell, 1983) suggesting a middle to late Carboniferous age of mineralization. However, the geological con-

straints at the Navan Mine suggest that these dates are suspect. K/Ar determinations have also been made on clay separates from the Tynagh and Silvermines deposits yielding ages of 265-299Ma and 295-310Ma respectively (Halliday and Mitchell, 1983) which are also not in agreement with the geological evidence. The K/Ar dates may represent a cooling age subsequent to Hercynian deformation.

Geological evidence suggests that the stratabound Irish Zn-Pb deposits were formed during the latest Courceyan to Chadian, with mineralization in the more northerly Navan Group deposits continuing into the earliest Arundian. The latest Courceyan to Arundian corresponds to a period of tectonic activity, including limited bimodal volcanism in Central Ireland following the relatively quiescent early and middle Courceyan. Proximity to faults active during this period appears to have been the most important factor in channelling sulphide-bearing hydrothermal solutions, as mineralization is hosted by a variety of lithologies and is not restricted to a single unit or facies. The restriction of mineralization to this relatively short time span (7 million years) suggests that an almost simultaneous hydrothermal event caused the widespread Zn-Pb mineralization of Ireland.

Ohle (1980) and Sangster (1983 and this vol.) have highlighted both the importance and problems of dating mineralization in MVT deposits. Mineralization may be very extensive within one particular stratigraphic horizon, but geological controls for dating the mineralizing event usually define a very broad time interval. The Irish deposits are hosted by carbonates deposited in a relatively short time interval, and textural and petrographic evidence suggests that mineralization must have occurred very shortly after, or even during, deposition of the host rocks. This is comparable to the syngenetic to syndiagenetic ages interpreted for the sediment-hosted massive sulphide deposits.

Sulphur isotopes

Sulphur isotopic data is currently available for a number of the Irish deposits (Silvermines, see Graham, 1970; Grieg et al., 1971; Coomer and Robinson, 1976; Boyce et al., 1983; Tynagh, see Boast et al., 1981; Grieg et al., 1971; Keel, Moyvoughly, Ballinalack and Tatestown, see Caulfield et al., this vol.)

Vein-type sphalerite and galena from Keel and the Shallee and Lower G Zones at Silvermines yields $\delta^{34}S$ values around 0 per mil suggesting that a component of "deep seated" sulphur was carried by the mineralizing fluids. Galena and sphalerite in these two mineralized zones yield isotopic fractionation temperatures which match the available fluid inclusion data suggesting that they were precipitated in isotopic equilibrium. This heavy sulphur could have been derived either from leached sulphides and/or from inorganic reduction of sulphate.

The majority of the Irish deposits (Ballinalack, Silvermines Upper G and B Zones, Tynagh and Moyvoughly) have generally light sulphide $\delta^{34}S$ values. However, each of these deposits shows a distinct range (Ballinalack -36 to +1 per mil; Moyvoughly -16 to +1 per mil) of sulphide isotopic values. Isotopic fractionation temperatures derived from sphalerite-galena pairs in these deposits are commonly unreasonable compared with the available fluid inclusion data suggesting that the sphalerite and galena are not in isotopic equilibrium. The abundance of light sulphur indicates that the majority of sulphide sulphur in these deposits was probably derived from bacterially-reduced
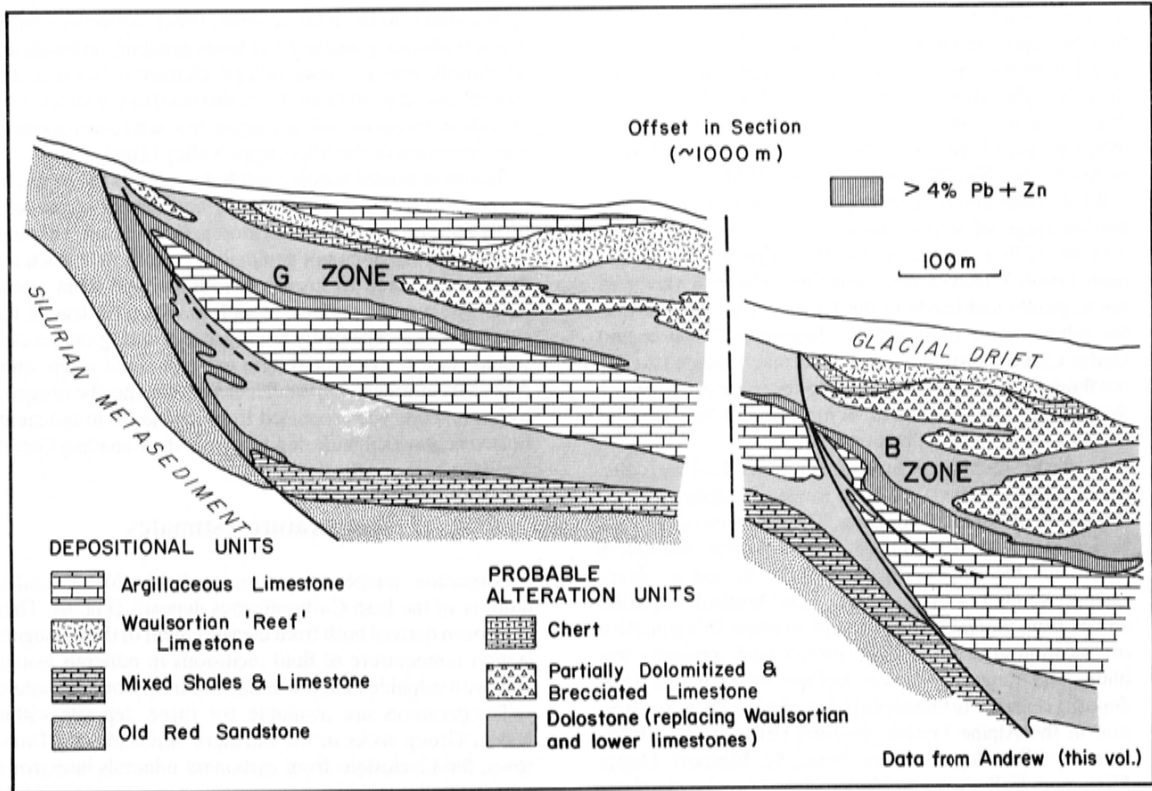
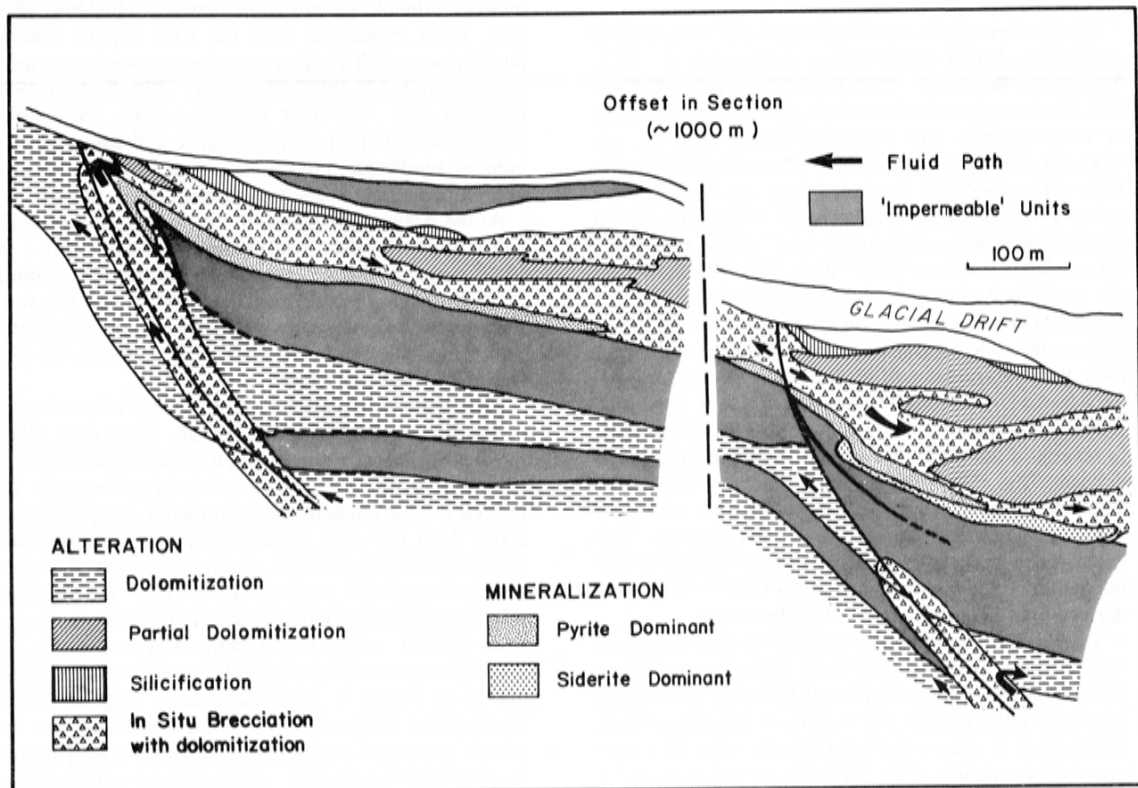**Figure 4.** Stratigraphic cross section through the Silvermines deposit.

Figure 5. Cross section through the Silvermines deposit showing zones of alteration and mineralization.

sea-water sulphate much of which may have been initially fixed in diagenetic pyrite. Sphalerite and galena δ^{34}S isotope values from the Tatestown deposit are significantly heavier than the other deposits sampled in Ireland. This may be due to the involvement of evaporite-derived sulphur, as minor gypsum is relatively common in the Navan Group within the northern Midlands (Philcox, 1984).

Barite from all the Irish deposits studied to date has a narrow range of sulphur isotopic valves (approximately +18 to +23‰) indicating that the sulphur was derived from Lower Carboniferous seawater. The δ^{34}S values of the sulphides and barite in the Irish deposits suggest that the sulphur came from both a "deep-seated" source and Lower Carboniferous seawater. This may indicate that the ore fluids carried some of the sulphur necessary to generate the deposits but that much of the sulphur was derived locally at the site of deposition.

In clastic sediment-hosted massive sulphide deposits, pyrite usually shows a broader range of sulphur isotope ratios than sphalerite and galena. This has been interpreted as indicating a bacterially-reduced seawater sulphate-S source for the isotopically light pyrite S, and a "deep-seated" sulphur source, either from leached sulphides and/or from inorganic reduction of sulphate in a primitive ore solution at depth, for the galena- and sphalerite-sulphur. The range of sulphur isotope ratios in the Irish deposits is similar to that reported for the Zn-Pb mineralization in the Alpine Triassic deposits (Brigo et al., 1977). In many MVT deposits (Pine Point, SE Missouri, Upper Mississippi Valley), the sulphide-sulphur isotope ratios are variable, but overall are heavier compared to the Irish deposits (Heyl, 1983).

Lead isotopes

Lead isotopic studies have been conducted on a number of the Irish deposits (Silvermines, see Greig et al., 1971; Tynagh, see Boast et al., 1981; Keel, Moyvoughly, Ballinalack, Tatestown, see Caulfield et al., this vol.; and a number of Carboniferous- and Palaeozoic-hosted deposits, see O'Keeffe, this vol.). Caulfield et al. (this vol.) and O'Keeffe (this vol.) using their combined data sets find that the galena Pb is isotopically homogeneous within each deposit and that there is a continuum of lead isotopic values that fall on a linear trend on a ^{207}Pb/^{204}Pb vs ^{206}Pb/^{204}Pb plot. From the available data it appears that lead isotopic values for individual deposits depends on geographic location rather than on the style of mineralization or the age of the host rock, with the exception of several vein-type lead deposits in Dalradian rocks from NW Ireland (O'Keeffe, this vol.). Leads in the Irish deposits are not of the J-type common in several of the North American Mississippi Valley-type deposits. The ^{207}Pb/^{204}Pb vs ^{206}Pb/^{204}Pb curve defined by Caulfield et al. (this vol.) and O'Keeffe (this vol.) does not give reasonable model ages for the deposits. This suggests the lead was probably derived by mixing of two isotopically distinct populations at least one of which was derived from the pre-Devonian Irish basement.

The regional lead isotopic pattern of the Irish deposits is similar to that noted by Heyl et al. (1966) for the Upper Mississippi Valley district. Although Heyl et al. (1966) were unable to relate directly this pattern to regional geology, Caulfield et al. (this vol.) and O'Keeffe (this vol.) have noted the parallelism of the regional lead isotopic trend in Ireland to the major faults in the pre-Devonian basement rocks.

In addition to the Irish deposits, other carbonate-hosted deposits also have distinctively homogeneous, although not necessarily uniform, lead isotope characteristics (e.g. the Alpine, Silesian, and Pine Point districts) that contrast with the inhomogeneous and radiogenic characteristics of galena mineralization in the Mississippi Valley (Heyl, 1983).

Sediment-hosted massive sulphide deposits are generally characterized by galena-Pb that is homogeneous and relatively uniform with respect to most growth curves, although model ages are often not geologically reasonable when the data is compared to growth curves derived from global data. The plumbo-tectonic model, in which the lead in the source rocks is repeatedly homogenized during orogenesis, would suggest that model ages are only valid when interpreted from growth curves developed for specific orogens, as has recently been reported from galena-Pb in sediment-hosted massive sulphide deposits from the Canadian Cordillera (Godwin and Sinclair, 1982).

Temperature estimates

Formation temperatures are available for a limited number of the Irish Carboniferous deposits (Fig. 6). They have been derived both from measurement of the homogenization temperature of fluid inclusions in minerals associated with sulphide mineralization and from isotopic studies.

Temperatures are available for three deposits within Navan Group rocks in the northern Midlands. At Tatestown, fluid inclusions from carbonate minerals intergrown with sulphides yield homogenization temperatures of 140-190°C with salinities of 10-12 weight % NaCl equivalent (Andrew and Poustie, this vol.) while apparently co-precipitated sphalerite and galena have isotopic fractionation temperatures of 137-178°C (Caulfield et al., this vol.). At Moyvoughly, fluid inclusion homogenization temperatures indicate sulphide precipitation between 140-220°C (Probert, 1983). Sphalerite from the Keel deposit contains fluid incluions with a homogenization temperature range of approximately 120-185°C (Patterson, 1970; Probert, 1983; Caulfield et al., this vol.). Sulphur isotopic fractionation temperatures derived from sphalerite and galena at Keel indicate equilibrium precipitation in a temperature range of approximately 100-250°C (Caulfield et al., this vol.).

At the Abbeytown deposit in the Sligo Basin, sphalerite and intergrown calcite contain fluid inclusions with a 90-145°C range of homogenization temperatures and salinities of 10-25 weight % NaCl equivalent (Hitzman, this vol.). Post-ore calcite, intergrown with pyrite, yields homogenization temperatures of 140-175°C and salinities of 10-13 weight % NaCl equivalent.

Temperatures are available for the two major deposits in the Waulsortian facies. At Tynagh, Boast et al. (1981) have calculated apparent sulphur isotope fractionation temperatures of 224-298°C from sphalerite-galena pairs and oxygen isotope equilibrium fractionation temperatures of 200°C from ore-stage silicate minerals. At Silvermines, fluid inclusions in sphalerite, quartz, barite and calcite from zones of epigenetic mineralization below the stratiform sulphide lenses have homogenization temperatures ranging from 80-240°C with a modal value of approximately 190-200°C (Samson and Russell, 1983); corresponding salinities are 12-22 weight % NaCl equivalent. Sulphur isotopic fractionation temperatures of minerals from these epigenetic zones give equilibrium fractionation temperatures of 150-280°C (Greig et al., 1971; Coomer and Robinson, 1976). Fluid inclusions in barite and sphalerite from the upper stratiform zones of mineralization yield lower tem-
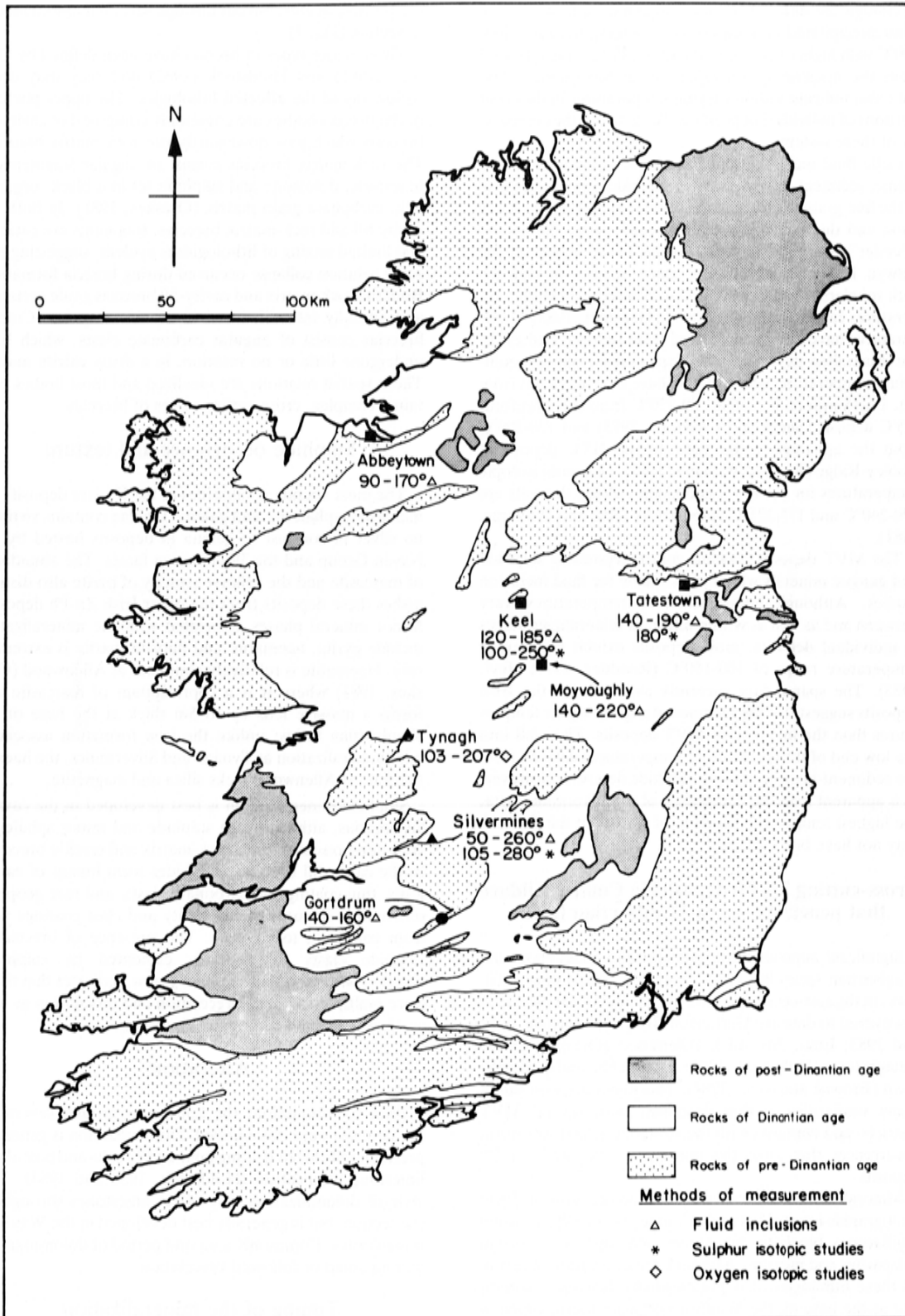
Figure 6.   Sulphide emplacement temperatures for some of the Irish Carboniferous deposits.

peratures (50-120°C) and higher salinities (20-24 weight % NaCl equivalent).

Though the data set is small, sulphides appear to have been precipitated at temperatures ranging between 100-200°C with higher temperatures up to 240°C being reported from the epigenetic mineralization at Silvermines. The data also indicate widely varying temperatures in different portions of individual deposits and emphasize the complexity of these systems.

Little fluid inclusion data have been reported from the clastic, sediment-hosted, massive sulphide deposits because of the fine-grained nature of the primary sulphide mineralization and the lack of associated coarse gangue minerals. "Feeder" type mineralization in the Jason deposit in the Selwyn Basin which contains coarse quartz, intergrown with sphalerite, yields fluid inclusion homogenization temperatures ranging from 180-284°C (Gardiner, 1983). Temperatures have also been derived from isotopic studies. In the Australian deposits, galena-sphalerite isotopic equilibrium temperatures of 290-350°C have been reported from Mt. Isa (Smith et al., 1978), 80-230°C from the stratiform HYC deposit (Smith and Croxford, 1973) and 120-290°C from the apparent feeder zone to the HYC deposit at Cooley-Ridge (Rye and Williams, 1981). Dolomite isotopic temperatures for the HYC and Cooley-Ridge deposits are 170-240°C and 175-325°C respectively (Rye and Williams, 1981).

The MVT deposits contain coarse crystalline sulphide and gangue minerals which are suitable for fluid inclusion studies. Although homogenization temperatures vary between and as well as within different mineralizing stages in individual deposits, most deposits exhibit an average temperature range of 100-150°C (Roedder, 1976; Heyl, 1983). The sparse data currently available for the Irish deposits suggest that they formed at slightly higher temperatures than the majority of MVT deposits. They fall into the low end of the spectrum of temperatures derived from the sediment-hosted, massive sulphide deposits. However, as is apparent from the complexity of the Silvermines data, the highest temperature portion of several of the deposits may not have been sampled.

Cross-cutting Zn-Pb deposits in County Kildare that penetrate supra-Waulsortian facies

Significant mineralization that crosscuts rocks above the Waulsortian facies has been described from County Kildare, in the east-central portion of Ireland. Major prospects discovered to date are Harberton Bridge (Holdstock, 1982 and 1983; Emo, this vol.), Allenwood (Oreskes, 1981), Betaghstown (Holdstock, 1983), Boston Hill and Rickardstown (Browne and Reid, 1984). This mineralization shows many similarities to that described from several MVT districts, and contrasts with the stratabound and stratiform occurrences that form the majority of the Irish Zn-Pb deposits.

Mineralization in these deposits occurs over a 700m stratigraphic interval between Courceyan, sub-Waulsortian argillaceous bioclastic limestones and supra-Waulsortian pelsparites and micrites. Although mineralization occurs in all these lithologies, it is preferentially developed within, and at the base of, the Waulsortian facies rocks, which in this area straddle the Courceyan-Chadian boundary.

Although minor disseminated and fracture-fill mineralization is present in Navan Group rocks at Harberton Bridge (Emo, this vol.), breccias host most of the mineralization at these prospects. These breccia zones range from

irregular to tabular zones at the base of the Waulsortian facies to pipe-like breccias which may be only a hundred metres in diameter, but cut through several hundred metres of section (Fig. 7).

Three major types of breccia have been defined by Oreskes (1981) and Holdstock (1982) and they may occur within any of the affected lithologies. The upper portions of the breccia bodies are commonly composed of cavity-fill breccias which pass downwards into rock-matrix breccias. The rock-matrix breccias consist of angular fragments of limestone, dolostone and sulphide set in a black, organic-rich, carbonate grain matrix (Oreskes, 1981). In both the cavity-fill and rock-matrix breccias, fragments are rotated, and limited mixing of lithologies is evident, suggesting that some solution collapse occurred during breccia formation. Both the rock-matrix and cavity-fill breccias grade vertically and laterally into dilational or crackle breccias. Crackle breccias consist of angular carbonate clasts, which have undergone little or no rotation, in a drusy calcite matrix. These spatial relations are idealized and most bodies contain a complex, cross-cutting series of breccias.

Sulphide occurrence and texture

The most abundant sulphides in the Kildare deposits are marcasite, sphalerite and galena. Galena contains virtually no silver in contrast to galena in deposits hosted by the Navan Group and the Waulsortian facies. The abundance of marcasite and the relative paucity of pyrite also distinguishes these deposits from the other Irish Zn-Pb deposits. Minor mineral phases associated with the mineralization include pyrite, haematite and fluorite; barite is extremely rare. Haematite is relatively abundant at Allenwood (Oreskes, 1981) where it is a coprecipitant of marcasite and forms a massive lens up to 5m thick at the base of the Waulsortian facies; unlike the iron formation associated with mineralization at Tynagh and Silvermines, the haematite lens at Allenwood lacks silica and magnetite.

Sulphide mineralization is best developed in the cavity-fill breccias, although iron sulphide and minor sphalerite are often present in both rock-matrix and crackle breccias. In the cavity-fill breccias, sulphides form linings of cavity walls, thin coatings on carbonate clasts, and rare geopetal sediments. Textures of the cavity and clast coatings vary from colloform to cockade. The presence of brecciated sulphide clasts subsequently cemented by sulphide, together with corroded sulphide grains, indicates that there were multiple pulses of brecciation and dissolution as well as of sulphide and carbonate deposition.

Alteration

Prior to brecciation, the limestones around several of the deposits were dolomitized. Dolomitization is generally preferentially located along high-angle faults and post-dates limestone lithification (Holdstock, 1982 and 1983). This style of dolomitization may affect limestones throughout the section, but is generally best developed in the Waulsortian micrites. Commonly a second period of dolomitization accompanied or followed brecciation.

Timing of the mineralization

Unlike either the deposits in the Navan Group or at the base of the Waulsortian facies, the Kildare deposits post-date lithification of their host rocks, and generally occur as cross-cutting, as opposed to dominantly stratabound, zones
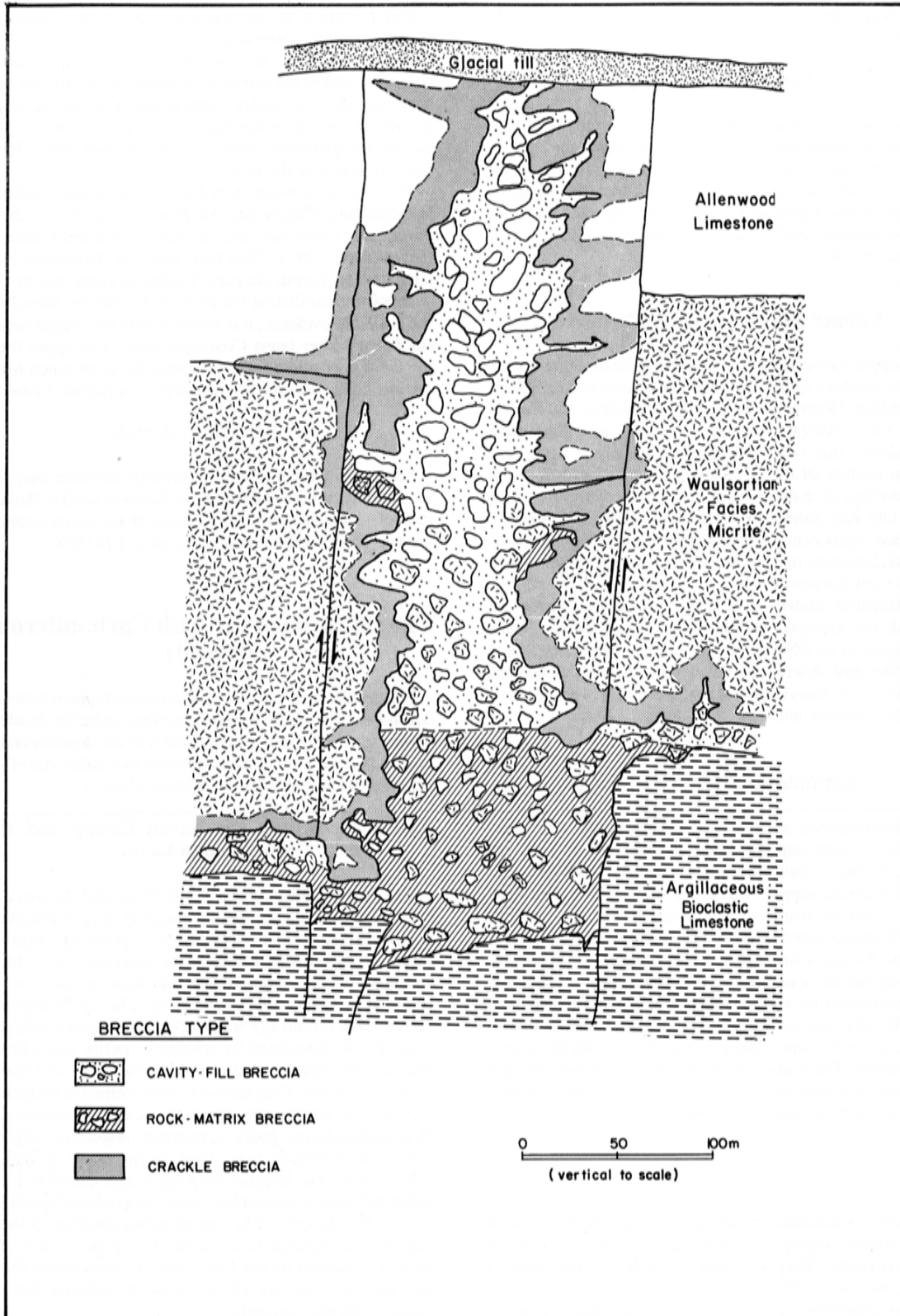
Figure 7. Schematic geology of a Zn-Pb-bearing breccia body similar to those of Co. Kildare. (Modified from Holdstock, 1983).

of mineralization. The deposits must have formed subsequent to the Chadian since they cut rocks of that age, but an upper limit to the time of mineralization cannot be defined.

Temperature estimates

No fluid inclusion homogenization, S- or O-isotope fractionation temperatures are available for any of the deposits that cross-cut the supra-Waulsortian facies. However, the relative abundance of marcasite as compared to pyrite suggests low temperatures since, at temperatures above approximately 200°C, marcasite rapidly inverts to pyrite (Skinner, 1967).

Copper deposits in the Carboniferous

Copper (-silver) deposits in the Carboniferous are restricted to southern Ireland. Deposits discovered to date include Gortdrum (Steed, this vol.), Mallow (Wilbur and Carter, this vol.), Aherlow (Romer, this vol.) and Ballyvergin (Andrew, this vol.). All the deposits occur within the basal portion of the Carboniferous sequence in a mixed assemblage of shales and limestones immediately overlying the Old Red Sandstone. These host rocks are lithostratigraphic equivalents of the basal clastic and Navan Group rocks; however, in this region of Ireland, this basal section is of early Courceyan age.

Structural control of mineralization is well developed in all the deposits. At Gortdrum, mineralization occurs adjacent to an ENE-striking fault zone. Mineralization at Mallow and Aherlow is developed in steep monoclinal flexures. At Ballyvergin, mineralization is restricted to a small elongated anticline.

Sulphide occurrence and texture

Mineralization occurs as disseminations and vein stockworks. Copper sulphides in the deposits include chalcopyrite, bornite, chalcocite and tennantite-tetrahedrite. At Gortdrum the copper minerals are zoned with a chalcopyrite-mercurian tennantite assemblage near the surface, which grades downwards to a chalcopyrite-bornite assemblage. Pyrite is a common accessory mineral in the deposits, but galena and sphalerite are rare. The copper deposits are characterized by a wider range of contained metals than Zn-Pb deposits to the north. At Gortdrum, significant mercury and minor uranium is intermixed with the copper sulphides. Trace amounts of arsenic and cobalt are also present at several of the deposits. Barite is a minor constituent of the mineralization at Aherlow.

Alteration

While dolomitization appears to be associated with all the copper deposits, its distribution in these systems is poorly known. The east orebody at Gortdrum is surrounded by, and coincident with, a fault-controlled zone of brecciated limestone which has been partially altered to dolomite. Similar, irregular zones of dolomitization within fractured and locally brecciated host rocks occur at Aherlow and Mallow. At Mallow, quartz veins and minor silicification accompany mineralization (Wilbur and Carter, this vol.).

Timing of mineralization

Mineralization in the Carboniferous copper deposits occurs in veins which apparently cut lithified rock. At Gortdrum, two high level basaltic intrusions and a series of basaltic dykes are intensely hydrothermally altered and have been cut by irregular bodies of intrusive breccia which are in turn cut by mineralization (Steed, this vol.). The basalts are probably related to the Chadian Pallas Hills volcanic centre to the west.

The structures which channelled hydrothermal solutions at Gortdrum, Mallow and Aherlow were probably active during the Hercynian deformation of southern Ireland (Sevastopulo, 1981). They may, however, have been initiated earlier, during the early Viséan, as suggested by the dyke swarm paralleling the faults at Gortdrum. Based on the available evidence, it is apparent that the copper deposits formed after latest Courceyan time. The upper limit for the age of mineralization cannot be determined from the available data, but is suggested to be middle Viséan.

Temperature estimates

Formation temperatures are currently available only for the Gortdrum deposit where fluid inclusion studies (Steed, this vol.) indicate that the majority of chalcopyrite-tennantite was precipitated at temperatures of 140-160°C.

Classification of the Irish Carboniferous deposits

It is evident that Ireland contains several types of deposits which have often been grouped together under the heading "Irish-type." The preceding summary of the deposits facilitates a discussion of their classification into either the MVT or sediment-hosted, massive sulphide class.

Zn-Pb deposits in the Navan Group and the Waulsortian facies

The Zn-Pb deposits in the Navan Group and Waulsortian facies contain evidence that the majority of mineralization post-dates sedimentation, although it probably occurred prior to complete lithification of the host rocks. At Tynagh and Silvermines, mineralization may have occurred on or within several metres of the sea floor. The Zn-Pb deposits in the Navan Group and Waulsortian facies share a sulphide suite that is dominated by sphalerite, pyrite and galena, but includes significant silver-bearing sulphides and minor copper sulphides. They appear to have formed at temperatures of 100-300°C, with the more southerly deposits in Waulsortian-facies rocks apparently displaying slightly higher temperatures than those to the north in Navan Group rocks. The majority show definite structural features which influenced the location, metal zonation and morphology of the deposits. The age of mineralization in these deposits corresponds to a period of tectonic activity and limited volcanism on the Irish Lower Carboniferous shelf. All these features are characteristic of sediment-hosted, massive sulphide deposits.

However, the deposits in Navan Group and Waulsortian-facies rocks also display MVT-like sulphide textures. The presence of these textures in deposits which otherwise resemble other sediment-hosted, massive sulphide deposits, is probably due to the presence of carbonate host rocks

in the Irish mineralization which differ from the clastic sediments (dominantly shales) which host the majority of sediment-hosted, massive sulphide deposits. The only group of generally accepted sediment-hosted, massive sulphide deposits occurring in carbonate host rocks are the Proterozoic deposits of Australia, including McArthur River (Williams, 1978), Mount Isa (Mathias and Clarke, 1975) and Lady Loretta (Loudon et al., 1975). However, the host rocks for the Australian deposits are carbonaceous and mildly argillaceous dolostones rather than the poorly argillaceous limestones of the Irish deposits.

The hydrothermal solutions responsible for most sediment-hosted massive sulphide and MVT deposits were probably derived from, or passed through, silicic rocks, either a permeable sandstone-arkose-conglomerate sequence or a fractured silica-rich "basement." Such solutions should be in relative chemical equilibrium with a quartz/clay-rich sediment such as the shales, greywackes and sandstones which contain most sediment-hosted massive sulphide deposits. In these silicic-dominant sediments, base metals would precipitate when the hydrothermal solutions underwent a change in chemistry due to a shift in pressure, temperature or pH as a result of interaction with other solutions (such as seawater) or non-silicic minerals such as carbonate.

Hydrothermal solutions discharging through silicic rocks would maintain relative equilibrium to the near surface or seafloor. The passage of hydrothermal fluids from silicic to poorly argillaceous carbonate rocks would be expected to alter solution chemistry significantly, through alteration of the host carbonate rocks (dolomitization), thus resulting in precipitation of sulphides. The point of discharge from a siliciclastic aquifer to carbonate rocks could range from near the seafloor surface to the deep subsurface. In zones of deep interaction, the degree of sulphide precipitation would be partially dependent on the surface area available to the hydrothermal solutions, which is largely a function of the permeability and porosity, as well as structural fracturing. The similarity in textures of Irish deposits with those described from MVTs may be primarily due to the reaction of relatively similar hydrothermal solutions with carbonate sediments rather than siliciclastic or argillaceous sediments.

Although the Zn-Pb deposits in the Navan Group and Waulsortian facies have textural features similar to many MVT deposits, the stratabound and often stratiform morphology of these deposits contrasts with the morphology of the Zn-Pb deposits of County Kildare and the majority of MVT deposits which commonly cross-cut stratigraphy. The morphology of the Irish deposits may be indicative of the poorly lithified state of the host carbonates for these deposits, compared to the generally fully lithified host rocks for the MVT deposits.

Though the Irish deposits within the Navan Group and the Waulsortian facies can be broadly grouped within the sediment-hosted, massive sulphide class in terms of tectonic setting, mineralogy, morphology and temperature of formation, they still form a distinct subset due to their host rocks.

There are certain similarities between these Irish deposits and the Zn-Pb deposits in the Alpine Triassic. The Alpine deposits were also deposited in poorly argillaceous limestones during a period of active tensional tectonism. They are located along faults which were active during sedimentation, contain laminated geopetal sulphide sediments, and have isotopically light sulphur (Bechstaedt, 1977; Brigo et al., 1977; Klau and Mostler, 1983). The similarities between the Irish and Alpine deposits, and the differences between

these deposits and the majority of MVT deposits, have been noted by Sangster (1976).

Zn-Pb deposits occurring in rocks above the Waulsortian facies

The Zn-Pb deposits of County Kildare can be distinguished from the deposits hosted in the Navan Group and Waulsortian facies by their morphology, mineralogy, and relative timing of mineralization. They appear to have many similarities with MVT deposits elsewhere in the world such as Pine Point (Rhodes et al., 1984) and the East Tennessee district (Briskey et al., this vol.). Like the Pine Point district, the currently known mineralization occurs in small-tonnage, pipe-like, breccia zones.

Copper deposits in the Carboniferous

The copper deposits of southern Ireland formed in a similar tectonic and lithological setting to the Zn-Pb deposits to the north. Like the Zn-Pb deposits of County Kildare they cross-cut stratigraphy. However, unlike the other Carboniferous deposits in Ireland these deposits contain little zinc or lead, although they do contain numerous trace metals.

Carbonate-hosted copper deposits are known from several other Zn-Pb districts, notably Mount Isa (Mathias and Clarke, 1975), McArthur River (Williams, 1978) and the SE Missouri MVT district (Woolverton, 1975). In these deposits copper sulphides occur in veins or as massive replacements. Mineralization in most of these deposits appears to post-date early diagenesis of the host rocks. At McArthur River and in SE Missouri the small copper deposits apparently form "feeder" zones for Zn-Pb mineralization while the silica-dolomite copper orebody at Mount Isa may have formed significantly later than adjacent Zn-Pb orebodies (Perkins, 1984).

The lack of spatial association between the copper and Zn-Pb orebodies in Ireland, their contrasting metal suites and the tentative evidence for possibly differing ages of mineralization, all suggest that the two deposit types may not be related.

Genesis of the Irish deposits

The genesis of the Irish deposits has been a controversial issue and two general schools of thought have emerged. One proposes that ore fluids are derived from convection cells developed in the upper crust centred on extensional fault zones and involving modified seawater (Russell, 1983 and this vol.). The other theory, derived from regional MVT studies, invokes large-scale, lateral transport of fluids from an adjacent basin (South Munster Basin) through a siliciclastic basal aquifer (Old Red Sandstone and Carboniferous basal clastic rocks) with fluid release occurring along extensional fault zones. Distances of proposed fluid movement in Ireland, however, are less than those postulated for several North American MVT districts such as the Upper Mississippi Valley district (Lydon, this vol.).

In the basin-expulsion model, fluids derived from a normal basin must be expelled episodically from significant depths to retain temperatures in the 100-150°C range in a near-surface environment (Cathles and Smith, 1983). Since temperatures of mineralizing fluids in Ireland are known

to have exceeded 150°C, this presents a problem. However, due to a well-developed basal aquifer, a tectonically active regional setting and a presumed abnormally high heat flow during the Carboniferous, high-temperature fluids could conceivably be transported over the 250km required by the deposit locations (Lydon, this vol.).

In both models, metals are extracted from the basement to account for the available lead isotopic data (Caulfield et al., this vol.; O'Keeffe, this vol.). In the convection model this is done directly, while in the basin-expulsion model metals are scavenged from detritus eroded from the basement. The spatial gradation of lead isotope values noted by Caulfield et al. (this vol.) appears to be more compatible with the convection model.

Both models also use extensional structures as points of fluid release, but they predict different spatial relation of deposit locations. In the convection-cell model Russell (1983) suggests that each convection cell would have an "area of influence" of several kilometres with major cells usurping adjacent cells through time. Thus, major ore deposits should be separated by several kilometres. The basin-expulsion model predicts that fluids moving out of a basin will travel through an aquifer until they cool and deposit their metals, or until they intersect a structural or stratigraphic "trap" which brings them in contact with either host rocks or fluids which cause them to release their metals. This could result in clusters of deposits in a single area due to favourable "trapping" conditions.

The distribution of deposits within the Navan Group, specifically the nearly 5km long trend in the Navan area (Andrew and Ashton, 1985) is difficult to reconcile with the convection cell model, unless either a 5km long feeder system derived from a single cell is invoked, or lateral transport of basement-derived fluids within the carbonate section is called upon. However, such a trend of deposits would be compatible with the basin-expulsion model. Deposition along the trend might be due to a facies change in the underlying aquifer, structural tapping of the aquifer, or, more likely, a combination of these factors.

The Zn-Pb deposits of County Kildare are sufficiently different from the other Irish Zn-Pb deposits, and sufficiently similar to most MVT deposits, to suggest they were formed through similar processes (basin-expulsion). Their location, approximately 200km from the shelf-basin break, is similar to the location of several North American MVT districts such as the Upper Mississippi Valley and Tri-State districts.

Detailed petrological study of the potential basal aquifers such as the basal mixed clastics and the Old Red Sandstone is required to determine the validity of the basin-expulsion model, while extremely deep drilling of basement rocks below major deposits may be necessary to test the convection cell hypothesis. The debate has practical implications for exploration both in Ireland and in other sediment-hosted, massive sulphide districts.

Conclusions

The Irish Carboniferous contains a spectrum of carbonate-hosted ore deposit types within a relatively small area. Elsewhere in the world there are areas which contain similar combinations of deposits, notably the Batten Trough of Australia which contains the sediment-hosted, massive sulphide deposits at McArthur River and the nearby Coxco MVT deposit (Walker, et al., 1983), and the Selwyn Basin area of northern Canada which contains the sediment-hosted, massive sulphide deposits of the Macmillan Pass area and MVT deposits in adjacent shelf facies (Macqueen and Thompson, 1978). However, in Ireland, both types of deposits occur within the same lithological units.

The range of deposit types in Ireland may be due both to the manner in which hydrothermal solutions interact with carbonate sediments and the regional tectonic setting of Ireland during the Carboniferous. As can be seen in a number of Irish deposits, sediment composition and texture profoundly influenced the style and distribution of mineralization. Much of the mineralization in the Zn-Pb deposits hosted by the Navan Group and Waulsortian facies appears to post-date sedimentation.

Mineralization by selective replacement during diagenesis has been previously proposed for several other sediment-hosted, massive sulphide deposits. At McArthur River, Williams (1978) demonstrated that the Zn and Pb sulphides show petrological evidence of having crystallized subsequent to diagenetic pyrite. These observations suggest that Zn-Pb sulphide formation by diagenetic replacement may be more significant than has been previously realized, especially in sediment-hosted, massive sulphide deposits associated with carbonate sediments.

The Irish deposits also demonstrate that lithological variations in poorly consolidated to fully lithified sediments influence the distribution of mineralization. In sediment-hosted massive sulphide deposits associated with the Waulsortian facies, the contact of the Waulsortian micrites with the underlying argillaceous bioclastic limestone is a preferred location for mineralization. Similarly, in the MVT deposits of County Kildare, breccia bodies are commonly stratabound, or form "flats", along the same stratigraphic contact.

The Irish deposits are also distinguished by their regional stratigraphic and tectonic setting. The Irish shelf, on which the deposits are located, is similar in stratigraphy to many MVT districts. However, unlike most carbonate environments which host MVT deposits, the Irish shelf was tectonically active during the late Courceyan to Arundian period of major mineralization, a feature it shares with most sediment-hosted, massive sulphide districts. The MVT deposits of County Kildare apparently formed later, perhaps as the shelf area became more tectonically quiescent and gravity-driven basin-dewatering occurred during uplift of the South Munster Basin as a result of the Hercynian orogeny.

Other areas where "Irish-type" deposits, such as those hosted by the Navan Group and Waulsortian facies, occur include the previously cited Alpine Zn-Pb district. In addition, the Carboniferous of Nova Scotia, Canada, contains numerous, stratabound, carbonate-hosted Pb-Zn and barite occurrences, one of which, the Gays River deposit, shows textural and structural similarities to the Irish stratabound deposits (Akande and Zentilli, 1984). Zn-Pb mineralization in the Lower Carboniferous of the Bonaparte Gulf Basin at Sorby Hills, Western Australia, also shows a strong structural control, an early age of mineralization relative to sedimentation, and a regional setting suggestive of "Irish-type" mineralization (Crowe, 1980). In the Ordovician of western Thailand, stratabound Pb-Zn deposits in the Song Tho district are hosted by carbonates deposited in an environment similiar to that of the Irish Carboniferous shelf (Diehl and Kern, 1981). "Irish-type" deposits are not unique to Ireland, and, in the future, deposits will probably be found in regions containing a carbonate shelf adjacent to a large clastic basin which formed in a tectonically-active setting, like Ireland during the Carboniferous.

Acknowledgements

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