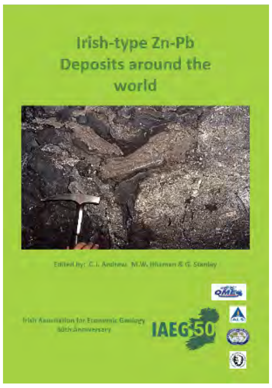

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Irish Zn-Pb deposits – a review of the evidence for the timing of mineralization. Constraints of stratigraphy and basin development.

Colin J. Andrew

Independent Consultant
Navan, County Meath, Ireland

Corresponding Author: Colin J. Andrew candrew@iol.ie

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Irish Zn-Pb deposits – a review of the evidence for the timing of mineralization. Constraints of stratigraphy and basin development

Colin J. Andrew

Independent Consultant
Navan, County Meath, Ireland

Abstract: The Irish Midlands is ranked first in the world in terms of zinc metal discovered per sq. km. with over 14 Mt of contained metal found to date. The largest deposit at Navan exceeding 150 Mt of production plus remaining resources, and four other deposits having been brought into production since 1962 and a further 20 prospects discovered including the major Pallas Green deposit.

The deposits such as Navan, Tynagh, Silvermines, Lisheen, Galmoy and Pallas Green and others that host this vast resource show varying host-rocks, mineral textures, thermo-chemical and isotopic signatures. However, amongst this apparent diversity lie some major similarities that form the basis of the definition of being "Irish-type" which form a specific spectrum of styles that lie between MVT-type and SedEx-types.

In order to develop any robust model for ore deposit formation it is critical to establish reliable age constraints and an understanding of the depositional and structural environments for the host rocks and thus the mineralizing processes. In the Irish Midlands there is an abundance of geological and isotopic evidence that places the age of the mineralization within a short time frame related to two extensional periods around 347Ma and 345Ma in the late Courceyan to early Chadian.

The host carbonate sequences that host the mineralization encompass an upward deepening transgressive sequence initially deposited in shallow basins. By using isopach plots of conodont biozones sedimentation patterns show that both lithological and thickness variations are strongly influenced by active basin evolution around these times. Mineralization is geologically constrained to have occurred at relatively shallow depths and is largely contemporaneous with diagenesis and dominantly occurred before locally catastrophic basin breakup (rifting) occurred setting the shape of later (post-ore) carbonate sedimentation.

Although intra-cratonic basalt dominated volcanism is present in the Irish Midlands the mineralization generally pre-dates these volcanics, which appear to be coeval with the rifting in the latest Chadian to early Arundian.

The critical factor in the size of the mineralized bodies appears to be the degree of "openness" of the mineralizing system. Thus, near surface exhalation and/or the unroofing by erosion of, or dissolution and collapse of hangingwall units, appears to be a critical aspect in the development of large-scale mineralizing systems. Closed "tight" deep fracture-controlled systems where lithification had advanced are not economic. In simple terms mineralization occurred at relatively shallow burial depths of between 250m and the contemporaneous seafloor and this is possibly the defining feature of the Irish-type deposits.

Key Words: Dating of mineralization, Basin Development, Rifting, Carbonate Sedimentation Patterns

Introduction

According to Leach *et al* (2010) sediment-hosted Zn-Pb deposits can be divided into two major sub-types. The first sub-type is clastic-dominated zinc-lead ("CD Zn-Pb") ores, which are hosted in shale, sandstone, siltstone, or mixed clastic rocks, or occur as carbonate replacements within a clastic dominated sedimentary rock sequence. This sub-type includes deposits that have been traditionally referred to as sedimentary exhalative ("SedEx") deposits. The CD Zn-Pb deposits occur in passive margins, back-arcs and continental rifts and sag basins, tectonic settings that, in some cases, are transitional into one another. The second sub-type of sediment-hosted Zn-Pb deposits is the Mississippi Valley-type ("MVT Zn-Pb") that occur in platform carbonate sequences, typically in passive-margin tectonic settings.

Deposit and Stratigraphic Setting	Mt	% Zn	% Pb	g/t Ag	% Ba	References
Navan Group Deposits						
Navan (1)	122.6	7.4	1.8	11		Farrelly (2020)
Navan - Tara Deeps (2)	22.4	7.8	1.4			Farrelly (2020)
Clogherboy	0.3	5.8	1.2			Andrew (1991)
Tatestown	3.6	5.3	1.5	37		Andrew & Poustie (1986)
Oldcastle (Drumlerry)	3.0	4.3	0.6			Brand & Emo (1986)
Keel (2)	1.9	7.7	1.0	40		Slowey (1986)
Moyvoughly	0.1	6.5	1.0			Andrew (1991)
Waulsortian Mudbank Deposits						
Tynagh (1)	9.2	5.0	6.2	66	8.3	Boast, A.M., *et al* (1981A).
Silvermines (1)	17.7	6.4	2.5	23		Andrew (1986)
Magcobar (1)	5.2				84.0	Mullane & Kinnaird (1998)
Lisheen (1)	22.2	11.5	1.9	26		Shearley *et al* (1995)
Galmoy (1)	6.9	12.8	1.3			Doyle & Bowden (1995)
Ballinalack (2)	5.4	7.6	1.1	9		Gordon, P., *et al* (2019)
Garrycam (2)	1.4	2.7	0.2		36.1	Slowey (1986)
Courtbrown	1.0	3.5	2.0	14		Grennan (1986)
Carrickittle	0.2	6.1	1.5			Hitzman & Large (1986)
Stonepark (2)	5.1	8.7	2.6	2		Gordon, P., *et al* (2018)
Pallas Green (2)	45.4	7.0	1.0			Glencore (2019)
Kilbricken	2.6	4.7	2.9	50		Colthurst & Reed (2019)
Other host rocks						
Abbeytown (1)	1.1	4.3	1.0			Persellin (2006)
Kildare District						
Allenwood West	10.1	1.6	0.4			Dixon (1990)
Harberton Bridge (Canal Zone – Mac-Gregor Zone) (2)	7.0	8.1	1.4	10		Zinc of Ireland NL - Annual Report 2020
Harberton Bridge (Bridge Zone – Shamrock Zone) (2)	3.5	7.1	0.9			Zinc of Ireland NL - Annual Report 2020
Harberton Bridge (FC3 Zone) (2)	0.9	8.5	1.0			Zinc of Ireland NL - Annual Report 2020
Rickardstown	3.5	2.2	1.1			Andrew (1991)
Boston Hill	0.8	2.7	1.1			Andrew (1991)

Notes:

Figures shown are for "geological resource" and intended only to demonstrate the approximate size of the mineralized bodies and includes historical mined tonnages plus various categories of formally reported Reserves and Resources.

(1) Mined to date, P&P Reserves, M&I Resources, and I2 Resources.

(2) M&I Resources and/or I2 Resources.

Figure 1: *Tabulation of the currently known Irish Zn-Pb deposits.*

The Irish Midlands is ranked first in the world in terms of zinc metal discovered per sq. km, and second for lead (Singer, 1995) and so on this basis alone surely can be considered unique and worthy of its own classification as a third sub-type. In excess of 14 Mt of contained zinc metal has been found to date with the largest deposit at Navan exceeding 150 Mt of production and remaining resources with four deposits (Tynagh, Silvermines, Lisheen, Galmoy) having been brought into production since 1962 and a further 20 prospects discovered to date including the major Pallas Green deposit (See Figures 1 & 2).

The deposits such as Navan, Tynagh, Silvermines, Lisheen, Galmoy and Pallas Green (Figure 2) and others that host this vast resource show varying host-rocks, mineral textures, thermo-chemical and isotopic signatures that together neither equate to SedEx or MVT types. However, amongst this apparent diversity lie some major similarities that form the basis of the definition of being "Irish type".

This paper argues that Irish-type zinc-lead deposits represent a distinctive sub-class of the carbonate-hosted zinc-lead deposit family, having geological features and genetic models that are hybrid between SedEx and Mississippi Valley-type deposits both in their setting and in their genesis.

But what are "Irish-type" Zn-Pb deposits? There are Zn-Pb deposits in Ireland that most geologists working on Irish deposits do not consider to be typical Irish-type (Kildare) and there are Irish-type deposits that are not in Ireland. So, what

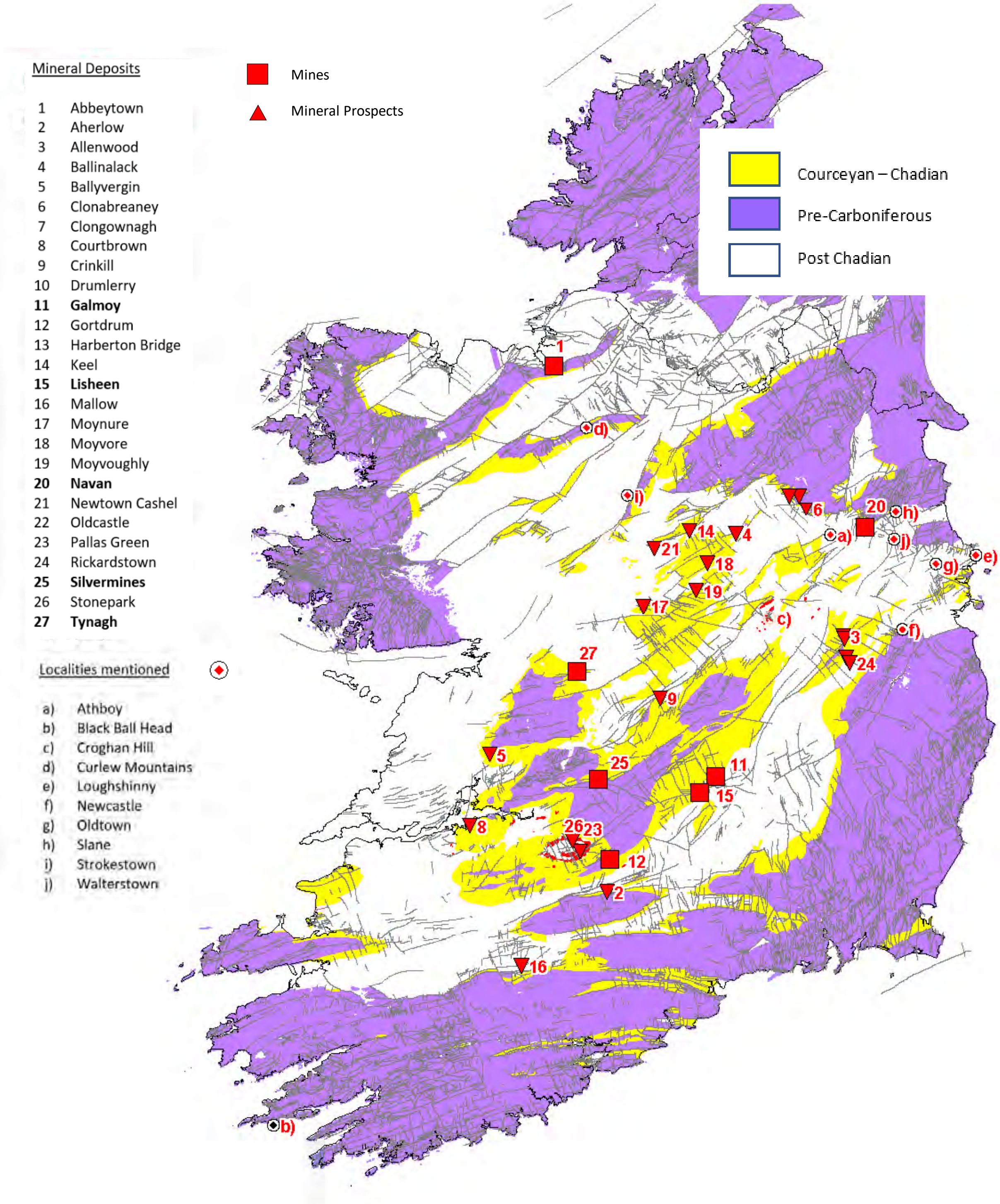

***Figure 2**: General map of Ireland showing the extent of the sub-crop of the ore-hosting part of the lower Carboniferous stratigraphy, mines, prospects, and locations discussed in the text.*

exactly are "Irish-type Zn-Pb deposits" and is the term useful or not?

Taylor & Andrew (1978) recognized that Silvermines could be regarded as being a hybrid between MVT and SedEx styles of mineralization and thus coined the term "Irish-type Zn-Pb deposits" which eventually came into informal use in the 1980s but is now used to classify similar deposits world-wide. Such similarities have been claimed far away from Ireland and globally a number of other deposits have been classified as "Irish-type" based on a range of similarities with the type example at Silvermines. These include the Cretaceous Mediabad and

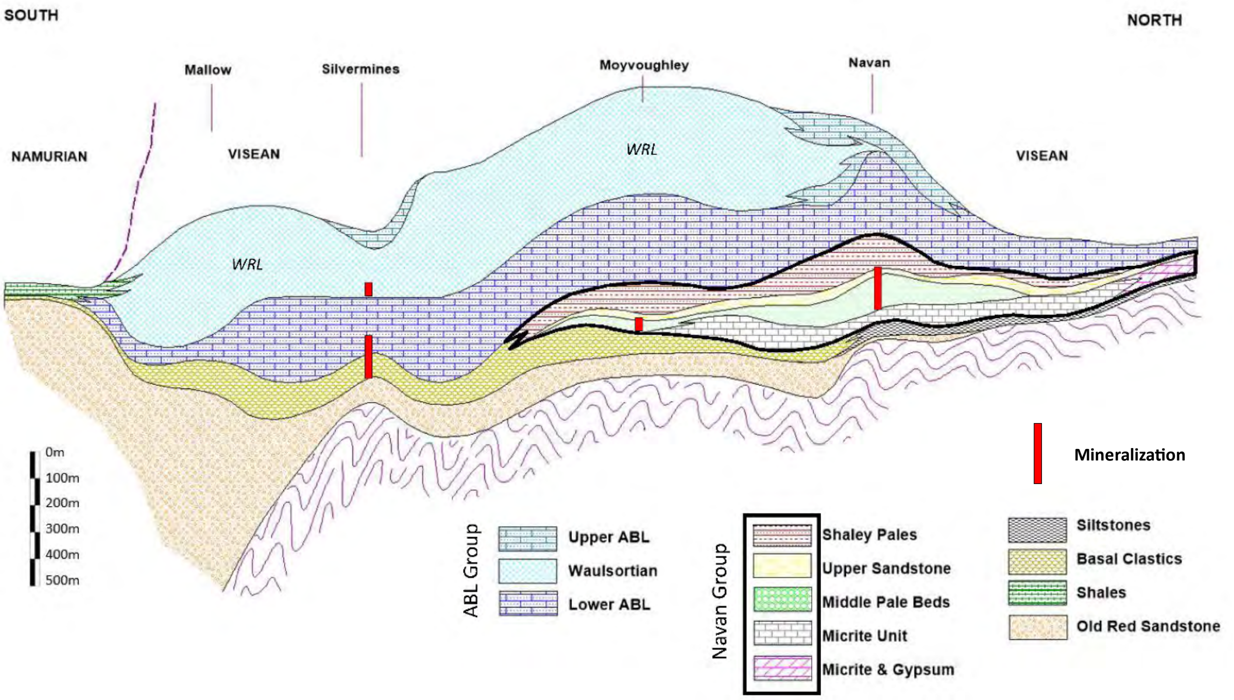

Figure 3: *Schematic section from the south coast (Innishannon) to north of the Longford-Down Inlier of the Courceyan Stage. Horizontal axis not to scale. Redrawn from Andrew (1986).*

Irankuh (Iran) deposits, the Neoproterozoic Morro Agudo deposit (Brazil), the pre-Cambrian Zawar deposits, (Rajasthan, India), Gays River (Nova Scotia, Canada), deposits in Kanchanaburi (Thailand), Dengiashan (China), Jabali (Yemen), and Prairie Creek (NWT, Canada). In the Kootenay Arc of British Columbia, the Reeves MacDonald, HB, Aspen, Jack Pot, Jersey, Duncan and Wigwam deposits amongst others have also been considered to be "Irish-type". Elsewhere the "Alpine-type" deposits hosted in the Triassic Muschelkalk of Slovenia, Austria, Italy and Bulgaria also have been claimed to share a range of features common in Irish-type deposits.

Two models have commonly been proposed for "Irish-type" deposits: (1) syngenetic seafloor deposition: such evidence includes stratiform geometry of some deposits, the occurrence of bedded and clastic sulphides exhibiting sedimentary textures, and, where determined, similar ages for mineralization and host rocks; *or:* (2) diagenetic to epigenetic replacement: such evidence includes replacement and open-space filling textures, lack of laminated sulphides, alteration and mineralization above sulphide lenses, and a claimed lack of seafloor oxidation.

However, the reality is that both models form end members of the Irish deposits, and this makes the term "Irish-type" distinct from "MVT-type" and "SedEx" and fills a useful gap between the two extremes. Within the classic "Irish-type" deposits the style and nature of the mineralization depends upon the environment of deposition; *i.e* the nature of the host sediments, their state of lithification and proximity of contemporaneous tectonism.

In Ireland all of the Zn-Pb deposits are hosted within the Lower Carboniferous diachronous pre-rift transgressive sequence which passes from marginal marine siliciclastics via shallow water lagoonal or platform carbonates to deeper water argillaceous bioclastites with Waulsortian carbonate mud-mounds before being overlain by a post-rift mosaic of shelf limestones and basinal calcareous wackestones. Within this sequence considerable local facies variations occur as do large thickness variations, such variations can be shown to have occurred during certain microfaunal (conodont) biozones permitting a detailed understanding of the transgression and subsequent basin development.

Whilst it is now generally agreed that the widespread hydrothermal activity that formed the Irish Zn-Pb deposits was linked to transtensile basin development in the Lower Carboniferous, greater definition as to exactly when, and at what stage of sedimentation and diagenesis the mineralization took place is less clear. Some aspects of deposit formation are manifestly clear, such as the syn-rift Boulder Conglomerate at Navan that contains clasts of subjacent earlier mineralization deposited in the Courceyan (359.2 to 346.7 Ma) which was unroofed and eroded in the Chadian (346.7 to 341.0 Ma) only to be included in the conglomerates; and the presence of laminated sulphides in the hangingwall units imply that hydrothermal activity extended into the Arundian (341.0 to 339.0 Ma) (Dates from Menning *et al.*, 2006). However, the precise dating of the mineralizing event at the other Irish deposits is less than clear.

Wilkinson & Hitzman (2016) have succinctly described the Irish carbonate-hosted zinc-lead deposits as being both stratigraphically and structurally controlled, with the ore deposits restricted to two stratigraphic units of Lower Carboniferous

Figure 4: *Correlation of the various stratigraphic nomenclature within the study area compared to the terminology used in this paper.*

(Courceyan to Chadian) age: (1) the Waulsortian Mudbank formation, a relatively clean typically stromatactid biomicrite in southern and central Ireland; and (2) the Navan Group of north central Ireland, a sequence of clean micrites, grading upwards into bio-grainstones and calc-arenites, with variable argillaceous beds throughout (see also Ashton *et al*., 1986; Wilkinson *et al*., 2003) (Figures 3 & 4).

The Waulsortian-hosted deposits are found largely in the complexly faulted hangingwalls of large (>150m offset) pre-rift normal faults within relay-ramp systems formed during transtensional fault movement (Kyne *et al*, 2019). The giant Navan deposit hosted in the Navan Group occurs broadly within a degraded footwall uplift zone of a very large normal fault that was also subject to syndepositional, syn-rift submarine mass wastage which removed a significant thickness (up to 250-300m) of sedimentary cover above the mineralized zone, which unroofed the mineralizing system whilst active. Such ore-controlling faults in the Irish Orefield formed in response to extensional tectonism in the Tournaisian (Courceyan, Chadian and early Arundian Stages) but their location and orientation were probably controlled by pre-existing Caledonian-aged faults within the Lower Palaeozoic basement (Wilkinson & Hitzman, 2016; Wilkinson *et al*, 2005, Ashton *et al*, 1986; Andrew 1990). It is the spatial and temporal relationship to such faulting and this fault development within basin formation and fill that is the critical aspect of the Irish deposits and maybe the defining aspect of "Irish-type" deposits worldwide.

What is an "Irish-type" deposit?

In the simplest terms it is a zinc-rich Zn-Pb-Ag-Ba mineral deposit that formed close to the palaeo-seafloor during lithification (diagenesis) of the host sediment (normally carbonates) at relatively shallow depths of burial (from a few metres to typically less than 200m) and exhibits most or all of the following characteristics:

- The deposits comprise single or multiple stacked lenses; they are stratabound and display generally stratiform morphologies and preferentially occur within platform limestones and often within the stratigraphically lowest, non-argillaceous carbonate unit with or without dolomitization.
- The host sediments may contain debris-flow breccias and conglomerates, laminated sulphidites and banded ironstones.
- They are structurally controlled, often occurring immediately adjacent to extensional normal (generally listric) syn-sedimentary active fault complexes which provided conduits for ascending hydrothermal fluids.
- Some deposits display pre-mineralization, diagenetic or hydrothermal dolomite alteration of the host rocks but, importantly, dolomitization is not necessarily pervasive nor a prerequisite for mineralization.
- They display complex sulphide mineral fabrics and textures ranging from laminated and graded exhalites to diagenetically early replacement of the host rock by colloform sulphides and infill of diagenetic solution cavities exhibiting geopetal fabrics, open-space fill, disruption brecciation and re-sedimentation, to replacive masses of coarse-grained crystalline sulphides. Mineralogically they are relatively simple comprising sphalerite, galena, Fe sulphides & barite, (minor Cu, Ag, As, Ni) in a gangue of calcite, dolomite & silica.
- Metals are laterally and horizontally zoned, typically being Pb-rich closest to feeder structures and at the base of the orebody.
- Sulphur isotopes show $\delta^{34}S$ from -44 to +14‰ indicative of two sources - bacteriogenic and hydrothermal - with the role of bacteria playing a major role in sulphur availability. This is a distinctive feature of classic Irish-type deposits.
- Evidence from fluid inclusions of fluid mixing is commonplace with a hot (100-240°C) metal-bearing low salinity (4-6 wt% NaCl eq.) fluid interacting with a saline to hypersaline (10-23 wt% NaCl eq.) H_2S-rich formation water.

- Importantly, and this perhaps is the defining aspect, mineralization almost certainly occurred within a few million years of the deposition of the host rocks. This is unlike MVT deposits where the migration of ore fluids is not a natural consequence of basin evolution; rather, MVT districts formed mainly where platform carbonates had some hydrological connection to orogenic belts often long after basin closure and even inversion (Leach *et al* 2001).

Regional Setting of the Irish Orefield

The geology of the Irish Zn-Pb deposits has been studied by various workers over the past 50 years of mining and exploration activity, producing a number of comprehensive reviews (such as Philcox, 1983; Andrew, 1993; Hitzman & Beaty, 1996; Phillips & Sevastopulo, 1986; Shearley *et al*., 1995; Sevastopulo & Wyse-Jackson, 2001; Hitzman *et al*., 2002; Wilkinson *et al*., 2005; Wilkinson, 2013; Wilkinson & Hitzman, 2016; and de Morton *et al*., 2015).

The formation of the Irish Carboniferous basins hosting the Irish Zn-Pb deposits, followed the closure of the Iapetus Ocean and the collision of the Laurentian and later Eastern Avalonian continents during the Ordovician-Early Devonian Caledonian orogeny (Chew & Stillman, 2009; Wilkinson & Hitzman, 2016). The resulting Iapetus Suture is generally considered to extend from beneath the Shannon Estuary where it is E-W, through the Irish Midlands where it trends NE-SW and out into the Irish Sea to the Scottish Borders. This continental suture dips shallowly to the north 15–25°NW and is believed to be coincident with a subduction zone where the intervening Iapetus Ocean was consumed (Phillips & Sevastopulo, 1986). Deformation associated with the Caledonian orogeny comprised generally ENE- to NE-trending folding and major terrane-bounding strike-slip faults developed within Ordovician and Silurian metasedimentary basement rocks.

During the late Devonian to early Carboniferous, a series of interconnected extensional basins developed in response to early manifestations of N-S to NNW-SSE episodic extension over the back-arc of the N-dipping European Variscan subduction zone (Gawthorpe *et al*., 1989; Philcox *et al*., 1992; Johnston *et al*., 1996; Philcox, 1989). Associated with this extension was the development of E-W- to NE-SW-trending normal faults within the Irish Midlands basins, the localization and evolution of which is believed to have been controlled by the geometries of reactivated Caledonian basement structures (Brown & Williams, 1985; Phillips & Sevastopulo, 1986; Johnston *et al*., 1996) (Figure 5).

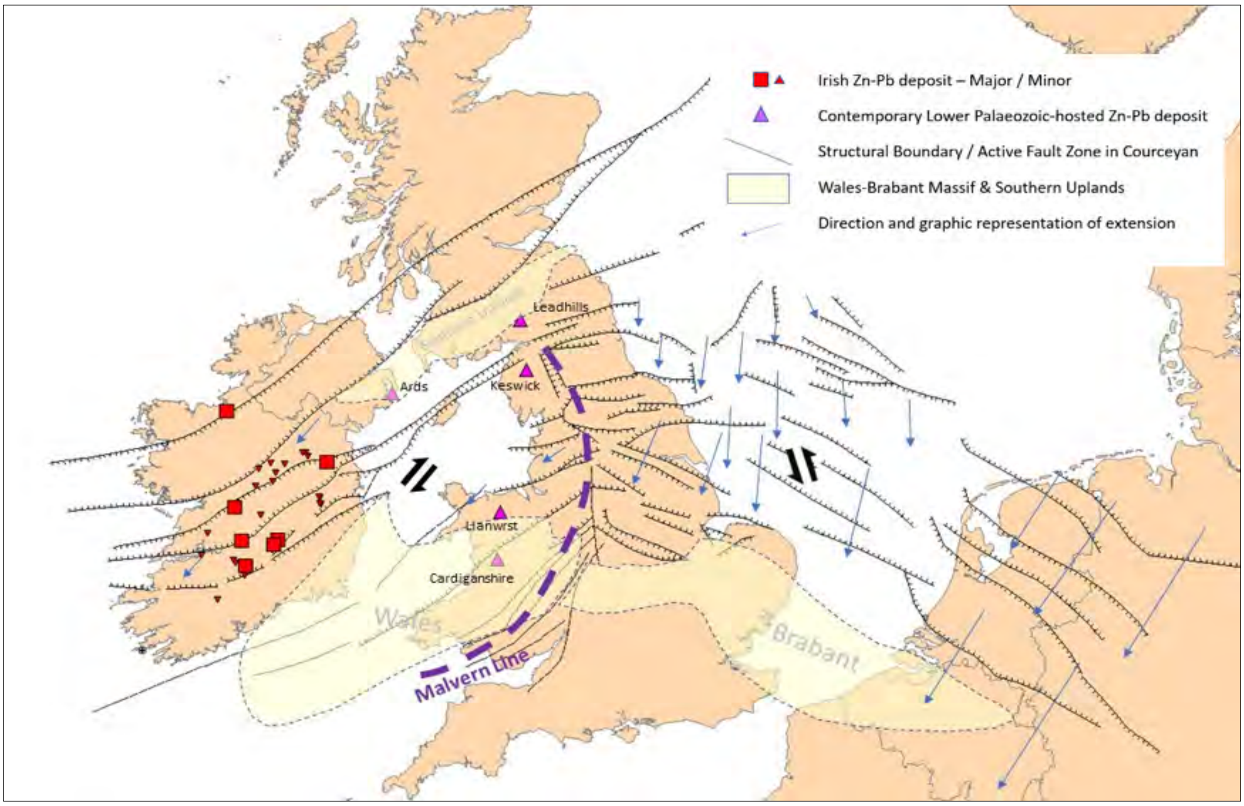

Figure. 5: *Map view restoration of the geography of the early Variscan, (Courceyan) extension of Avalonia. Deformation was by SSW-SW directed dextral transtension west of the Malvern Line and rotational sinistral transtension east of it. The map shows the principal Irish Zn-Pb deposit and Lower Palaeozoic vein-hosted Zn-Pb districts age dated to an equivalent age range as the Irish deposits. Palaeogeography after Smit et al (2018).*

Leadhills District includes Wanlockhead (dated as "Lower Carboniferous"); Keswick District includes Thornthwaite, Force Crag and Threlkeld (dated at 330-350Ma); Llanwrst District (dated at ~350Ma); Cardiganshire (Plynlimon District) dated at 353-356Ma).

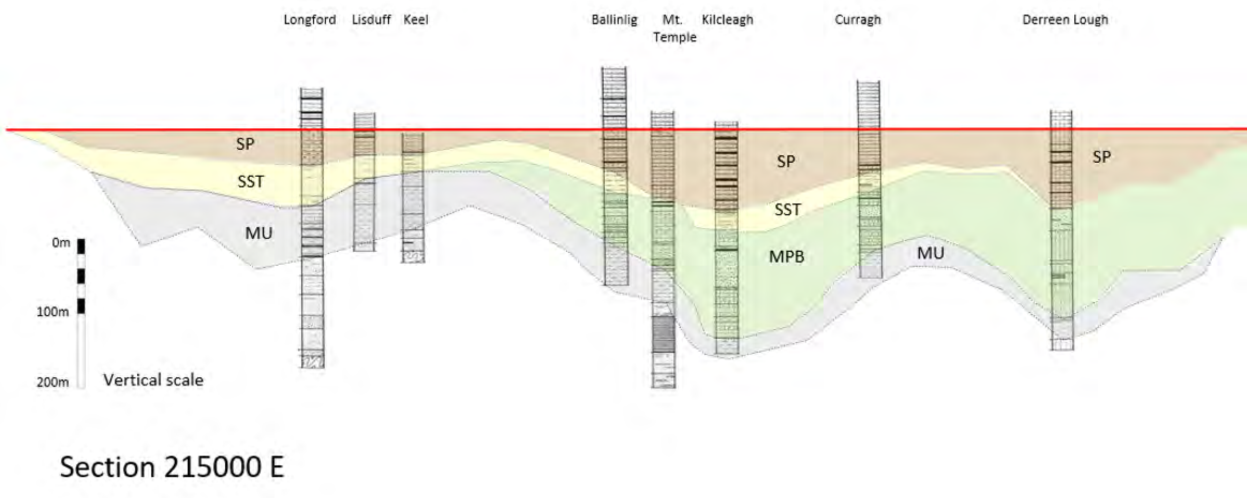

Figure 6: *N-S schematic section of the Navan Group across the Central Midlands showing disposition of the Micrite Unit (MU), Middle Pale Beds grainstones (MPB), Upper Pale Beds Sandstone (SST) and Shaley Pale (SP) from a datum at the base of the overlying ABL.*

Deposition of Lower Carboniferous limestones in Ireland resulted from a northward directed marine transgression and they have been described in detail by Philcox (1983), Phillips & Sevastopulo (1986), Andrew (1992; 1993); Hitzman (1999) and Strogen *et al*. (1990). Depositional patterns and thicknesses were strongly influenced by the development of basinal areas, which generally follow earlier Caledonian trends.

Whilst formal stratigraphic frameworks have been defined by numerous authors the plethora of unit and often local formation names can be confusing, thus for this paper a simplified informal stratigraphic nomenclature is used and set out in Figure 4.

The basal Lower Carboniferous rocks, the so-called "Navan Group" (Andrew & Ashton, 1985), lie above an irregular unconformity on pre-Devonian metasediments and intrusives and pass from a thin basal northerly prograding transgressive sequence of juxtaposed floodplain fluvial sandstones, flood-deposited sandy siltstones, palaeosols and evaporites into distinctive peritidal pale carbonate mudstones that display evidence of several exposure surfaces. These are succeeded by higher energy, shallow water, bioclastic and oolitic grainstones, sandy calcarenites and sandstones. These, together with the underlying micrites, are informally termed the Pale Beds (Figure 6). Evidence of intermittent subaerial exposure and minor cyclicity occurs within the carbonate successions (Rizzi & Braithwaite 1996). The Navan Group becomes increasingly arenaceous towards the NW containing sabhka evaporites with gypsum and halite in the basal Navan Group at the northern marine margin of the diachronous transgression.

At the top of the Navan Group Pale Beds a distinctive wavy cross-bedded weakly calcareous sandstone is developed over a widespread part of the NW Midlands. This sandstone, ranging up to a maximum of 45m in thickness typically passes via a diastem or rapid facies change into the dominantly silty Shaley Pales comprising shaley bioclastic calcarenites, calcsiltites, shales and sandstones, representing a deepening depositional environment. Notably the depocenter changes from the NW Midland to the northern part of the incipient Midlands Basin at the onset of the deposition of the Moathill Formation at the base of the *P.mehli mehli* sub- biozone whereupon a number of dominantly E-W pre-rift fault segments developed to control sedimentation patterns through to the *P. bischoffi* biozone.

Isopach plots of the Navan Group demonstrate mild differential subsidence during the Courceyan (essentially during *Pseudopolygnathus multistriatus* to *Polygnathus bischoffi* conodont biozones) in shallow basins developed due to transtension affecting movement along NE'erly Caledonian trends. (Andrew, 1990). These early Central Midlands pre-rifting basins were gulf-like, with initially, hypersaline seas, apparently tideless, but with variable influx from freshwater river systems.

The Navan Group is the main host to the giant Navan deposit and its satellites and also the prospects at Clonabreaney, Drumlerry, Keel, Moyvoughly, Moyvore, Moynure, Newtown Cashel, Oldcastle, Sion Hill and Tatestown.

In the central part of the Midlands the Navan Group is succeeded and passes laterally into the Argillaceous Bioclastic Limestone (the so-called "ABL" or "Ballysteen Formation") comprising deeper water well bedded argillaceous bioclastites with an abundant fauna of crinoids, bryozoa, rugosa and brachiopods. The ABL is around 300-450m thick across much of Central Ireland but shows rapid thickening within the Dublin Basin (Nolan, 1989; Strogen *et al*., 1996). The ABL is overlain by the Waulsortian Mudbank Limestone comprising pale grey wackestones and packestones that frequently contain well developed spar and/or mud-filled 'stromatactis' cavities. The Waulsortian Limestones show rapid thickening in the Dublin Basin (up to 800m; Strogen *et al*., 1990), and a strong tendency for isopachs to parallel Caledonian trends in Central and Eastern Ireland is evident (Andrew, 1993). Towards the edges of

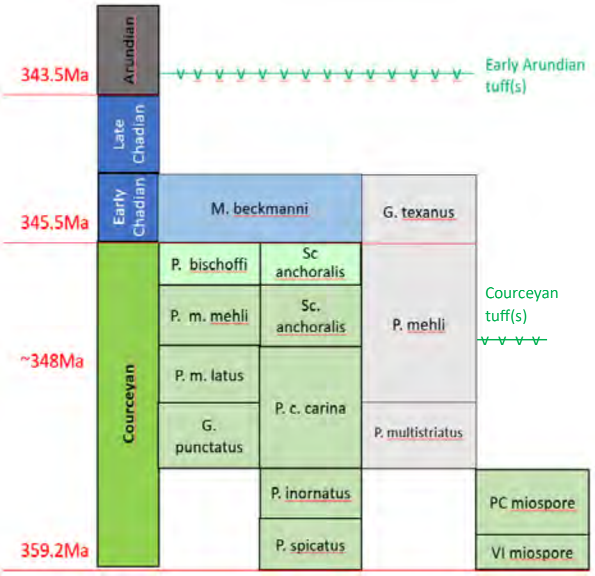

Figure 7: *Conodont biostratigraphy as determined in the Irish Midlands and used in this paper.*

Conodont biozones from Riley (1993) and Jones & Sommerville (1996).

Waulsortian development isolated mud mounds occur within ABL-type lithologies. Such thickness variations can be shown to have occurred during certain conodont biozones permitting a detailed understanding of basin development.

The lowermost Waulsortian is the host to the deposits at Tynagh, Silvermines, Lisheen and Galmoy and to the prospects at Stonepark and Pallas Green.

After the deposition of the ABL / Waulsortian the level of syndepositional faulting increased during the late Courceyan and Chadian (the rifting phase), with the development of varied, structurally controlled shelf and basin depositional areas. In several areas of the eastern Midlands, notably at Navan, Walterstown, Crossakeel and Newcastle low-angle submarine slides, mass wasting and erosion surfaces developed (Figure 11). Locally these drastically reduced the thickness of the earlier limestone sequence and were accompanied by the deposition of a variety of debris-flow and fault-talus style breccia conglomerates. The submarine slides are of Chadian age at Navan and cut out up to and possibly greater than 600m of earlier Carboniferous lithologies down and into Lower Palaeozoic rocks (Philcox, 1989; Ashton *et al*., 2015).

This syndepositional faulting led to the creation of a mozaic of both post-rift basins and shelves. In shelf areas argillaceous limestones, clean packestones and oolitic grainstones of the Allenwood Beds and Oakport Limestone were deposited, whilst in the basins deeper water carbonate turbidites and argillites (informally known as ‘Calp’ or ‘Upper Dark Limestones’ including the basal Tober Colleen Mudstones), locally containing terrigenous quartz pebble horizons and reworked bioclastic debris were deposited. Hence the ABL/Waulsortian is overlain by a mosaic of shelf and basinal lithologies within which considerable local facies and thickness variations occur.

The Waulsortian and superceding oolites of the Allenwood Beds are host to the MVT-type mineralization at the Allenwood and Harberton Bridge prospects in County Kildare.

Basinal sedimentation proceeded in the Dublin Basin, where Nolan (1989) and Strogen *et al*., (1990) have described successive periods of growth faulting, tilt block formation and platformal/basinal sedimentation in the Arundian, probably persisting intermittently to Brigantian times.

The total thickness of pre-Arundian Carboniferous rocks in Central Irela nd has been estimated as attaining a maximum of ~2km in the Dublin Basin (Nolan, 1989; Strogen *et al*., 1990). However, average thicknesses are substantially less (Phillips & Sevastopulo, 1986; Andrew, 1992).

Whilst there is a wide range of both formal and informal stratigraphic nomenclatures across the country (Figure 5) for simplicity these can be understood as being a simple pre-rift diachronous transgressive sequence deposited within a subsiding marine environment subject to both passive sag and eventual rapid breakup and transtensional tectonism leading to post-rift block / basin sedimentary environments in post mineralization times.

Mineralization Dating

The age of mineralization for the Irish Zn-Pb deposits has been a matter of some conjecture and intense debate for many years. The first models for Tynagh (Derry *et al*, 1965; Morrissey, 1970) and Magcobar (Silvermines) (Barrett, 1975) favoured early mineralization with fluids escaping via mineralized feeder zones onto the contemporaneous seafloor. Later models (*eg*. Taylor & Andrew, 1978; Taylor 1982; Andrew, 1986, 1990; Andrew & Ashton, 1985, Ashton *et al*, 1986) favoured combined epigenetic and syngenetic models and established the term “Irish-type” for such syn-diagenetic mineralization, whilst later workers such as (*eg*. Peace & Wallace, 2000; Reed & Wallace, 2002, 2004; Pannalal *et al*, 2008) proposed a late epigenetic, post-lithification model.

There is an abundance of compelling evidence regarding dating the relative age of the ore minerals ranging from simple observable geological constraints such as clasts of pre-existing mineralization included in overlying lithologies, and the presence of biota and micro-biota in ore stage minerals, to precise isotopic dating of sulphides and ore-hosting lithologies. Unfortunately, some dating techniques, such as some palaeomagnetic results, require careful assessment in the context of the overall setting of the orefield.

Magnetic Dating

A number of palaeomagnetic dates have been published over the past twenty years or so, the most significant being 269±4 Ma for Silvermines (Magcobar) (Pannalal *et al*, 2008), 333±4 Ma for Navan (Symons *et al*, 2002), 290±9 Ma for Galmoy and 277±7 Ma for Lisheen (Symons *et al*, 2002).

Wilkinson *et al* (2017) noted that regional remagnetization of Irish Carboniferous carbonates dates Variscan orogenesis, not the Zn-Pb mineralization as unaltered rocks distal to mineralization that are of equivalent age to the ore host sequence have comparable characteristic remanent magnetic directions to those previously derived from the ores. This indicates that remagnetization of the rocks was independent of the ore-forming process. Recent thermal demagnetization studies in a variety of rock types have indicated that the remagnetization event was quite pervasive extending from near the Hercynian Front to the English Lake District and Scotland and also across Ireland as seen at numerous locations throughout the Lower Carboniferous in the UK (McCabe & Channell, 1994; Channell *et al*, 1992).

Importantly, Symons *et al.* (2002) did not show how the remanent magnetism was related to the generally non-magnetic ore and gangue minerals. However, Cruise (2000) obtained magnetic ages from magnetite in the Tynagh Iron Formation in the range of 337 to 354Ma broadly spanning the likely mineralization age.

Morris (1972) and Howard & Morris (1980) in an extensive palaeomagnetic study across unmineralized sediments of the Dublin Basin noted that the predominant magnetic trend indicated magnetic ages from the late Carboniferous (early Namurian) to Permian (Variscan), equivalent to most of the ages reported by Pannalal *et al (*2008) and Symons *et al* (2002).

Comparison with the apparent polar wander path for Europe suggests an age of *ca.* 265 to 310 Ma for this remagnetization event, consistent with the timing of the Variscan orogeny (Reinhardt et al., 2022) We can therefore discount these magnetic ages as they all do not reflect mineralization ages and appear to be due to resetting during Hercynian orogenesis in the late Stephanian to early Permian (Figure 8).

Isotopic Dating

Hnatyshin, *et al* (2015, 2020) provided Re-Os geochronology to show that ore-stage pyrite from the Lisheen Main Zone formed at 346.6 ± 3.0 Ma and 343.0 ± 6.7 Ma for the Bog Zone; whilst pyrite from the B-Zone at Silvermines returned an age of 334.0 ± 6.1 Ma. Such a discrepancy in the Re-Os data from the host-rock age has been interpreted in the Derryville Zone (322 ±11Ma) at Lisheen to potentially involve fluids associated with Variscan deformation (<310Ma) and that the Re-Os data does not reflect the timing of the iron sulphide mineralization due to mixing (Hnatyshin *et al*, 2020).The early ore-stage pyrite samples from both Lisheen and Silvermines yield Courceyan Re-Os ages that place the timing of sulphide mineralization within ~15 Ma of host rock deposition. The Re-Os age from Lisheen (346.6 ± 3.0 Ma) overlaps with the depositional age range of the host Waulsortian constrained by precision zircon dating of 350.08 ± 0.68Ma to 348.92 ± 0.95Ma of underlying and overlying tuff horizons (Koch *et al.*, 2022).

Hence Zn-Pb mineralization at Lisheen most likely developed during the latter depositional stages of the Waulsortian, or during deposition of the overlying Crosspatrick Formation at a depth of no more than 200m below the palaeo-seafloor. This interpretation is consistent with dissolution and collapse

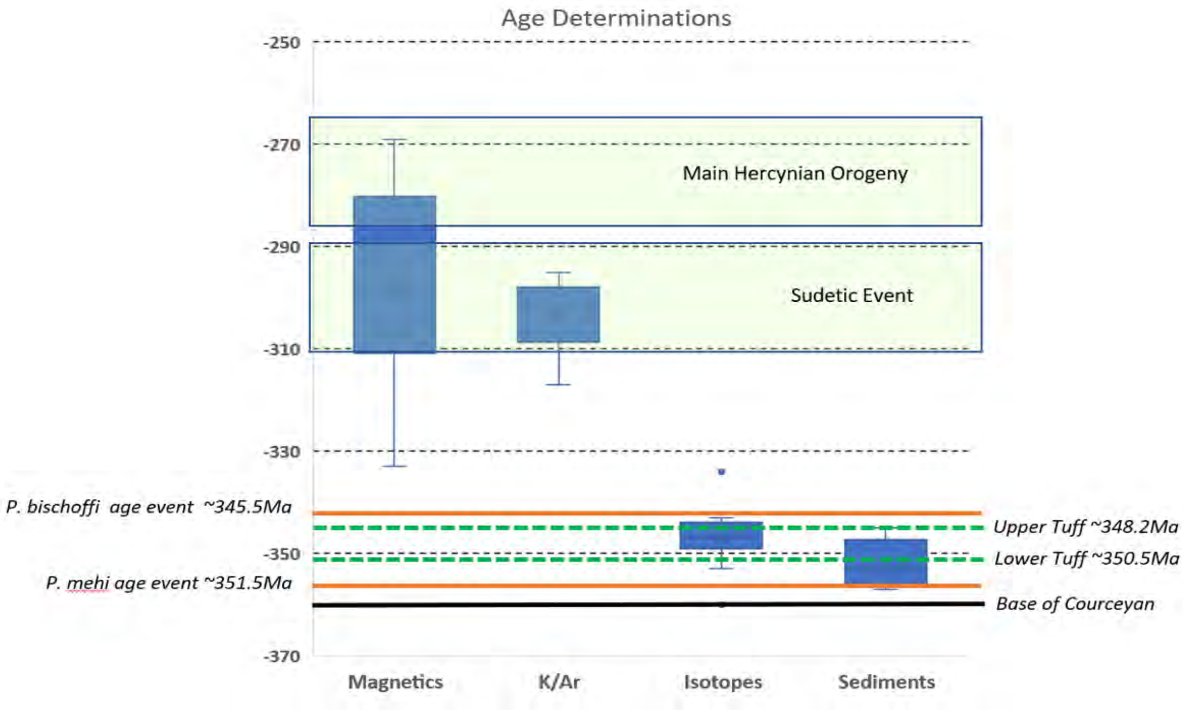

Figure 8: *Diagram showing the spread of age determinations by various methodologies and the tectonic events affecting the Irish Midlands. Data described in text from numerous sources.*

brecciation occurring prior to and contemporaneous with deposition of the Crosspatrick Formation dated by conodonts to the early Chadian *M. beckmanni* biozone (Wilkinson, 2013; Eyre, 1998).

Schneider *et al* (2007) revealed a well-defined Rb-Sr isochron age of 360 ± 5 Ma on five sphalerite samples from the Silvermines Upper-G and Cooleen Zones; this, taken with the occurrence of exhalative features such as vent fauna and the sedimentary reworking of sulphides (Andrew, 1986; Taylor, 1982; Boyce *et al*. 1983; Lee & Wilkinson, 2002) indicate that at least some syngenetic and near-seafloor mineralization took place.

Boast *et al* (1981) obtained a Pb/Pb age of 348 ± 22 Ma for Stage 3 galena mineralization at Tynagh overlapping with the depositional age range of 353-347 Ma of the Waulsortian mudbank host rocks; (Waters *et al*. 2011). Boast *et al* (1981) also reported a Pb/Pb age of 348.4 ± 22 Ma for 2-3 Lens galena from the Navan deposit (Figure 9).

Duane *et al* (1986) provided both Pb:Pb, U:Pb and Rb:Sr age determinations on the cupriferous mineralization at Gortdrum of 359 ± 22 Ma and 348 ± 22 Ma respectively.

Vafeas *et al* (2023) obtained a U-Pb age of 331±5.6 Ma from apatite grains extracted from “Black Matrix Breccias” well into the hangingwall of the barite orebody at Magcobar but without any paragenetic context. Such an age lies within the latest Asbian to early Brigantian and hence is coeval with the inversion of the Limerick and Shannon Basins (Strogen, 1988; Strogen *et al*, 1996) and thus may relate to a late dewatering event.

Absolute ages of 303 - 306 Ma at Navan and 302 - 317 Ma at Keel have been obtained from K/Ar dating of clay mineral concentrates associated with the Zn-Pb mineralization (Halliday & Mitchell, 1983). Ages in a similar range were also determined for Tynagh (265 – 299 Ma) and Silvermines (295 – 310 Ma). However, these age determinations are not in agreement with clear geological evidence and are thus thought to represent an age related to Hercynian tectonism between *ca*. 265 to 310 Ma.

It is interesting to note that these K/Ar age determinations fall across a similar range to the palaeomagnetic determinations which are also thought to relate to post mineralization tectonism.

Dating by Biota

Larter *et al*. (1981) reported the occurrence of fossil hydrothermal vents and a highly pyritic vent field at the Magcobar pit at Silvermines. These were among the first reported fossil vents in the world. Subsequently, Banks (1986) described the occurrence of both fossil vents and a vent biota at the Tynagh deposit. These fossil polychaete worms, which occur in pyritic mounds at Tynagh and Silvermines, have affinities to *Paralvinella*, an organism that lives attached to hydrothermal chimneys at the Juan de Fuca hot spring site in the Northeast Pacific (Desbruères, *et al*., 1985; Russell, 1996).

Fossil evidence of the presence of a vent-related worm tube provides compelling evidence that sea-floor exhalative hydrothermal activity did occur at Silvermines and Tynagh. This implies that at least some of the mineralization occurred contemporaneously with deposition of the carbonate host rocks during the Courceyan at about 348 Ma (Boyce *et al*., 1983).

Filamentous haematite microfossils in Magcobar (Silvermines) jasper were described by Boyce *et al* (2003) showing a strong similarity to Fe-oxidizing bacteria and provide evidence of microbial activity, a feature typical of modern and ancient vent fields. These were further described in detail by Kucha (2017) who noted filamentous and peloidal ZnS and FeS_2 whose microtextures, nano textures and sulphur valences are suggesting the involvement of sulphate reducing bacteria in sulphide precipitation. Kucha (*op cit*) also noted the presence of sub-micron, filamentous hollow tubes of haematite cemented by quartz interpreted to be fossil iron-oxidising bacteria, support the existence of a chemo-autotrophic, near-seafloor habitat that is typical of both fossil and modern seafloor hydrothermal systems.

The stratiform barite orebody at Magcobar, which thins over Waulsortian footwall knolls and thickens in troughs between such knolls has been convincingly shown to be an exhalite by Mullane & Kinnaird (1998); whilst rip-up clasts of barite occur in the immediate debris flows of the hangingwall (Barrett, 1975; Taylor, 1982; Andrew, 1986). Such features suggest strongly that the ore depositional environment was on or just below the contemporaneous seafloor at around 348 Ma.

At Magcobar Barrett (1975) showed that the silica content of the immediate footwall to the barite body attains levels of up to 60% and then diminishes upwards through the barite orebody. This silica within the barite is amorphous and cryptocrystalline and often associated with haematite in the lowermost parts of the orezone (jasperoidal). As at Tynagh the iron-silica zone infills a palaeotopographic low or sag on the downthrown side of the fault complex.

The presence of framboidal iron sulphides within the host rocks to mineralization has been described at Navan (Yesares *et al*, 2019, 2022), Tynagh (Boast *et al*, 1981A) and at Silvermines (Taylor, 1983; Andrew, 1986). Whilst there is no consensus on the origin of pyrite framboids, two conditions must be fulfilled for their formation: the availability of iron and of sulphur (of organic or inorganic origin). These conditions can be met in organic-rich carbonates with a high level of activity of bacteria in a near surface environment. At Navan, Silvermines and Tynagh the framboidal sulphides are most abundant in argillaceous organic-rich lithologies in the hangingwall units above the mineralized bodies.

Other Dating Methods

Braithwaite & Rizzi (1997) noted that the scatter of homogenization temperatures (59.7ºC – 159.3ºC) from fluid inclusions in dolomites from the Navan deposit suggested that the dolomite crystals grew over a long period (late Courceyan or Chadian, perhaps to early Arundian, a maximum of ~10 Ma) from progressively higher temperature hydrothermal fluids.

Peace & Wallace (2000) on the basis solely of petrological cathode luminescence studies of thin sections from Navan, considered that diagenetic analysis revealed that all of the mineralization post-dated the erosion surface and therefore must be post-Arundian (339-341 Ma) in age. Furthermore, Peace & Wallace (*op cit*) concluded that the Navan mineralization must be entirely epigenetic in origin (*i.e.*, similar to Mississippi Valley–type deposits) and is likely to be Holkerian (339-337.5 Ma) in age or younger.

Unfortunately, their constraining argument of pre-ore stylolites forming at depths of greater than 800m cannot be sustained as the total thickness of sediment existing between the mineralized part of the sequence and the erosion surface that unroofed the Navan mineralization (leading to the Boulder Conglomerate debris flows) is no greater than 250m, by which time virtually all of the Navan mineralization had been emplaced, and locally eroded and resedimented in the Boulder Conglomerate.

Equally it is now also known that stylolite formation can occur at shallow depths as soon as chemical compaction begins at depths as shallow as 30-40m in carbonates (*eg.* Rustichelli *et al*, 2015). Many recent studies have called into question the validity an inferred depth of burial necessary to create stylolites (~800m per Peace & Wallace, 2000) as Shinn & Robbin (1983) demonstrated that significant compaction and dissolution can occur at pressures equivalent to ~300m of burial and Railsback (1993) found pressure solution features in carbonates buried to a depth of only 30m.

At the Pallas Green and Stonepark prospects the base of the mineralization is frequently some tens of metres above the base of the Waulsortian and combined mineralization / alteration packages frequently reach over 100m (and locally >200m) in thickness within the Waulsortian, which is between 140m to 440m in thickness. Such thickness variation having been interpreted to be related to differential subsidence across syndepositionally active structures (Gordon *et al.*, 2018; Blaney & Redmond, 2015; Elliot *et al.*, 2019).

The mineralization at Pallas and Stonepark and elsewhere in the Limerick Basin are cut and partially removed by the late Chadian Knockroe Volcanic maar-diatremes (Blaney & Redmond, 2015) and clasts of mineralization and ore-related breccias have been seen within diatreme lithologies equivalent to the Lough Gur volcanics thus clearly demonstrating that mineralization preceded volcanism dated between 350.5 ± 3.9Ma to 348.2 ± 2.4Ma (Koch *et al.*, 2022) (Figure 9).

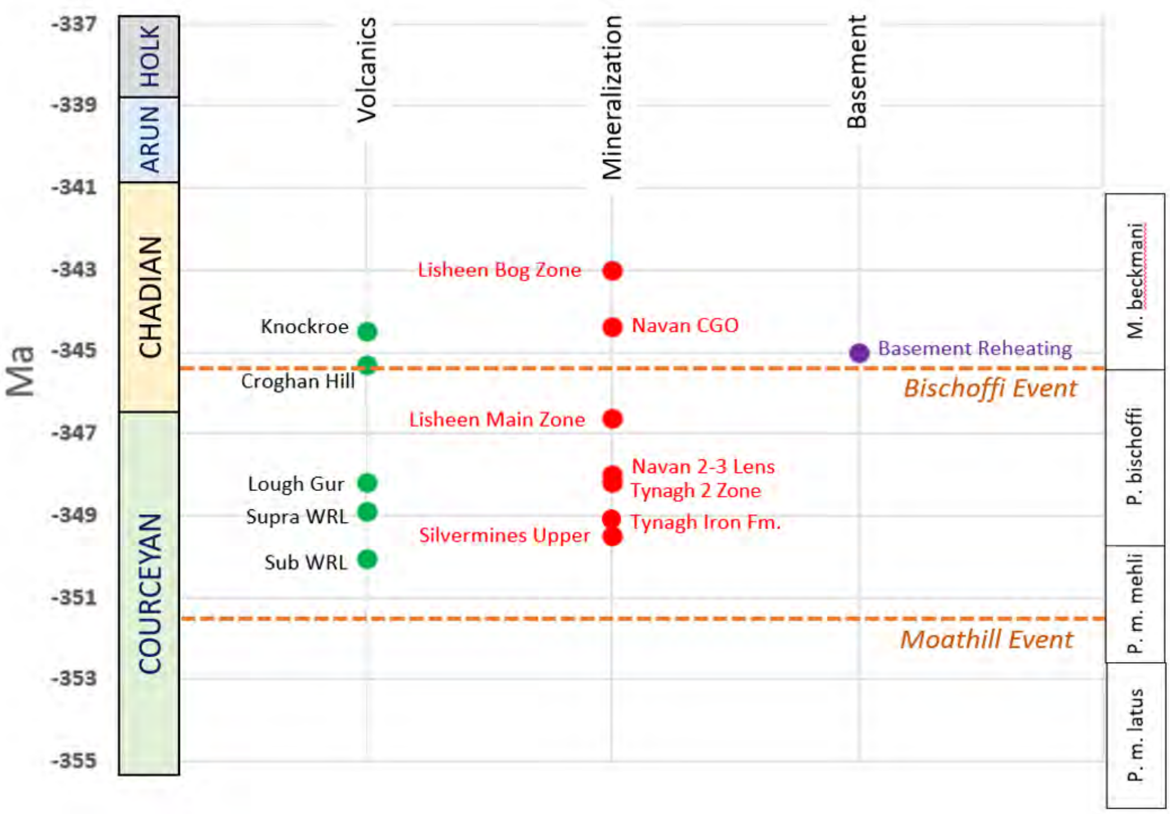

Figure 9: *Age determinations by various isotopic methodologies plotted on conodont biostratigraphy.*

Volcanic dates from Koch et al (2022) and Timmerman (2004), Mineralization dates from Hnatyshin et al (2015, 2020), Boast et al (1981a), Basement reheating date from Daly et al (2016). Note – error bars on isotopic dating methods removed for diagrammatic simplicity.

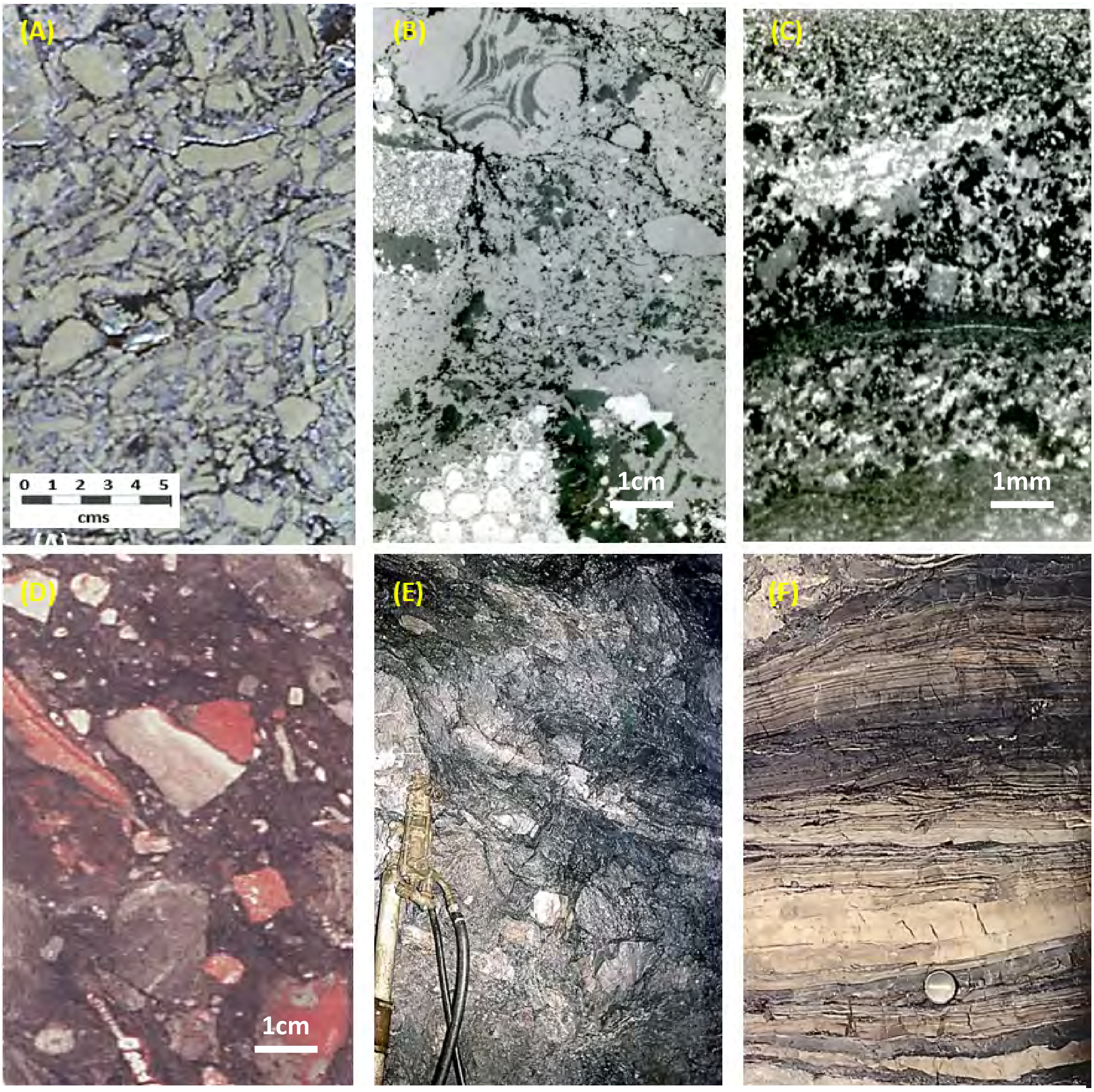

Figure 10: *Examples of sedimentary ore textures and fabrics: **(a)** – Cut slab of exfoliated detrital collomorph fragments of marcasite forming a fringe to mounds of massive collomorph marcasite, Upper G Zone, Silvermines. **(b)** - Photomicrograph of clastic pyrite breccia showing varying styles of iron sulphides, B-Zone, Silvermines. (Ashton, 1985). **(c)** - Photomicrograph of graded clastic pyritic sediment forming distal fringe to collomorph mounds, B-Zone, Silvermines. (Ashton 1985). **(d)** – Clasts of reddened (haematite stained) limestones in a matrix of argillaceous crinoidal limestone, Waulsortian fringe debris flow, Tynagh Zone 3. (Cruise, 1996). **(e)** - Waulsortian fringe debris flow with a large angular clast of barite lower centre, Upper G-Zone, Silvermines. Jack-leg drill for scale. **(f)** – Laminated marcasite (framboidal) exhalate, Conglomerate Group Ore, 2 Zone Navan. Lens cap for scale.*

Geological Constraints

There is abundant geological evidence at Tynagh, Silvermines and Navan that confirm that mineralization existed prior to erosion and clastic re-deposition stratigraphically above the pre-existing sulphide mineralization. The sediments that contain clasts of sulphides have been dated to specific conodont biozones and thus definitively constrain the latest age of mineralization.

Evidence for sedimentary breccias and debris flows containing mineralized clasts are seen at Silvermines (Taylor & Andrew, 1978; Taylor, 1984; Andrew, 1986; Lee & Wilkinson, 2002) at Tynagh (Clifford *et al*, 1986; Boast *et al*, 1981A) (Figure 25d & 25e) and at Navan in the Boulder Conglomerate (Ashton *et al*, 2015). Clearly such mineralized clasts must have formed

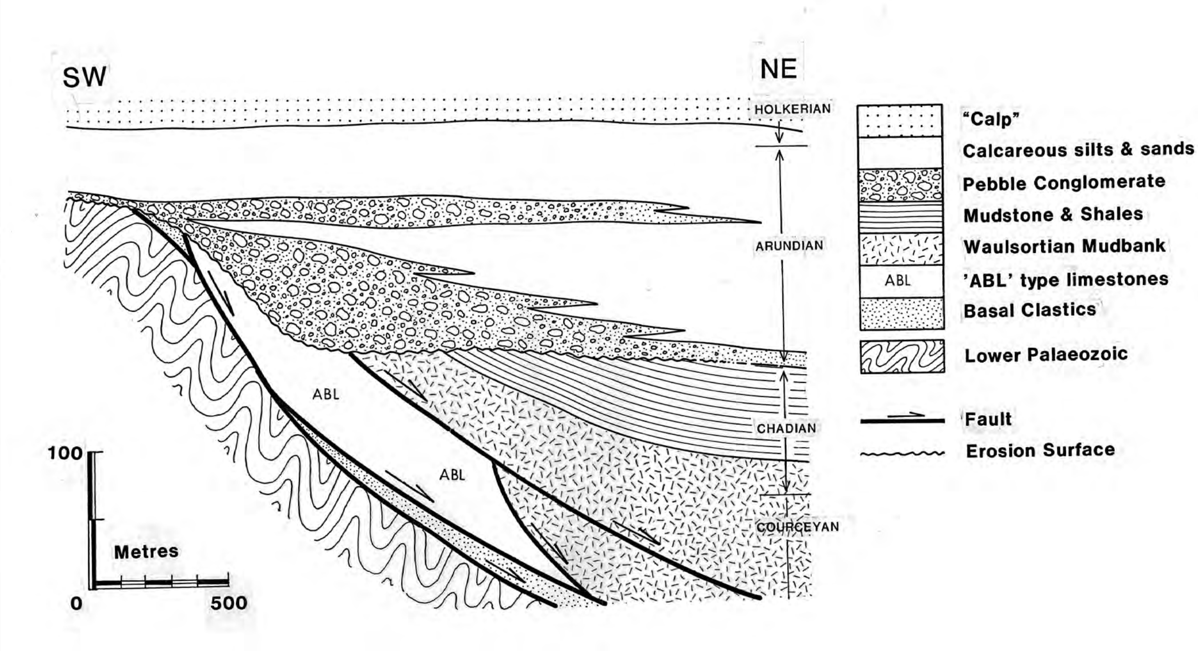

Figure 11: *Schematic NS-SW section at Newcastle, County Dublin, showing the relationship between faulting and erosion surfaces and debris flows.*

prior to the mass-wasting and sedimentary reworking event that transported them into the debris flows. Such mineralized clasts have sharp boundaries to laminated collomorph sulphides and are sometimes distorted from abrasion within the debris flows.

Granular graded particulate sulphide sediments are seen at Silvermines (Upper G-Zone) flanking disaggregated mounds of large fragments of collomorph iron sulphides suggesting a simple sedimentary process of winnowing adjacent to iron sulp hide mounds (Figures 10a, 10b & 10c).

At Silvermines in the Magcobar pit Mullane & Kinnaird (1998) described sedimentary cycles within the hangingwall breccia sequence, which is up to 32m thick, composed of a number of pale-grey, debris-flow deposits, typically around 1m in thickness, separated by thin, subordinate, impersistent horizons of bioclastic breccia, typically 20cm thick, and minor lenses of banded limestone. These debris-flow deposits are poorly bedded, poorly sorted and matrix-supported, with angular, sometimes imbricated clasts ranging in size from 0.3 to 30cm. The clasts are mainly of calcite, but there are some of low-iron dolomite. *In situ* brecciation of the clasts is common, ranging from a single fracture to intense brecciation. Close to the contact with the underlying orebody up to 15% of the clasts are angular and include rip-up clasts of massive pyrite and barite, with flame structures of pyrite in the base of the breccia sequence. Syn-sedimentary slumping is well developed throughout the stratiform barite body, most obviously when the barite is of different colours and when it is intercalated with pyrite. Debris-flow clasts of red silicified barite and jasperoidal haematite are present in the lowest parts of the barite body Mullane & Kinnaird (1998), Barratt (1975), Taylor & Andrew (1978), Taylor (1982), Andrew (1986) and Lee & Wilkinson (2002).

Reworked clasts of sulphide and dolomitized limestone also occur in breccias within the Waulsortian Limestone Formation at the Cooleen Zone near Silvermines (Lee & Wilkinson, 2002). The clasts consist of pyrite with a laminar texture, sometimes distorted and sharply truncated at the clast boundaries, and of colloform or layered sphalerite and pyrite.

At Navan, the Boulder Conglomerate, overlying a deeply incised Chadian-aged erosion surface, contains angular clasts of Zn-Pb mineralization up to 1m in size and identical to that seen within the underlying Pale Beds clearly indicating derivation from up-slope sub-cropping ore lenses. This convincingly confirms that most of the Navan mineralization was *in situ* prior to the Chadian erosion surface unroofing the orebodies. This indicates that mineralization occurred between the age of the host rocks (*P. mehli latus* - *c.* 353 Ma) and the age of the erosion surface (late *P. bischoffi* / *M. beckmanni* - *c*. 345.3 Ma).

There is some evidence (Yesares *et al*, 2019, 2022) that subeconomic mineralization at Navan hosted in the Thin Bedded Unit (*c.* 341 Ma) overlying the Boulder Conglomerate and comprising sphalerite replacing framboidal pyrite may represent late-stage seafloor exhalation of mineralizing fluids resulting from the unroofing of the underlying mineralized system (Figure 10f).

This key observation remains the best constraint on the exact timing of the principal mineralization at Navan.

Time equivalent erosion surfaces are also seen at Oldtown, Loughshinney, Walterstown and Newcastle (Figure 11) around the Dublin Basin and at Clonabreaney, Longford, Keel, Granard and Newtown Cashel amongst other locations in the north-central midlands.

At Tynagh sedimentary debris flows flanking the Waulsortian mudbank knolls are formed dominantly by poorly sorted subangular clasts of Waulsortian set in slumped crinoidal argillaceous limestones, where occasionally they contain Zn-Pb mineralized and haematite-stained clasts of Waulsortian (Clifford *et al*, 1986) (Figure 10e). Considering the carbonate mud mounds characteristic of the Waulsortian developed in a relatively deep-water distal ramp setting below storm wave-base any coarse sediment or fault talus breccias must have formed as a result of tectonic triggering and mass flow down slope confirming syn-sedimentary tectonism. Such tectonism is likely to have been approximately coeval with mineralization.

These observations, added to the occurrence of hydrothermal chimneys and fossil worms reported by Banks (1986) strongly suggest that at least some of the mineralization occurred at or near to the contemporaneous seafloor.

In the basin north of the Tynagh fault, "Waulsortian Equivalent" calcilutites typically have early cements comprising bladed Fe-free calcites which are superseded by Fe-rich calcite and sphalerite suggesting an early appearance of mineralization within sediments distal to the fault. These rocks all return conodont faunas of the *P. mehli mehli to P. bischoffi* biozones of the late Courceyan around ~349Ma (Geological Survey of Ireland, 2019).

The "Iron Formation" at Tynagh lies downdip and down the time equivalent palaeoslope of the Waulsortian knolls hosting the Zn-Pb mineralization. Haematite and chert are the most abundant constituents of the ironstone beds, which also contain small amounts of chlorite, magnetite, pyrite, stilpnomelane and minnesotaite. The "Iron Formation" comprises up to 15 individual ironstone beds each up to a maximum of 6m and containing up to 40% Fe within a sequence of interbedded argillaceous limestones with abundant crinoids up to a total of 50m in thickness (Schultz, 1966). Tuff horizons within the iron formation are possibly the time equivalent of the tuffs dated by Koch *et al*., (2022) in the supra Waulsortian at Lisheen at ~348.2Ma.

Several observations suggest that the introduction of haematite at Tynagh occurred before the host sediments had been buried to any great depth. Textures preserved within the ironstones indicate an algal origin in which case the ironstones must have formed on or close to the seafloor. Cavities within the Waulsortian limestone containing haematite, are cut by veins of radiaxial-fibrous calcite - a marine cement formed at very shallow depths. This shallow depth at which haematite must have formed at Tynagh is also evidenced by clasts of haematized Waulsortian limestone within debris flows flanking the Waulsortian knolls. Although there was contemporaneous movement on the North Tynagh Fault it seems unlikely that the source of the clasts could have been exhumed from more than a few tens of metres.

Cruise (2000) found that oxygen isotope values from the "Iron Formation" could only be reasonably explained if the fluids from which the haematite formed contained isotopically very heavy oxygen. The only widely available oxygen sufficiently isotopically heavy would have been atmospheric oxygen dissolved in seawater. Therefore, the haematite mineralization involved ingress of seawater containing dissolved atmospheric oxygen which can reasonably only have occurred within the upper few metres of the sedimentary column. Cruise (2000) also reported that minor, early sphalerite, overlapped with haematite precipitation at Tynagh clearly suggesting near seafloor precipitation of sulphides occurred.

Boast *el al* (1981) state that the range of textural features displayed by the Zn-Pb-Ba ores at Tynagh demonstrate unequivocally that mineralizing fluids were introduced along the fault structure and into the adjacent sediment coeval with their deposition and diagenesis.

At the Drumlerry prospect Brand & Emo (1986) noted that early barite and pyrite occur within the birdseyes in the Navan Group Micrite Unit and that selective early-stage replacement of pelloids and ooliths by disseminated sphalerite suggests that mineralization was occurring during early diagenesis and the lithologies becoming impermeable.

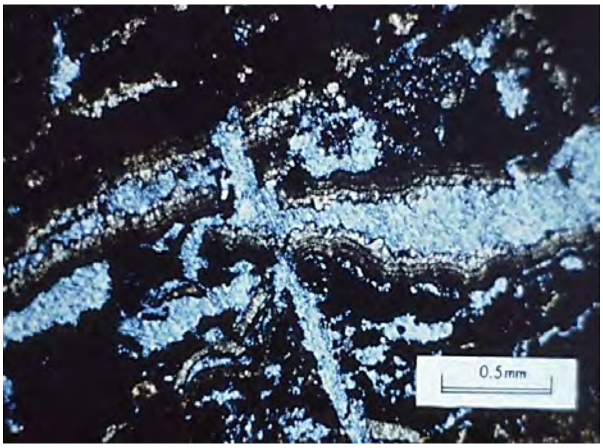

Figure 12: *Thin section of Waulsortian Mudbank limestone from Ballinalack (Drillhole B67 at 214.8m) showing early colloform sphalerite predating ferroan calcite within (black) micrite.*

At Ballinalack Jones & Brand (1986) and Gordon *et al* (2019) provide detailed descriptions of several stages of mineralization with the earliest being collomorph sphalerite and marcasite cavity linings to stromatactis voids within the Waulsortian mudbank (Figure 12). Clearly this confirms early mineralization at relatively shallow depths below the contemporaneous seafloor. Similar early sulphides are also seen in similar settings at Silvermines, Tynagh, Garrycam and elsewhere.

Summary of age dating of mineralization

If we discount the geologically unsustainable magnetic dates, and taking all of the radiometric ages into consideration, an average age of the mineralization of 348.9 Ma emerges, which is extremely close to the assumed stratigraphic age of the host Courceyan (359.2 – 346.7 Ma) to Chadian (346.7 to 341.0 Ma) sediments. Taking the dating that coincides with geological evidence such as mineralization contemporaneous fauna and debris flows containing pre-existing clasts of mineralization, what emerges is a very narrow age range for the host-rocks around 350 Ma.

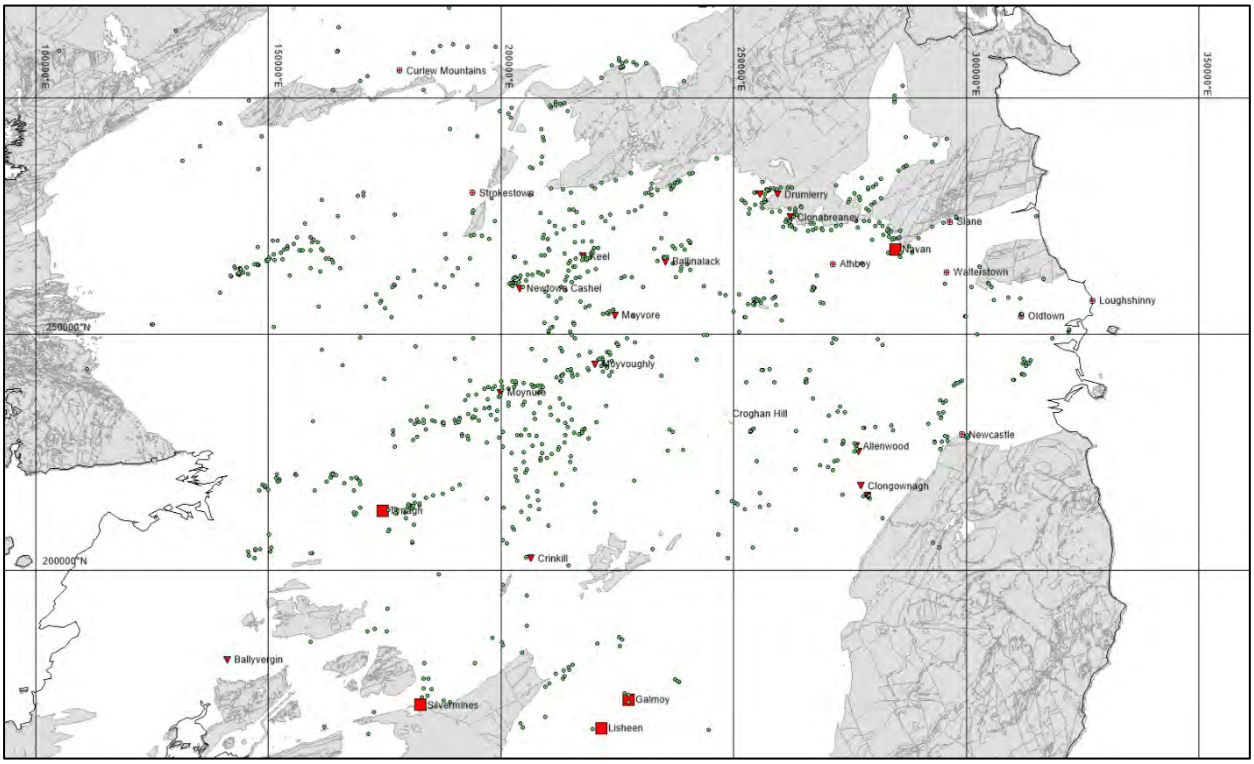

Figure 13: *Area of the study showing the 1,255 >100m length drillholes used in the study.*

In order to evaluate the controls to the development of the Lower Carboniferous Irish Midlands basins a database was compiled comprising 1,255 summary drill logs of exploration diamond drill hole cores greater than 100m in length. This data was captured from individual logs downloaded from the Geological Survey of Ireland "Goldmine" database, the stratigraphy then being captured as simplistic stratigraphic unit thicknesses with lithological notations and any biostratigraphic data. Any angle holes or logs reporting steep dips were discounted. The data was sorted using Excel and MapInfo software and each unit contoured using 3D-Field software within a geographically defined polygon using a nearest neighbour algorithm. The resultant contours were then gridded to enable the generation of standardized cross sections showing the thickness variation of the individual and composite units.

See Figure 13 for the locations of these drillholes.

Whatever genetic model is espoused this remarkable observation demonstrates that mineralization is restricted to rocks deposited in a time gap of perhaps no more than 5 Ma during the late Courceyan to early Arundian stages of the Lower Carboniferous. This is contemporaneous with evidence of active rift tectonism impacting the establishment of a complex facies mosaic consisting of fault-controlled carbonate basins and high standing carbonate platforms, local facies controls caused by uneven subsidence and elevated heat flows due to basement thinning and reheating. This combined with clear evidence of hydrothermal fluids exhaling onto the contemporary seafloor indicates that this was a remarkable period in the Irish Midlands confirmed by high precision isotopic methods indicating that the bulk of mineralization predates a late Chadian to Arundian-aged major extensional event (rifting).

Basin Development

Assuming that the mineralizing event can be temporally constrained to a period approximately between ~350 Ma and ~345 Ma it is now possible to examine the basin development and structure at this time and the environments that the mineralization occurred within. To evaluate this relatively narrow time period this study has analysed the lithological patterns and sedimentation rates by using conodont microfaunal biostratigraphy.

Methodology

Since the discovery of the Tynagh deposit in 1962 and thereafter the Irish Midlands has been subjected to extensive exploration drilling and more recently to deep seismic reflection surveying in the search for zinc deposits. Records of this drilling is available via the Open File system of Geological Survey Ireland, and, in addition, a number of authors have provided correlations of this stratigraphic record (Philcox, 1983 - amongst others).

For the last two decades there have been considerable advances in the dating and correlation of the Lower Carboniferous

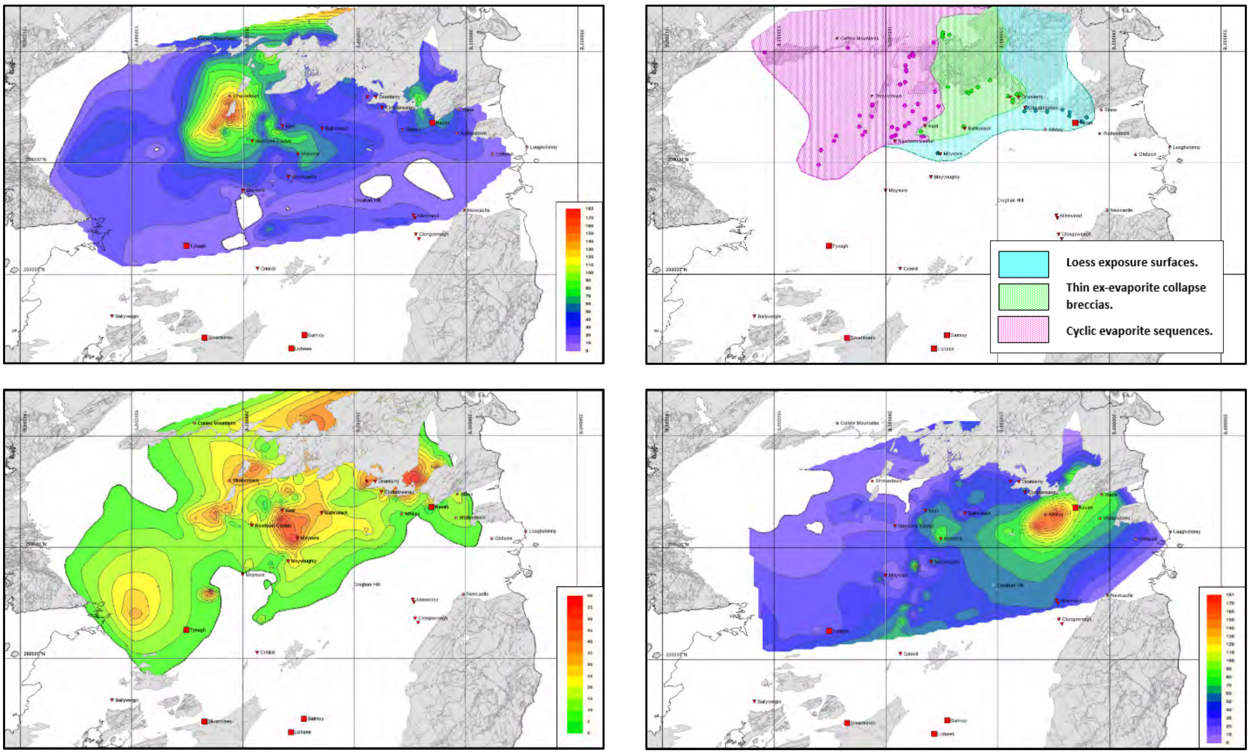

Figure 14: a) *Isopachous plot of the Navan Group Micrite Unit. b) Navan Group Micrite Unit also showing distribution of evaporitic lthologies. c) Isopachous plot of the Navan Group Upper Sandstone Unit. d) Isopachous plot of the Navan Group Shaley Pales.*

carbonate sequences in Ireland, primarily through increased precision made possible by the use of microfossils, such as conodonts, foraminifers and miospores, together with macrofossils such as rugose corals. This advance was accelerated by the availability of boreholes up to 2000m deep drilled by mineral exploration companies who now routinely use biostratigraphy. Detailed biozonations are now established and are used for geological mapping and stratigraphic analysis (Jones & Sommerville, 1996; Riley 1993; Sommerville *et al*, 1992, Strojen *et al* 1990).

The dominant part of the ore-hosting succession lies within three or four conodont biostratigraphic zones all lying within the Courceyan and Chadian Stages of the Tournaisian dated between 359.2 Ma and 341.0 Ma. These conodont zones have been defined by Somerville *et al* (1992), Pickard *et al* (1992), Riley (1993) Jones & Somerville (1996) and others and are summarized in Figure 7.

Whilst the conodont biostratigraphy is a complex issue for micropalaeontologists and generally beyond the reach of this paper, it is possible to simplify the microfaunal biostratigraphy of the Courceyan and Chadian ore-hosting sequences. This biostratigraphy ranges from the lowest conodont biozone, that has been identified across the Irish Midlands, is the Pseudopolygnathus multistriatus *(Ps. multistriatus*) sub-biozone. This is overlain by the Polygnathus mehli (*P. mehli*) Biozone which can be sub-divided into the Polygnathus mehli latus (*P.m. latus*), Polygnathus mehli mehli (*P. m. mehli*) and Polygnathus bischoffi (*P. bischoffi*) sub-biozones. All of these biozones lie within the Courceyan stage. The overlying lowest Chadian stage biozone falls within the Mestognathus beckmanni (*M. beckmanni*) biozone (Jones & Somerville, 1996; Riley, 1993; Strogen *et al*, 1990; Jones *et al*, 1988).

The Courceyan marine incursion and onset of carbonate ramp and shelf sedimentation commenced with varying proportions of flood-deposited sandy siltstones, palaeosols and evaporites being laid down in the *PC* Miospore Zone, roughly time equivalent to the *Polygnathus inornatus* conodont biozone. As the transgression migrated northwards during the *Polygnathus multistriatus* conodont biozone tidal flat flaser and linsen mudstones and siltstones gradually gave way to increasingly carbonate-rich lagoonal and shallow shelf limestones of the Navan Group.

The Navan Group, largely deposited in the *Polygnathus mehli latus* conodont sub-biozone is developed over some 8200 square kilometres of the east-central Midlands and thins from 400m at its maximum to 50m at its northern and southern extremities (Andrew, 1991, 1993). These thickness variations, in part due to local facies changes also indicate that gentle passive sag had commenced at this time. The group is typically 150-200m thick and generally consists of a basal, thin, upward fining terrigenous sequence of shallow marine barrier sandstones, tidal flat/lagoonal mudstones and sabhka evaporites which pass upward with increasing carbonate and argillite content, into pale oncolithic and birds' eye micrites interpreted to represent prolonged stable lagoonal conditions – Micrite Unit (Andrew, 1991, 1993) (Figures 14a & 14b). Towards the west

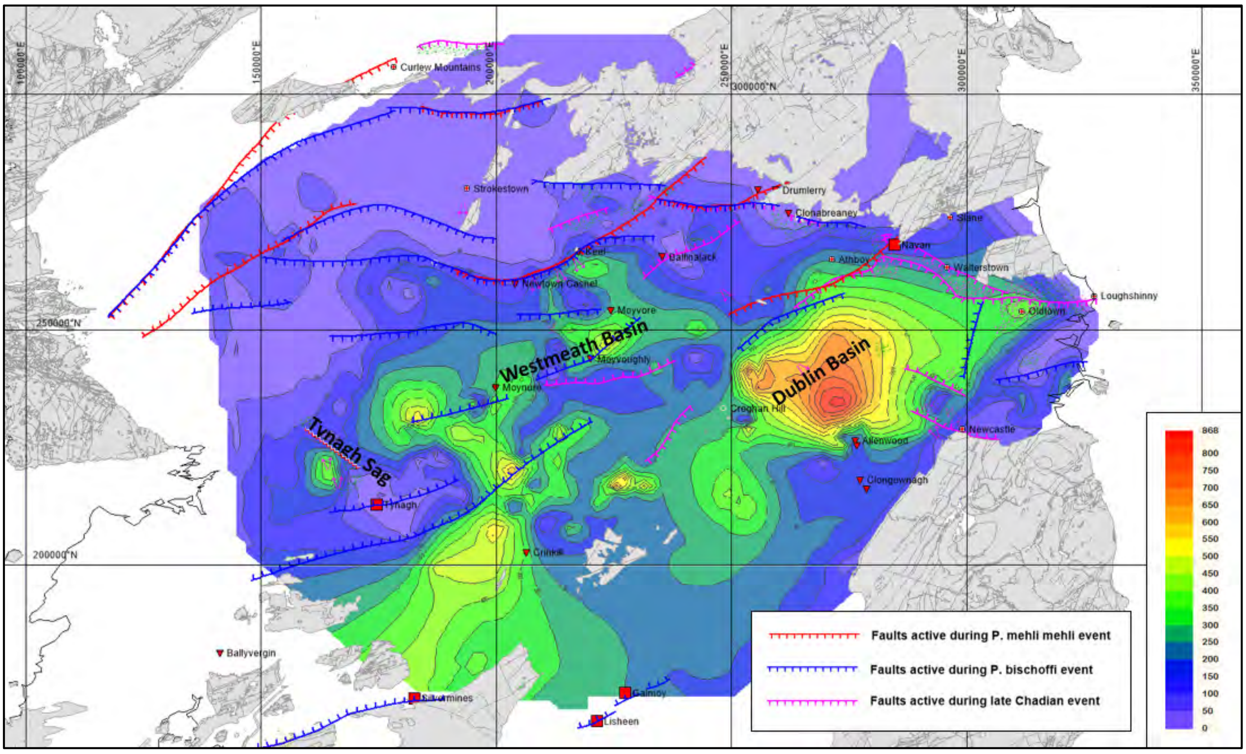

***Figure 15:** Isopachous plot of the Waulsortian mudbank facies with interpreted synsedimentarily active faults and principal mineral deposits and prospects.*

increasing parts of the sequence are evaporitic with cyclic units of sand, silt and gypsum. These, in turn, are overlain by shallow water, high energy, multiple cycles of peritidal calcareous sandstones, sandy and bioclastic grainstones and oolites of the Middle Pale Beds and Upper Sandstone (Andrew, 1991, 1993) (Figure 14c). The top of the Upper Sandstone is locally erosional with thin micro-conglomerates developed at the base of the overlying Moathill Formation.

The uppermost part of the Navan Group (the Moathill Formation or Shaley Pales of Philcox (1983)) was deposited during the *Polygnathus mehli mehli* conodont sub-biozone (Figure 14d) and comprises distinctive sequences of locally mud-rich, thinly bedded shales and silts, argillaceous limestones and locally massive cross-bedded mature white sandstones. The Formation is characterised by a gradual upward increase in carbonate content, and corresponding decrease in argillaceous lithologies deposited below thre fair-weather wave base.

In the southern part of the country the Navan Group is poorly developed and is represented by 30-50m of argillaceous, skeletal calcareous shales and siltstones with thin oolite and sandstone shoals and sandbanks (Andrew, 1991, 1993). Lateral facies variations within the Navan Group appear to have resulted from eustatic changes in sea level, local fluctuations in shorelines and the influence of sedimentary environmental barriers on sediment dispersal (Andrew, 1992) rather than syn-sedimentary tectonism.

The overlying Ballysteen (or "ABL – Argillaceous Bioclastic Limestone" in this review) Formation was deposited during the *Polygnathus mehli mehli* to *Polygnathus bichoffi* conodont sub-biozones mostly in an offshore open shelf to outer ramp, below fair-weather wave-base but above storm wave-base, in which fine-grained carbonate accumulated with some fine siliciclastic input. It is associated with a major deepening episode following the deposition of the shallow water siliciclastic-rich sediments of the Navan Group. The biota is rich and diverse with abundant crinoids, brachiopods and solitary corals. The lack of sedimentary structures, poor sorting of bioclasts and abundance of bryozoans implies low-energy, relatively quiet water conditions. Sparse isolated carbonate clasts in the basal ABL probably represent allochthonous debris, indicating a slope environment.

The Waulsortian facies comprises coalesced mudbanks which average 150-250m in thickness (Andrew, 1991) was deposited in biozones equivalent to the *Polygnathus mehli mehli* to *Polygnathus bichoffi* conodont sub-biozones and even up into the early Chadian (*Mestognathus beckmanni* biozone) (Figure 15). Significant diachronism of the Waulsortian can be determined with the basal parts of the Waulsortian being earlier in the southern midlands and south of the country. The facies consist of poorly bedded, dense, pale/medium grey micrite to calcarenite containing well developed stromatactis structures. In southern Ireland the facies is well developed with coalesced mudbanks up to 800m thick (Hitzman, 1991). However, in the northern Midlands, the Waulsortian thins into individual knolls which are enveloped by flank facies and set within argillaceous packestones and grainstones if the Upper ABL, lithologically similar to the Lower ABL (Andrew, 1991).

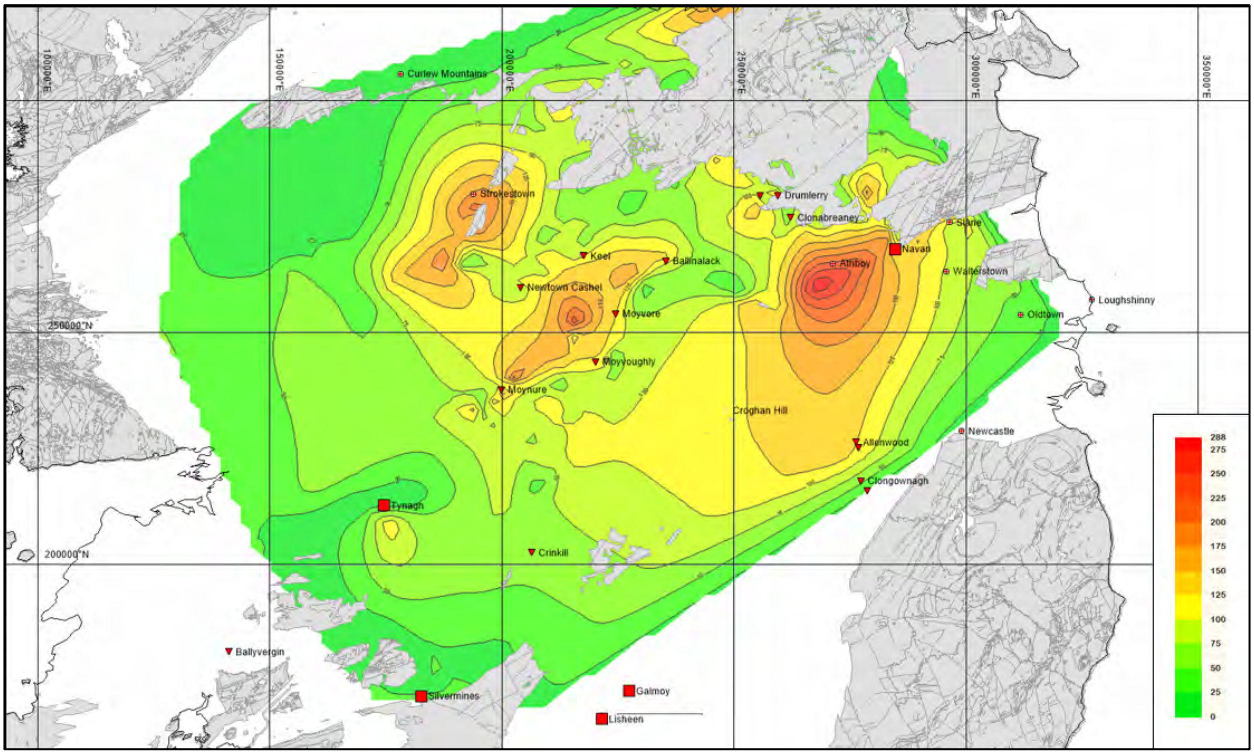

Figure 16: *Isopachous plot of the P. mehli latus biozone showing mineralized occurences.*

The carbonate mud mounds characteristic of this formation developed in a deep-water distal ramp setting below storm wave base. Low-energy conditions prevailed during the formation of the massive fine-grained limestones and their laterally equivalent bedded bioclastic limestones dominated by crinoids, sponges and bryozoans. Lees & Miller (1985, 1995) conclude that the basal Waulsortian bank facies (Phase “A”) was perhaps produced in aphotic conditions in *c*.300m water depth. Phases “B” to “D” accumulated in moderately shallow-water depths, close to or within the photic zone with minor spasmodic current activity presumably generated by minor tectonism.

At the fringes of the Waulsortian development isolated mudbanks are sporadically developed in the upper portions of the Ballysteen Formation where the supra-Waulsortian facies overlying the Waulsortian knolls comprise shaley bioclastic carbonates similar in general character to the Ballysteen Formation.

Locally the Waulsortian passes laterally into well-bedded medium grey calcilutites with interbedded bioclastites, conglomeratic biomicrites and fossiliferous black shales known as “Grey Calp” at Tynagh and Carn Park, County Westmeath (Clifford *et al* 1986). This unit is interpreted as being a direct equivalent to the Waulsortian but restricted to local basins where subsidence was too great, leading to water depths too deep to allow Waulsortian mudbank growth.

The Navan Group, ABL and Waulsortian form a clearly transgressuive and deepening succession with a reduction oftransgressive and deepening succession with a reduction of terrigenous siliciclastic and argillaceous input upwards. This is confirmed by palaeo-environmental interpretations showing a passage from marginal marine to tidal flat to lagoonal shoals and sand bars up into mud-rich carbonates and thus to fossiliferous limestones and eventually into clean stromatactid micrites.

This strongly suggests that there was a general deepening of the region corresponding to a subsidence-controlled environment.

Above the Waulsortian rapid facies changes and irregular lithological distribution characterize the latest Courceyan to Arundian, unlike the widespread distribution of facies during the Courceyan (Hitzman, 1991).

The late Chadian to Arundian was a period of tectonic activity with syn-depositional tilting apparent at some places (*e.g.*, Navan; Ashton *et al.*, 1986, 2015) and extensional deformation (Johnston *et al*, 1996). Facies distribution was largely controlled by fault-controlled basins, such as in the Dublin Basin (Andrew, 1992).

By analysis and correlation studies of both facies and biozones (palynological and conodonts) paleogeographic reconstructions can be made for the various timelines and isopachous plots can be assembled for each biozone. These plots enable an understanding of the time frame and scale of basin development across the Irish Midlands and the lithologies of the ore hosting framework to Zn-Pb mineralization.

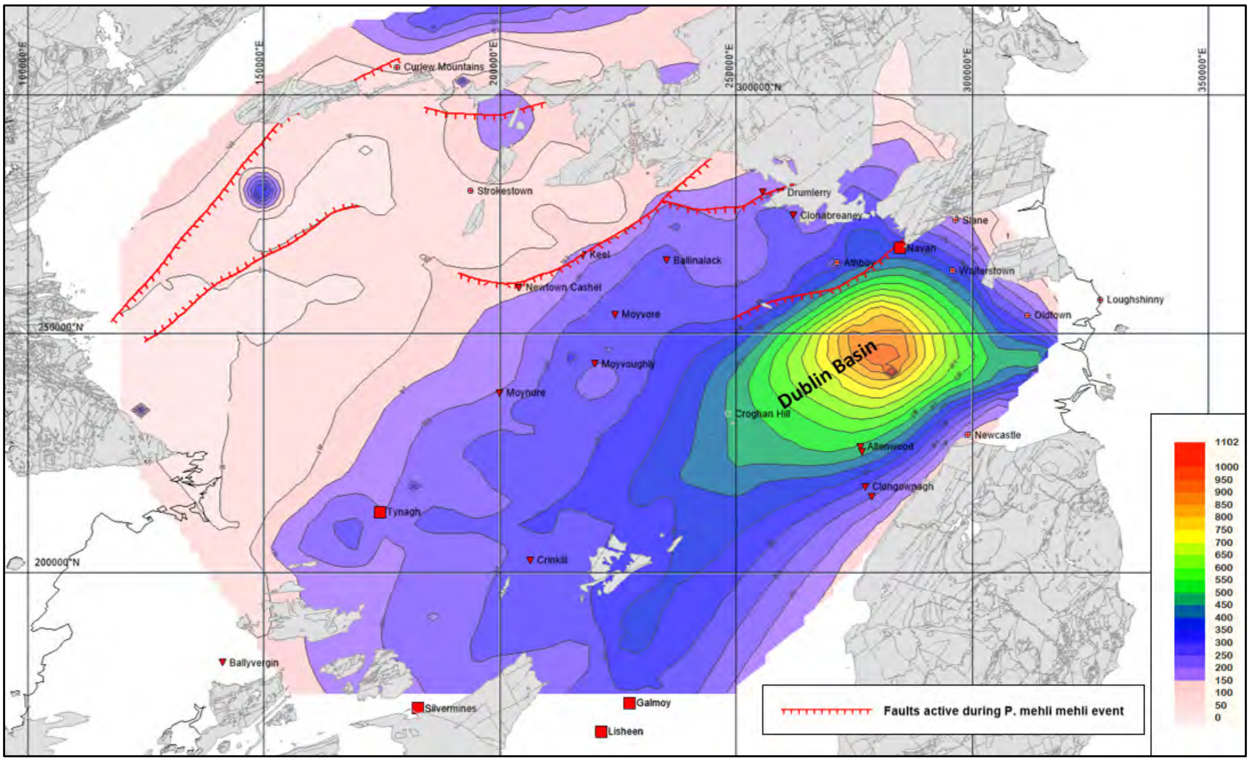

Figure 17: *Isopachous plot of the P. mehli mehli biozone showing mineralized occurences and principal active structures during time zone.*

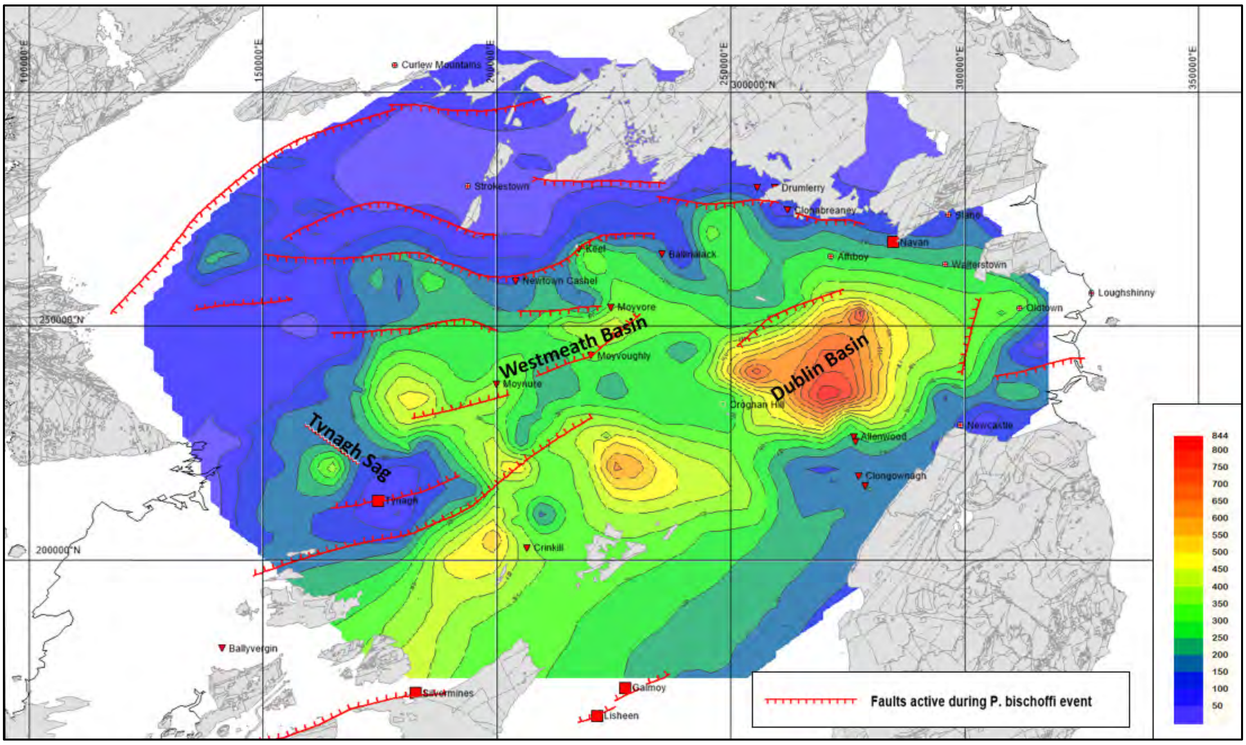

Figure 18: *Isopachous plot of the P. bischoffi biozone showing mineralized occurences and principal active structures during time zone.*

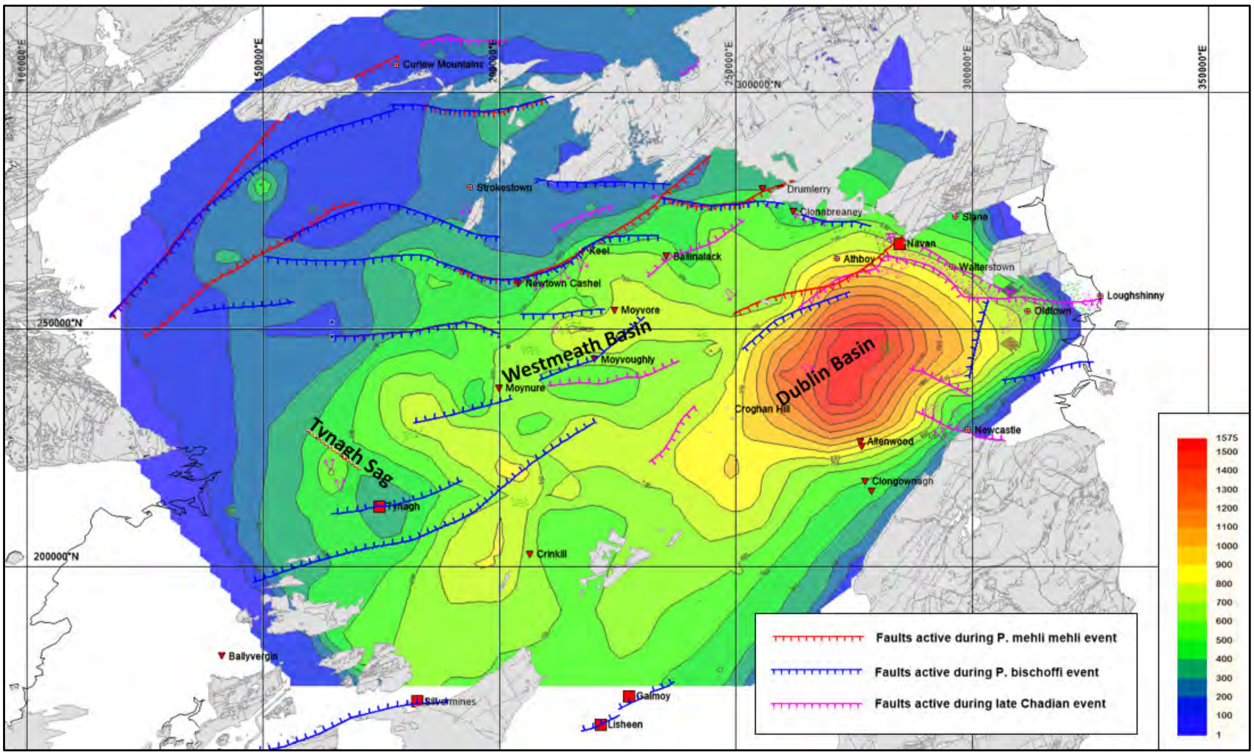

Figure 19*: Isopachous plot of the total Courceyan Stage showing mineralized occurences and principal active structures during time zone.*

Tectonic Setting

Regional

From Ireland to western England, the main early Carboniferous basins are oriented NE-SW, sub-parallel to the Caledonian Iapetus Suture. Based on fault and mineralized vein geometries, Johnston *et al.* (1996) concluded that most of the observations agree with dextral transtension (oblique extension with a component of clockwise rotation), resulting from northeast-southwest directed extensional reactivation of east to northeast-trending Caledonian basement structures. The early Variscan rifting phase created the typical horst-and-graben structure of much of East Avalonia's crust that is well known from the British Isles and Ireland where the horsts and the graben infill are located at or near the surface (e.g., Leeder, 1982; Gawthorpe, 1986, 1987; Strogen *et al*., 1990) (Figure 5).

In the early Carboniferous Ireland lay on the south-eastern margins of the Laurentian continent at a palaeolatitude of 4°S. During the Strunian and early Carboniferous, a northerly directed transgression brought marine conditions progressively northward over the former Old Red Sandstone Continent in Britain and Ireland. The progress of the transgression was episodic, whilst the causes underlying the northward shift of the shoreline are difficult to assess, this may have been due to back-arc stretching causing subsidence in the south of Ireland and in southwest England. This was very rapid, but there is a suggestion that some of the transgressive pulses, particularly those in the late Strunian, in the Courceyan and within the Chadian, may have been caused by extension in response to back-arc stretching causing isotherm bunching and elevated heat flows (Clayton *et al*, 1986).

Regional north northwest-south southeast directed tensile extension reached a climax in the late Chadian to early Arundian, and caused widespread shallow listric faulting, unconformities, basin development, the development of syn-diagenetic base-metal mineralization and alkaline volcanism. Basement faults of Caledonian inheritance orientated obliquely to the extension vector probably suffered oblique extension during this time giving normal displacements. Above these erosion surfaces olistostromes record significant local tectonic uplift.

In the late Dinantian to Namurian regional WNW–ESE directed compressive shortening may represent the Sudetic Event of the Hercynian orogeny in the Irish Midlands. Early Carboniferous normal faults were reactivated and transformed into reverse faults and ENE-WSW trending faults had dextral transcurrent shear reactivation at this time and linear folding and cleavage development occurred to be later reactivated by sinistral transcurrent shearing and vein development. The main Hercynian orogeny is represented by a simple NW-SE directed compression leading to the development of major regional folds and thrusting and high-angle faulting normal to the main fold trends. Some of these thrusts have substantial throws of well in excess of 1000m as at Knocksigowna, Kildare and Navan.

Using isopach maps, Andrew (1992) provided the initial convincing evidence of Courceyan tectonically induced differential subsidence. Isopach maps of various conodont biozones

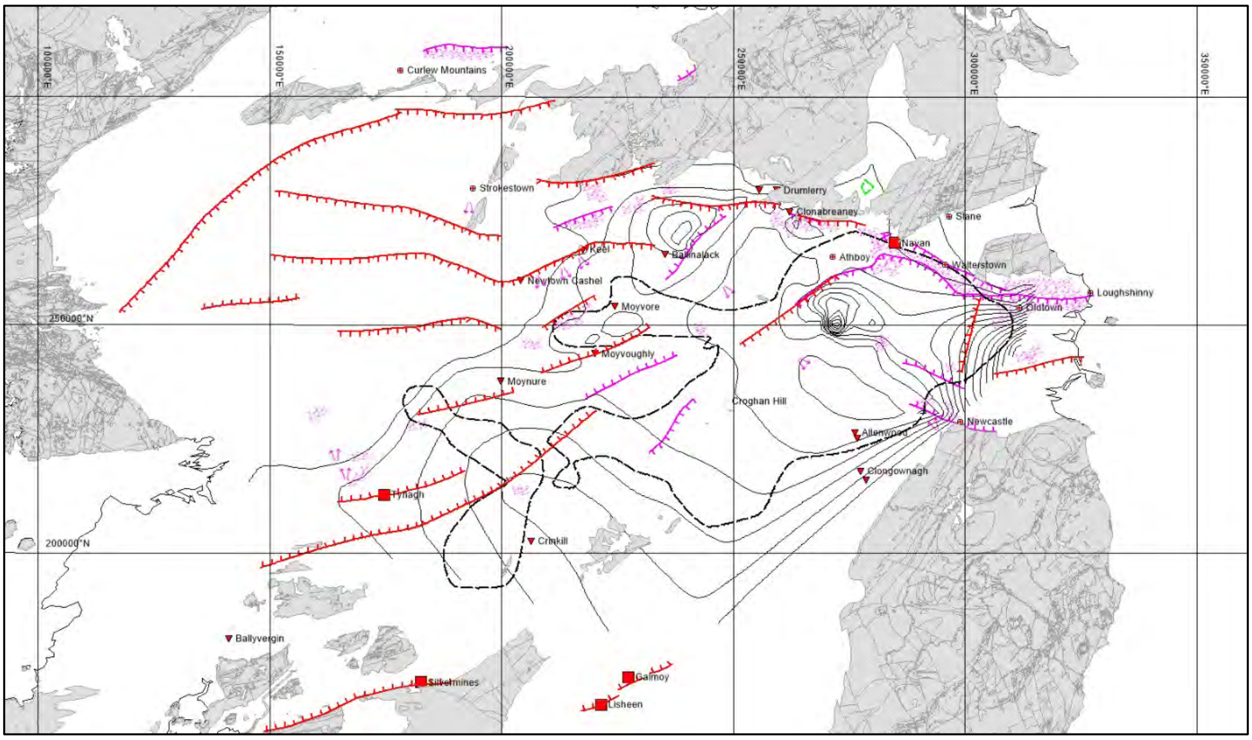

Figure 20: *Isopachous Plot of the Tober Colleen also showing the extent of the end Chadian Rift Basin, principal active structures, conglomerate debris flows and mineralized occurrences.*

also showed apparent fault control on sediment thicknesses. Initially the tectonic history was interpreted to be (1) Courceyan "gentle extension" leading to "down-warping" and (2) Chadian faulting leading to block-basin geometries, tilt-blocks with marginal uplift, and the development of erosional surfaces (and gravitational slides). Whilst in essence this interpretation is generally correct these assumptions did not recognize the specific timing of the tectonic events.

This data from the early 1990s (Andrew, 1990, 1992) was subsequently elaborated upon by de Moreton *et al* (2015) using seismic reflection data, combined with detailed stratigraphic relationships and stratal thickness variations (and associated faulting) to define a tectonic event initiated during the mid to late Courceyan, the so-called *Moathill Event*.

The interpretation by de Moreton *et al* (2015) of a shallowing-upward cycle through the ABL Group to indicate sedimentation outpacing the generation of accommodation space, suggesting that tectonic subsidence had decreased through ABL time. This, in turn, suggests that there was an initial pulse of tectonic subsidence during the *Polygnathus communis carina* biozone that decreased into *Polygnathus mehli mehli* times (Figures 16 & 17).

This interpretation relies upon a conventional interpretation of the gamma log pattern as being indicative of shallowing upwards, but an alternative explanation is that the reduction of argillaceous and siliciclastic input as the strand line continued to transgress northwards impacted the gamma logs. This perhaps better fits a deepening from shallow water sediments to the relatively deep-water environment that Waulsortian mudbanks are generally thought to form in (Lees & Miller, 1985, 1995).

Evidence from this study suggests that a series of essentially E-W faults (such as the B- and T-Faults at Navan, the Longford-Down Boundary Fault in Meath, the Balbriggan Inlier Fault, part of the Keel Fault and the Lough Sheelin Fault) were developing as short segments and commenced to have an influence of sedimentation patterns during the *Polygnathus mehli mehli* biozone (Figure 18). Such fault patterns bear close similarity to the modelled fracture patterns demonstrated by Liu & Konietzky (2018) where extension is orientated at a small angle (c. 5º) to the principal dextral strike slip (Figure 5).

The *Moathill Event* is widely recognized across the Irish Midlands, suggesting that it is of regional significance and potentially of importance in the development of mineralization. The *Moathill Event* occurred during the *Polygnathus mehli* sub-biozone and was dominated by transtension and simple dip-slip listric faulting giving rise to local over-riding and stratigraphic inversion as in the "T-Fault" trough at Navan. Locally the sedimentary sequences show evidence of exposure and minor erosion surfaces in the uppermost Navan Group which are also stratigraphically equivalent to evaporite development in the NW Midlands.

At Navan Ashton *et al* (2015) recognized several phases of fault activity. The "E" and "L" normal faults have been identified as being of “early Courceyan” age and clearly localize the 5-Lens mineralization and the “E” Fault appears to have been a major feeder for hydrothermal fluids. A series of ENE to NE-trending faults identified as the “F” Faults (“F1, F2” etc) show that mineralization increases in their vicinity, and they are related to widespread fracturing. Blakeman *et al* (2002) showed that these extensional (growth) faults, active during deposition of the Pale Beds (circa *Pseudopolygnathus multistriatus* biozone*)*, acted as conduits for the hydrothermal fluids and have a significant control on the lateral development of mineralization. Later faults such as the “B”, “T” and “Y” dislocate the mineralized lenses and are thus clearly post-mineralization and would fall within the “*Moathill Event*” in the *Polygnathus mehli* sub-biozone and all terminated at the early Chadian-aged rotational slide and erosion surface developed during the *Tober Colleen Event* in the *Polygnathus bischoffi / M. beckmanni* biozones. At Navan Philcox (1989) recognized complex faulting in the hangingwall of the “T”-Fault where several large low angle slabs of Shaley Pales are stratigraphically inverted indicating of large-scale lateral transposition.

This simple geological evidence provides definitive age relationships to the faulting and mineralization constraining it to a narrow time interval around 348 Ma under relatively shallow burial depths.

A second major tectonic event, dominated by rifting and regional subsidence occurred during the Chadian to early Arundian. The so-called *Tober Colleen Event* (de Moreton *et al*, 2015) occurred during the *Polygnathus bischoffi / M. beckmanni* biozones and was associated with widespread basin subsidence, basin margin collapse and inversion associated with the development of major extensional slide complexes leading to erosional degradation of footwall units at Navan, Newcastle and on the flanks of the Balbriggan Inlier. Products from this major event include the Boulder Conglomerate at Navan with tumbled blocks up to 18m in diameter (Philcox, 1983) and lithic clasts of mineralization, debris flows such as the Lane Conglomerate and coarse quartz pebble beds and mature white sands in the lowermost Arundian calcwackes probably derived from the emergent Lower Palaeozoic Leinster Granite.

In the Dublin Basin the Courceyan ramp phase of sedimentation was followed in the Chadian by tectonic break-up of the basin into distinct shallow-water platforms, on which production of carbonate sediments continued in considerable volume, and 'deep' basinal areas in which it ceased, terminating Waulsortian mudbank development. Progradation of the platforms across these basinal areas was limited, and mainly confined to the dip-slope of hanging wall blocks; progradation across fault scarps was rare. In the Dublin Basin around Swords the Courceyan main shelf conodont biozones are greatly thickened with the *Pseudopolygnathus multistriatus* Biozone (> 300m thick) being succeeded by a very thick (> 900m) *Polygnathus mehli* Biozone.

Some 15km SE of Navan, in the Walterstown-Kentstown area, Pickard *et al*. (1992) provided direct stratigraphic evidence that the St. Patrick’s Well Fault was synsedimentary in nature and began movement in late *Pseudopolygnathus multistriatus* or early *Polygnathus mehli* times. Furthermore, this fault is truncated by a Chadian-aged unconformity, indicating that faulting had ceased by this time. Continued subsidence and/or sea-level rise in the late Chadian to early Arundian resulted in transgression of the Kentstown and Balbriggan Blocks. Carbonate ramps developed on the hangingwall dip slopes which transgressed southward with time. Several coarse conglomeratic intervals within the contemporaneous basinal sequences of the Fingal Group attest to periodic increases of sediment influx associated with the development of shelves on the Balbriggan inlier.

Sedimentological evidence by Pickard *et al*. (1992, 1994) suggests that the Kentstown and Balbriggan Blocks possessed tilt-block geometries developed during an episode of basin-wide extensional faulting in the late Chadian. Rotation of the blocks during extension resulted in the erosion of previously deposited sequences in footwall areas and concomitant drowning of distal hangingwall sequences.

Similarly, at Newcastle in south County Dublin the Courceyan sequence is cut by a number of rotational listric faults of probable *P. mehli* sub-biozone timing which are all terminated by a major erosional surface of *P. bischoffi* sub-biozonal age (probable Tober Colleen Event) and overlying debris flow conglomerates (Figure 20).

By Chadian times the Dublin Basin was subsiding by synsedimentary fault displacements and basinal limestones contain shallow water faunas and littoral sand and pebbles derived by turbidite flows from the margins of the higher blocks (Figure 21 & 22). The early subsidence was apparently by pure flexure or sag, but during the Visean the Dublin Basin was fault-controlled (Jones *et al*, 1988).

To the south of Slieve na Calliagh near the Drumlerry prospect drilling has defined a shallow erosion surface separating Chadian-aged Argillaceous Bioclastic Limestones (“ABL”) from dark basinal limestones of “Calp” affinity and dating from the early Arundian. Thin debris flow conglomerates comprising clasts of the underlying limestones occur within an argillaceous matrix (Brand & Emo, 1986). This erosion surface is at the same time horizon as the major downcutting surface at Navan.

Further west at Newtown Cashel, Crowe (1986) reported that the Waulsortian and its equivalents are overlain by a non-sequence and superseded by vuggy dolomitized peloidal calcarenites of Oakport Limestone type (late Chadian) (Figure 21). The basal dolomites contain palimpsest breccia textures and fabrics and the underlying Waulsortian may be reddened and locally haematitized possibly suggesting sub-aerial exposure during the uplift and erosional event. This erosion surface is seen to have significant incision as deep as the Navan Group thus removing in excess of 150m of sequence.

On the southern margin of the Curlew Mountains in north-west Ireland drilling has revealed a substantial unconformity on the southern downthrown side of the Curlews Fault. Above this unconformity is a laterally variable complex succession of sandstone breccias, conglomerates with limestone and sandstone clasts, varied carbonates including mudbank limestones

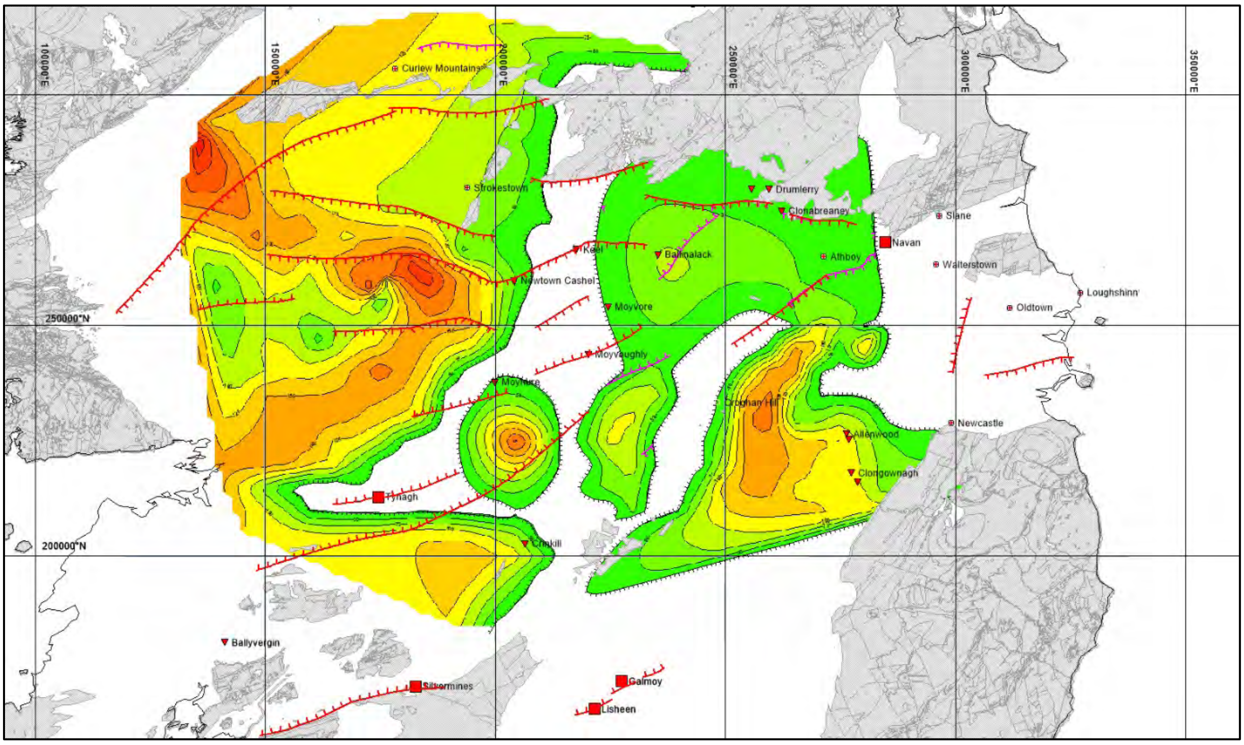

***Figure 21**: Isopachous plot of the Chadian shelf sediments (Allenwood Beds and Oakport Limestone with principal active structures and mineralized occurrences*

and shales up to 100m in thickness and containing very large olistoliths up to several metres in diameter. Where it has been dated these lithologies are of late Chadian to Arundian age confirming a Chadian-age for the erosional event. In the areas where the unconformity is most developed an estimated 360m of earlier Dinantian rocks have been eroded (Philcox *et al*, 1989).

This unconformity is represented to the south across County Roscommon by a non-sequence with an intra-formational conglomerate dated as being early Arundian (Pracht & Somerville 2015). This non-sequence feathers out towards the deeper water sequences in the Tynagh-Galway Trough.

Within this timeframe the initiation of synsedimentary tectonic events, both as passive sag and fault-controlled basin margins led to facies variations within localized sub-basins such as the North Tynagh Basin where sag exceeded the rate at which Waulsortian mudmounds could grow and deeper water carbonate wackestones predominate. Similar local controls in sediment thickness as well as local lithological variations are seen across the north midlands within the Navan Group and Argillaceous Bioclastic Limestone (ABL) / Waulsortian sedimentary package.

The supra-Waulsortian shelf limestones or Allenwood Beds comprise peloidal skeletal grainstones and oolitic limestones, commonly dolomitized and may either lie on a karstic surface of Waulsortian on which large karst cavities are sometime infilled with oolites. The Allenwood Formation interfingers with the basinal mudstone of the Tober Colleen Formation north of the Kildare Block (Somerville *et al*. 1992) or overlie a rapidly changing sequence of the Tober Colleen Formation of initially deeper and subsequently shallower water carbonate wackestones. (Nagy *et al*, 2004). The Tober Colleen Formation (Nolan, 1989) comprises mostly cleaved grey mudstone with nodular and graded beds of calcisiltite and micrite near the top. In boreholes, the bulk of the formation is characterized by monotonous, bioturbated, slightly calcareous mudstone, interbedded with thin fine-grained argillaceous limestone and spiculitic micrite.

On the southern side of the Balbriggan Inlier, and at Navan, Clonabreaney and several other locations surrounding the Central Midland Basin (Figure 22), coarse-grained debris-flow sediments comprise a varied suite of lithologies including polymict cobble and boulder conglomerates, graded bioclastic limestones and slumped mudrocks. Occasional clasts of Lower Palaeozoic lithologies are seen in the conglomerates suggesting a widespread impact of rotational faulting during rifting.

Calp limestones (formally the Lucan Formation (Nolan, 1989)) forms the bulk of the basinal rocks throughout the Midlands Rift Basin, and is characterised by graded, intraclastic skeletal grainstones interbedded with shale, laminated calcisiltite and argillaceous micrite. Its base is defined by the appearance of thick graded beds of limestone, and a marked decrease in the proportion of interbedded shale, compared with the underlying Tober Colleen Formation.

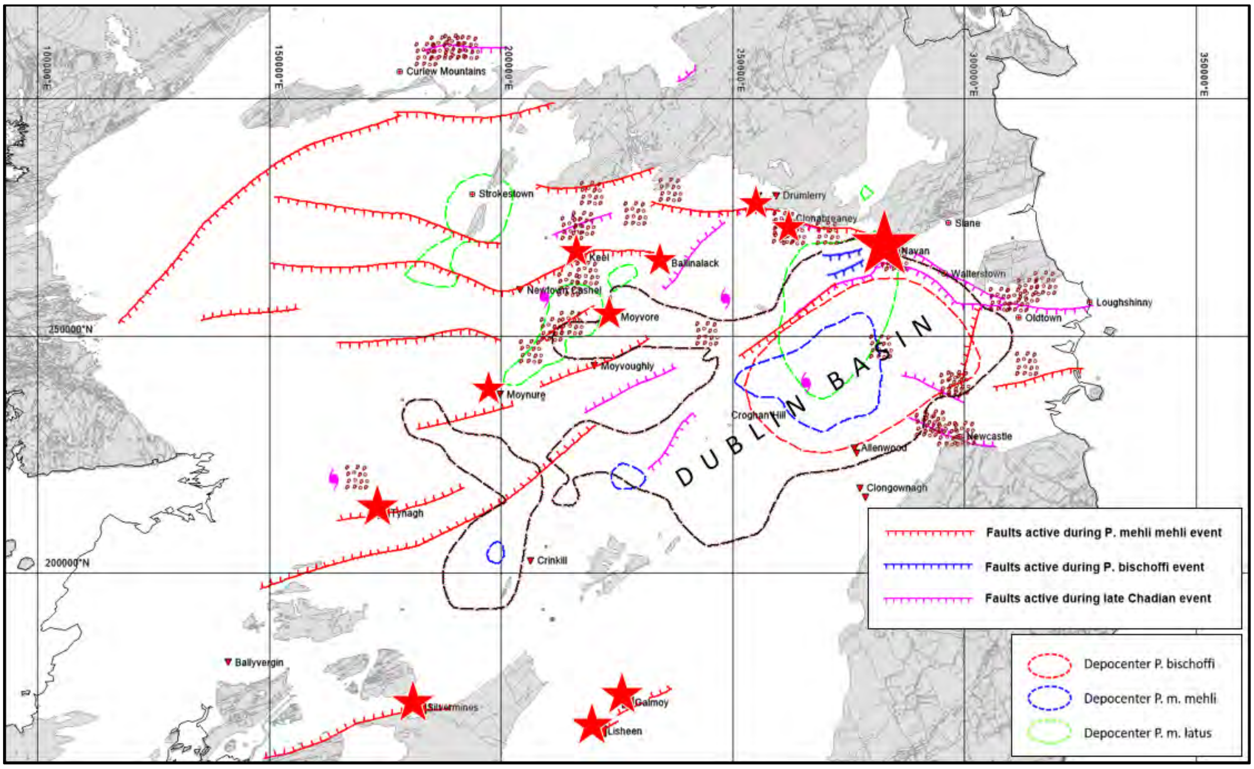

Figure 22: *Map showing the depocenters during specific biozones and the extent of the overall Midlands Rift with contemporaneous faults.*

Over the past 25 years this data based largely on conodont biostratigraphy in the Irish Midlands has enabled greater detail to be applied to the recognition of how and when faults were active in the basin and what impacts and association they had with mineralization. The timing of these fault movements is virtually identical at Ballinalack, Tynagh, Newcastle, Walterstown, Silvermines, Lisheen and Navan demonstrating that these were widespread events developing across the Central Midlands. It can hardly be a coincidence that the timing of these geological events coincides with the acceptable isotopic age dating for many of the Irish Zn-Pb deposits.

Summary of Events

There is ample stratigraphic evidence in terms of both thickness and facies variation to suggest that The *Moathill Event* during the *Polygnathus mehli* sub-biozone comprised the initial onset of gentle NW-SE extension orientated at a shallow angle to the regional dextral strike-slip reactivation of basement Caledonide faults leading to the initial development of shallow, generally E-W listric faults controlling shallow basin development in the lithifying carbonates. This extension gave rise to the initial depocenters in the Irish Midlands throughout ABL and Waulsortian deposition into the early Chadian. Contemporaneously with this extension was an incursion of clean mature sands from the north, possibly as a result of tectonism in the northerly hinterlands.

By plotting a series of sections, it is possible to clearly see the variation in depositional thicknesses across the Midlands Basin during the Courceyan and to identify active tectonism during these biozones (Figure 23). The later *Tober Colleen Event* during the *Polygnathus bischoffi / M. beckmanni* biozones was associated with widespread major basin margin collapse and major extensional slide complexes leading to erosional degradation of footwall units and appears to mark the final stages of the tectonically induced extension. This event leading to the development of major depocenters coaxially continued into the Arundian and Holkerian (Figure 22).

One of the most remarkable aspects of the giant Navan deposit is that it provides definitive dating on unequivocable grounds as to the age of mineralization. The host sediments were laid down in the *Ps. multistriatus* biozone and a series of syn- to post-ore faults cut the mineralization and are themselves terminated by a deeply incising erosion surface above which clasts of lithified mineralization occur. The major erosion surface can be placed in the P. *bischoffi* sub-biozone or "*Tober Colleen Event*" whilst the earlier faulting is of *P. mehli* sub-biozonal age (the "*Moathill Event*"). This precise dating constraining mineralization has important consequences when considering the depth below the contemporaneous seafloor the mineralization occured.

It seems unlikely in the extreme that such a major sedimentological / tectonic event was unrelated to the mineralization which has been shown to be largely co-eval by various dating techniques. The contemporaneity of such factors suggests that mineralization cannot have occurred at any great depth below the contemporary seafloor.

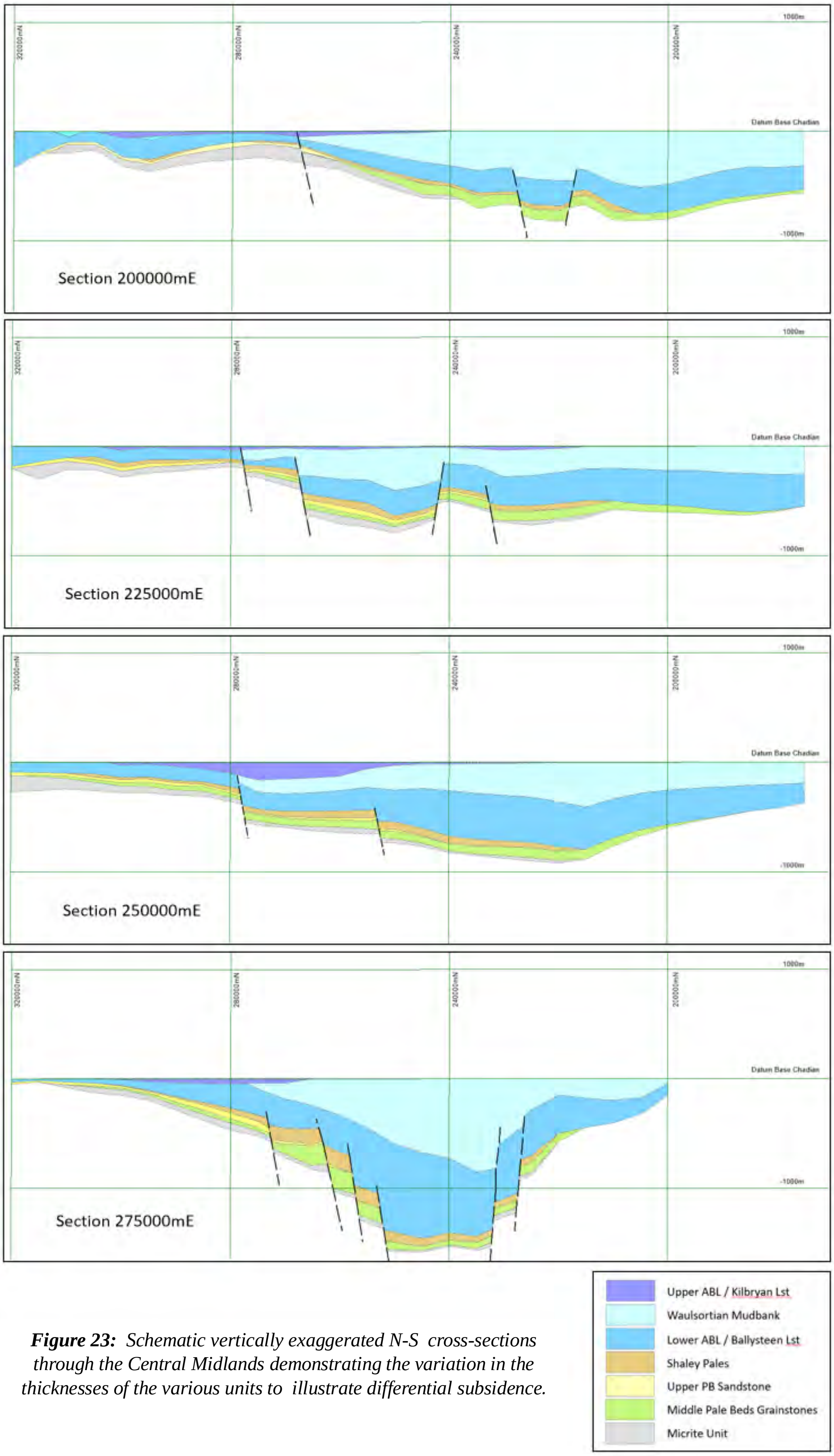

Figure 23: *Schematic vertically exaggerated N-S cross-sections through the Central Midlands demonstrating the variation in the thicknesses of the various units to illustrate differential subsidence.*

Volcanism

Alkali basalt volcanism in the Irish Midlands is focussed on two principal areas – Croghan Hill in County Offaly in the Midlands and around Pallas Green in the Limerick Basin.

One, and locally up to three, thin green tuff horizons are seen across much of the Midlands from Slane in the NE, to Roscommon in the NW, and across much of Munster to the south. These tuffs occur as discrete waterlain layers within argillaceous bioclastic limestones and shelf calcarenites and have been dated by Koch *et al* (2022) at between 350.5 to 348.2 Ma well within the upper Courceyan equivalent to the Lough Gur and Knockroe Volcanic Formations.

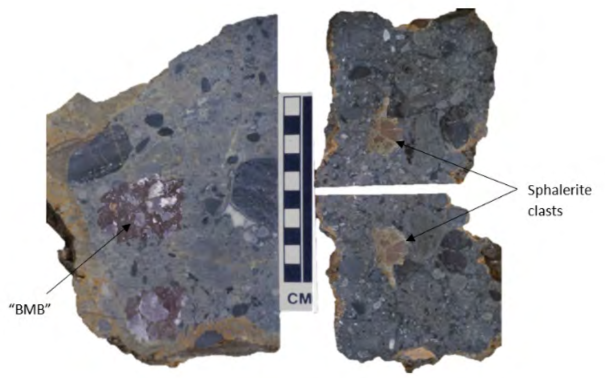

Figure 24: *Cut slabs of maar diatreme breccias (Lower Chadian-aged Knockroe Volcanics) from Longford West prospect, County Limerick collected in 1983 by the author showing:* ***(A)*** *– Fragments of Black Matrix Breccia ("BMB") in diatreme breccia and,* ***(B)*** *Fragments of pale brown sphalerite within diatreme breccia strongly suggesting mineralization was present before the volcanic diatremes.*

The effusive basalts at Croghan Hill in the Midlands (Haigh, 2014), presumably the source of the tuffs, also fall within this time frame of the early Chadian (345 ± 3 Ma $^{40}Ar/^{39}Ar$ amphibole age Timmerman, 2004).

The agglomerates at Croghan Hill locally contain biotite megacrysts and granulite-facies crustal xenoliths that recorded P-T conditions of 6-8 kbar and 700-800°C (Strogen 1974). Interestingly Sm-Nd garnet dating of these basement rocks shows that the lower crust remained hot or was re-heated to ~600°C at ~345Ma associated with extension and, in part, coincident with the mineralization (Daly *et al*. 2016) which strongly suggests that enhanced basement heat flows may have been temporally related to the mineralization. Leeder (1988) estimated that in the period from lower Dinantian to mid-Namurian the lithosphere in the British Isles was thinned by a stretching factor of 2 leading to increased heat flow. Helium isotopes (Davidheiser-Kroll *et al* 2014) indicate crustal extension whilst elevated heat flow from maar-diatreme basaltic volcanism in the Limerick Basin and at Croghan Hill in Offaly and the presence of the widespread tuff horizons at around 344Ma within relatively low energy carbonates precisely coincide with these events.

For both the Croghan Hill and Limerick / Shannon Trough volcanics, the presence of injections of thixotropic lava breccias with a limestone matrix, evidence for phreato-magmatic explosions and the limited amount of volcanic detritus together all indicate eruption in a sub-aqueous, marine environment.

Turner *et al* (2019) recorded a spike in Ni/Co-V-Hf/Zr levels at the top of the late Chadian-aged Crosspatrick Formation thought to be a result of additional (mafic-intermediate) volcaniclastic input accompanying the detrital components in the sediment budget.

Whilst not traced to a specific volcanic event however, both the Limerick and Croghan Hill volcanics have been dated to a relatively similar period (Elliott *et al*, 2015; Sommerville *et al*., 1992). It is of interest that the Crosspatrick Formation was deposited into a zone of collapse caused by hydrothermal cavitation (and mineralization) approximately synchronous with the onset of this effusive volcanic phase (Guven *et al, this volume*).

This phase would temporally correlate with the spike in Ni/Co-V-Hf/Zr levels at the top of the Crosspatrick Formation (Turner *et al*, 2019) suggesting an important thermal event potentially coeval with late-stage mineralization. De Brit (1989) noted the presence of an yttrium anomaly (*circa*. 1000pm) in brown late-stage sphalerite in mineralization at the Ballinalack deposit which may also be temporally coeval to this spike.

At the Pallas Green and Stonepark prospects observations from drillcore suggest a close spatial and temporal association between Zn-Pb mineralization and alkaline basalt-trachyte maar-diatreme volcanism (Blaney & Redmond, 2015; Gordon *et al*., 2018; Slezak *et al*, 2023). Phreato-magmatic eruption of these diatremes into a local shallow-water graben resulted in the deposition of >450 m of extra-vent pyroclastic deposits of the Knockroe Volcanic Formation whose upper part is interbedded with, and overlain by, shallow water oolites and algal-rich bioclastic limestones interbedded with wackestones and cherts (Elliott *et al*., 2019). Stratigraphic constraints suggest diatreme emplacement occurred during the late Chadian stage (345.3 to 341.0 Ma). Critically this volcanism is seen to post-date breccia-hosted Zn-Pb mineralization hosted within the underlying Waulsortian limestones and occasional clasts of mineralization and host black-matrix breccias are seen within the diatreme lithologies providing good evidence that the Zn-Pb mineralization and associated brecciation preceded the volcanism (Figure 24).

In summary volcanism in the Irish Midlands post-dates the Zn-Pb mineralization and occurs at the final rifting stage of the Midlands depocenters.

Depth of Mineralization

Irish-type deposits are thought to link the differences between "MVT-type" Zn-Pb deposit formed at some considerable depth in fully lithified rocks and "CD-type" Zn-Pb deposits formed at or near to the sediment water interface.

For the Irish-type deposits the style and morphology of each individual mineralized zone relates to the relative age between sedimentation and the onset of mineralization, and to the local conditions of lithification and diagenesis of the host sediments. This clearly implies that the depth below the seafloor that mineralization occurred was particularly significant in controlling not only the style of mineralization but also in elucidating the nature of the mineralizing process.

Wilkinson *et al*., (2003) calculated effervescence-depth curves spanning the inferred range of CO_2 and NaCl concentrations (up to ~4 mol% CO_2 and ~12wt% NaCl) in the interpreted principal mineralizing hydrothermal fluid. On the assumption that boiling did not occur as no indicative mineral textures have been noted, the range of depths for entrapment can be interpreted to be between 84 and 465m although the addition of any hydrostatic head from the depth of seawater would reduce the minimum depth to close to or even at the sediment/water interface. Considering that Waulsortian mudmounds are believed to form at depths of between 200-300m this hydrostatic head falls within the range to allow exhalation on the contemporaneous seafloor.

Additional unambiguous evidence provided by the occurrence of clasts of hydrothermal dolomite and sulphides in intraformational debris-flow breccias is consistent with mineralizing processes occurring in the near-seafloor environment, relatively soon after host-rock deposition.

At Navan the mineralizing system was clearly unroofed by the late Chadian basin margin collapse and development of a regional erosion surface and olistostrome. We know that the late Courceyan to early Chadian sediments were no thicker than ~200m above the “U-Lens” and mineralized clasts derived from this lens are seen within the Conglomerate Group Ore immediately overlying and down palaeoslope relief of its subcrop, thus burial depth can have been no greater than this thickness equating to no more than 250m when lithified mineralization had formed. It is noteworthy that the SE’erly extending “U” Lens trends parallel to the sub-crop of the host Pale Beds with the erosion surface and is constrained to no more than 600-700m laterally from this palaeo-sub-crop (Ashton *et al.*, 2015).

At Lisheen and Galmoy, collapse within the Waulsortian mudmounds has been interpreted to be due to a combination of low angle listric faults and hydrothermal dissolution brecciation prior to and possibly contemporaneous with deposition of the Chadian-aged Crosspatrick Formation which predated mineralization. This implies that mineralization had occurred under no more than ~250m of Waulsortian.

Larter *et al*. (1981) reported the occurrence of fossil hydrothermal vents and a highly pyritic vent field at the Magcobar pit. Pyrite botryoids (bubbles) appear to have formed at surface at a warm spring feeding part of the Tynagh lead-zinc deposit and microbialite iron-sulphide mounds showing a micro-porosity architecture indicative of a bacterial mat have been described from samples collected in the Magcobar Pit at Silvermines. (Kucha, 2018; Boyce *et al* 1983; 2003; Banks, 1986). Such evidence, taken along with the sedimentary features seen within the mineralized zones including graded sulphidites and clastic mineralization with isotopic evidence of the dominance of lower Carboniferous seawater strongly suggests near surface exhalation for at least part of the mineralizing event.

In summary it can be demonstrated quite convincingly that mineralization in the Irish deposits cannot have occurred at depths much greater than 300m and probably at considerably shallower depths from the sediment water interface down (Figure 25).

Syndiagenetic Mineralization

The term “syndiagenetic” has been coined by several authors for the Irish-type deposits, hence in order to understand these deposits we must look at the sedimentary environment and diagenesis of the ore-hosting sediments. If mineralization is truly “syndiagenetic” the state of lithification of the host rocks becomes significant and this depends on many factors including permeability, porosity, grain size of the sediment and especially the percentage of carbonate.

Schlager & James (1978) noted that carbonate ooze in the deep troughs between the Bahama Banks is a mixture of pelagic and bank-derived material and it consists of aragonite, calcite and magnesium calcite in a ratio of about 3:2:1. Where exposed in erosional cuts at the sea floor, this ooze lithifies within 100,000 years and is transformed into calcite micrite with only 3.5-5 mol % $MgCO_3$. Where buried, the ooze maintains its original composition for at least 200,000-400,000 years and remains unlithified for tens of millions of years (Shinn & Robbin, 1983).

Koch *et al* (2022) implied a sedimentation rate of 240m per Ma for the Waulsortian at Stonepark (Co. Limerick) with some

	Minimum		*Maximum*	
Lisheen	Base of WRL to base of Crosspatrick	190m	Base of WRL to top Crosspatrick	250m
Silvermines	Exhalation Barite-Siderite-Pyrite	0m	WRL Equivalent Breccia Thickness	200m
Navan	"U" Lens to Erosion Surface	50m	"2-5" Lens to Erosion Surface	200m
Tynagh	Exhalation Iron Formation	0m	Base WRL to anomalous Mn horizon	150m
Pallas Green	Base WRL to HW Tuff Horizon	200m	Base WRL to Knockroe Volcanics	350m

Figure 25: *Table setting out the interptreted depth constraints to mineralization.*

550m of micrites accumulating over a 2.3Ma period. Whilst fabrics within the Waulsortian such as stromatactis suggest early lithification it is possible that fine micritic muds may have remained unlithified for some considerable period of time.

Dix & Mullins (1992) discussed the rates of burial diagenesis and subsurface distribution of chalk and limestone in modern deep-water carbonate slopes from the Ocean Drilling Program drill transects in the northern Bahamas. They noted that most of the dolomite precipitates after initial aragonite dissolution, typically in the upper 70m, with Mg derived from alteration of magnesian calcite and diffusion from overlying sea water. Considering dolomitization is generally not pervasive at most of the Navan Group hosted Irish deposits and is usually only a mineralogical component of the host rocks, much of the dolomite present may well have been precipitated during shallow diagenesis.

In the Navan Group-hosted deposits there would exist a significant diagenetic potential still present in carbonate grainstones at up to 300m burial depths. Here carbonate-mineral stabilization and early limestone formation with secondary porosity in a sea-water-mediated environment highlights the high diagenetic potential of peri-platform carbonates.

Catlin & Danielli (1983) examined an extensive suite of samples from throughout the Midlands and concluded that marine calcite cementation and lithification of the carbonate sediments occurred at or near the seafloor. This sequence comprises early fibrous calcite, also referred to as radiaxial fibrous marine calcite (RFMC) or crypto-fibrous calcite (CFC), which forms isopachous coatings and skins on bioclasts, ooliths and siliceous grains and within cavities (“Stage A”). This is overgrown by inequant (variously described by numerous authors as palisade, scalenohedral or dog-tooth spar) and equant (or blocky) calcite cements which show a consistent non-bright-dull series of luminescent zones (“Stage B–D”) - e.g., Catlin & Danielli (1983), Rizzi & Braithwaite (1996), Andrew & Poustie (1986), Pickard *et al.* (1992).

Deposition in the Navan Group was not continuous and was punctuated by relative changes in sea-level causing emersion and resulting in the formation of a variety of emersion surfaces. Palaeosols have also been reported in the Navan Group at Moyvoughly, and meniscus cements and rhizoliths have been reported from Kentstown and Walterstown coupled with early very shallow stylolite development. These ‘hard grounds’ acted as barriers to hydrothermal fluid migration causing lateral development of massive sulphides within the breccia zones and resultant cavitation. Petrographic and diagenetic features suggest that evaporative conditions were dominant during the deposition of such tidal flat units.

In the north-west Midlands in north Galway, Roscommon and west Longford evaporites are well developed within the Navan Group micrites with gypsum, halite and even native sulphur being recorded in numerous drillhole logs (*e.g.* at Strokestown and Knockadrinagh) (Pracht & Somerville 2015). These evaporitic sequences are of Courceyan age (*P. mehli mehli* biozone) thus providing an early source of sulphate sulphur within the ore-hosting sequence

The evaporites in the peritidal sequence of the Irish Midlands were replaced before the formation of medium crystalline planar dolomite, and also before the late diagenetic dolomite cementation of the shelf sequence (Nagy *et al.*, 2003, 2005).

Braithwaite & Rizzi (1997) suggested that at Navan the scatter of fluid inclusion temperature measurements suggests that the dolomite crystals grew within the ore-hosting Navan Group sediments during early diagenesis for an extended period (late Courceyan or Chadian, perhaps to the Arundian, a maximum of 10 Ma) from progressively higher temperature fluids.

Virtually identical cementation histories have been described by many authors for the Waulsortian Mudbank and as elegantly and convincingly discussed by Lees & Miller (1985), there are many lines of evidence to suggest that much of the calcite cementation in the Waulsortian was early, forming in the upper few tens of metres of the sediment column (Somerville *et al.* (1992). This view agrees with work by Hammes (1995) on the development of carbonate mudmounds in the late Jurassic, where significant volumes of marine cement are believed to form on or within a few metres of the seafloor.

High porosity in the Waulsortian due to an abundance of stromatactis cavities was reduced by the deposition of internal sediment and the precipitation of marine fibrous calcite (probably high magnesium calcite) cement, now seen as radiaxial fibrous calcite. These inferred marine cements can form more than 50% of the rock volume (de Brit, 1989). The early cementation probably produced the rigidity necessary to sustain the high depositional dips observed in many of the Waulsortian mudmounds (Lees, 1964; Philcox, 1971). Studies by Lees (1964), Sevastopulo (1982) and Miller (1986) demonstrated that the Waulsortian had a complex diagenetic history and became lithified soon after deposition. Early Fe-Zn mineralization is seen at Silvermines, Tynagh, Ballinalack and elsewhere infilling such stromatactis cavities as an early stage indicating the presence of mineralizing fluids very early in the diagenetic history of the mudbanks (Figure 12).

Gregg *et al.* (2001) showed that marine cementation reduced primary porosity to less than 1% in much of the Waulsortian Mudbank. If early diagenetic dolomitization enhanced porosity in the strata overlying the Waulsortian, this porosity was largely occluded by subsequent evaporite (and silica) cement. Consequently, if there was no open pore space for further fluid migration, and late diagenetic flow was restricted to fractures thus the age of mineralization would be constrained.

Evaporite cementation of the shelf carbonate strata in SE Ireland, was completed within a few million years (Nagy *et al.* 2004, 2005). Former evaporite cements are restricted to late Chadian to Arundian shelf strata, implying that the migration of hypersaline brine from the upper Chadian peritidal sequence to the shelf lasted approximately 3-5 Ma. This high salinity seawater, generated on the peritidal area by evaporation, may be a candidate for the recharging fluid, which was responsible for supplying magnesium for regional dolomitization and excess chloride ions for the base-metal ore-fluids responsible for

Zn–Pb mineralization in the Rathdowney Trend further to the west (Nagy *et al*., 2005).

Here the implication from Nagy *et al* (2005) is that the timing of Zn-Pb mineralization in the Rathdowney Trend is likely to be early as the late Chadian – early Arundian if the excess concentration of chloride found in the fluid inclusions of ores indicative of halite dissolution, originated from evaporites proximal to the Leinster Massif (Gleeson *et al.* 1999). Banks *et al.* (2002) have also suggested that areas of evaporated seawater formed the recharging fluids responsible for mineralization.

These fluids may have been involved in regional dolomitization of Chadian and possibly underlying Courceyan strata. A relatively early, fine-grained, grey replacive dolomite, preferentially developed in micrite, is widely developed in the Waulsortian Mudbank Formation and is pervasive in the south-east Midlands in proximity to the Leinster Massif.

A late Chadian age for Zn-Pb mineralization in the Rathdowney Trend is possible, based on the interpreted age of emplacement of evaporite cements in the post- Waulsortian strata. Wilkinson (2003) notes that this dolomitization formed after the first four main stages of calcite cementation but probably also developed within tens of metres of the seafloor as evidenced by incorporation of clasts of dolomite in intraformational sedimentary breccias.

However, no matter how the diagenetic history is interpreted what is beyond doubt is that there is broad agreement that ore-stage sulphides in the deposits form after the early, fine planar dolomite as at Navan (Braithwaite & Rizzi, 1997); and at Lisheen (Hitzman, 1995; Eyre, 1998; Hitzman *et al*. 2003) at Silvermines (Andrew, 1986, Lee & Wilkinson, 2002); Tynagh (Clifford *et al* 1986), Moyvoughly (Poustie & Kucha, 1986) and elsewhere.

The so-called "Black Matrix Breccias" were first described at Harberton Bridge by Holdstock (1982) in a clear collapse breccia setting. Subsequently the term gained traction at Lisheen and more latterly in the Limerick prospects (Blaney & Coffey and Guven *et al* - this volume). Such breccias are relatively common in the Irish Midlands but are <u>not always</u> associated with mineralization and do NOT share a common origin. Unfortunately attempts to use such nomenclature has retrospectively been applied to Silvermines and other occurrences in a "one size fits all" approach. Breccias at Silvermines are invariably polymictic with both dolomitized matrix and dolomitized clasts and even clasts of pre-existing mineralization occurring in close juxtaposition, unlike the oligomictic "Black Matrix Breccias" at Harberton, Pallas Green and Lisheen.

At Silvermines there is no doubt that the breccias are thicker overlying the stratiform upper ore zones (B and Upper G). In these areas the breccias equivalent to the entire Waulsortian is <u>thickened</u>. If they were formed by dissolution and collapse the sequence would, logically, have to be thinner over mineralization as at, for example, Lisheen and Galmoy, thus they must be debris flows. This interpretation is backed up by clasts of mineralization included within the breccias, rip-up and flame structures and scouring. Both the underlying and overlying sequences to the breccias have a well-developed tabular "layer-cake" aspect with little if any thickness variation and, as such demonstrate that the breccia sequence represents an anomalous time period in the sedimentary record.

An additional important observation is that the footwall rocks at Silvermines are generally evenly bedded and maintain a uniform pattern until the very uppermost beds immediately below the footwall to the upper orebodies. Here the uppermost beds below the major stratiform mineralized bodies laterally show a significant increase in crinoid ossicle size and abundance before passing laterally into grey and black non-fossiliferous cherts sometimes with distorted laminated pale sphalerite.

Barrett (1975), Andrew (1986) and Mullane & Kinnaird (1998) regarded the massive barite at Magcobar (Silvermines) as being sedimentary in origin and all described bedding features, slumping/debris flows and rip-up clasts as all having a primary sedimentary origin. Barrett (1975) convincingly demonstrated that the only elements of importance to be emplaced with the barite were iron and silicon (as haematite/siderite, jasper and quartz. A waning of the iron-rich phase heralded the bulk of the barite mineralization which initially was very siliceous. The microspherultic fabric of the barite suggests rapid crystallisation. With the possible exception of minor (biogenic?) pyrite the barite was free of accessory mineralization possibly due to bottom water conditions being sufficiently oxic to support a marine bottom fauna (at least episodically during barite precipitation) and would have been insufficiently reducing and sulphidic to induce efficient precipitation of sulphides. A gradual cessation of barite mineralization witnessed the introduction of sphalerite and galena muds which were the forerunners of the stratiform, sulphide cap to the orebody.

If we accept the thesis that the haematite and siderite are of synsedimentary origin and were laid down in a marine basin, a restricted environment (partial stagnation) would be required for the formation of the siderite. It is considered probable that the palaeotopography of the localized basins between the footwall knolls of Waulsortian mudbank may have controlled this low Eh and pH environment.

Savard *et al* (1998) have discussed whether the abundant siderite at the Walton barite deposit in Nova Scotia (which has striking age and geological similarities to Magcobar) represented a diagenetic replacement during early burial or whether it represents the first stage of hydrothermal mineralization, concluding that the petrography, and isotope geochemistry supported sideritization during diagenesis under shallow burial conditions.

Cruise (2000) concluded that the iron-oxide-silica mineralization seen at Tynagh, Silvermines, Crinkill and elsewhere forms the paragenetically earliest hydrothermal product within the Central Midlands Basin, pre-dating both hydrothermal dolomitization (regional dolomites, black and white matrix breccias) and base-metal sulphide mineralization. Geochemical modelling using iron-oxide-sulphide stability diagrams indicates that the iron-oxide-silica mineralization was deposited from oxygenated, that is SO_4^{2-} dominated fluids.

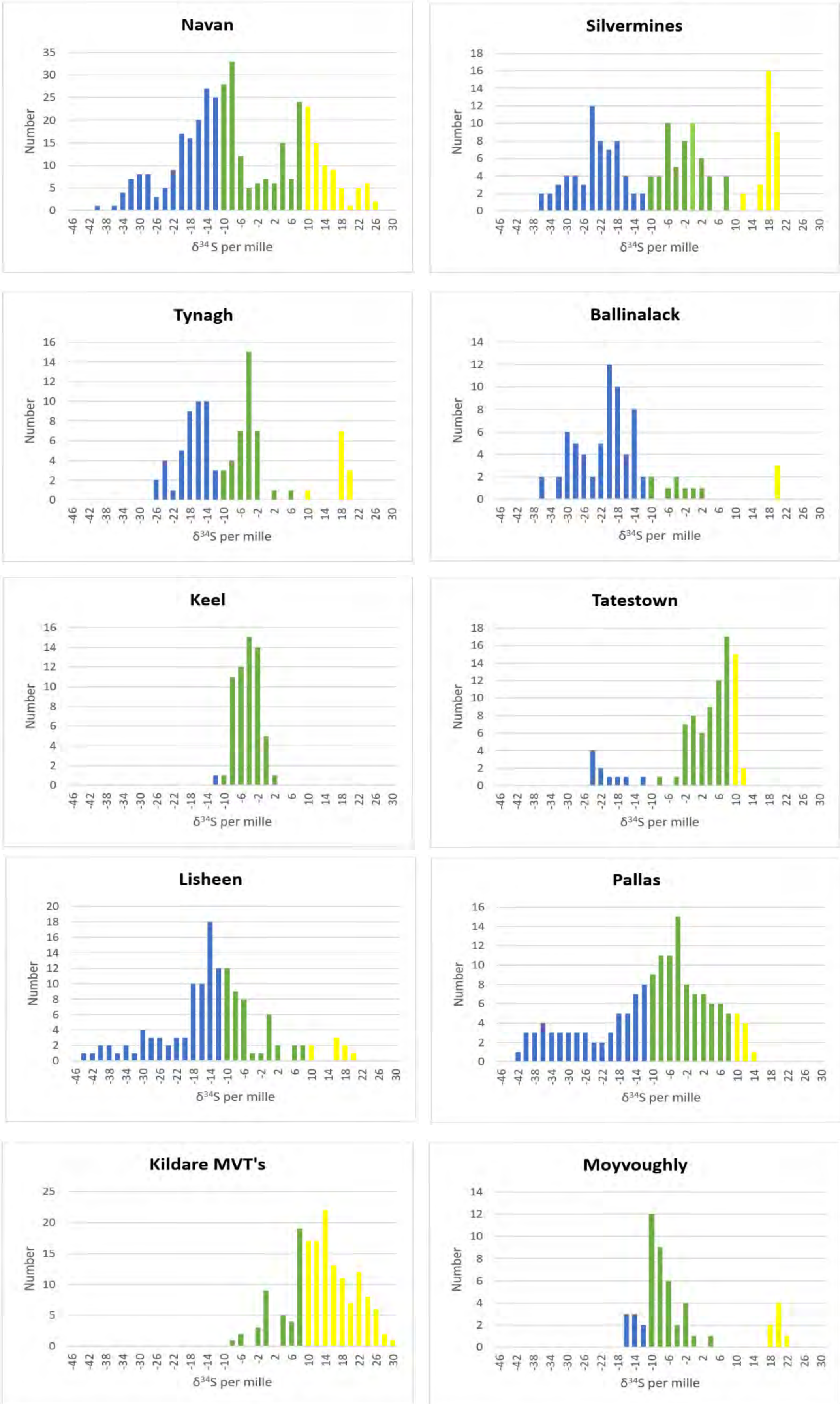
Navan
Silvermines
Tynagh
Ballinalack
Keel
Tatestown
Lisheen
Pallas
Kildare MVT's
Moyvoughly
Number
δ34S per mille

Figure 26 (opposite page) : *Histograms of sulphur isotope data obtained from the various deposits and prospects. Blue stacks represent sulphur exhibiting the range of a bacteriogenic signature; green the range of a deeper-seated sulphur source and the yellow representing the range of contemporary seawater sulphate.*

Data from multiple sources including: (A) Navan - Blakeman et al (2002), Fallick et al (2001), Yesares et al (2019); (B) Silvermines – Coomer & Robinson (1975); (C) Tynagh – Boast et al (1981); Boast et al (1981a); (D) Ballinalack - Caulfield et al (1986); (E) Keel - Caulfield et al (1986); (F) Tatestown – Caulfield et al (1986); (G) Lisheen – Yesares et al (2019); Wilkinson et al (2005) (H) Pallas / Stonepark - Elliot et al (2019); (I) Kildare – Dixon (1988); Gallagher et al (1992); (J) Moyvoughly – Caulfield et al (1986).

Isotopes and Fluids

Sulphur isotopic results from virtually all of the Irish deposits have demonstrated that there are two main populations of sulphur: one with negative $\delta^{34}S$ values and derived from bacterial sulphate reduction of seawater sulphate ("BSR"); and a second population with positive $\delta^{34}S$ derived from thermochemical (hydrothermal) sulphate reduction of seawater sulphate (Blakeman *et al*, 2002). At Navan calculations suggest ≥90 percent of the Navan sulphides were derived through bacteriogenic reduction of Courceyan-Chadian seawater sulphate, whereas metals were acquired from a local, orogenic crustal source beneath the orebody (Fallick *et al*, 2001).

Studies conducted on mineralization along the Rathdowney Trend provide evidence for regionally persistent brines derived from seawater evaporated beyond the point of halite precipitation, which mixed on more localized scales with other fluids, some of which likely circulated through basement rocks (Eyre, 1998).

In all deposits a temporal evolution of the ore forming fluids occurred, generally showing an increase in temperature and decrease in salinity with time (Banks *et al* 2002; Wilkinson, 2013). Si, Ba and Fe are usually but not always early, with Zn, Pb and Cu (Ni, As) later.

Isotopic signatures constraining timing and depth of mineralization

Sulphur isotope studies over the past 30 years or so have revealed two sources of sulphur in most of the Irish deposits (Anderson *et al*., 1989, 1998; Boast *et al.*, 1981; Blakeman *et al*., 2002; Fallick *et al*, 2001; Wilkinson & Hitzman, 2016). The dominant sulphide source was derived from the bacterial reduction of the Lower Carboniferous seawater sulphate. However, a significant component often termed deep-seated or hydrothermal sulphur has also been recognized in most deposits. Such sulphur is probably leached mainly from diagenetic sulphide minerals in the underlying Lower Palaeozoic sediments.

Results of measurements of sulphur isotopes for many of the Irish deposits are compiled in Figure 26. These have been colour-coded to reflect the following generalized ranges of values: blue stacks represent $\delta^{34}S$ sulphur values exhibiting the range of a bacteriogenic signature (-15 ‰ to -45 ‰ "BSR" or bacterial sulphate reduction); green the range of a deeper-seated sulphur source (-15‰ to +6‰) and the yellow representing the range of contemporary seawater sulphate (+6‰ to +30‰).

Sulphur isotopic characteristics of syngenetic and diagenetic sulphide minerals and organic sulphur in sediments are controlled primarily by three parameters: (1) initial ^{34}S value of aqueous sulphate; (2) the kinetic isotopic fractionation factor during bacterial sulphate reduction; and (3) the open or closed nature of the system.

The histograms in Figure 26 show remarkable similarities for certain deposits. For example, the profiles for Navan, Silvermines, Tynagh, Ballinalack, Lisheen and Pallas Green are all similar with only the relative amounts of seawater sulphate preserved in barite demonstrating any notable variation.

The profiles of Tatestown and Moyvoughly are similar whilst leaning towards that of Keel which shows a very tight profile limited almost entirely to the range of a deeper-seated sulphur source.

The Kildare deposits (Allenwood, Harberton, Rickardstown and Clongownagh) show a completely different profile with no evidence of bacterial sulphur being present.

This can be interpreted to represent the degree of "openness" of the mineralizing environment – the deposits with clear evidence of deposition near to the sediment / water interface dominantly show values in the range of BSR. In "tighter" or more closed systems such as the Navan satellite deposit at Tatestown, Moyvoughly and the Ballinalack Navan Group mineralization lower rates of BSR restricted the development of mineralization. The vein-breccia hosted Keel mineralization was a very tight deep environment and is restricted to hydrothermal deeper seated sulphur values.

At Navan the unroofing of the system and the largely extensile environment during mineralization enabled abundant BSR from the abundant seawater derived evaporite-rich pore fluids. Combined with the ongoing erosional degradation of higher units meant that the Pale Beds maintained a relatively shallow depth. Fallick *et al* (2001) suggest that ≥90 percent of the Navan sulphides were derived through bacteriogenic reduction of Courceyan seawater sulphate. Enhanced bacterial activity was fundamental to ore deposition at Navan: no bacteria, no giant ore deposit.

The Pallas Green profile is interesting as some authors (Elliot *et al* 2019; Blaney & Redmond, 2015) have suggested a relationship to the locally widespread late Chadian volcanism. The sulphur isotope profile can be interpreted to refute this, and as clasts of the mineralization have been seen within later volcanic breccia pipes (Figure 24), together this suggests that mineralization is not directly related to the volcanics. Contemporaneous volcanics at Croghan Hill in the Midlands have no similar mineralization spatially or temporally associated with them.

At Tynagh sulphur isotope values of the earliest stages of mineralization (pyrite and sphalerite) show a distinct spatial zoning away from the fault (Figure 27) Boast (1981a). Two fluids can be discerned with Phases 1 (pyrite) and 2 (sphalerite) being isotopically light ($\delta^{34}S$ values between -45 to -25‰) showing that mixing of a deeper-seated fluid occurred with bacterial reduced seawater sulphate, whilst the later epigenetic galena-chalcopyrite-tennantite mineralization (Phase 3) is dominated by a more deep-seated sulphur signature ($\delta^{34}S$ values of -22 to +14‰).

As at Tynagh, Silvermines a mixing of seawater sulphate and deep-seated sulphur can be seen from the spatial distribution of the sulphur isotopic results (Figure 28). The former was the dominant source of all sulphate and, via BSR, of the sulphur in the bulk of the upper stratiform orebodies. The latter was the source of the sulphur in the lower epigenetic orebodies.

At both Tynagh and Silvermines there is some evidence to show a gradual increase in heavier sulphur with depth of mineralization below the inferred seafloor as well as with timing.

In general, shallow loci of mineralization enabled rapid bacteriogenic sulphate reduction ("BSR") from the abundant evaporite rich pore fluids. In "tighter" or more closed systems such as the Navan satellite deposit at Tatestown and at Moyvoughly, Keel and the Ballinalack Navan Group mineralization lower rates of BSR and higher TSR restricted the development of mineralization. Deeper and "feeder" systems show a much tighter spread of sulphur isotopic values restricted to TSR and deeper sources of sulphur. The Kildare deposits show a very different pattern to the Irish-type deposits reflecting their more typical MVT style and likely later age of formation.

Oxygen isotopic results have been published for most of the Irish deposits (Boast *et al.* (1981), Eyre (1998), Everett *et al* (1999) amongst others. Cruise (2000) modelling $\delta^{18}O$ results from Tynagh, Silvermines, Crinkill, Ballinalack and Keel demonstrated that the iron-oxide mineralization occurred very early in the depositional and diagenetic history of the Waulsortian Mudbank Complex in a shallow oxic sub-seafloor environment.

Boast *et al* (1981) obtained a spread of oxygen isotope compositions with the $\delta^{18}O$ (SMOW) values ranging from 22.2 to 28.1 ‰ (mean: 26.3 ‰) from unmineralized Waulsortian micrites and associated diagenetic calcites with ore-stage carbonates returning values between 17.1 and 19.3 ‰.

Hall & Friedman (1969) have reported a linear relationship between $\delta^{13}C$ and $\delta^{18}O$ in host limestones at increasing distances from ore bodies in a number of MVT deposits. The lightest values were found closest to the deposits where temperatures were highest, clearly suggesting isotopic re-equilibration of limestones with hydrothermal fluids.

Walshaw *et al* (2006) at Navan identified an early fluid represented by replacive dolomite exhibiting the lowest initial $^{87}Sr/^{86}Sr$ ratio (0.7083–0.7086), close to that of the host limestones. Later generations of dolomite, barite and calcite, contemporaneous to sulphide precipitation, reported higher initial $^{87}Sr/^{86}Sr$ ratios (to a maximum 0.7105) interpreted to indicate mixing of sulphide-rich, limestone-buffered brine, with a

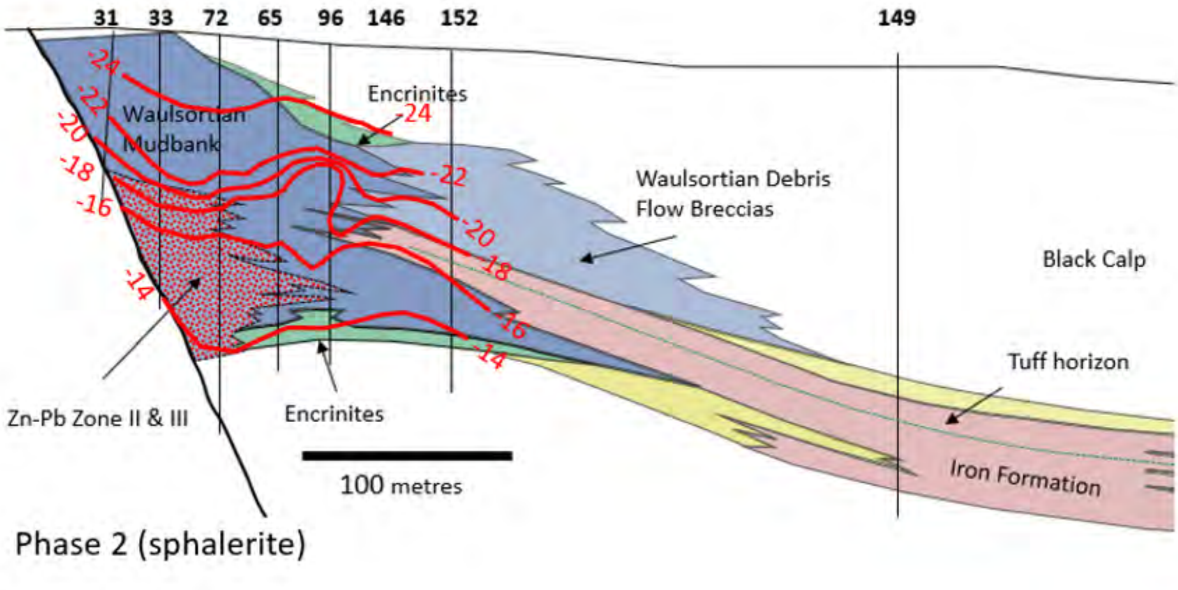

***Figure 27**: Cross section through Zone 2 at Tynagh showing the ore zone and the sulphur isotope values from Stage 1 pyrite and Stage 2 sphalerite showing a clear mixing pattern away from the Tynagh Fault. Data from Boast et al (1981 &1981a)*

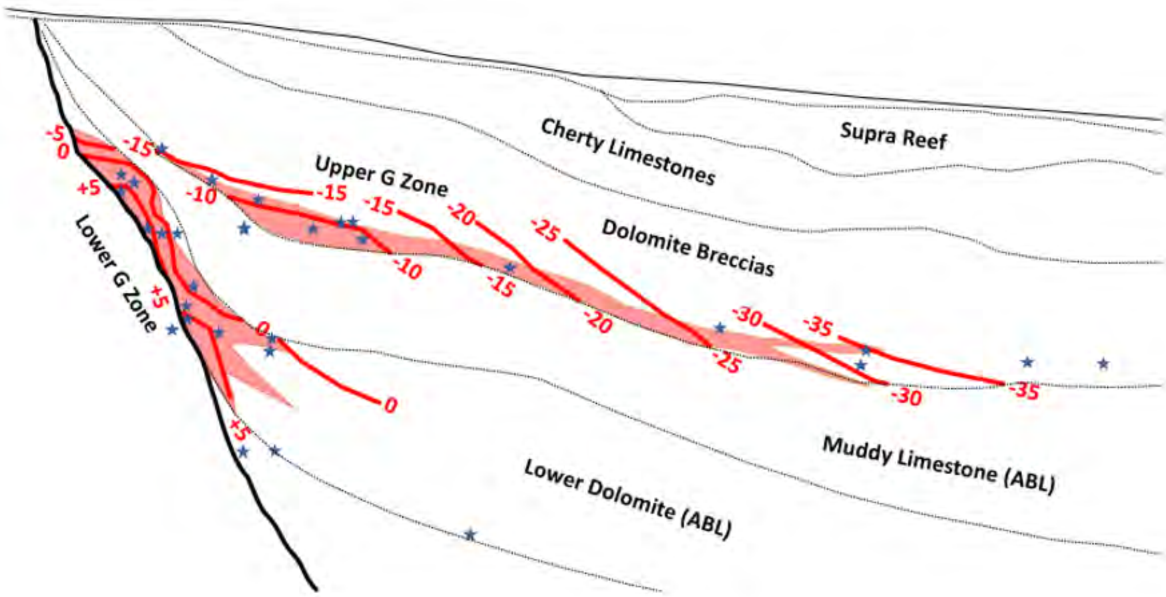

Figure 28: *Cross-section through the G-Zones at Silvermines showing the ore zones and the sulphur isotopic values from pyrite (data from Coomer & Robinson, 1976). Note the clear mixing curves both vertically through the Lower G Zone and laterally along the Upper G Zone.*

metal-bearing hydrothermal fluid (Walshaw *et al*, 2006). $^{87}Sr/^{86}Sr$ ratios range for seawater range from a high of 0.707908 in the early Courceyan to a low of 0.707650 in the late and mid-Chadian, with an early Chadian maximum at 0.707800. This data trend is consistent with mixing between crustal and seawater strontium reservoirs.

Irish Zn-Pb deposits that are not "Irish-type"

The Kildare deposits - Harberton Bridge and Canal Zones (now renamed "McGregor" and "Shamrock" by the current operator – ZMI Corp), Allenwood, Clongownagh and Rickardstown are significantly different to the other Irish Zn-Pb deposits being associated with the development of classic MVT-type breccias at the base of the Waulsortian and within chimney breccias extending up through the Waulsortian into the overlying Chadian-aged Allenwood shelf limestones. These "non-Irish-type" deposits contain less than 2% of the total metal endowment of the Irish orefield.

Mineralization within these breccia bodies has been classified into three types (Trude & Wilkinson, 2001): rock-matrix; precipitate-cemented; and crackle breccias, with individual breccia bodies varying from a few tens of centimetres to a few hundreds of metres in vertical extent from sub Waulsortian into post-Chadian sediments. Each body typically consists of rock-matrix breccia at the base overlain by precipitate-cemented breccia, with both passing laterally into crackle breccias. Features not well developed in Ireland outside the Kildare district.

Ore textures at Harberton Bridge show many of the characteristics observed in MVT deposits with a simple paragenesis with limited phases. Abundant marcasite (rather than pyrite as at all other Irish-type deposits) and sphalerite are the dominant sulphides. Sphalerite and galena are commonly interlayered with coarse marcasite and occur as concentric colloform overgrowths on limestone clasts or in clasts of colloform banded sulphides, whilst marcasite–calcite-only mineralization is seen in some of the breccias.

The most striking differences between the Kildare deposits and the classic Irish deposits are the geometry and structure of the mineralization as they have quite different, vertical pipe-like geometries and mineralization that is clearly post-lithification.

An important difference between the Kildare deposits and the mainstream Irish deposits is that they display quite different (non-bimodal) $\delta^{34}S$ isotopic signatures notably with no bacteriogenic sulphur. In addition, fluid inclusions show a single low temperature fluid of 45-70ºC at 12-17wt% NaCl equiv. – quite different from all other Irish-type deposits (Trude & Wilkinson, 2001).

The deposits also have textural and geological aspects indicating a later genetic relationship suggesting at least a post Holkerian age. Their proximity to a major Hercynian thrust structure (Kildare Inlier bounding fault) and late structures suggests a genetic relationship to early Brigantian (Variscan) thrust tectonics around 335-310Ma (Gallagher *et al*, 1992; Trude & Wilkinson, 2001), considerably later than the typical Irish deposits.

Wider Implications

During the Early Carboniferous (Courceyan – Arundian, 359.2 – 339.0 Ma), Ireland lay on the south-eastern margins of the Laurentian continent at a palaeolatitude of 4°S with the area of the Irish Midlands and northern England developing basins in response to back-arc stretching causing isotherm bunching and elevated heat flows.

In the early Carboniferous final subduction and closure of the Rhenohercynian Ocean, followed by accretion of a magmatic arc and docking of microcontinents in the Variscan Orogen, caused reactivation of older lineaments in the foreland. This resulted in extension and the formation of fault-controlled basins, such as the Dinantian basins in Britain and Ireland, and decompression melting of asthenospheric (deep) mantle sources by lithospheric stretching. The magmas thus generated ponded and fractionated at various crustal levels before intruding as high-level sills and erupting as generally mildly alkaline basaltic volcanics and more felsic differentiates. (Timmerman, 2004). Sm-Nd garnet dating of basement xenoliths included within these volcanics shows that the lower crust remained hot or was re-heated to ~600ºC at ~345Ma associated with extension and, in part, coincident with the mineralization (Daly *et al*. 2016) strongly suggesting that enhanced basement heat flow existed at this time.

Smit *et al* (2018) concluded that early Carboniferous extension takes into account well-constrained geometries of crustal structural elements and basin architecture. The Malvern Line and its continuation towards the Iapetus suture as well as the proto-North Sea Central Graben were major crustal-scale transcurrent faults that accommodated important rotations during early Carboniferous extension.

Basins to the west of the Malvern Line are parallel to the Iapetus suture, and extension was accompanied by a clockwise rotation of the London-Brabant massif and Midland micro-craton along the Malvern Line. Deformation was by SSW-SW directed dextral transtension west of the Malvern Line and rotational sinistral transtension east of it (Figure 5).

The emphasis on Chadian and younger faulting in Ireland also appears to be similar to the timing of tectonics in the British Carboniferous Basins.

In the Bowland Basin the lower part of the Bowland-Hodder unit comprises a thick, syn-rift, shale-dominated facies which passes laterally to age-equivalent limestones that were deposited over the adjacent highs and platforms. The presence of slumps, debris flows and gravity slides (Gawthorpe & Clemmey, 1985; Riley, 1993) are evidence for relatively steep slopes, which may have been the result of instability induced by tectonic activity. A combination of syn-depositional tectonics, fluctuating sea levels caused by extensive southern hemisphere glaciation at this time (Espeleta *et al.*, 2020) and evolution of the carbonate ramps/platforms surrounding the basin resulted in a variety of sediments being fed into the basin at different times. Localised breccias are present close to the basin-bounding faults (Smith *et al*. 1985, Arthurton *et al*. 1988). This lower unit is dated as late Chadian. Gawthorpe (1986, 1987) Leeder & Gawthorpe, (1987) have suggested that the Bowland Basin experienced two periods of tectonism during the late Chadian to early Arundian around 341 Ma largely contemporaneous with syn-rift fault movements in the Irish Midlands.

Lower Palaeozoic-hosted fault/vein Zn-Pb mineralization elsewhere in the British Isles such as in the Plynlimon Dome, Llanwrst, Isle of Man, Lake District and in the Southern Uplands of Scotland have returned lower Carboniferous ages in the range of 360-330 Ma and may thus be time equivalents of the Irish orefield (Fletcher *et al*., 1993; Haggerty *et al*., 1995).

Discussion & Conclusions

Over the past two decades there has been a trend to regard all Irish deposits as being epigenetic and to ignore evidence to the contrary such as fossil polychaete worm tubes and casts with affinities to *Paralvinella*, microbialite sulphide and silica mounds and clear sedimentary features such as sulphide talus mounds. There is no doubt that at least some mineralization occurred on or close to the seafloor (Russell, 1996). Dating from tuff horizons and implied sedimentation rates closely define the mineralizing time interval even for replacive mineralization. However, we know that carbonate sediments deposited quickly can remain not fully lithified for intervals greater than this time interval.

Large extensional fault systems initiated in the Courceyan controlled depositional patterns of the transgressive carbonate sequence and developed in the late Courceyan to early Chadian causing rapid basin margin gravitational degradation and subsidence. Within the basin, networks of smaller relay faults developed, often as rapid, catastrophic events, enabling hydrothermal fluids to enter the sedimenting basin. The nature of the sedimentation rate, level of egress of the fluids and the lithification state at that point largely controlled the style and process of the formation of the Zn-Pb mineralization. In simple terms the closer to the contemporaneous seafloor the larger the system as this allowed the interaction of bacterial sea-water sulphate reduction as an essential pre-requisite for large scale sulphide deposition.

Tynagh and Ballinalack are hosted in in knolls of Waulsortian mudbank located on the hangingwall of synsedimentarily active faults. At Tynagh the hangingwall sag hosting the Iron Formation shows development contemporaneous to fault activity and mineralization with clasts of mineralized Waulsortian seen in debris flows.

At Ballinalack Waulsortian knolls developed preferentially on the hangingwall of the Ballinalack Fault which appears to have been active during sedimentation in the Chadian.

At Ballinalack, Tynagh and Silvermines the sulphide mineralization is interpreted to have initiated very early in the diagenesis of the Waulsortian Mudbank (post stage 1 “Radiaxial Marine Fibrous Calcite” precipitation.) Cruise (2000) noted that haematization must have occurred prior to sulphide mineralization, that is, very early in the diagenesis.

At Tynagh and Silvermines extensive parts of the hangingwall succession are dominated by debris flows and slump units with included clasts of pre-existing mineralization (Figure 14a and 14d)

At Lisheen, palaeotopographic sags trending perpendicular to the main faults are infilled by the post-Waulsortian Crosspatrick Formation of early Chadian age. It can be interpreted that

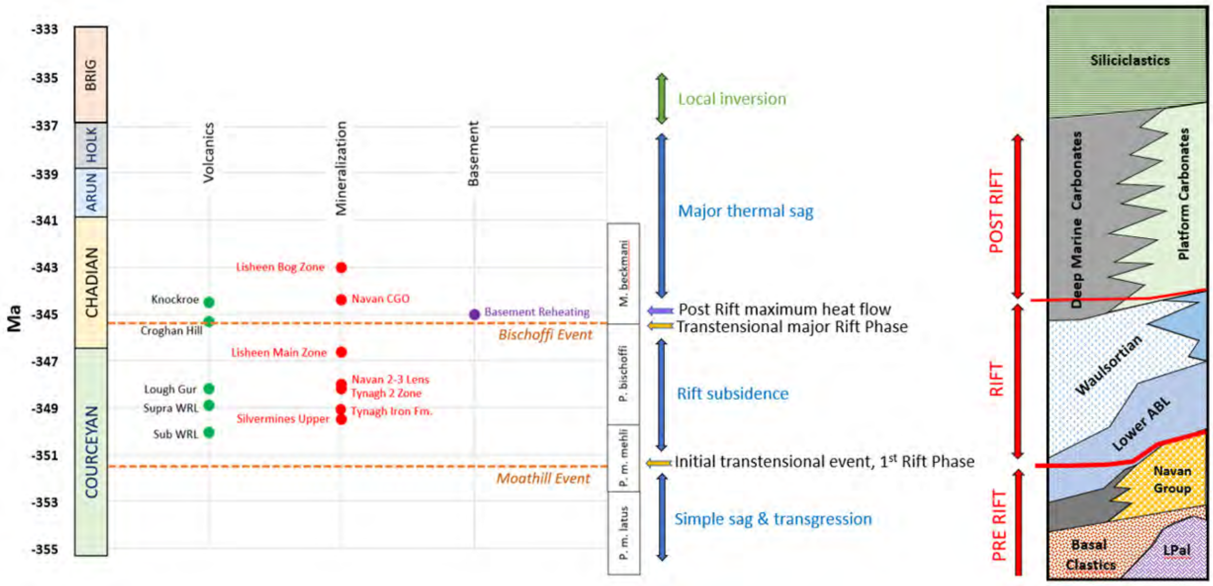

Figure 29: *Summary of the mineralizing event(s) in the Central Irish Orefield.*

dissolution and collapse of the dolomitized Waulsortian, and emplacement of the main base-metal mineralization had occurred prior to the deposition of the Crosspatrick.

An important conclusion is that at Lisheen the thickness of the Waulsortian equivalent is reduced above mineralization whereas at Silvermines the breccia sequence is thickened above mineralization indicative of the importance of active syn-sedimentary faulting, local subsidence and focussing of debris flows.

Evidence of rapid subsidence on the hangingwall side of the faults is also provided by the presence of debris flows and deeper water Waulsortian mudbank equivalent lithologies such as the so-called "Grey Calp" at Tynagh and Carn Park and shows rapid subsidence above the rate of coeval sedimentation.

Evidence from isopachous plots of various conodont biozones demonstrates reveals a parallelism of such isopachous contours to the marginal faults revealing that the onset of active subsidence commenced during the P. *mehli* biozone (the *"Moathill* event) and continued ephemerally to the *P. bischoffi* biozone (*the "Tober Colleen"* event). Such faults developed sporadically and initially as isolated segments which eventually coalesced into larger structures with time.

As described earlier the age of mineralization is now accurately defined by isotopic and geological parameters to average around 348.9 ± 3 Ma placing it astride the two events defined by the isopachous plots at ~351 Ma and ~346 Ma.

The depth at which mineralization took place can be constrained from several sources. At Navan, the unroofing of the system clearly constrains the depth of mineralization within the Pale Beds to less than 250m and at or near the seafloor for the Conglomerate Group Ore. At Silvermines the main orezones clearly show some synsedimentary fabrics and textures whilst the underlying epigenetic mineralization only extends to approximately 250m below the Upper Ore horizon. At Tynagh, the exhalite Iron Formation formed at or near the sediment-water interface and thus constrains the time equivalent mineralization within the Waulsortian bank to no more than 200m. At Lisheen and Galmoy the localization of the Crosspatrick Formation within a localized collapse basin above the mineralization implies that the sulphides were deposited at a depth of between 150 and 200m. Minor mineralization at Tatestown, Moyvoughly and Ballinalack (Navan Group) appears to have been emplaced at depths of between 300-500m and this greater depth appears to have constrained the size potential of the mineralization.

There is overwhelming evidence as to the timing of the development of the Irish Zn-Pb deposits based upon detailed evaluation of the host sedimentary package. Such data confirms unequivocally that mineralization must be relatively shallow between the sediment-water interface and a few hundred metres depth.

We know that micrites formed on tidal flats (Navan Micrite) and had hard grounds formed as exposure surfaces (Rizzi & Braithwaite, 1996). Equally Waulsortian micrites also appear to have lithified rapidly. Grainstones such as in the Navan Group and argillaceous limestones would lithify quite slowly allowing lateral migration of hydrothermal mineralizing solutions and replacement of sparry horizons such as oosparites. Within this layer-cake of lithified and partially lithified units' vertical permeability would be restricted and lateral replacement under such impermeable horizons would occur.

It would appear that the state of lithification (and thereby loss of permeability) by increasing burial depths restricted the potential for economic mineralization. Unroofing of the mineralizing system by basin margin collapse and footwall degradation at Navan would seem to be one of the key constraints as to why Navan became so large. Equally the "tightness" of the environment in terms of permeability, porosity and fracturing constrains the development of the mineralizing system and probably explains why "deeper" systems hosted in the Navan Group at Moyvoughly, Keel, Ballinalack and elsewhere did not develop into economic deposits as they lay at depths of between 350-400m of the contemporaneous seafloor. This advanced lithification coupled with a lack of bacteriogenic sulphur which is believed to be a fundamental aspect of the larger Zn-Pb deposits ensured that the "lower orezones" such as Silvermines and Lisheen within ABL units and at Keel and Ballinalack in the Navan Group could only have a restricted size.

Walshe *et al* (2018) demonstrated that faults can actively affect fluid flow by a variety of associated processes, including seismic pumping and pulsing, or can provide pathways for the upward flow of over-pressured fluids or the downward sinking of heavy brines. The sinking of dense brines and the rise of hot hydrothermal solutions are facilitated by the passive and active role of normal faults in the migration of fluids during the synrift and post-rift phases of basin evolution. The emergence of convective flow provides a sustainable flow system capable of generating mineral deposits, at least until crustal extension-related thermal and tectonic drivers decline and/or the source is depleted.

Schardt *et al* (2008) using heuristic mass calculations for heat and fluid flow have suggested that the ore grades and base-metal accumulation comparable to that of the Anaarraq deposit in the Red Dog District of Alaska (18 Mt at 18% Zn, 5.4% Pb, and 85 g/t Ag) can be predicted to have occurred within a time period of about 0.3Ma with around 20% depositional efficiency. Such a short time frame would appear to equate to that prevailing in the Irish Midlands for the likely time frame of mineralization.

Thus, having established that in the Irish Midlands mineralization clearly occurred as the sedimentary basin subsided from an open platform to a deepening marine basin within a transtensional tectonic setting. This situation mirrors many similar deposits around the world such as Dengjiashan (Ma *et al* 2007) and Gushfil (Konari *et al*, 2017 and the barite mineralization at Fancy Hill, Arkansas where Okita (1983) has described the occurrence of worm burrows and other bioturbation structures in sedimentary massive barite.

The Irish-type ore deposits can be viewed as intermediate between classic shale-hosted, deeper water SedEx ("CD") Zn-Pb deposits and platform carbonate-hosted MVT deposits in that they formed in a ramp environment beneath water depths of up to a couple of hundred meters; they formed at around the time of host-rock deposition to up to a few million years later; and they are hosted by carbonates within a carbonate-shale sequence deposited in an incipient rift environment with active synsedimentary faulting.

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