Basement structural controls on Carboniferous-hosted base metal mineral deposits in Ireland

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Abstract: Explorationists have long recognized the importance of structural control of Irish base metal deposits, but the kinematics and timing of the structures relative to the mineralization are subject to wildly differing interpretations. This paper presents a combination of structural, magnetic and gravity data that show that the fundamental structural controls are easterly to northeasterly-trending basement (Caledonian) structures which have been reactivated in dextral transtension by northeasterly to north-northeasterly extension during the Dinantian. In general, in the north of the country the ore-controlling faults dip south, while in the south of the country they dip north. The structures have evolved through a temporal kinematic history of early normal faulting, later oblique slip, and some show evidence of later reverse movements. Part of this evolution may reflect burial history, although it also reflects the transition from Dinantian transtension to Variscan (Hercynian) compression. The bulk of the mineralization appears to post-date the normal faulting, and pre-date Variscan compression. Mineralization is thought to be post-compactional and could have occurred during the dextral transtension, although some of the sulphides could post-date most of the transtensional movement.

The Lower Carboniferous of Ireland is host to a large number of base metal deposits (Fig. 1). These range in size from small occurrences up to the Navan deposit of more than 70 million tonnes (Mt) of 12% combined Zn-Pb (Table 1). Vein-hosted copper ores in red beds are abundant in the south of the country, while further north Zn predominates in carbonate-hosted deposits. Metal ratios vary regionally, with Cu and Pb decreasing and Zn increasing northwards (Johnston 1996). This suggests that all the mineralization may be generated by the same regional phenomenon. All of the major deposits occur in the hanging walls of normal faults. Copper deposits at Aherlow, Mallow and Ballinalack are in compressional structures, and no faulting has been documented at Courtnrown or Carrickittle. These latter cases may reflect limited exploration, rather than absence of faults. Generally, individual faults trend between ESE (Silvermines) and NE (Keel). Local faults with lengths of hundreds of metres, controlling ore lenses (ESE at Silvermines and E at Lisheen), are made up of en echelon segments defining ENE to NE-trending fault zones many kilometres long, which are inferred to be expressions of controlling basement structures. The local faults, although generally clockwise of the trend of the zones, show a larger variation in orientation than the zones themselves. Although the empirical relationship is well known, only a few studies of the structural settings of the deposits have been published (Moore 1975; Coller 1984; Reilly 1986; Shearley et al. 1992, this volume).

Russell (1968, 1972) and Russell & Haszeldine (1992) invoke N-S geofractures to explain the mineralization in the Irish Midlands. However, as pointed out by Leeder (1988), there is almost no field or geophysical evidence for the existence of such structures. Rather, both field and geophysical evidence suggest that reactivated Caledonian (E to NE-trending) basement structures were the key in focusing mineralizing fluids. There is extensive hydrothermal alteration around these faults where they cut Devonian and Carboniferous rocks. Alteration is less extensive in the basement, but may be observed at Navan. In this study, both structural and petrographical observations and magnetic and gravity data are used to locate basement structures. On the basis of fault and mineralized vein geometries, most of the deposits are seen to lie in dextral transtensional settings (oblique extension with a component of clockwise rotation), which are the result of northeasterly extension of east to northeast-trending basement structures. Each mineral deposit has been further localized by...
specific secondary structures: termination zones, bends in faults, or intersections of second or third order shears with the primary basement structures.

There is abundant evidence (feeder veins, alteration zones, changing metal ratios, fluid inclusions) that hot brines came up these fault zones and deposited metals in the hanging-wall carbonates. Most of the deposits in the northern half of the Midlands lie in south-dipping faults, while those in the southern half lie in the hanging walls of north-dipping faults. Generally, the mineralized structures are en echelon and left-stepping, trending clockwise of the underlying basement structure. The displacement prior to the mineralization is predominantly dip-slip, indicating that the ore-controlling structures are extensional, and it is postulated here that these are rooted in dextral transtensional shears in the basement.
BASE METAL MINERAL DEPOSITS, IRELAND

Table 1. Tonnages and grades of the main Irish sediment-hosted base metal deposits

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<th>Deposit</th>
<th>Host</th>
<th>Tonnage (Mt)</th>
<th>Zn + Pb (Wt%)</th>
<th>Zn (Wt%)</th>
<th>Pb (Wt%)</th>
<th>Zn/Pb</th>
<th>Ag (gm/t)</th>
<th>Cu (Wt%)</th>
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Based on data from Andrew et al. (1986), Bowden et al. (1992). W, Waulsortian; N, Navan Group & equivalents; S, late Chadian or younger; Mt, millions of tonnes.

* Primary ore.

It is possible that Variscan inversion of south-dipping normal faults has resulted in uplift and subsequent erosion of other mineral deposits.

Regional stratigraphical setting

Irish Zn–Pb deposits are hosted primarily in Lower Carboniferous rocks; most are in rocks of Courceyan to Chadian age, but in several deposits hydrothermal alteration and sulphides extend up into Arundian rocks. Some of the copper deposits in the south of the country are hosted in Devonian elastic sediments. Stratigraphic and palaeogeographical settings of the Lower Carboniferous sequences are described in detail by Phillips & Sevastopulo (1986) and Philcox (1984). The Irish Courceyan has been subdivided into four provinces based on differences in the local succession: (1) the South Munster Basin; (2) the Limerick Province; (3) the Midlands Province; and (4) the mainly post-Courceyan North West Province (Fig. 1; Phillips & Sevastopulo 1986).

The South Munster Basin (Naylor et al. 1989) is filled with a carbonate-poor, clastic-dominated succession. Fluviatile red beds are overlain by marine sandstones and shales. Clastic (shale) deposition continued throughout the Courceyan, with starvation of the basin later in the Early Carboniferous.

Lithological units are widespread and laterally persistent in the carbonate-dominated Limerick Province (Philcox 1984; Somerville et al. 1992; see also Fig. 1). Transgression occurred during the early Courceyan. The base of the sequence comprises non-marine red beds and marginal-marine sandstones and shales. Overlying these are calcareous shales (Ringmoynlan Shale Formation), the principal hosts to small copper-dominated deposits. The shales pass up into muddy bioclastic limestones (Ballymartin and Ballysteen Limestone Formations), which are in turn overlain by Waulsortian carbonate mud banks (Lees 1964). These units host the Silvermines, Lisheen, Galmoy, Courtbrown and Tynagh deposits. Overlying the Waulsortian are either shelf, or in some areas basinal, carbonates.
In the Midlands Province, transgression took place later, during the mid-Courceyan (Sevastopulo 1981; Phillips & Sevastopulo 1986). A formal stratigraphy for the region was erected by Strogen et al. (1990). The region is characterized by lateral facies variation, and has been divided into sub-provinces by Philcox (1984) and Strogen & Somerville (1984). A widespread basal red bed lithology is overlain by a series of shallow-water micritic and oolitic deposits. The Pale Beds in turn are overlain by the argillaceous bioclastic limestone of the Lucan Formation, widely referred to as the Upper Dark Limestones. The late Chadian to Arundian deposits are characterized by dextral transgression (Sanderson 1984, 1986), or thick-skinned and related to dextral transpression (Sanderson 1984). While thrusting definitely occurs (e.g. Ford 1987), there is abundant field evidence for dextral transpression in the western part of the South Munster Basin. Rocks in this region have undergone gentle folding with shortening of less than 20%. However, evidence for dextral transpression continues northwards (Johnston 1993; Fitzgerald et al. 1994). Although there are stable blocks of almost undeformed limestones, approximately 50 kilometres across, these are bounded by corridors of deformation (Coller 1984). These are large scale ENE-trending dextral transpression zones, up to several kilometres wide, which are characterized by dipping beds, en echelon vein arrays, and weak stylolitic cleavages that transect gentle folds. Both the folds and the cleavages generally trend anticlockwise of the high strain zones (Coller 1984). Conjugate NNE-trending sinistral zones are consistent with a NNW-trending compression direction which is to be expected from regional tectonic reconstructions of the Hercynian (Ziegler 1988).

Regional structural setting

The structural history of the Carboniferous in Ireland may be divided into two main events: Dinantian extension, and late Carboniferous to early Permian (Variscan–Hercynian) compression. Beginning in the Courceyan and continuing through the Dinantian, 6000 m of shallow-water sediments accumulated in the South Munster Basin, (Matthews et al. 1983; Price & Todd 1988; Naylor et al. 1989). South of a line drawn from Dingle to Dungarvan (Fig. 1), major south-dipping faults controlled sedimentation. In the Midlands, a slightly different structural style existed. A series of interconnected basins developed, with north-dipping faults dominant in the south and south-dipping faults in the north. Typically, sediments adjacent to these faults display rapid facies and thickness changes from the late Chadian onwards (e.g. the Tynagh Fault; Philcox 1984). These faulting events were sometimes accompanied by chaotic breccias in the Midlands Province (Nolan 1986, 1989; Crowe 1986; Philcox 1989; Pickard et al. 1992), and in the NW Province (Philcox et al. 1989).

During the Variscan Orogeny these basins were inverted. Details of the structure of the Variscan deformation are given by Dolan (1983), Sanderson (1984), Coller (1984), Cooper et al. (1984, 1986), Ford (1987), Rothery (1988a,b) and deBrit (1989), and only the salient points are summarized here. In the south of the country the rocks have undergone extensive shortening (50–60%) with upright folding. The deformation has been interpreted as being either thin-skinned and thrust-related (Cooper et al. 1984, 1986), or thick-skinned and related to dextral transpression (Sanderson 1984). While thrusting definitely occurs (e.g. Ford 1987), there is abundant field evidence for dextral transpression in the western part of the South Munster Basin. Folds are transected anticlockwise (i.e. the cleavage related to the development of the folds appears axial planar in cross-section, but in plan trends anticlockwise of the fold hinge). En echelon fold trains (arrays of right-stepping folds) occur, and pressure fringes (fibrous mineral fibres, interpreted to indicate the stretching direction) growing on pyrite flattened in the cleavage indicates sub-horizon-tal extension. There is an abrupt drop in strain north of a line from Dingle to Dungarvan (Gill 1962; Cooper et al. 1984). Rocks in this region have undergone gentle folding with shortening of less than 20%. However, evidence for dextral transpression continues northwards (Johnston 1993; Fitzgerald et al. 1994). Although there are stable blocks of almost undeformed limestones, approximately 50 kilometres across, these are bounded by corridors of deformation (Coller 1984). These are large scale ENE-trending dextral transpression zones, up to several kilometres wide, which are characterized by dipping beds, en echelon vein arrays, and weak stylolitic cleavages that transect gentle folds. Both the folds and the cleavages generally trend anticlockwise of the high strain zones (Coller 1984). Conjugate NNE-trending sinistral zones are consistent with a NNW-trending compression direction which is to be expected from regional tectonic reconstructions of the Hercynian (Ziegler 1988).
**Geophysical framework**

The deep structure of the Irish Midlands can be discerned through use of regional aeromagnetic and gravity data. The Geological Survey of Ireland holds an aeromagnetic data set which may be processed under licence. The magnetic map and its interpretation were summarized by Max et al. (1983) and Morris & Max (1995). Murphy (1952, 1960, 1974, 1981) collected and compiled gravity data over most of the country with an approximate 1 km spacing. With fairly simple processing, these data sets reveal a great deal about the deep (sub-Carboniferous) structure. Using these data, Williams & Brown (1986) and Brown & Williams (1985) identified pronounced NE-trending gravity anomalies, which they interpreted in terms of horsts of Ordovician volcanic rocks (highs) beneath the Carboniferous, separated by intervening grabens filled with Carboniferous sediments (lows). Exploration drilling has confirmed the ridge and trough geometry of the Carboniferous in the Irish Midlands (Andrew, 1992). However, the Lower Palaeozoic inliers that expose the basement rocks do not always match the interpretations of Williams & Brown (1986) in detail. Nevertheless, their work identified the existence of NE-trending, steeply dipping lithological contacts in and beneath the basin. The magnetic data also show a similar Caledonian grain (Murphy 1981; Max et al. 1983). Filtering of the gravity data for the south of the country by Ford et al. (1991) has placed some constraints on the deep geology of the Munster Basin.

In this study, the same regional aeromagnetic data sets and the Bouguer gravity data have been studied. The magnetic data are illustrated in Figs 2 and 3. The gravity data are illustrated in Fig. 2 of Readman et al. (1996), and a summary of the gravity data for the Irish Midlands is shown in Fig. 4. Comparison of the magnetic first derivative maps and the gravity map of Readman et al. (1996) and Murphy.

![Fig. 2. Residual magnetic anomaly map of the Irish Midlands in pseudo-relief, illuminated from NW. The NNW-trending grain is an artefact of the flight lines, and the bright ENE lines (e.g. between Tonduff and Rickardstown) are artefacts of splicing of different data sets.](image-url)
Fig. 3. Magnetic first derivative anomaly map of the Irish Midlands. Artefacts as in Fig. 2.

(1974) highlights regions of steep contacts, juxtaposing rocks of differing densities and magnetic susceptibilities. In many instances such contacts are tectonic. There are many examples where this has been confirmed in boreholes and Lower Palaeozoic inliers such as in the Loughshinny-Skerries region (Fig. 1).

Geology, geophysics and structure of the deposits

A number of reviews of the deposits have been published in recent years (Hitzman & Large 1986; McArdle 1990; Andrew 1993; Johnston 1996) summarizing the main geological features of the deposits. Detailed descriptions of most of the deposits can be found in Andrew et al. (1986) and Bowden et al. (1992). Here, just the structural settings and those petrographic relationships relevant to constraining the timing of mineralization are described.

Gortdrum

In the south of the Irish Midlands, a group of copper deposits occur within the carbonate bearing sequence. Gortdrum (Fig. 5) is the only one of these deposits to have been mined. The sulphides occur in Courceyan shales and bioclastic limestones in the hanging wall of the ENE-trending, steeply NNW-dipping Gortdrum Fault (Steed 1986). The footwall is composed of Old Red Sandstone. The hanging wall is intruded by E-trending, hydrothermally altered mafic dykes and plugs. The deposit post-dates the host rocks, including the volcanic rocks, but pre-dates Variscan deformation.

Mineralization is associated with both the main faults and an en echelon array of more E–W striking extensional faults (Fig. 5a). Both normal and thrust faulting is present. There is a compressional overlap of the main faults to the south of the deposit consistent with WNW compression and complementary to the dilation area (Fig. 5a) of E-trending en echelon normal
faults, which define a NW-trending zone consistent with NNE extension. This pattern of faulting is typical of a dextral shear zone fault complex. In section (Fig. 5b) it has the geometry of a negative flower (oblique extensional) structure. This geometry is thought to be the product of Dinantian dextral transtension. The fault zone is also characterized by a series of en echelon folds that show a strong clockwise rotation in strike into the fault zone at the deposit, indicating a large dextral shear displacement in the mineralized area. The folding, which is compressional and deformed consolidated rocks, is interpreted to be Variscan.

This rotation into the footwall is also shown by the magnetic and gravity data. The principal geophysical elements are shown in Fig. 5c. The deposit lies on the southern margin of a NE-trending magnetic high in a region where the strike of the magnetic (basement) signature changes from NE- to E-trending (Figs 2, 3). A steep S-dipping magnetic gradient is coincident with the main, N-dipping fault. First derivative processing of the magnetic data yields an anomaly that is slightly oblique to the fault trace (Figs 3, 5c).

Major gravity linear features (enhanced by first derivatives) are NE-trending and reflect the distribution of lithologies in the folds adjacent to Gortdrum. The gravity features are oblique to both the magnetic fabric and the main fault (Fig. 5c), and they intersect the fault at the deposit. This suggests that a sedimentary basin developed oblique to the basement structure. The folds are likely to have formed in the cover during the Hercynian deformation, along and oblique to the basement structure.

**Navan**

The geology of this deposit (over 70 Mt) is summarized by Ashton et al. (1986, 1992). The ore body is subdivided into five stratigraphically stacked lenses hosted in the Pale Beds.
Structural control on the mineralization is apparent as the ore lenses overlie steeply dipping and ENE-trending veins of sulphides, inferred to be feeder veins. The ore lenses are cut by the so-called ‘Navan unconformity’ (a major listric slide surface of Chadian age), which is overlain by the Boulder Conglomerate and Upper Dark Limestone. The ore body is also subdivided laterally into three zones by the B, T and A faults, (Fig. 6a). The B and T faults are spoon-shaped, have a normal component of displacement and die out up-section. They trend oblique to, and occur between, the A and C faults. Minor folding occurs above the T fault in the Upper Dark Limestone. The B and T faults trend on average about ENE and dip to the SSE. Adjacent to the T fault and beneath the ore lenses there is a concentration of sulphide veins that trend ENE. Zone 2 lies in the footwall of the T fault, and the mineralization is less well developed in its hanging wall block. Significant rotation of bedding in the Pale Beds occurs in the hanging wall of the B and T faults, suggesting that they are rotational extensional normal faults. The Boulder Conglomerate represents the chaotic deposit produced by synsedimentary rotational slumping. Both the T and the B faults are truncated by the A–C fault complex (Fig. 6a). Folding in the Upper Dark Limestone that trends anticlockwise of the A and C faults intensifies in the vicinity of the A fault, which has a large consistent reverse component of displacement.

As all of the faults offset the stratigraphic markers that define the ore lenses, they appear to offset the lenses. However, a case can be made for the ore lenses being selectively replacive, and post-dating movement on the B and T faults. While some mineralization terminates at the faults, at least in some cases, within the footwall block, grade increases towards the faults. Close examination of mineralization in the footwall of the T fault reveals that, at several levels, mineralization terminates several tens of centimetres short of the fault, and is not strictly truncated by it. The thickest ore in Zone 2 is in the hanging wall block of the B fault. Although displacement on the B fault is well constrained by stratigraphic displacements, ore lenses cannot be identified in the footwall, suggesting that the distribution of mineralization is influenced by the B fault. Where sulphides abut the B fault, the ore terminates against stylolitic surfaces defining the fault zone margin. In general terms, where an argillaceous unit lies in the hanging wall of a fault, sulphides terminate at the fault. Where the succession is shale poor, the ore extends across the faults. It is therefore possible that the mineralization occurred after much of the displacement had occurred on the B and T faults.
All of the ore lenses terminate beneath the unconformity, and clasts of mineralized Pale Bed lithologies occur within the Boulder Conglomerate. Where Zn–Pb ore lenses abut the unconformity, iron-rich Zn mineralization occurs above the unconformity (the Conglomerate Group Ore). The timing of the mineralization with respect to the unconformity is not clear-cut. Stratiform pyritic, sphalerite ore occurs in the matrix above the unconformity. Clasts of massive sulphides occur in the Boulder Conglomerate at the base of the Conglomerate Group Ore. Some carbonate clasts have been replaced in situ by sulphides (for example, many clasts show a concentric zonation of pyrite, sphalerite, dolomite from margin to centre). The replacement is highly selective: some bioclasts are preferentially replaced by sphalerite. In others, however, complex paragenetic sequences are preserved and some layers of sulphides appear to have been truncated by erosion (Ashton et al. 1986). This suggests that some of the mineralization occurred both prior to and during the slumping that generated the Boulder Conglomerate.

The Navan ore body is located near the hinge region of a SW-plunging anticline, and overlies a linear SW-plunging basement horst that produces a regional magnetic high (Figs 3, 4). In this region the main magnetic trends range from NE–SW to almost E–W. Magnetic gradients from the first derivative processing, like the main axes of anomalies, follow the two main fault trends, NE and ENE, diverging at the deposit. South of the mine, a gravity high trends NNW, and swings in strike to ENE in the area of the deposit (Fig. 2 & Fig. 2 in Readman et al. 1996), similar but oblique to the main trend of the magnetic anomalies. To the SE, a large gravity low has been interpreted as a buried granite (Murphy 1952).

The structural location of Navan and the generation of the ENE-trending feeder veins oblique to the main B and T faults is considered, therefore, to be related mainly to dilation created during regional extension. They may be en echelon rotational slump structures developed on a precursor of the NE-trending A–C fault complex which controlled the localization of the deposit. Reactivation and offset on the original structure was the result of dextral shear.

The Tatestown-Scallenstown and the Clogherboy deposits are satellite deposits to Navan and are associated with similar strike swings in the main faults (‘basement’ structures) as Navan. They have similar lensoid geometries to the Navan ore bodies.

**Keel and Newtown Cashel**

The Keel deposit (Slowey 1986) is hosted in an ENE-trending, S-dipping normal fault zone (Fig. 7). Mineralization is discordant and occurs in fractures related to the faulting. The host rocks range from Lower Palaeozoic slates to upper Navan Group rocks. Fault segments extend into the Waulsortian, and the wallrocks are extensively dolomitized adjacent to the faults. A series of N-dipping, NE-trending magnetic gradient boundaries occur on the northern margin of a major magnetic high which lies 10 km to the south. At the Keel Fault, the anomalies parallel the strike of the adjacent Lower Palaeozoic inlier, trending ENE; away from the main fault line, they swing NE. Mineralization at Newtown Cashel was controlled by an en echelon array of E–W faults, forming a dilation zone at the termination or overlap area of the main ENE-trending Keel Fault (Fig. 7b). The faulting and dilation zone is a mirror image of the controlling faults at Silvermines (see below).

The geometry of the fault system at Keel is consistent with dextral transtension. The Keel deposit occurs where the main fault on a regional scale has a minor strike swing; with dextral strike-slip motions this position is favourable for dilation and enhanced fracturing. The adjacent Newtown Cashel deposit (Crowe 1986) lies on the same ENE-trending structure as at Keel. This structure was active throughout the Dinantian, as there are lateral facies variations along and across the fault and a Chadian unconformity is associated with it (Crowe 1986). The fault pattern is reflected by a gravity lineament swing to E–W, and step off en echelon to the south. E-trending faults at Newtown Cashel deposit are also reflected by magnetic lineaments.

**Silvermines and Magcobar**

The geology of the Silvermines and Magcobar deposits (Fig. 8) was summarized by Andrew (1986). The local geology is dominated by the ENE-trending, steeply north-dipping, oblique-slip, dextral–normal Silvermines fault (Fig. 8). Dolomitic breccias that are spatially associated with the tabular mineralization form the hanging wall; these have been interpreted as debris flows (Andrew et al. 1986) and also as hydrothermal alteration products (Hitzman & Large 1986). Observations by one of the authors (J.D.J.) suggest that elements of both hypotheses may be correct: some parts of the breccia
Fig. 7. (a) Keel cross-section, redrawn from Slowey (1986), showing the intimate relationship between faulting and mineralization. (b) Schematic map of the fault system Keel–Newtown Cashel fault system, showing a dextral transtensional setting with a termination zone at Newtown Cashel.

units show clast alignment and sorting, parallel to bedding. Some of the clast margins are sutured and stylolitized, but others show rounding, and soft-sediment slump folds have been observed underground in the limestones adjacent to these breccias (Andrew et al. 1986). Superimposed on both the sedimentary breccias and the Waulsortian is a dolomite-matrix breccia. This comprises angular fragments of dolomitized wallrock with a filigree matrix of extremely fine-grained dolomite. In parts of this breccia the clasts can be matched and fitted together, while in other parts clasts have clearly moved relative to each other. This breccia appears to be hydrothermal in origin. Base metal mineralization occurs both in immediately sub-Waulsortian stratiform lenses and in discordant feeder zones parallel to the fault. The ore lenses thicken towards the Silvermines fault, as do the stratigraphic units and the Zn/Pb ratios increase. There is an upper, tabular, predominantly stratiform ore body of barite, siderite and marcasite (Fig. 8). In the deeper parts of the ore bodies the mineralization occurred in veins which lie en echelon along the Silvermines Fault.

The structural history has been documented by Coller (1984). A number of en echelon WNW-trending faults with predominantly normal displacement localize the mineralization. The
Silvermines Fault is parallel to, and lies on the southern margin of, a regional magnetic high, and north of a smaller magnetic low. Silvermines ore bodies lie where the axis of the high swings from ENE to E. West of the deposits, the boundary to the magnetic high is approximately coincident with the Silvermines Fault. However, this boundary side-steps to the SE at Silvermines, suggesting an en echelon side-step or offset of the main fault (see inset on Fig. 8). Magnetic linears apparent on the first derivative map (Fig. 3) show this same offset. The axis of a NNE-trending gravity low (Murphy 1974) passes through the deposit. North of the fault this low is coincident with a regional syncline in the Carboniferous. However, in the vicinity of the deposit, this fold has been tightened and rotated into the Silvermines Fault, while the anomaly has not been deflected.

The overall geometry suggests an ENE-trending dextral motion, but the component of motion on individual WNW-trending segments is extensional (i.e. normal). Mineralization was most intense at points of maximum normal throw. All structures show evidence of post-ore dextral reactivation (sub-horizontal slickensides are developed on some ore lenses). Thus, the faults appear to have been active during sedimentation and mineralization, and have been subsequently reactivated.

**Tynagh**

The Tynagh deposit occurs in the hanging wall of the Tynagh fault, with E-trending mineralized sections linked by short barren NE faults (Clifford et al. 1986). The role of the Tynagh Fault in the development of the deposit (Fig. 9) has been discussed by Moore (1975). Early faulting with a major normal component (greater than 600 m) is reflected by thickness changes and slumping in the Courceyan sedimentary record. The throw is variable along the fault, with the ore concentrated in the vicinity of the maximum throw. Later reverse movement was the result of NW horizontal compression. This is the same orientation as the regional Variscan shortening direction, producing dextral transpression. Mineralization overgrows stylolites, which lie at a high angle to bedding adjacent to the fault, suggesting that significant burial and deformation pre-dated at least some of the mineralization. Detailed petrography reveals the occurrence of carbonate pressure fringes with horizontal and vertical fibres growing on sulphides. This observation suggests that at least some of the reverse movement, with associated high pore-fluid pressures, post-dated at least some of the mineralization. Late stage veins and slickensides indicate that later sinistral strike-slip motion of unknown magnitude occurred.
Tynagh is on the northern margin of a magnetic high, and the main Tynagh Fault is coincident with a major magnetic boundary that extends ENE to the Moyvoughly prospect. First derivative structures diverge from ENE to NE in the vicinity of the deposit. Minor linears trend ENE parallel to the main mineralized zone, and oblique to the E–W controlling faults. Gravity features trend NE, with the deposit located on the north side of a linear low and to the south of a large gravity gradient associated with a regional high.
The Tynagh deposit, like Silvermines, is a classic example of mineralization controlled by en echelon extensional faults that conform to an oblique extension with dextral shear on the main ENE fault (Fig. 9). Further evidence is provided by en echelon veins and slickenfibres. The reason for the dilation at this segment of the fault is either related to the main strike change in the basement (magnetic) fabric from near E-W to NE, or a dilational termination zone of the fault strand.

Lisheen and Galmoy

Lisheen (Hitzman et al. 1992; Shearley et al. 1992, this volume) and Galmoy (Doyle et al. 1992) are both fault-controlled tabular deposits at the base of the Waulsortian. Both deposits lie on the NE-trending Killoran Fault Zone (Shearley et al. this volume). Other minor prospects have been discovered further north along this trend at Derrykearn and Glasha. The Killoran Fault is a dextral transtensional fault with individual E to ENE-trending strands (Shearley et al. this volume). At Lisheen, as at Silvermines and Tynagh, sulphides are spatially associated with an ENE-trending feeder fault zone. Aggregate normal displacement across the Killoran Fault at Lisheen is 210m. Its dip varies between 40° and 70° to the north. Three main ore lenses have been identified: the Main, Derryville and North zones. Most of the mineralization occurred within 30m of the base of the Waulsortian. Several sulphide bodies, containing iron sulphides, sphalerite and chalcopyrite, occur within oolitic limestones in the footwall at approximately the same elevation as the orebodies at the base of the Waulsortian.

A series of parallel magnetic lineaments (060°-trending) define changes in gradient in a zone parallel to the main Killoran Fault between Lisheen and Galmoy. A magnetic high to the NE of Galmoy cannot be traced in the Lisheen-Galmoy region. All of the gradients dip south and a second derivative linear is coincident with the main mapped fault. In addition, NNW-trending cross-lineaments occur at both Lisheen and Galmoy.

Discordant deposits hosted in the Waulsortian and supra-Waulsortian succession

A cluster of small pipe-like, breccia-hosted deposits have been discovered in County Kildare. The largest of these are Harberton Bridge (Fig. 1; Emo 1986) and Allenwood (Andrew 1993). These prospects are hosted in pipes that crosscut the Waulsortian and extend into the overlying Chadian and Arundian carbonate sediments. There are no magnetic signatures associated with the pipe-like deposits in Kildare, but the gravity trends are oblique to the main faults.

Several of the smaller occurrences are vein-hosted. At Allenwood (Andrew 1993), E-trending faults are mineralized, and brecciation occurs in patches which coincide with bends on the faults. Mineralized faults in the prospect area step eastwards and northwards in an en echelon manner, consistent with dextral transtension. NW-directed thrusting is assumed to be post-mineralization and Hercynian in age.
Discussion

There is clear structural control of all of the major Irish Carboniferous-hosted sulphide deposits. Mineralization in the Pale Beds sequence either abuts a fault (Tatestown, Moyvoughly, Keel; Fig. 7) or an 'unconformity' (Navan; Fig. 6). All of the Waulsortian-related deposits are in the hanging walls of normal faults (Fig. 9). The Harberton Bridge, Allenwood and related deposits are in breccia pipes related to normal faulting.

A fault map of the Midlands of Ireland (Fig. 10) reveals that the mineralized faults generally dip north in the southeast and to the south in the northwest. A cartoon of the structural geometries of each of the deposits shows that most of the deposits (Keel, Navan) that occur in the north of the basin are located on southerly dipping structures, while those in the south all dip to the north (Silvermines, Lisheen, Tynagh; Fig. 11). In the central part, faults dip in both directions. They usually have a normal throw with a mineralized hanging wall and barren footwall. All of the faults have some element of post-mineralization strike-slip reactivation. Many faults appear to have had predominantly dip-slip motions during an early, synsedimentary history. They almost all trend ENE to NE.

In every major fault associated with the Irish deposits where sufficient exposure is available,
there is evidence of early dip-slip. The evidence to support this view is a combination of stratigraphical (e.g. formations thicken in the hanging wall at Tynagh, Silvermines and Lisheen) and textural (e.g. the orientation of fibres in the fault zones at Gortdrum, Tynagh, and Silvermines, of slickenlines and shear bands in the case of Navan, and early compacted veins at Ballinalack). In all cases the dip-slip motions were followed by strike-slip motions as indicated by the orientation of fibres, veins and faulting. In every case the strike-slip post-dates the mineralization. This is because mineralization occurred in pure extensional orientations in en echelon systems (see below) of overall transtension. In localized occurrences, these structures were subsequently reactivated by reverse movements.

Millar (1990) demonstrated the same general sequence of structural events on a regional basis in the North West Province, and Nolan (1986, 1989), de Brit (1988) and Johnston (1993) have identified the same sequence in the Irish Midlands. To a certain extent the division of structures into strike-slip and dip-slip is an
artificial one. Individual, en echelon, pure extension veins (dip-slip fractures) can link and rotate with depth to form oblique extension veins (strike-slip fractures) as is apparent at Silvermines (Fig. 8), where ESE-trending dip-slip faults rotate and link at depth to form an ENE dextral fault.

In an attempt to semi-quantify the motions, McCoss constructions (McCoss 1986; Fig. 12a) for the Irish deposits were evaluated. It was assumed that the magnetic first derivative trend gave the deformation zone boundary. This is justified on the grounds that it is likely to give the orientation of the major basement structure, which in turn has controlled later deformation in the Carboniferous. Secondly, the best estimate of the orientation of extension fractures at the time of mineralization was used to define the strike of extension veins. Every one of the deposits sits in dextral transtensional zones (Fig. 11). These were the product of a NE extension of Carboniferous rocks deposited on a pre-existing Caledonian template.

As pointed out by Millar (1990), the transition from dip-slip through strike-slip to thrusting throughout the Irish Carboniferous may simply reflect increasing burial depths (Fig. 12b). All of the textural evidence presented here suggests that the mineralization is related to NE-extension. At deeper structural levels, this may have been contemporaneous with NW-compression. Therefore, some of the copper deposits in the South Munster Basin (Fig. 1; Reilly 1986) may have formed at the same time as the dextral transtensional deposits in the Irish Midlands.
during the mid to late Dinantian. However, it is generally accepted that the transpressional deformation associated with the Hercynian deformation post-dates the late Dinantian. Marine sedimentation persisted into the Namurian. Nevertheless, it is possible that the deformation was diachronous and the Irish Midlands may have been in transtension while the Munster Basin was in transpression.

A generalized model for the structural controls of the deposits is shown in Fig. 13. Each of the deposits is in a unique setting related to the precise basement geometry of its location. However, they are all located adjacent to basement structures, in regions of strike swings along these structures. This is seen in the geophysical data as a divergence of the gravity and magnetic linears. This may reflect obliquity of lithological and structural grain, or obliquity of major and minor structures. Either way, complexity of the trends in the basement greatly enhanced the potential for dilatancy in the cover during reactivation, and favoured the generation of ore deposits.

Conclusions

Most of the Irish carbonate-hosted base metal deposits appear to sit in dextral transtensional structural traps. The precise geometry of the traps varies from one deposit to another and the variations are the product of different basement structural geometries. Most of the deposits appear to have formed at intermediate burial depths, rather than on the sea floor. Precise timing is difficult to constrain, but the best estimates seem to be early Chadian for Navan, and late or post-Chadian for Lisheen. The fundamental structural controls are E- to NE-trending basement (Caledonian) structures, which have been reactivated in dextral transtension by NNE- to ENE-extension during the Dinantian. In general, in the north of the country, the ore-controlling faults dip south, while in the south of the country they dip north. The structures have evolved through a temporal kinematic history of early normal faulting, later oblique slip, and some show evidence of later reverse movements. Part of this evolution may reflect burial history, but it also reflects the temporal transition from Dinantian transtension to Variscan compression, which propagated northwards with time. The bulk of mineralization appears to post-date the normal faulting, but pre-date the Variscan compression.

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BASE METAL MINERAL DEPOSITS, IRELAND

