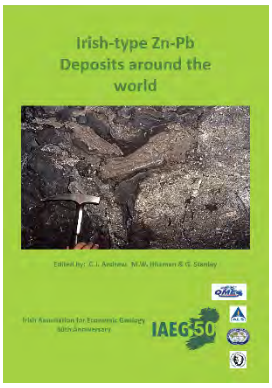

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The Rathdowney Trend, Ireland: Geological evolution and controls on Zn-Pb mineralization

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The Rathdowney Trend, Ireland: Geological evolution and controls on Zn-Pb mineralization

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Abstract: The Rathdowney Trend in south-central Ireland, is a NE-SW trend of fault-controlled Zn-Pb deposits that includes the Galmoy and Lisheen orebodies. The deposits are broadly stratabound and flat-lying occurring at or near the base of the Waulsortian Limestone Formation - a 200m thick massive biomicrite that is regionally dolomitised. The ore is largely developed by replacement of a dark, hydrothermal dolomite and dolomitic breccia - the black matrix breccia that is intimately associated with the mineralization event. Faulting exerts a major control on the ore thickness and distribution. The largest structures provided conduits for hot, metal-bearing fluids from basement to enter the Waulsortian at discrete feeder zones. Metal distribution patterns indicate that fluids progressed northwards from these feeder zones, facilitated by a network of small-displacement, low-angle extensional structures developed at the base Waulsortian contact with the underlying Ballysteen Formation. Significant dissolution of carbonate by hydrothermal fluids was important in developing conduits and promoting fluid flow. Fluid inclusion and isotope studies indicate that mineralization resulted from the mixing of hot, metal-bearing fluids with colder, saline fluids bearing sulphur derived from the bacteriogenic reduction of Carboniferous seawater sulphate. Mineralization developed during growth of the fault systems associated with basin development. Hydrothermal activity initiated shortly after rifting commenced during mid to late-Waulsortian sedimentation.

Keywords: Rathdowney Trend, Galmoy, Lisheen, Rapla, structural controls, breccias, timing of mineralization.

Introduction

The Rathdowney Trend is a NE-SW trend of mineral deposits with similar geology that includes the orebodies of the Lisheen and Galmoy deposits, and a number of other smaller prospects including Rapla. It is located in the south Irish midlands in the north of counties Tipperary and Kilkenny and in southern Co Laois (Fig. 1). All the deposits are developed within Mississippian carbonate rocks. The location of mineralization is strongly controlled by normal fault segments, each part of an en-echelon fault array trend that defines the Rathdowney trend (Fig. 2). This fault array is sited above a NE-SW trending basement lineament that is identified in various geophysical surveys (Johnston *et al.*, 1996; O'Reilly *et al*., 1999). This lineament extends for tens of kilometres to the southwest and northeast where it possibly also underlies and controls the location of the Gortdrum deposit in Co Limerick and the Derrykearn deposit in Co Laois.

The exact extent of the Rathdowney trend is not well defined, and many may consider it to include all faults and deposits sited on the full extent of the basement lineament. In this paper however, an approximately 45km strike length portion of trend, from the towns of Thurles, Co Tipperary to Abbeyleix in Co Laois, that includes the Lisheen, Galmoy and Rapla deposits will be discussed (Fig. 2). These deposits share similar stratigraphy, structure and mineral genesis and are, therefore, discussed collectively. There are, however, subtle but important differences that provide insights into ore genesis that may have had a bearing on deposit size and ultimately economics.

There has been much debate on the genesis of the Rathdowney Trend deposits since their discovery and in particular, how they fit in with our understanding of other Irish Zn-Pb deposits. Observations during twenty years of mining together with extensive petrological and analytical research over that time have elucidated many key model parameters such as: timing; the source of the metals and the sulphur, and the nature of the fluids, their conduits and what drives them.

While there is still further research required on some parameters, this contribution presents an integrated interpretation of several aspects of the evolution of mineralized systems in the

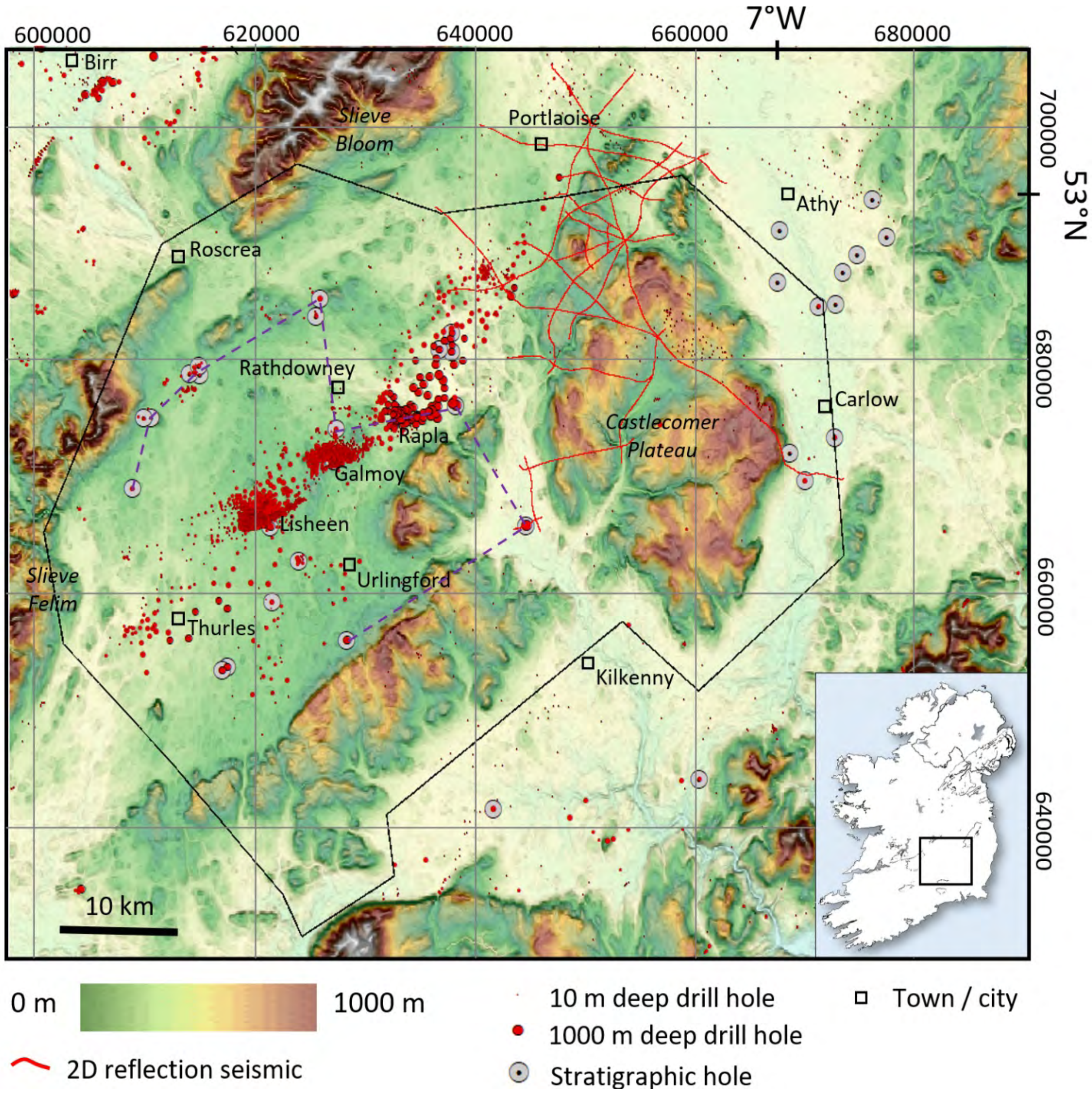


Figure 1: *Overview map of the study area. The background map is a slope-shaded topography using Shuttle Radar Topography Mission data at 1 arcsec resolution. The position of 2D reflection seismic lines is taken from the Geoscience Regulation Office. Drillholes used in the model are shown in red, with each point scaled by their total length. Stratigraphic boreholes are shown in grey circles with black dots. The area outlined in the black polygon represents the area of the 3D subsurface model of the base Waulsortian Fm. Dashed purple line outlines the lithostratigraphic borehole correlation section.*

Rathdowney trend, and how it relates to development of stratigraphy and its structural evolution. We will first provide an overview of lithostratigraphy and structural evolution in the Rathdowney trend, followed by an overview of pertinent observations of diagenetic and authigenic phases, including mineralization. We also discuss timing of these phases with respect to tectonostratigraphic evolution, and factors controlling their distribution and broader metallogenesis.

Summary of discovery and mining

The Galmoy orebody was discovered in 1986 by drilling a chargeability anomaly in an area of known anomalous soil geochemistry (Doyle et al., 1992). Mining commenced in 1997 and by the time mining ceased in 2012 a total resource of 10Mt @ 12.8 Zn and 1.3% Pb had been defined. The discovery of the Lisheen orebody in 1990 followed the Galmoy discovery using geological deduction, soil geochemistry and to a lesser extent geophysics (Hitzman *et al*., 1992). Mining of the resource (23Mt @ 13.3% Zn and 2.3% Pb) began in 1999 and ceased in 2015. Both Galmoy and Lisheen mines were relatively shallow at an average depth of 100m and 180m respectively. The deeper, c. 550m, Rapla prospect was discovered by Ennex International in 1983 and subsequently added to by

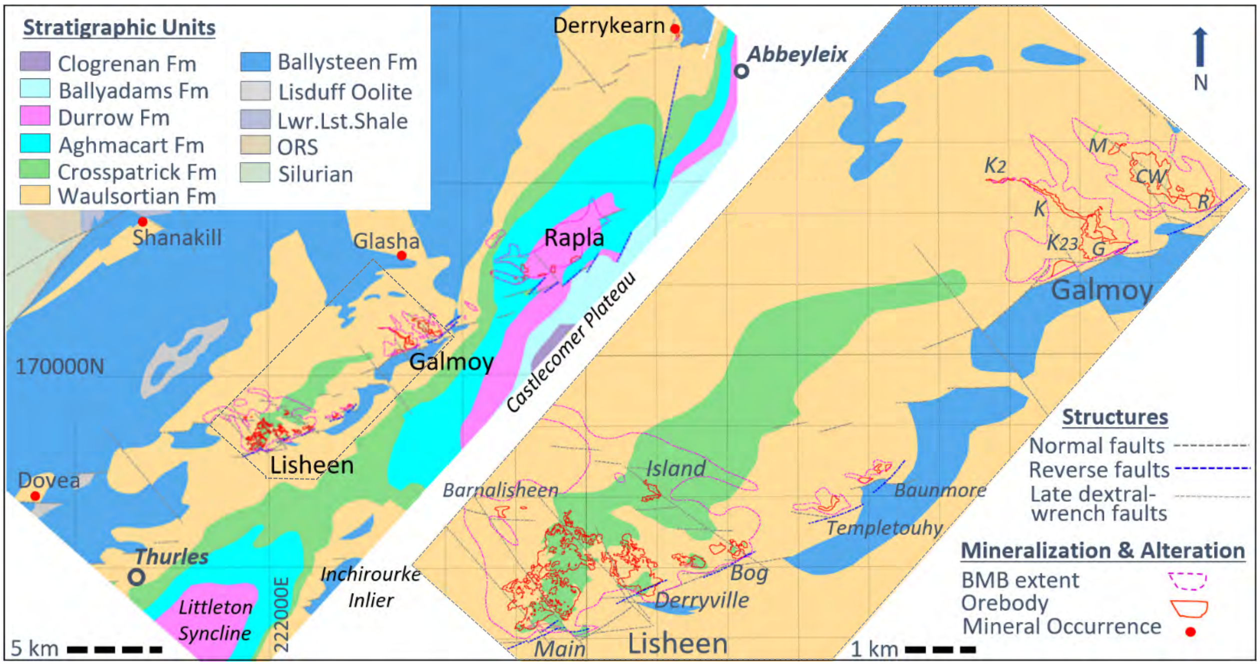


Figure 2: *Simplified geological map of the Rathdowney Trend with the normal fault array that controls the location of deposits. Detail of the Lisheen - Galmoy area showing the various ore zones that comprise each deposit.*

Arcon Mining in 2000. Although further drilling by Vedanta in 2014 identified additional mineralized pods the scale of mineralization was deemed insufficient to warrant mining at this depth. No formal resource was compiled but an approximate estimate would be 3-5 million tonnes at approx. 10% Zn+Pb combined.

Regional Geology

The Rathdowney Trend sits within a sequence of Mississippian carbonate rocks that outcrop in a NE-SW belt between the Lower Palaeozoic inliers of the Slieve Felim and Slieve Bloom mountains, to the northwest and the Castlecomer outlier – a Serpukhovian to Bashkirian series of sandstones, siltstones, shales and coal seams to the southeast (Figs. 1 & 2).

Figure 4 presents the results of regional 3D geological modelling of the depth of the top Ballysteen Fm / Base Waulsortian Limestone Fm surface. This work was underpinned by public and proprietary onshore 2D reflection seismic, mapping data, drillhole datasets, micropalaeontological data, and associated aeromagnetic, electromagnetic, and ground gravity interpretations (data shown in Fig 1.; Torremans et al., 2020a; 2020b). The rocks dip gently to the southeast on the limb of a large regional fold that plunges gently to the northeast (Fig. 4). On the north-western flank of the belt the Mississippian stratigraphy is eroded to a level below the stratigraphic ore target horizon, which conversely, towards the southeast flank, becomes increasingly buried under younger rocks (Fig. 4).

For this reason, exploration and drilling has been mainly concentrated within the '*goldilocks zone*' where the ore target is present but not at great depth. This includes the areas around and between the Lisheen, Galmoy deposits and, to a lesser extent, the Rapla prospect where extensive drilling, geophysical, geochemical and underground-mapping data is available. Considerable geological uncertainty remains however, over large areas of the trend where there is a paucity of drilling and generally poor outcrop exposure (Fig. 1).

Stratigraphy

The stratigraphy of the Lisheen and Galmoy mine areas is presented in Hitzman *et al*., (1992) and Doyle *et al*. (1992) respectively. Figure 5 shows a lithostratigraphic correlation section across the Rathdowney Trend, based on a more recent and detailed description that covers the whole Trend presented by Doyle (2022) building on prior descriptions by Philcox (1984), and incorporating observations by others (e.g., Sevastopulo & Redmond, 1999; Somerville *et al*., 2011).

Sub-Waulsortian stratigraphy

The Carboniferous succession begins with c.220-250m of variable, fluviatile, red-bed and yellow siliciclastics of Courceyan age that lie unconformably on tectonised Silurian metasedimentary rocks. These are conformably overlain by the Lower Limestone Shales – a group of formations that together record a transgression to marine shelf conditions (Fig. 5). This includes: the Mellon House beds (c. 30-40m) – a marine influenced siliciclastic sequence (McConnell & Philcox, 1994); the Ringmoylan Shale (c. 35-45m) – a thinly inter-bedded sequence of marine silts and shales with thin bioclastic limestone beds (Philcox, 1984); the Ballyvergin Shale (c. 6m) – dark-grey, interlaminated non-calcareous, mudstone and siltstones which is believed to represent a unique and short-lived depositional event unrelated to volcanism (Clayton *et al*., 1980; James, 2004) and the Ballymartin Formation (c. 30m) – an argillaceous shallow shelf bioclastic carbonate with thick shale beds (*sensu* Somerville & Jones, 1985).

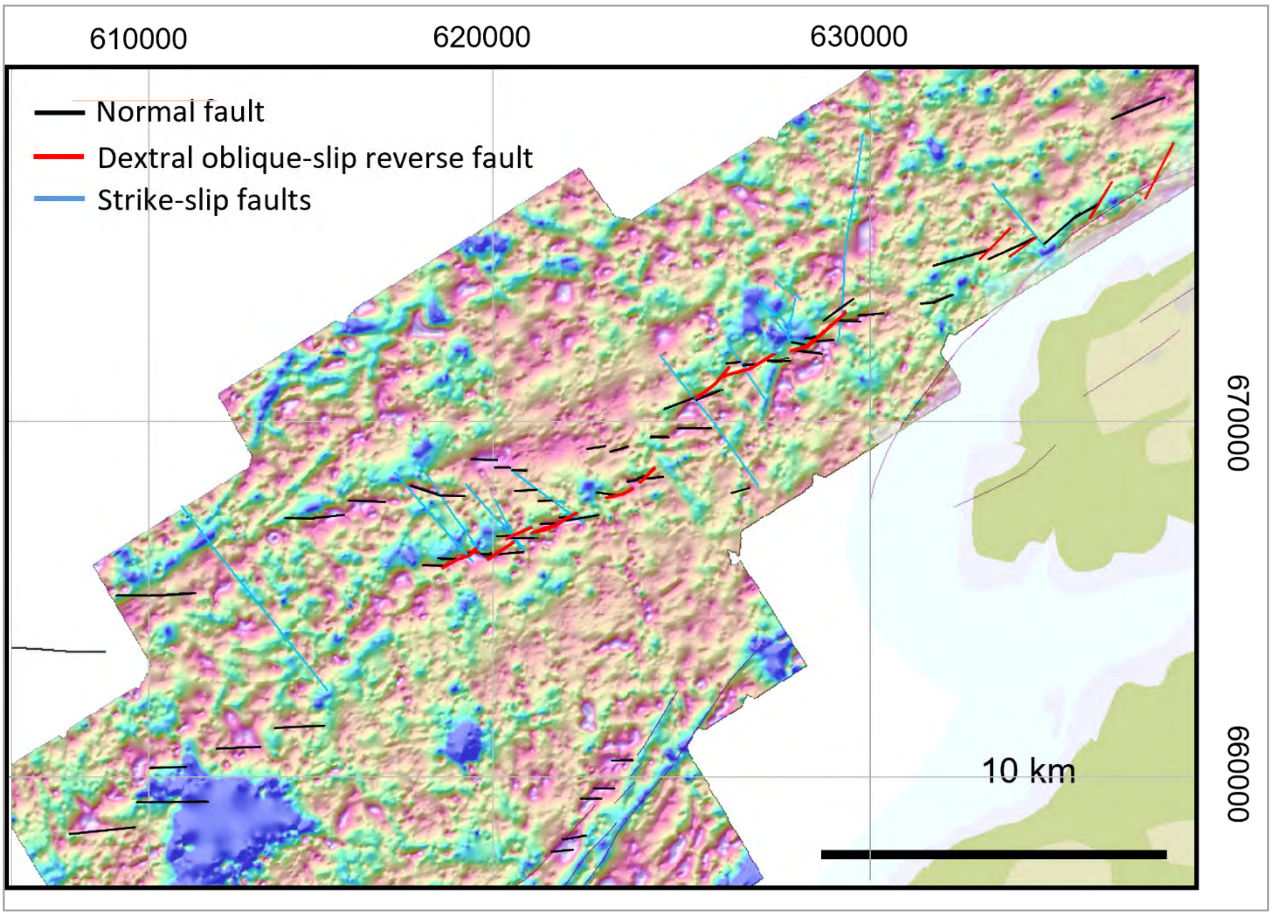


Figure 3: *Third order residual magnetic intensity image removing deep sources of the Minorco Lisheen Ltd airborne magnetic survey (1997) over the Rathdowney area. This was flown at line spacing of 100m at 147 degrees at terrain clearance of 80m, using a Geometrics G-822A Cesium Vapour magnetometer with a sensitivity of 0.001nT and sample rate of 10 samples/sec. Image has an amplitude range of 4 nT between blue (low) and red (high). The independently picked and modelled (from boreholes) Mississippian normal faults, Variscan oblique-slip reverse faults and later strike-slip faults are plotted in different colours on top of the magnetic survey, showing the excellent correlation between both for normal faults and reverse faults.*

This is followed by the Ballysteen formation (commonly referred to as the Argillaceous Bioclastic Limestone or ABL) which exhibits quite variable thicknesses across the trend (Fig. 5; Doyle, 2022). The thickest unfaulted intersection from a borehole at Galmoy is c. 392m. The formation contains a 70-80m thick oolitic member, the Lisduff Oolite Member, which divides the Ballysteen into upper and lower divisions. The Lower Ballysteen (c. 150-220m) is composed of thick, uniform beds of argillaceous limestone with thin shale interbeds (Fig. 5). The Upper Ballysteen (c. 120-130m) consists of moderately argillaceous bioclastic limestone becoming very argillaceous in the upper half.

The Lisduff Oolite consists mainly of pale grey, variably oolitic calcarenites. At Lisheen the Lisduff Oolite contains two thin c. 5-10m thick argillaceous units, similar to those in the Upper Ballysteen, that can be mapped across the mine area, but these units do not extend to Galmoy. These interbedded units can make identification of the true top and bottom contacts of the Lisduff Oolite difficult when only partial borehole intersections are available or when the oolite is heavily faulted.

The Waulsortian Limestone Formation

Towards the top of the Upper Ballysteen individual beds become thinner, more laterally impersistent and lithologically variable. Lenticular beds of shale, clean calcarenite and encrinite up 30cm thick can all occur together and pass laterally to variably argillaceous, nodular micrites. This uppermost unit of the Ballysteen – the Ballynash Member or 'Nodular Micrite Unit', likely represents the onset of Waulsortian bioherm, as precursors to micritic mud-mound development occurring elsewhere laterally (Devuyst & Lees, 2001). These contain numerous clotted or peloidal carbonate muds (similar to the prebank precursor muds in Devuyst & Lees, 2001). A very thin, (typically 0.5cm but up to 4cm thick) green, bentonitic tuff horizon is sometimes preserved within this unit, or sometimes within units more akin to, and logged as Waulsortian facies (cf. Koch, 2021; Koch *et al*., 2022). Its presence within different units indicates that the lithological contact of the Ballysteen and Waulsortian is diachronous. The presence of the Green Tuff in Waulsortian transition facies at the Island Pod indicates

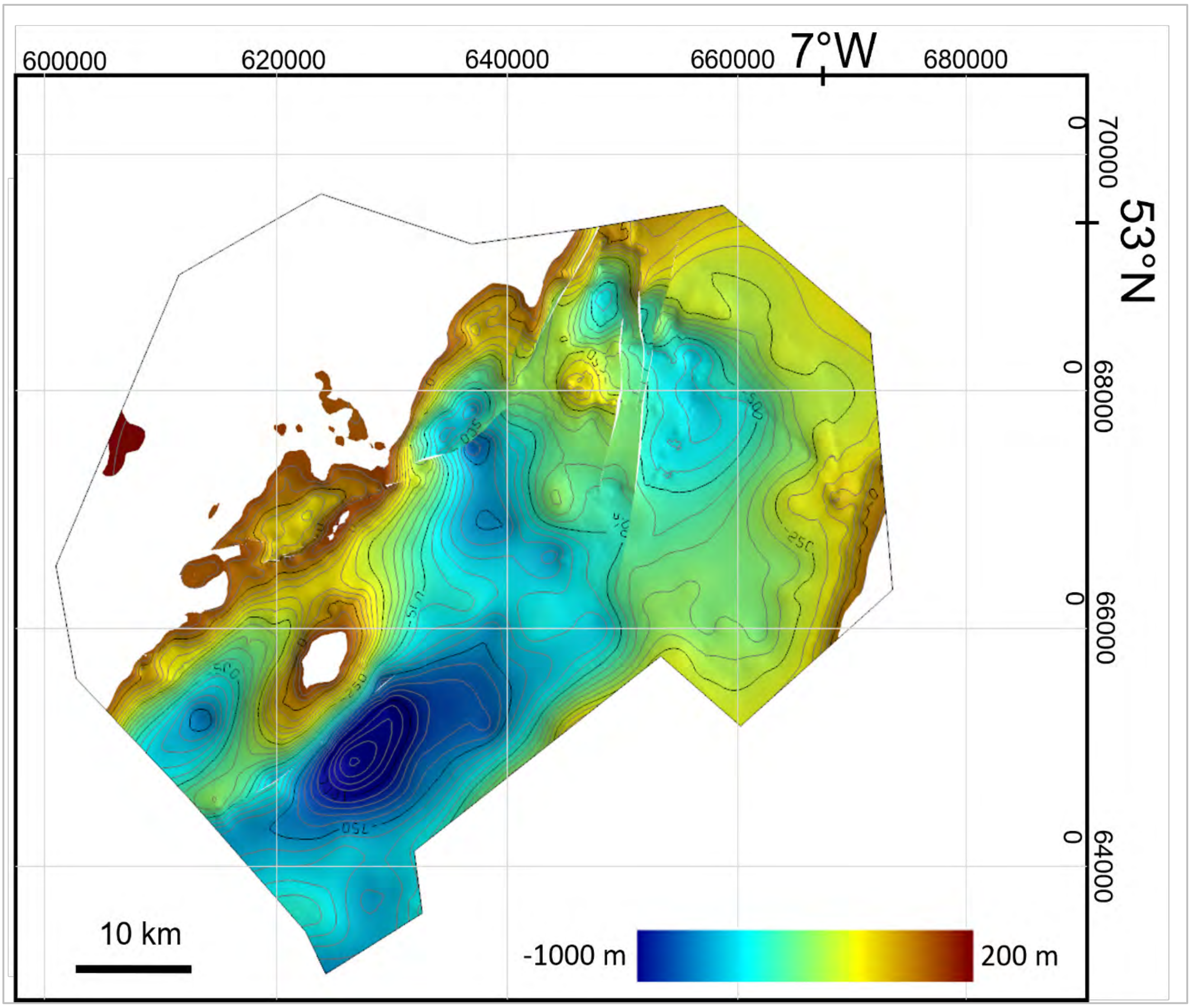


Figure 4: *Map showing the elevation of the top Ballysteen Formation / base Waulsortian Formation within the study area in SE Ireland, relative to sea level (Malin Head). The surface is crosscut by myriad complexly segmented normal faults through this level of the stratigraphy. The 3D model underpinning this map was made using public and proprietary onshore 2D reflection seismic, mapping, drillhole, micropalaeontological, aeromagnetic, electromagnetic, and ground gravity data.*

that Waulsortian development began earlier here than elsewhere and may partially explain the thicker Waulsortian development here and along the northern flank of the trend (c. 200m; explored further in Doyle, 2022). Further south, near Urlingford, the Waulsortian is typically thinner (c. 150m).

The facies transition from Ballysteen to the Waulsortian is extremely location specific and variable laterally (Devuyst & Lees, 2001). Locally slumping has occurred where biohermal massive micrites have developed out over flank facies shales resulting in instability and collapse of large micritic blocks into the intra-mound area where they may be draped by argillitic sedimentation (cf. Lees & Miller, 1995; Somerville, 2003).

The contact zone between the Ballysteen and the overlying Waulsortian Limestone is of particular importance as it is the position of the vast majority of mineralization. Its lithological complexity has had a profound influence on fluid flow and structural development at the base of the Waulsortian and by extension, on the mineralization itself.

In the Rathdowney Trend, the Waulsortian developed as a complex of many individual mudbanks and mounds that a stacked to form a thick sheet of Waulsortian Limestone. The mudbank consists of a massive core of micrite and bryozoa in which a number of facies are recognised including the characteristic stromatactis cavities and veines bleues – a fenestellid bryozoa encrusted with many generations of fibrous spar. The wavy-laminated facies are a flank and inter-mound facies consisting of micritic muds with argillaceous laminae and sometimes bioclastic debris, usually crinoidal, both between and as a cover facies to the mounds.

As the Waulsortian bioherm development progresses, argillitic input is greatly diminished. It has also been suggested that the reduced argillite content may be due to greatly increased carbonate production, although a combination of both are likely operating. In some areas along the trend argillitic input was periodically more significant and here 'reef equivalent' facies developed that in appearance are similar to the nodular micrites of the Ballysteen. These developments within the Waulsortian

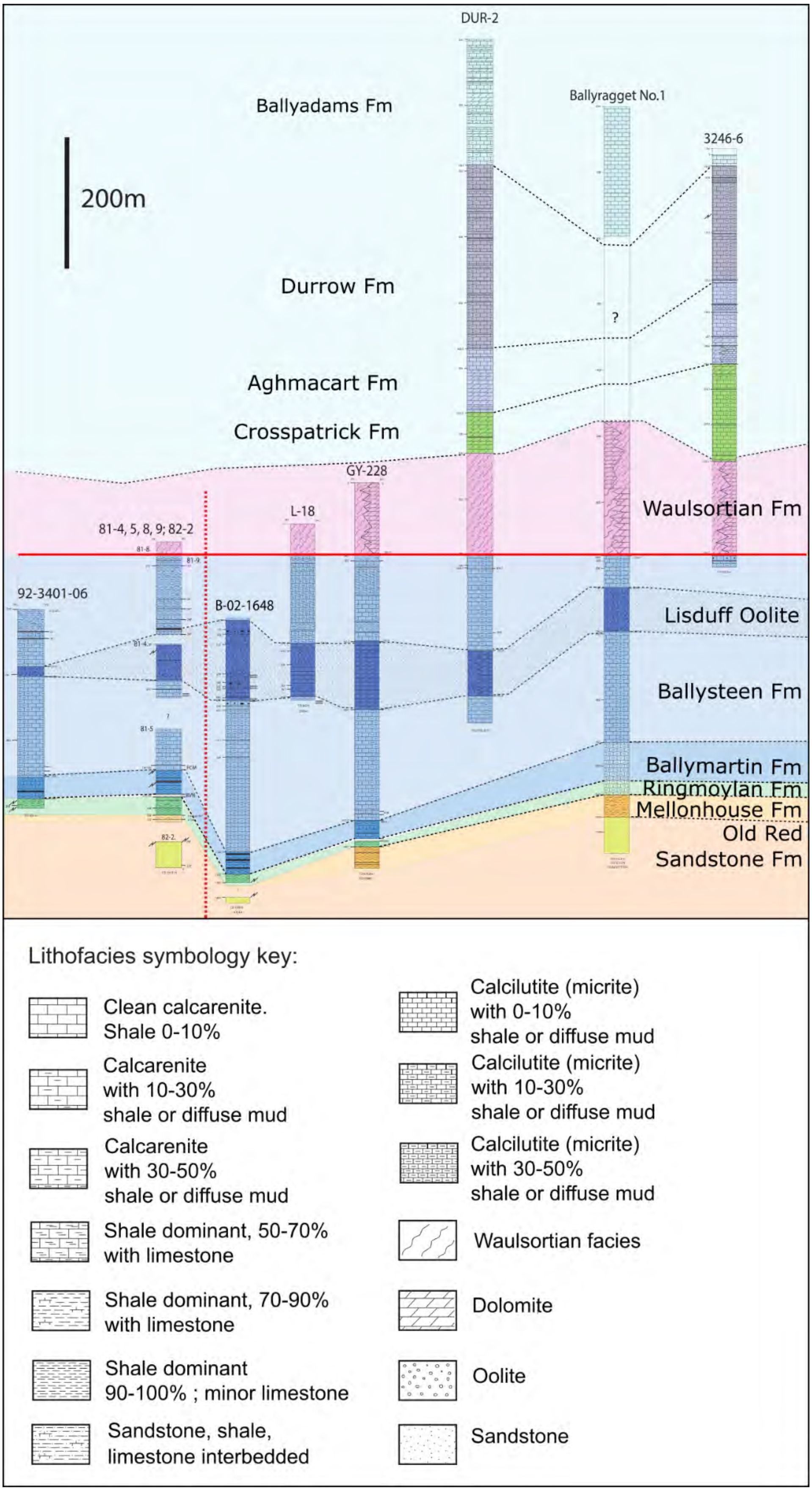


Figure 5: *Lithostratigraphic correlation across the Rathdowney trend. Locations of the boreholes are shown in Fig. 1.*

are typically 5-10m thick and are more commonly encountered higher up in the formation, particularly to the east and north of the trend. To the southwest of Thurles town, however, there is no biohermal development and only equivalent facies is developed (Sevastopulo & Wyse-Jackson, 2009; Dunlevy *et al*., in press).

Towards the top of the Waulsortian the core facies become subdued and the relative argillitic, fine carbonate and bioclastic component increases resulting in a return to the development of a more variable facies. At Lisheen, where there is good borehole control, the wavy laminated facies become more abundant and laterally persistent forming a cover facies. Bedded, units with affinity to the overlying Crosspatrick Formation are locally developed within the Waulsortian. The cessation of the Waulsortian development appears to have been a gradual process as bioherm development becomes increasingly restricted and eventually ceases. The top Waulsortian lithological contact with the Crosspatrick is therefore a transition zone that is both irregular and diachronous. Waulsortian facies within the transition zone may be variably rich in chert nodules – a feature that is ubiquitous in the lower part of the Crosspatrick.

Supra Waulsortian stratigraphy

The stratigraphy above the Waulsortian Formation is shown in Figure 5 (based on Doyle, 2022). Recently, a baseline geochemical was established for stratigraphy of the Rathdowney Trend, which derived a heuristic methodology for chemical classification of units, which is of particular use in units in these upper parts of the stratigraphy (Turner *et al.*, 2019). The Lower Visean Crosspatrick Formation has variable thicknesses from 150 to 220m. It consists of pale to dark grey, fine calcarenites and calcisiltites (ranging from wackstones to grainstones) with abundant fine crinoid bioclasts (Nagy, 2003; Gatley *et al*. 2005). It also contains chert nodules which are more abundant at lower levels.

The proceeding Lower Visean to Arundian Aghmacart Formation begins with a thick (c. 16m) oolitic grainstone, the Basal Grainstone Unit, that can be mapped across the Rapla area and heralds the onset of shallow-water conditions (Nagy, 2003; Gatley *et al*. 2005). The rest of the formation (c. 250m in the Rapla area) is a varied succession that includes shales, oncolites, birds-eye micrite and oolite (Nagy *et al.,* 2003). The overlying Arundian to Asbian, Durrow Formation (c. 220m at Rapla), consists of a varied succession of clean calcarenites and finer, more argillaceous limestones, locally with common colonial corals, and minor argillaceous micrite (Nagy, 2003; Nagy *et al*., 2004, 2005; Somerville *et al*., 2011).

This then followed by the Asbian, Ballyadams Formation (>300m) which consists mainly of thick-bedded, shallow-water peloidal, crinoidal and algal grainstones (Cozar & Somerville, 2005; Somerville & Cozar, 2005). This is the youngest unit preserved at Rapla area where c. 200m has been drilled (Fig. 5).

Further to the east the overlying Asbian – Brigantian, Clogrenan Formation (c. 100m) is preserved and consists of well bedded, shallow-water limestones with common chert. This is the last carbonate formation before a return to siliciclastic sedimentation of the Castlecomer Plateau.

Structural evolution

The Rathdowney Trend is defined by Mississippian extensional structures that control the location of mineralization at Lisheen, Galmoy and Rapla (Figs. 2, 3 & 6). Two additional structural features followed these structures, namely, various types of structures related to compressional deformation during the Variscan Orogeny, and a transtensional event that has been attributed to N–S Alpine shortening accommodated by sinistral displacements on older NE-striking Carboniferous normal faults and the widespread development of smaller NNW trending dextral strike-slip faults leading to the opening of the Atlantic (Cooper *et al.*, 2012; Anderson *et al*., 2018). How these structures developed and are expressed at Lisheen is described in detail in Kyne *et al*. (2019). The same tectonic regime described there is common to other deposits along the Rathdowney Trend.

East-Northeast trending extensional faults

North-south extension during the Lower-Visean and possibly as early as the late Ivorian, resulted in the development of many small, east-west trending, faults segments with displacements in the order of 5-15m (mapped out in Figs. 2 & 3; building on Hitzman *et al*., 1999; Hitzman *et al*., 2002; Kyne *et al*., 2019). These faults mainly dip to the north but some dip to the south thereby generating small grabens (Figs. 2 & 4). The main Rathdowney Trend fault system corresponds with clear changes in the Bouguer anomaly ground gravity, with steep horizontal gradients in northeast-southwest trending lineament broadly aligning with the Trend (Johnston *et al.*, 1996; O'Reilly *et al*., 1999). This has been interpreted to represent changes in underlying Caledonian geology, possibly delineated by structures, and the subtle changes observed in the trend of the lineaments may reflect interacting basement fault trends or local variation in fault zones (Johnston *et al.*, 1996; O' Reilly *et al*., 1999; Kyne *et al*., 2019).

Initially, many ENE trending structures were generated (e.g., Fig. 6), however, as extension progressed, displacement became confined to fewer structures and ultimately to one main fault array that accommodates the vast majority of the total c. 160-220m of displacement (Kyne *et al.*, 2019). This array forms an east-northeast trending, left-stepping, *en-echelon* fault trend with individual fault segments trending east-west and typically dipping at c.50° to the north. The array exhibits classic ramp-relay geometries where fault segments are separated by structural ramps (Fig. 6; Camanni *et al*., 2019). In these ramp zones tensional stress between the fault segments is accommodated by bedding flexure (Roche *et al*., 2021). The structural integrity of these ramp zones is a function of displacement and the distance between segments (Childs *et al.*, 2009). As displacement is fairly constant along the Rathdowney Trend, the structural integrity of ramp zones is largely determined by fault separation. This is variable along the trend; from large intact ramp zones between the deposits, to variably faulted ramp zones between the individual fault-controlled ore zones of each deposit.

There is very little data to the east of Rapla with which to constrain the continuation of the extensional fault array. Drilling near Durrow has intersected structures and indicated displacement based on stratigraphic thicknesses of syn-rift formations.

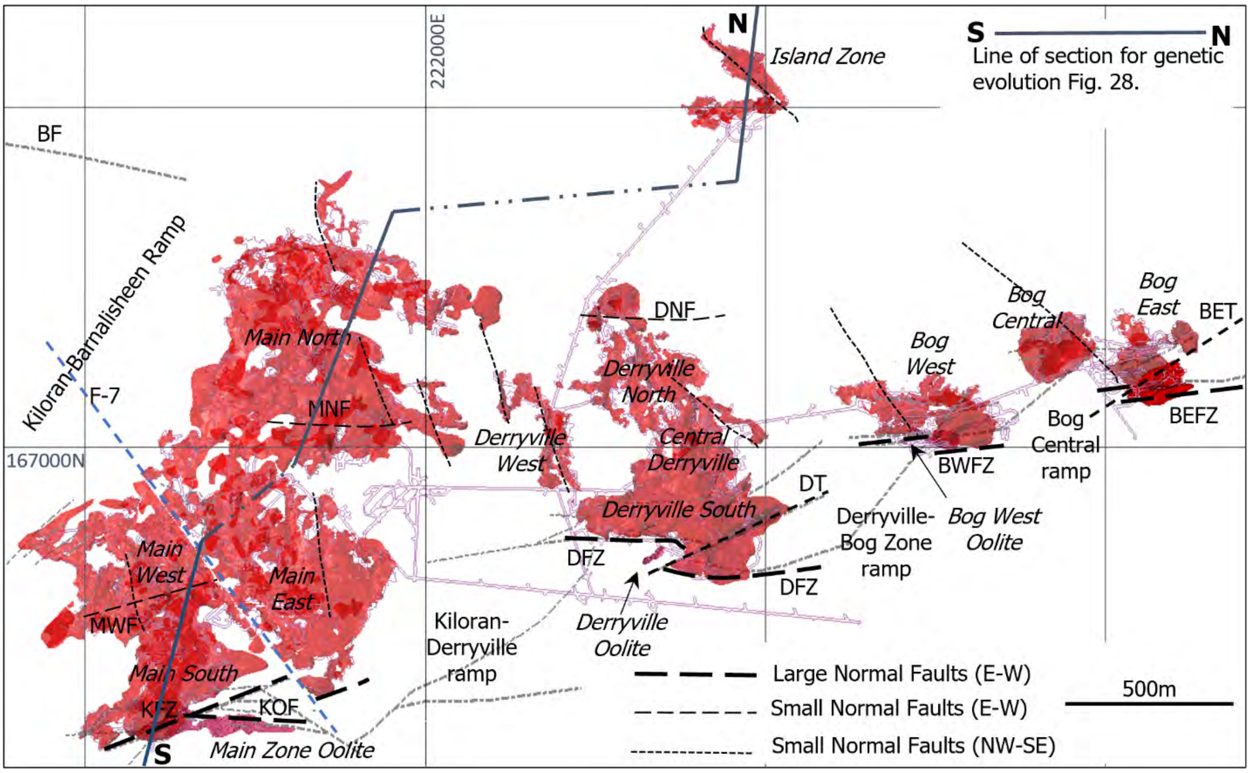


Figure 6: *The Lisheen orebodies with location of ore zones and structures mentioned in the text. (Large ore –controlling faults: BF- Barnalisheen Fault, BEFZ-Bog East Fault Zone, BWFZ- Bog West Fault Zone, DFZ- Derryville Fault Zone, KFZ- Kiloran Fault Zone (inverted), KOF- Kiloran Fault oolite segment. Smaller extensional faults: MNF- Main North Fault, MWF- Main west Fault (south dipping), DNF- Derryville North Fault. Thrusts: BET-Bog East Thrust, DT- Derryville Thrust, DFZ-Derryville Fault Zone.*

Complications related to reverse faults here make the structural picture very uncertain, however. To the southwest of Lisheen the trend, which has been consistently left-stepping to this point, steps to the right to the Barnalisheen fault to the northwest. The broad, east-south-easterly dipping Kiloran-Barnalisheen Ramp, that bounds the western flank of the Main Zone mineralization at Lisheen, is developed between the two and relays the displacement (Fig. 6). The geometry of the Barnalisheen fault is more of a faulted monocline but, based on sparce drilling, may become more fault-like as it trends further west.

Further southwest, the array is identified again at Dovea where there is a small preservation of mineralized Waulsortian bounded to the south by a normal fault (Fig. 2). South of this near Thurles town, hydrothermal breccias have been drilled although these may possibly be on a separate but parallel trend. There is insufficient data further to the southwest with which to establish the continuation of the fault trend. Here the Waulsortian is not developed and instead replaced by equivalent facies of seeming little exploration interest.

Other normal fault trends paralleling the Rathdowney Trend

There is evidence of some faulting to the south where the northern margin of the Inchirourke inlier is at least partially fault controlled (Figs. 2 & 3). There is insufficient drilling along strike of this however, to determine if these are part of a larger trend. To the north, the Waulsortian is largely eroded and consequently has received little exploration attention. At Shanakill, some 14km northwest of Lisheen however, zinc and lead mineralization is encountered, hosted within both the Waulsortian and Lisduff Oolite that are in fault juxtaposition (Fig. 2). There is also fault controlled mineralization to the north of Galmoy at Glasha (Fig. 2). Both these occurrences are unlikely to be on the same trend but offer strong evidence for the existence of parallel trends that may, as at Shanakill, have displacements comparable to that of the main Rathdowney fault array.

Base of Waulsortian extensional structures

A complex network of low-angle, small displacement structures is seen at the contact between the Waulsortian and the Ballysteen below (Fig. 7). Figure 8 shows several examples of these structures, locally truncating Ballysteen beds at the contact with the Waulsortian Formation. These structures exhibit a huge variability in trend and dip as they are strongly influenced by facies variability at the contact. They only extend a few meters into the Ballysteen where they truncate bedding at very low angles and eventually sole off into bedding (Fig. 8A and B). They are typically associated with calcite veins and thin gouges (Fig. 8D). It is difficult to determine how these structures are expressed up-dip in the Waulsortian as these are completely mineralized or have been lost to dissolution processes, or both (Fig. 8A to C). These structures likely formed due to

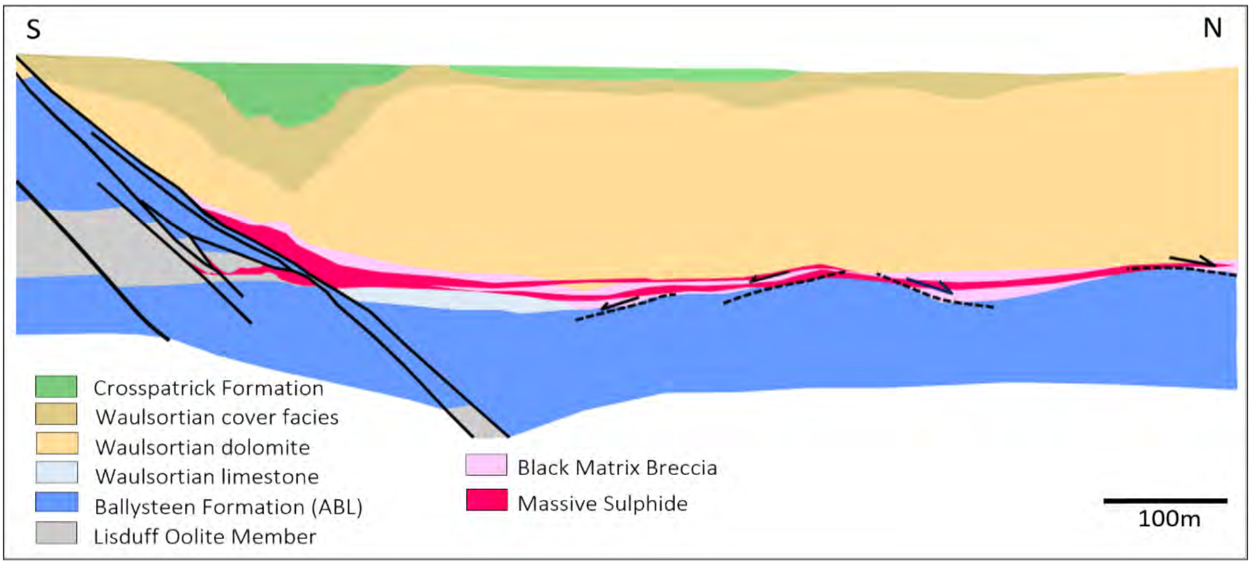


***Figure 7**: Schematic cross-section through the ore-controlling faults at Main Zone, Lisheen. Small-displacement, low-angled faults are widely distributed along the contact.*

an inherently different response to extension between the bedded argillaceous Ballysteen and the massive Waulsortian dolomitised biomicrites (cf. Camanni *et al*., 2019; Delogkos *et al*., 2022).

Northwest-Southeast extensional fault arrays

An important feature of the extension at the Rathdowney Trend is the development of narrow, low-displacement northwest-southeast trending fault arrays (not to be confused with the NW trending strike-slip faults described in section 4.6; Torremans *et al*., 2018; Kyne *et al*., 2019). These consist of short, left-stepping, en-echelon fault segments individually orientated north-northwest to north-south. They have very small displacements typically <10m and can dip both west and east. It is difficult to establish their original dip as many of these structures have been the focus of folding during later inversion. In both Galmoy and Lisheen these faults are important conduits for zinc-rich mineralization – the K-Zone at Galmoy and the Derryville West Zone at Lisheen being two good examples (Figs. 2 & 6). In the latter example, sphalerite veins associated with the extension suggest coeval zinc mineralization (Fig. 8C and D). This trend can be difficult to identify from drilling alone especially where they overlap mineralized, east-west trending structures but they are readily discernible through underground mapping. The overall northwest development of the Galmoy orebodies out from the main east-northeast trend to the south has likely been accommodated by these structures (Fig. 2). The origin of the northwest-southeast extensional fault trends is not certain but is most likely related to the same extensional episode as the east-west faults (Kyne *et al*., 2019). One possibility is that they developed late in the extensional episode when displacement was sufficient for conjugate arrays to form that relayed stress from one major east-northeast fault array to a possible parallel trend to the north. The significant heterogeneity within the mechanical stratigraphy and the interbedded nature of the sequence, could easily lead to generation of low-angle subsidiary structures in and near relay zones, relating to the variability in the amount of slip and bed rotation that can be achieved in argillite versus cleaner limestone beds (e.g. Bonson *et al*., 2007; Long & Imber, 2012; Mercuri *et al*., 2020; Roche *et al*., 2021; Delogkos *et al*., 2022).

Variscan Compression

The Rathdowney Trend experienced generally north-south oriented Variscan compression at the end of the Carboniferous to mid Permian (Graham *et al*., 2009; Woodcock & Strachan, 2009). This compression is expressed at different scales across the trend, ranging from bedding-parallel slip, through inversion of the existing normal fault architecture, to newly generated bespoke reverse faults. It is most prominently expressed as localised inversion on pre-existing extensional structures (Figs. 2 & 3).

The type of Variscan inversion depends on the orientation and nature of the pre-existing normal fault array (Kyne *et al*., 2019). The largest scale compressional structures are developed on the main extensional fault segments, either by dextral oblique-slip on existing fault segments (e.g. Kiloran fault at Lisheen, (Fig. 6 & 24A) or by new reverse faults localized on and offsetting normal faults (see example at Bog Zone in Fig. 9A). These inversion-related faults focussed on fault plane irregularities such as breached ramp zones related to normal fault development (Torremans *et al*., 2018; Kyne *et al.*, 2019; Walsh *et al.*, 2019).

Faults that are developed in structural ramps have also been inverted. At the R-Zone, Galmoy, the main reverse displacement is to the south of the main normal displacement where it likely reactivated a ramp fault developed there. Since these normal faults had generally small displacements of probably less than 20m to begin with, this structure has present-day net-reverse displacement.

Most of the deformation associated with inversion is seen in the immediate hanging-wall of the large extensional structures. Here ductile deformation of the argillaceous Ballysteen, and to

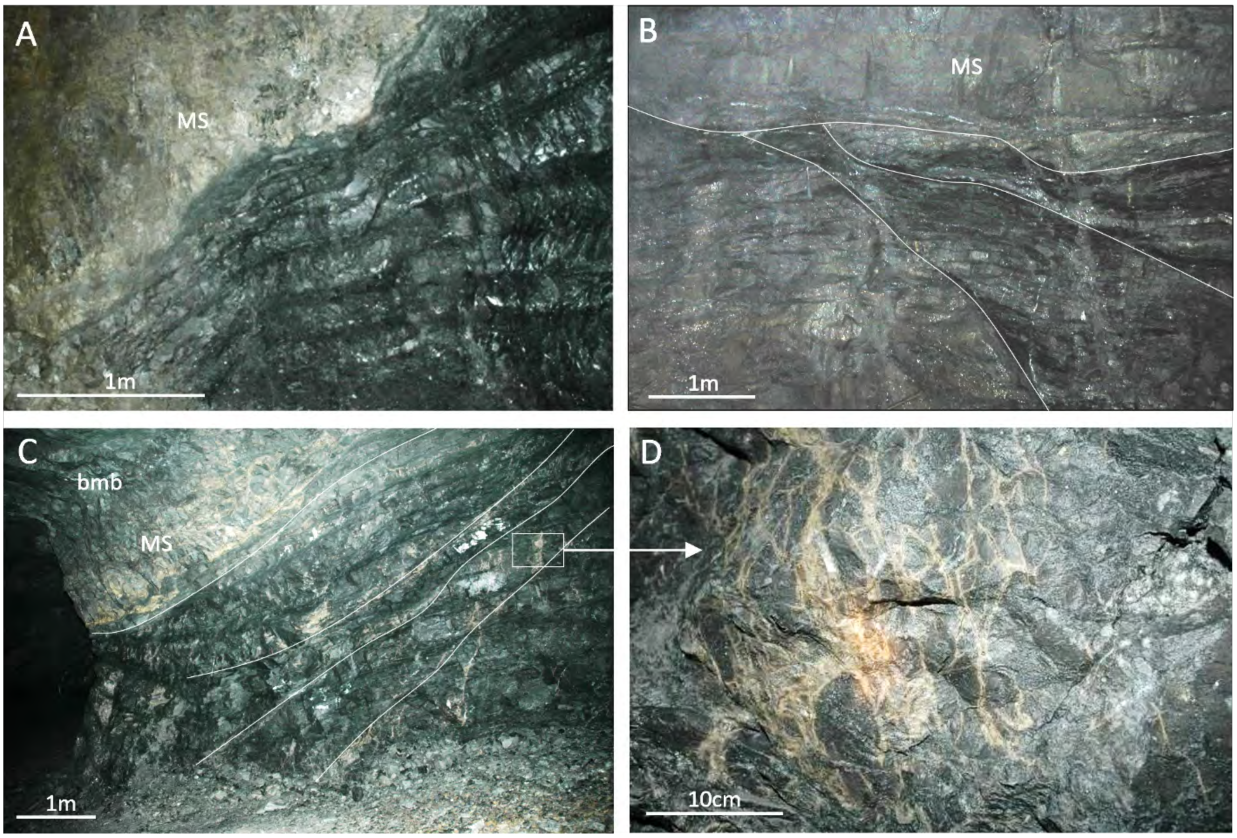


Figure 8: *Low-angle, extensional faults truncate Ballysteen beds at its contact with the Waulsortian. The latter is nearly always strongly mineralized in these settings, (A,B,C). These faults may be single structures,* ***(A)*** *from central Derryville Zone or more complex,* ***(B)*** *from Derryville South, closer to the main ore controlling structures. In the example (C) from Derryville West, multiple, small-displacement, paralleling faults are developed. Extensional veins associated with these structures,* ***(D)*** *are filled by coarse dark sphalerite with pale sphalerite replacing adjacent wall-rock limestone. (MS: massive sulphide, bmb: black matrix breccia)*

some extent the massive sulphides, has permitted the development of very complex thrust, back-thrust and fold geometries as the package was buttressed against the normal fault plane (Fig. 9D).

The fault planes of smaller, normal structures are commonly folded during inversion and are commonly expressed as folds, with the faut and associated truncated beds on one limb (Fig. 9B). Some, especially on northwest-southeast trending normal fault arrays are recumbent. Inversion along the contact has formed steep pinch folds (Fusciardi *et al.*, 2003), likely sited on original low-angle structures and small thrusts within the Ballysteen (Fig. 9C).

The result of the various types of inversion localising on normal faults, is that the associated orebodies may be displaced and repeated such as in the Derryville and Bog East zones at Lisheen (Fig. 6 and 9A). Here the displacement vector is seen to be largely transverse with relatively minor dip-slip reverse movement.

As a consequence of this, the present-day footwall \ hangingwall juxtapositions along many of the larger structures are not those which were in place during mineralization (e.g., examples in Figs. 7 & 17). This is an important consideration when attempting to relate or even explore for mineralization on either side of these structures.

The structural expression of inversion along the trend is quite variable. While the net displacement along the trend is still normal, reverse displacement on structures appears to increase to the east (Fig. 4). At Rapla drilling has indicated some very large reverse displacements on structures that are not reactivated normal faults. Initial drilling would suggest that net displacement across the Rathdowney trend here may be reverse overall, but the structural picture is still far from clear. Large reverse- apparent faults are encountered in the Rapla area and their location appears to coincide with regional NNE-SSW lineaments on regional airborne residual magnetic maps (Fig. 3). Large north-northeast trending reverse structures are known further to the northeast, and it is likely that the Rathdowney Trend thrusts ultimately tie in with these.

Post-Variscan Structures

Post-Variscan faults and joints of undetermined age are ubiquitous in both Lisheen and Galmoy where they are seen to post-date all previous structures (Fusciardi *et al.*, 2003; Bonson *et al.*, 2005; Kyne *et al.*, 2019). Several different structures are recognised, and all are likely not genetically related.

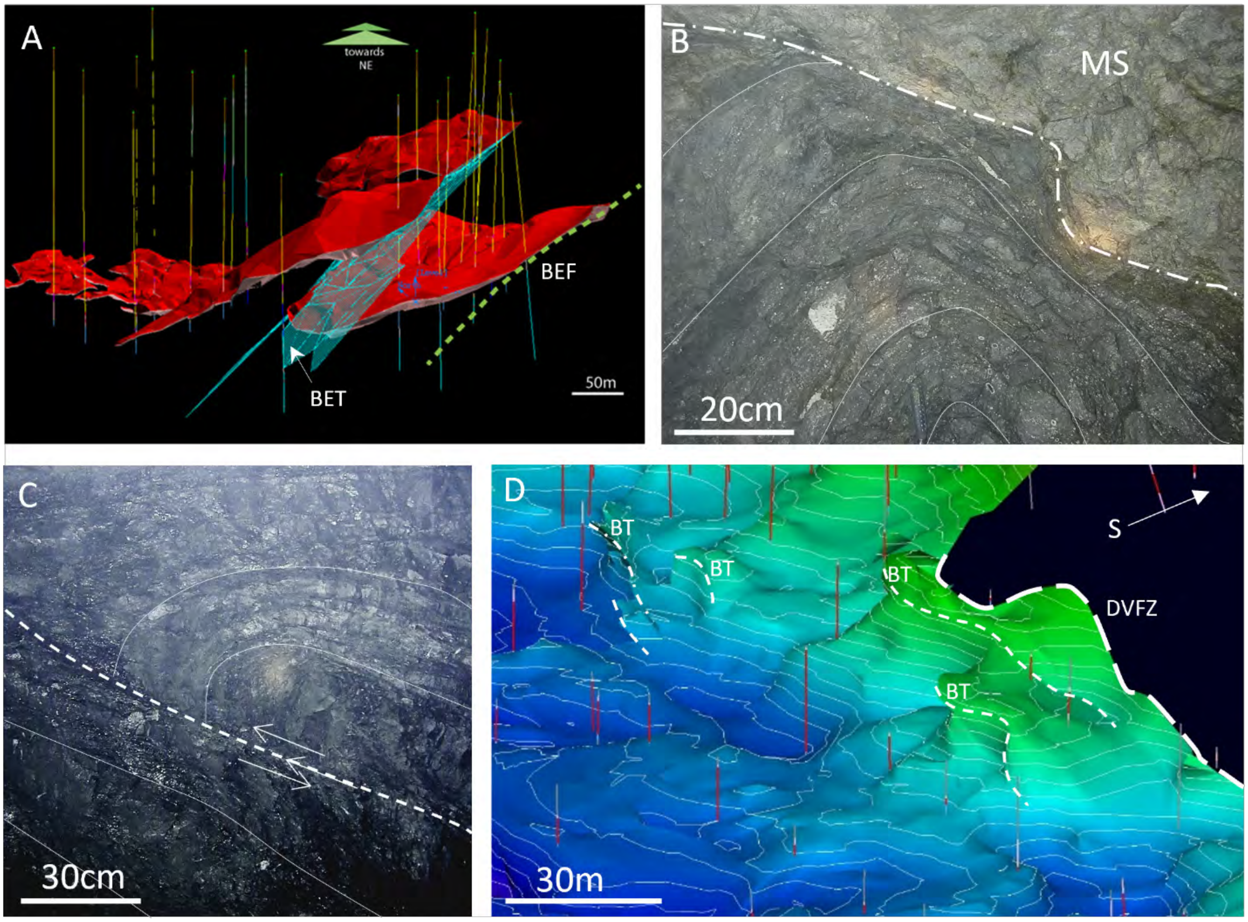


***Figure 9:** Inversion tectonics: (**A**): The Bog East Thrust, (BET), has truncated the ore-controlling, Bog East Fault, (BEF), thus duplicating the orebody into upper and lower parts. Matching grades and thickness of each part has enabled the thrust vector to be established. (**B**): Low –angle extensional faults are commonly the locus for fold development. They are expressed as folds with truncated beds on one limb. Ore is often only present on this limb also. (**C**): A small thrust developed within the Ballysteen beds near the contact. (**D**): Isometric view looking southeast of the surface topography of base massive sulphide – top Ballysteen, Derryville South, Lisheen. Several back thrusts are indicated, (BT), that developed as the massive sulphide was buttressed against the Derryville fault, (DVFZ), to the south. Inversion has resulted in significant geometrical complexity of the base contact that is not elucidated sufficiently by the drilling indicated. (Contours every 2m).*

The most consequential faults are northwest-southeast trending, dextral wrench faults which have been interpreted to be part of a Cenozoic conjugate set of dextral NNW and sinistral NE trending strike-slip faults, attributed to N-S Alpine shortening (Anderson *et al*., 2018; Moore & Walsh, 2021). These typically have small displacements generally <5m, but some, such as the F7 fault at Lisheen (Fig. 6), have significantly more than this, >100m. The largest structures are fault zones with multiple fractures defining lenticular fault blocks that have moved in a range of directions relative to each other. The fault zones pinch and swell along strike varying anything from 5-30m in width possibly related to dilation and compression bends on the fault trace. A compressional bend is suspected to be the cause of local developments of chevron folding of Ballysteen beds adjacent the F7 fault.

It is very likely that other structures with similar scale of displacement to the F7 fault at Lisheen exist elsewhere along the Rathdowney Trend. The “Great Fissure” at Galmoy is another such structure but with less displacement (Doyle *et al*., 1992; Bonson *et al*., 2005). Based on drilling, others are likely developed to the East of the R-Zone at Galmoy and at Rapla. These structures, where present, are difficult to detect with conventional drilling orientations and can seriously complicate the structural interpretation of drilling results where they are intercepted.

A set of north-northwest, trending faults and joints is developed between the northwest- southeast wrench faults. These can be open fractures or gangue filled and have typically minimal or no displacement. They are usually singular, regular fractures typically 20-50cm wide but can be as wide as 2m. They are commonly open and water conducting (Moore & Walsh 2021; Wheeler *et al.*, 2021). Closer to the surface they are generally karstified but some of the larger fissures may be karstified to the base of the Waulsortian (Fig. 10). They are very commonly developed at both Lisheen and Galmoy where they were responsible for most water ingress to the workings (Moore & Walsh 2021; Wheeler *et al.*, 2021). They tend not to be karstified in the Ballysteen and their aperture is diminished in this bedded unit.

Figure 10: *Pyritic ore is often extremely weathered adjacent to northwest-southeast structures and associated joints and locally causes considerable geotechnical challenges for mining. Sphalerite rich ore, as at the base of this image, is less susceptible.*

A number of northeast-southwest trending fractures have been mapped at Lisheen that are probably unrelated to the northwest-southeast structures. They appear to be associated with broad similarly trending monoclines with long strike length and of unknown origin.

All these structures contain a variety of carbonate gangue minerals including white calcite and white and pink dolomites (e.g., Doran *et al.,* 2022; Wilkinson *et al*., 2003; 2005; 2011). Many fractures contain multiple carbonate cements. There are likely many authigenic gangue phases and their relationship with a particular fault or fracture generation is not well established.

Diagenetic, authigenic and mineralization phases

The Rathdowney Trend contains a series of variably sized, stratabound orebodies (Fig. 2). The location of each orebody is structurally controlled by fault segments that are part of the extensional ramp-relay fault array that defines the trend (Figs. 6 & 18). Between fault segments are broad intact structural ramp zones which are not mineralized and comprise much of the trend's strike length (Fig. 18). Ramp zones that are sufficiently deformed can occasionally host orebodies such as is the case in the Bog Central orebody at Lisheen (Torremans *et al*., 2018), especially where ramps are breached and in transfer zones with relative high fault displacements and low fault separations between the breaching fault segments (Kyne *et al.*, 2019).

The vast majority of mineralization is hosted within the Waulsortian Formation at or close to its bottom contact with the Ballysteen Formation, which may also host some minor mineralization (Fig. 7). It is largely developed by replacement of a dark-grey, hydrothermal dolomite and dolomitic breccia known as the 'black matrix breccia' or called 'rock matrix breccia' at Galmoy (Hitzman *et al.* 1992; 2002; Doyle & Bowden, 1995; Shearley *et al*., 1996; Fusciardi *et al*., 2003; 2007). Mineralization in both these formations is largely confined to the structural hanging-wall of the main extensional array. In the structural footwall however, the Lisduff Oolite member of the Ballysteen Formation is locally mineralized where faulted and especially so when in fault juxtaposition with Waulsortian-hosted, hanging-wall ore (Hitzman *et al*., 2002; Fusciardi *et al*., 2007; Torremans *et al*., 2018; Kyne *et al*., 2019).

Regional Dolomitization

The Waulsortian Limestone in south-central Ireland has been regionally dolomitized through contiguous paragenetically early planar dolomite, particularly pervasive near the Leinster Massif to the southeast of the Rathdowney Trend (Hitzman *et al*.,1998; Wilkinson, 2003; Mulhall & Sevastopulo, 2004; Nagy *et al.*, 2004). It consists of a buff to grey, fine-grained replacive dolomite and a coarse-grained, white dolomite cement within vugs, veins and minor breccia bands (Hitzman *et al*., 2002). The boundary between dolomitised and undolomitised Waulsortian occurs along a front that corresponds very closely with that of the mineralized fault array of the Rathdowney Trend (*cf.* Mulhall, 2004). To the southeast of the front, the Waulsortian is mostly but not completely dolomitised (Mulhall, 2004; Nagy *et al*., 2004). Remnant intervals of limestone are known from drilling south of Lisheen. The front is not a sharp contact but rather a zone, maybe 2km wide, over which the proportion of dolomitization progressively decreases northwards, possibly reflecting northward progression of the fluid front (discussion in Hitzman *et al*., 1998; Sevastopulo & Redmond, 1999; Gregg *et al*., 2001; Wilkinson 2003). Based on detailed work on cements by Wilkinson (2003), Mulhall (2004), Mulhall & Sevastopulo (2004) and Nagy *et al.* (2004), a facies control on dolomitization can be suggested for the Waulsortian Limestone, driven ultimately by host-rock permeability and the presence or not of argillaceous barriers to flow (following Davies *et al*., 2004). The dolomitizing brine may have contributed to the overall chemistry of the Zn-Pb mineralizing fluid and also to the creation and distribution of porosity within the carbonate platform.

Preservations of undolomitised Waulsortian are common at its contact with the Ballysteen where there are typically more argillaceous bands present. Dolomitization is also typically more prevalent in the upper Waulsortian towards its top contact with the Crosspatrick. Here the regional dolomite may extend into less argillaceous portions of the Crosspatrick (Hitzman *et al*., 1998; 2002).

Through petrological analysis the regional dolomite is seen to predate hydrothermal dolomites related to the mineralization on the Rathdowney Trend; the timing of regional dolomitization therefore places a maximum lower age constraint on the timing of mineralization and for this reason has been the focus of much research (e.g. Redmond & Sevastopulo, 1999; Hitzman *et al*., 1998; 2002; Gregg *et al.*, 2001; Mulhall & Sevastopulo, 2004; Nagy *et al*., 2004; Wilkinson, 2010; Doran *et al*., 2022). Despite this abundance of research, no clear consensus exists about its relative and absolute timing, its duration, whether it represents a single fluid phase, its relationship with hydrothermal cement phases, and its stratigraphic and structural controls (e.g., discussion in Wilkinson, 2003).

Since parts of the Crosspatrick Formation contain this dolomite phase it would suggest that this lithology must have at least been partially in place for at least a portion of regional dolomitizing events. The broad coincidence of the regional dolomite front's position to that of the Rathdowney Trend fault array might suggest that the fault array exerted some influence

Figure 11: ***(A)****: Sphalerite and galena replacing dark-grey hydrothermal dolomite, (hd), developed within regional Waulsortian dolostone. These 'pseudobreccias' can go on to develop into true breccias - weak black matrix breccia, (bmb), indicated. The strong spatial association of both sulphide and the hydrothermal dolomite suggests that they are likely contemporaneous, (Main East , Lisheen).* ***(B)****: Typical immediate hanging-wall black matrix breccia development. Clasts get larger to top and there is usually some blebby pyrite present, (Bog West, Lisheen).* ***(C)****: Fractures within regional dolostone filled with massive sulphides, mainly pyrite. Hydrothermal dolomite that replaces dolostone adjacent to fractures is likely contemporaneous with the sulphides, (Main West, Lisheen).* ***(D)****: Laminated beds of dark dolomite and graded beds of resistate material within a dissolution cavity generated within a black matrix breccia development. 'Dropstones' that deform the sediment have been either washed in or dropped from dissolving dolostone above (Main North, Lisheen).*

on the flow of regionally dolomitising fluids from the south, where dolomitization is most intense, and thus suggest that faulting must have at least been initiated before or during regional dolomitization. Given that faulting was possibly active during the Waulsortian and definitely during the Crosspatrick it is probable that this is indeed the case. Along the front the distribution of regional dolomite varies to the north of the fault array. At Lisheen it extends for about 1km to the northwest of the deposit. At Galmoy it is generally tighter to the fault array, and unfortunately the upper Waulsortian which might be expected to be more strongly dolomitised is eroded away. At Rapla the front extends some distance to the north beyond the deposit and there does not appear to be a clear relationship.

Although the Rathdowney fault array was likely present at the time of regional dolomitization, as argued in detail below, it is possible that it had very little influence on fluid flow and that their relationship is coincidental.

Iron oxides

Iron-oxide mineralization is commonly associated with Irish Zn-Pb deposits, consisting of zones of dolomite-chalcedonyhaematite alteration (Hitzman *et al.*, 1995; Cruise, 2000). On the Rathdowney Trend however it is relatively rare, having only been encountered in a few regional boreholes and mining developments. At Lisheen, its best development, over a few metres laterally, was located at the margin of Main East sulphide mineralization. Here, it occurs as broken, silicified, haematitic bands in the transitional Ballysteen facies near the base Waulsortian contact (Fusciardi *et al*., 2003). Sporadic occurrences of fragmental silicified ironstone embedded within massive sulphides, likely formed at a similar stratigraphic setting but were dislodged and transported during repeated phases of later sulphide mineralization (Fig. 23A). Iron-silica alteration pre-dates regional dolomite and black matrix breccias based on haematization of earlier diagenetic cements (Shearley *et al.*, 1996; Hitzman *et al*., 1995), and is argued to be hydrothermal in origin (Cruise, 2000), forming at 70-190°C (M. Cruise, *pers. comm*., 2003).

Silicification is not particularly well developed in the Nodular Micrite Unit at either Lisheen and Galmoy. Given the reducing nature of the hydrothermal and intense dissolution-precipitation reactions (Wilkinson, 2010; Wilkinson *et al*., 2011), the question arises if there once could have been a more extensive ironstone development present but that this, other than that which was silicified, was destroyed by later sulphide mineralization. Although it is likely that ironstone development was more extensive, it is considered unlikely, due to very limited preservation, that it was ever very extensive.

Black matrix breccia

The black matrix breccia is a dolomitic hydrothermal alteration that is intimately associated with sulphide mineralization along the Rathdowney Trend (e.g. Hitzman *et al.*, 2002; Lowther *et al*., 2003; Wilkinson *et al.*, 2011). The distribution of black matrix breccia intercepts in the Rathdowney trend was mapped out from boreholes, shown in Figure 2, revealing that the black matrix breccia have a similar but broader distribution than the sulphides. While it is true that not all black matrix breccias are associated with sulphides, it should also be noted that not all sulphides have a black matrix breccia association.

The black matrix breccia is a mixed bag of alteration styles resulting from the varied contribution from a number of inputs involved in their generation. Commonly, they all contain microcrystalline dark dolomite. This can form by replacement of regional dolomite or by precipitation of microcrystalline dolomitic rhombs from solution (e.g., Shearley *et al*., 1996; Redmond, 1997; Hitzman *et al*., 2002; Wilkinson, 2003; Wilkinson & Earls, 2000; Wilkinson *et al*., 2003, 2005, 2011). The black matrix breccia is interpreted to have formed through concomitant dissolution and precipitation, with significant secondary permeability creation and fracturing, the latter especially associated with its strongest developments (e.g., Wilkinson *et al*., 2003; Wilkinson *et al*., 2011).

Although they are often exclusively referred to as breccias, much of what is described as black matrix breccia is a variable replacement of the host-rock lithology by dark dolomite where no clasts are actually generated (e.g., Figs. 11A and 11C; Wilkinson *et al.*, 2011). These rocks with breccia-like textures or their precursors, termed pseudobreccia, involve dissolution and replacement along micro-fractures and remnant Waulsortian facies or diagenetic textures, that permitted hydrothermal fluids to variably permeate and replace the rock mass giving it a mottled appearance (Hitzman *et al*., 2002; Wilkinson & Earls, 2000; Wilkinson *et al*., 2011). This style of black matrix breccia alteration extends to the margins of the hydrothermal system where it is often thin and weakly developed and can be easily missed during core logging if not vigilant (mapped out in Fig. 2).

Faulting likely initiated the breccias, generating fracture-controlled fluid conduits which were then further enhanced and propagated via dissolution (e.g., Hitzman *et al.*, 2002; Wilkinson, 2003; Wilkinson *et al*., 2011; Riegler & McClenaghan, 2017). Large areas of well-developed black matrix breccia occur where there are no significant associated sulphides (note extent in Fig. 2). It has been suggested that regional dolomitization may also have enhanced Waulsortian permeability (Gregg *et al*., 2001; Hitzman *et al*., 2002; Mulhall & Sevastopulo, 2004). The presence of remnant, undolomitised Waulsortian limestone appears to inhibit the formation of dark dolomite and consequently these are very rarely mineralized. Any sulphides within remnant undolomitised Waulsortian usually occur as stringers or veins (Fig. 11C).

Breccias can be matrix or clast supported depending on their mode of formation (see range of textures within one borehole in Fig. 20). Associated dissolution generated open spaces into which liberated rock fragments of varying sizes from sand grade to large clasts could accumulate. Clasts commonly exhibit irregular boundaries and variable concomitant replacement by dark dolomite (Figs. 11, 12 & 20). Microcrystalline dolomite precipitated from solutions (Wilkinson *et al.*, 2011), and this and other liberated materials and neoprecipitates (e.g., phyllosillicates; Riegler & McClenaghan, 2017) accumulated into resulting secondary permeability, typically in unstructured masses. Towards the base the matrix can be finer grained and breccias are more likely to be matrix supported. The occurrence of graded beds and sedimentary structures within some black matrix breccia matrices, indicates that fluids present are able to deposit these authigenic and resistate phases as sediments or transport and redeposit them, likely in significant secondary permeability and cavities. These, often fine-grained, sediments are frequently deformed by angular and subrounded drop-stones which are then themselves draped by further graded beds (Fig. 11D). This process is recognised across a large range of scales from thin-section to mine face.

Where dissolution is particularly intense, caving of the overlying hanging wall rock may occur, with associated collapse breccias (Fig. 27). The resulting breccias tend to be clast-supported and have angular fragments which do not show signs of dark dolomite replacement (Fig. 11B), whereas their matrix is typically composed of microcrystalline dark dolomite. Large slabs of regional dolomite, resulting from this caving, can be incorporated into these breccias (Fig. 22). Up-section, these breccias become confined to collapse related fractures which quickly die out over a few metres into the rock mass above.

The black matrix breccia matrix mostly consists of microcrystalline dolomite rhombs, with the opaque nature of the matrix interpreted as an optical effect due to the microcrystalline nature of the grains. A study of gangue phases in the Rathdowney trend corroborated the prevalence of coupled brecciation and chemical corrosion processes during formation of the black matrix breccias (Riegler & McClenaghan, 2017). This study also indicated the formation of new, hydrothermal (Ba, K)-feldspar, adularia, and albite in the hydrothermal breccias, as well as rare quartz, illite and phengite during chemical brecciation resulting from sulphide precipitation processes. Importantly, the relative proportions of illite, phengite, (Ba-)K feldspars are indicative of the proximity to the source feeders near normal faults (Riegler & McClenaghan, 2017), in particular the proportion of Ba-feldspar over illite in the black matrix breccia matrix.

Geometry and distribution of black matrix breccia

Black matrix breccia development is relatively stratiform despite lateral host-rock facies heterogeneity and the presence of pre-existing structural displacements. It occurs within the Waulsortian Limestone Formation at or within 25m of its contact with the Ballysteen Formation. It can be present as a number of separate horizons but is best and most continuously developed at the base contact. Its intensity and thickness is structurally controlled by extensional faults. It is not developed in undolomitised Waulsortian limestone remnants that are locally preserved at the contact but other than this, Waulsortian lithofacies seem to exert little control. It is not seen in the structural footwall of the main controlling structures; however, rare thin developments have been logged up-dip within adjacent fractures presumably associated with these faults. Black matrix breccia generating processes were also presumably active within the Ballysteen Formation and Lisduff Oolite, however, possibly because of the paucity of significant precursor dolomite, the presence of argillaceous baffles to flow and argillitic resistate products of dissolution, these are not extensive, are usually very proximal to faults and have a very different appearance.

The thickest black matrix breccia development is associated with early ENE-trending faults. These breccias may or may not contain sulphide. This phase of faulting likely provided access for mineralizing fluids to the contact zone as black matrix breccia, although not always very well developed, is present even at some distance along the contact. By comparison, black matrix breccia associated with NW-trending structures, for example at Galmoy's K-zone, tends to be quite restricted to the structures themselves suggesting that flow along the contact zone was not possible.

There are differences in intensity of black matrix breccia development along the Rathdowney trend. The most extensive development is at Lisheen where even unmineralized areas between the economic orebodies have black matrix breccia developed at the contact. The northwest trends of black matrix breccia development are present but largely overlap that associated with ENE-trending structure. It's only further north where the influence of ENE-trending structure is diminished that clear NW trends are seen in the footprint maps (Fig. 2). Thickness maps however do show these trends. There is a similar situation at Galmoy but here the intensity is not as strong so that black matrix breccia development is tighter to the structures. There is consequently less overlap, and the two trends can be easily identified from the footprint map. At Rapla, black matrix breccia development is very weak. Most is proximal to the main ENE-trending normal fault. Fluids appear to have struggled to access the contact. It is possible that at Rapla the fluids were not contained at the base of the Waulsortian and migrated up to fault fractures to higher levels. Some of the black matrix breccia intervals logged in the Rapla region are higher in the succession, in upper Waulsortian or even Crosspatrick Formations although whether these are true black matrix breccias cannot be verified from core.

Overall, there is a strong correlation between black matrix breccia development and the scale of mineralization along individual Rathdowney Trend fault segments (Fig. 2) and this is surely an indication of the scale of hydrothermal fluid input. Despite having similarly scaled structures and lithological juxtapositions to the Lisheen and Galmoy orebodies, the mineralization at Templetouhy, Baunmore and Rapla is limited, and all have very limited black matrix breccia development.

The white matrix breccia

The white matrix breccia appears as irregularly and usually intensely fractured Waulsortian rock that is cemented by a white, coarsely crystalline, non-ferroan dolomite (Hitzman *et al*., 2002; Fusciardi *et al*., 2003). Its significance lies in its hydrothermal origin, being related in some way, directly or indirectly, to the mineralization process (Eyre, 1998; Wilkinson, 2003). Confident identification of the white matrix breccia in core can be difficult for there are many different carbonate cemented breccias and fractures typically encountered within the Waulsortian. Some are related to mud-mound growth and synsedimentary processes and predate the white matrix breccia. Others are related to a myriad of subsequent events including faulting, cataclasis, dissolution, and hydraulic fracturing (Fig. 15). In addition, many of these breccias overlap each other so suffice to say that caution is required when working with white matrix breccia data or sampling for white matrix breccia cements.

The white matrix breccia (*cf.* 'crystalline matrix breccia' at Galmoy) is confined to the Waulsortian Limestone Formation. When mapped underground it is seen to form broad, steeply dipping networks of generally small, irregular and interconnected fractures. The breccia fragments themselves are largely in situ, and typically represent crackle or mosaic breccias (Fig. 14). These fracture networks can develop laterally into areas of well-developed stromatactis facies if intersected, shattering the delicate texture as they do so.

Where black matrix breccia is developed at the base of white matrix breccia fracture networks, it is common to see, within the same fracture, coarse, white dolomite with dark hydrothermal dolomite developed beneath. Often the microcrystalline dark dolomite exhibits sedimentary features indicating that it precipitated from solution and filled the fractures as a sediment. It appears then that the unfilled fracture network above was then subsequently cemented by white matrix breccia dolomite.

The distribution of the white matrix breccia is not random within the Waulsortian Limestone. At Lisheen, it is most intensely developed proximal to extensional faults which also happen to be the areas of strongest mineralization and associated dissolution. White matrix breccia development, however, extends beyond the influence of mineralization so therefore hydrothermal activity does not seem to be a prerequisite for its formation. It seems more likely therefore, that the fracture

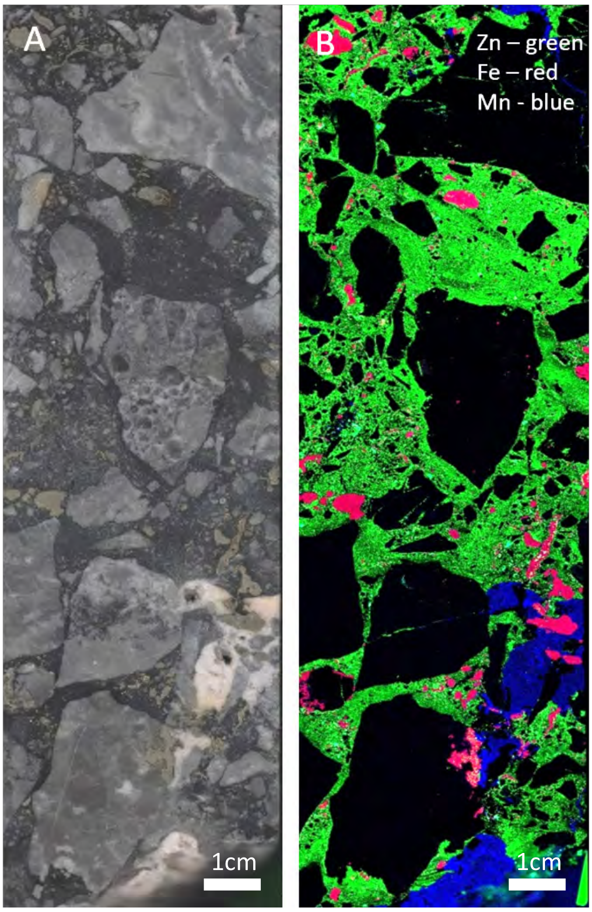


Figure 12: *Black matrix breccia,* ***(A)*** *with Maia Mapper micro-XRF map,* ***(B)****. The matrix contains significant zinc, up to 450ppm in places. Not all black matrix breccias are similarly enriched.*

networks of the white matrix breccias initially formed as a brittle rheological response of the massive Waulsortian Limestone to extensional faulting. Dissolution related to hydrothermal activity, if present, would have promoted additional development, particularly adjacent to controlling fault zones but also more generally over the developing orebody due to dissolution and collapse within the Waulsortian.

MicroXRF mapping of black matrix and white matrix breccia

The black matrix breccias and white matrix breccias have been extensively investigated to elucidate the physical and chemical properties of the causative hydrothermal fluids (Shearley *et al*., 1996; Redmond, 1997; Hitzman *et al*., 2002; Wilkinson, 2003; Wilkinson & Earls, 2000; Wilkinson *et al*., 2003, 2005, 2011). Most studies have focused on either the microanalytical scale, or deposit scale processes.

Several geologically contextualised polished slabs of NQ core of black matrix breccia and white matrix breccia at Lisheen were recently analysed using Maia mapper, a synchrotron beam powerd microXRF elemental mapping system, allowing quantitative mapping of trace elements (following methodologies in Ryan *et al*., 2014, 2018). Results are shown in Figures 12 and 14. Figure 12 reveals that the hydrothermal dolomite matrix of the black matrix contains significant zinc, up to 450ppm in places. Not all black matrix breccias are similarly enriched. This sample, and others not shown here indicate a wide range of concentrations of both Zn and Fe in the matrix of various breccias, and within breccias. The variations in metal contents at near sub-microscopic scale are largely thought to relate to different generations of black matrix breccia related to the developing mineral paragenesis.

Figure 14 shows that lesser but detectable levels of Zn occur on dark tops on host rock fragments. Importantly, dark dolomite tops with elevated base metal content are draped over breccia clasts, with very low or below detection contents in the white matrix breccia. This provides a tentative temporal constraint on development of the white matrix breccia (at least in the samples measured), with zinc and dark dolomite cements which must have precipitated from solution and alighted on the clasts prior to development of white dolomitic fracture fill.

Observations like the ones above can prove useful in identifying productive fluids that interacted with the breccias as well as helping to identify potential trends within the alteration footprint.

Sulphide mineralization

The main sulphide mineralization consists of massive and disseminated pyrite/ marcasite, sphalerite and galena. Other minor minerals of Cu and Ni including tennantite, chalcopyrite and niccolite occur, especially in oolite-hosted ores and in areas proximal to major extensional faults. Silver grades are locally elevated within galena and tennantite, and it also occurs locally as proustite. The ore exhibits a wide range of textures including complete and partial replacement of black matrix breccia, delicate replacement of host rock lithologies, multiphase sulphide breccias, and cavity-filling with both colloform and laminated, precipitated sulphides. Descriptions below are based on observations underground and in core, as well as building on detailed petrography by various authors (Shearley *et al*., 1996; Redmond, 1997; Hitzman *et al*., 1998, 2002; Eyre, 1998; Everett *et al*., 1999; Fusciardi *et al*., 2003; Wilkinson *et al*., 2003; Wilkinson *et al*., 2005; Barrie *et al*., 2007; Boni *et al*., 2007; Wilkinson *et al.*, 2011; Riegler & McClenaghan, 2017; Röhner, 2017; Turner, 2019; Yesares *et al*., 2019 and Doran *et al*., 2022)

Iron sulphides

Pyrite and to a lesser extent marcasite comprise the vast majority of iron sulphides and represent the earliest sulphides to follow initial black matrix breccia development (e.g., Hitzman *et al*., 2002; Wilkinson *et al.*, 2005; Turner, 2019; Doran *et al.*, 2022). Rare pyrrhotite is also present but only proximal to feeder zones where sulphide content was likely higher and is considered to be paragenetically late. Iron sulphides both replace black matrix breccias, filling any generated void with large botryoidal masses and finely laminated pyrite sediment precipitated from solution. Granular and brecciated colloform textures are common indicating repeated cycles of mineral precipitation and collapse due to host rock replacement.

The thickest pyrite, up to 20m, is developed in the immediate hanging-wall of ENE-trending structures including the G-fault at Galmoy and the Kiloran and Derryville Faults at Lisheen.

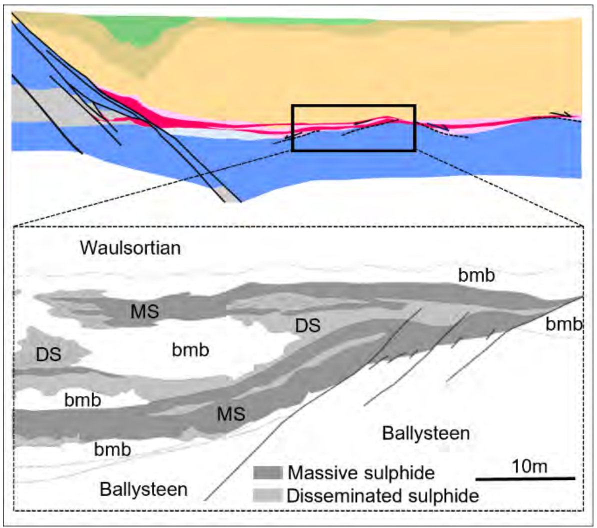


Figure 13: *Detail of ore development at contact fault structures showing rapid lateral geometrical variability. The strongest ore is concentrated in the hanging-wall of fault displacements. Ore often bifurcates in the hanging-wall with the best zinc grades concentrated in the lower lens. The top contact of the alteration / mineralization is relatively stratiform across the structures and the structural footwall is often poorly mineralized. Main West, Lisheen. (DS-disseminated sulphide, MS- massive sulphide, bmb-black matrix breccia)*

Other major ore-controlling faults including the R-fault at Galmoy and the Bog faults at Lisheen have significant but thinner pyrite developments. Here, much of the early pyrite was replaced by subsequent Zn\Pb mineralization. Thick pyrite development is not however restricted to the large-displacement, orebody-controlling, ENE-trending faults. All ENE-trending faults, regardless of their displacement or polarity have associated pyrite and some with appreciable thicknesses. The most notable is the Main North Fault at Lisheen, a 15m displacement, north-dipping, ENE-trending fault that hosts a 15m thick body of massive pyrite in its hanging-wall (Fig. 6). This structure is not thought to be large enough to be a feeder suggesting therefore that the pyrite here must have originated from the larger Kiloran Fault to the south and travelled along the contact to access and replace breccias associated with this and other smaller displacement ENE trending faults.

The top surface of these massive pyritic developments to either unmineralized black matrix breccia or regional dolomite above is generally remarkably sharp and relatively planar (Fig. 16). There is locally some evidence for dissolution of either related to pressure solution, but this is likely very minor, and therefore the present-day contact represents a relatively intact top of mineralization contact. The geometry of the pyrite caps and pyrite to host rock contacts is nearly horizontal and straight (when restored where needed), going straight across and overlapping underlying faults and mini-graben geometries as shown in Fig. 17. This strongly indicates that the mineralization was level at formation and cuts across pre-existing bathymetry, similar to the black matrix breccia (Fig. 18). Our interpretation is that this represents horizontal level stratification of the mineralizing fluids, likely ponding within the host-rock. Much of the massive pyrite at Galmoy and Lisheen is indeed

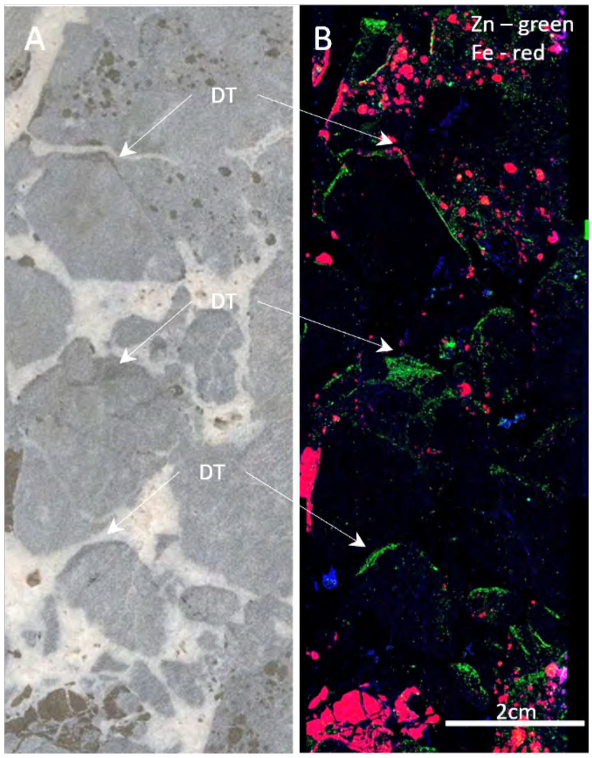


Figure 14: *White matrix breccia,* ***(A)*** *with Maia mapper micro-XRF map,* ***(B)****. The dark tops, (DT) on the clasts contain detectable zinc. This must have precipitated from solution and alighted on the clasts prior to development of white dolomitic fracture fill.*

developed in laterally extensive, stratiform bands or lenses within the black matrix breccias.

A number of different pyrite paragenetic stages are recognised (Hitzman *et al*., 2002; Fusciardi *et al*., 2003; Wilkinson *et al*., 2005; Röhner, 2017; Turner *et al*., 2017 Yesares *et al*., 2019; Doran *et al*., 2021). These predate and also continue through and after the main Zn\Pb mineralization phase. Detailed elemental maps and sulphur isotope composition transects across individual pyrite grains indicate changing isotope and fluid compositions and resulting from numerous fluid pulses representing the waxing and waning of hydrothermal fluid ingress (Barrie *et al*., 2009; Turner, 2017; Yesares *et al*., 2019; and Doran, 2022).

Pre-ore background diagenetic pyrites range from $\delta^{34}S$ -47.7 to -30.7 ‰, representing sulphur derived from bacterial reduction of seawater sulphate.

The earliest ore-stage pyrite typically range from $\delta^{34}S$ -34.3 to -14.7 ‰, significant lighter than the main ore stage sphalerite and late galena which range from $\delta^{34}S$ -15.5 to +1.7 ‰ and $\delta^{34}S$ -11.1 to +17.4‰, respectively (Yesares *et al*., 2019; Doran *et al*., 2022). A late-stage pyrite that post-dates Zn\Pb mineralization is most easily recognised in the oolite mineralization. Here extremely coarse botryoidal and colloform pyrite locally cements massive Zn\Pb sulphide breccias with remnant void space between botryoids being filled by late calcite. Isotopic and other geochemical analysis has yet to be conducted on these.

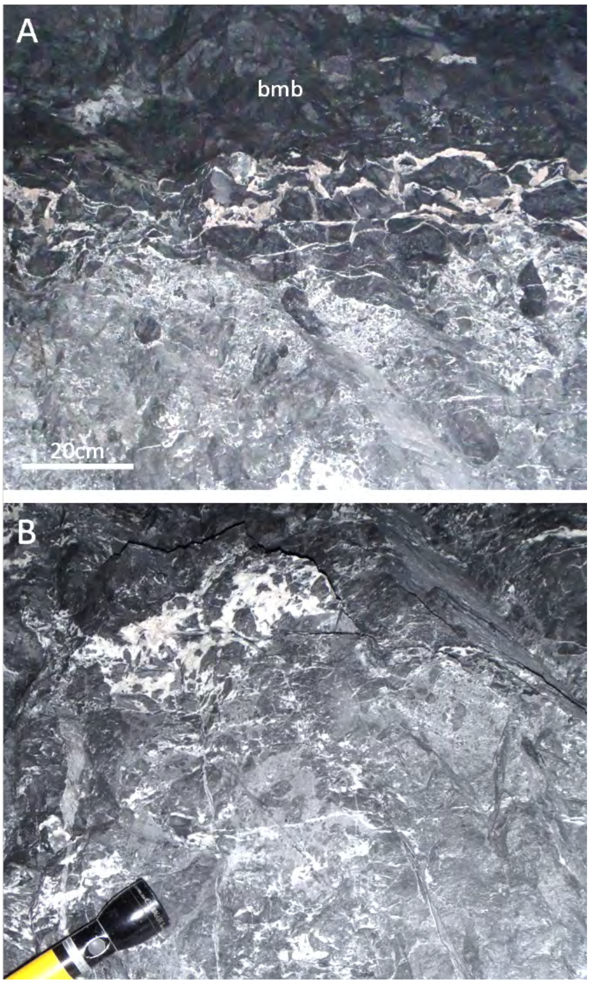


Figure 15: ***(A)****: Complex white dolomitic breccia developed beneath and incorporating clasts of black matrix breccia.* ***(B)****: This breccia also contains clasts of other white dolomitic breccias. Many of these breccias have an uncertain origin. Island Zone, Lisheen.*

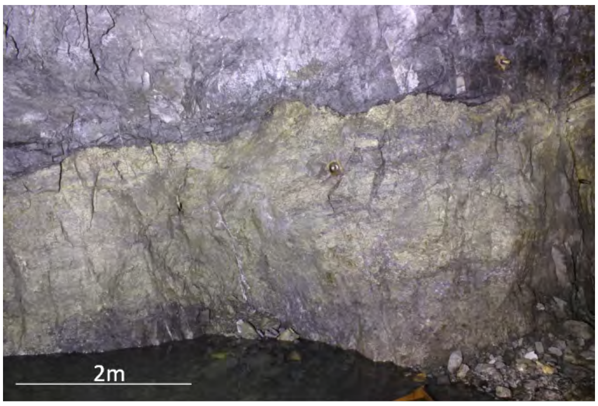


Figure 16: *Sharp hanging-wall contact between pyritic massive sulphide and black matrix breccia above (Main North, Lisheen). Some pressure solution has occurred but is not considered to be significant. Sharp hanging-wall contacts are a feature of many massive pyritic bodies and bands. Very often the contact is with Waulsortian dolostone and the black matrix breccia is not present.*

Main stage base-metal mineralization

Sphalerite and galena in an approximate ratio of 6:1 represent the vast majority of base metal sulphides. Mineralization largely occurred by replacement of hydrothermal dolomite, dolomitic breccias and early pyrite (Fig. 19 and Fig. 20). Locally there is replacement of certain susceptible lithofacies such as stromatacactid rich Waulsortian and clean encrinites and calcarenites developed at the contact transition with the Ballysteen Formation (Fig. 23B). The latter lithotype is an important host at the base of the high-grade, R-zone mineralization at Galmoy. Additional pyrite mineralization accompanies the base metal mineralization. The iron for this pyrite has two possible sources: either new iron that has accompanied the main stage base metals, or existing iron from pyrite that has been replaced by them. Sphalerites typically display low iron concentrations, suggesting that Fe partitioning was likely governed by the concurrent pyrite formation.

The replacive sphalerite is typically pale cream or tan coloured and very fine grained (Fig. 23) but locally can be coarser and more brown-red. Dissolution related to replacement has generated sulphide breccias and voids that were subsequently filled with colloform and fine-grained precipitated sphalerite sediment exhibiting a range of colours from pale cream, tan, dark-brown, grey and even black. Overall, the range of colours and textures indicate a very dynamic mineralization environment with multiple pulses of fluids with rapidly varying trace element compositions, crystal preferred orientation axes and $\delta^{34}S$ signatures between colloform bands (Barrie *et al*., 2009). Barrie *et al*. (*op cit*) also clearly showed that growth sequences are not always stratigraphic within stacked colloform bands.

The galena is also mainly replacive and broadly coeval with sphalerite mineralization. It also exhibits a variety of textures including buck-shot, finely-laminated, fine-grained massive and as colloform bands. It is generally coarser grained and patchier in its development than the sphalerite. Large single crystal grains >10cm are present but these have grown by replacement of host-rock and not as space-filling euhedral crystals (Fig. 23F).

The intensity and distribution of mineralization gives a strong indication of how the base metal mineralization progressed. In all of the orebodies the thickest developments of base metal sulphide is located in the immediate hanging-wall of the main structures (Fig. 13). Here replacement of thick, early, massive pyrite and hydrothermal breccias occurred (Fig. 19 and Fig. 20). This mostly occurred from the base of these bodies, at their contact with the Ballysteen, and progressed upwards through them. Consequently, the best base metal grades are typically found at the base of these pyritic bodies and decreases towards to top (Fig. 19 and Fig. 23G and H). In many cases the upper parts remain unmineralized and exist as barren 'pyrite caps' above the economic mineralization. In some pyritic bodies, base metal bearing fluids have also accessed the top contact thus creating two high-grade zones separated by weaker-grade or even barren, pyritic sulphide inbetween. Some peripheral parts of the larger pyritic bodies and other stratiform pyritic bands and lenses developed within the black matrix breccias have escaped base metal mineralization altogether and remain as barren pyrite.

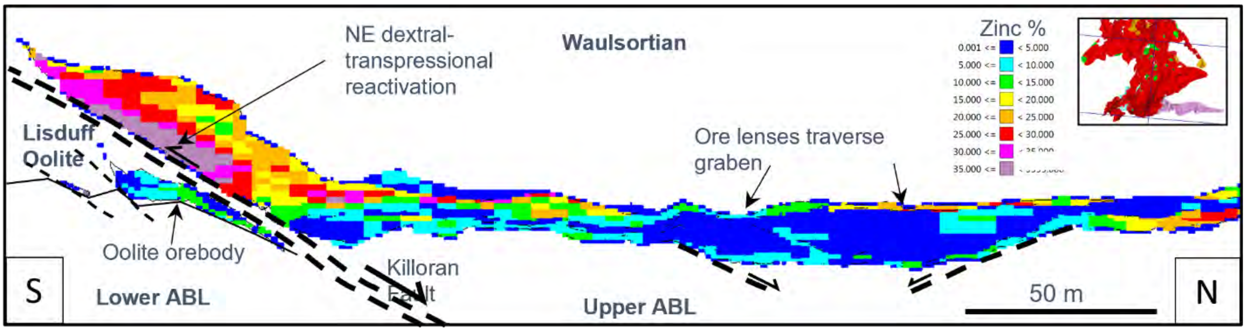


Figure 17: *South to north cross-section across southern Mian Zone, Lisheen, showing zinc grade distribution. Highest grades are typically at the orebody footwall particularly if in fault contact with the Ballysteen. The hanging-wall contact is relatively stratiform despite elevation variability at the Ballysteen contact resulting from extensional faulting. To the south, Zn grade stratification can be clearly seen. Later inversion on the Kiloran Fault has thrust this ore up-dip.*

On the orebody scale gross changes in the Zn:Pb ratio is recognised. At Lisheen it ranges from 3:1 proximal to the main controlling structures, up to 25:1 in distal mineralization in the Island Pod to the north (Fusciardi *et al*., 2007; Torremans *et al*., 2018). A similar trend is seen at Galmoy (Lowther *et al*., 2003). This is interpreted to suggest a general south to north direction of fluid flow, based on the respective mobilities of lead and zinc.

The most likely explanation of these patterns is that fluids, while migrating northwards, progressed along the lithological contact between Ballysteen and Waulsortian Formations, utilising a myriad of small-scale extensional structures as preferred conduits. The well-developed hydrothermal breccias and pyrite mineralization associated with these structures were preferentially and extensively replaced, as described in detail from petrographic studies (Hitzman *et al*., 2002; Fusciardi *et al*., 2003; Wilkinson *et al*., 2005; 2011; Röhner, 2017; Turner, 2017; Doran *et al*., 2022). From here, mineralization progressed into adjacent breccias by replacement but with a weakening fluid and no proper conduit to utilise, the degree of mineralization is much reduced resulting in semi-massive and disseminated sulphides (Fig. 21). Areas increasingly distal from the feeder source would be expected to receive less and depleted fluid pulses. Mineralization here is typically thin but high-grade and is tightly restricted to the structural fluid conduits.

Cu and Ni mineralization, mainly tennantite and niccolite, is associated with the Zn\Pb mineralization. These minerals are largely restricted to areas proximal to the source feeders on the main controlling faults. Only the largest orebodies at Lisheen (Main and Derryville zones) and at Galmoy (G and R- Zones) have this assemblage. Here massive tennantite which is often accompanied by massive galena is developed at the contact between the Ballysteen Fm and existing massive sulphides. At Lisheen, niccolite has a more erratic, poddy distribution being largely associated with fractures or small voids where it is sometimes accompanied by baryte. The tennantite is silver rich with several hand-samples from Derryville Oolite Zone returning grades of 500-1300g/t. In the Main Zone at Lisheen a resource of 40kt @ 7%Cu was defined. No significant Cu or Ni grades have been recorded at Rapla.

A paragenetically later stage of Zn-Pb mineralization is recognised that exhibits a change in the relative proportions and composition of the sphalerite and galena (Wilkinson *et al*., 2005; Barrie *et al*., 2009; Turner, 2017; Doran *et al*., 2021). The sphalerite becomes increasingly cadmium rich and the lead increasingly argentiferous. In areas accessed by this mineralization phase the proportion of lead increases from a Zn:Pb ratio of 6:1 to approximately 3:1. At Lisheen there is also an indication that the feeder source for this phase of mineralization shifted along the Kiloran fault to the south of Main East (Torremans *et al*., 2018). There is also further Cu and Ni mineralization at this new feeder location but here chalcopyrite and arsenopyrite are more abundant than tennantite. Chalcopyrite appears to be later than tennantite as the massive tennantite developments frequently contain thick, massive chalcopyrite veins.

Occurrences of base-metal sulphides at higher stratigraphic levels within the Waulsortian, outside of the main stratiform body, are rare at both Lisheen and Galmoy. Where they do occur, they are typically vein-hosted or within white dolomite breccias of unknown origin. The vein sphalerite is pale cream or tan coloured and is fine grained. In fractures it can be laminated or colloform. The galena is typically buckshot and developed within the dolomitic cement. Honey-blend sphalerite is commonly present in vughs developed within the ore horizon, but it is sometimes also seen in vughs higher up in the Waulsortian. The most notable example is in borehole 3312-

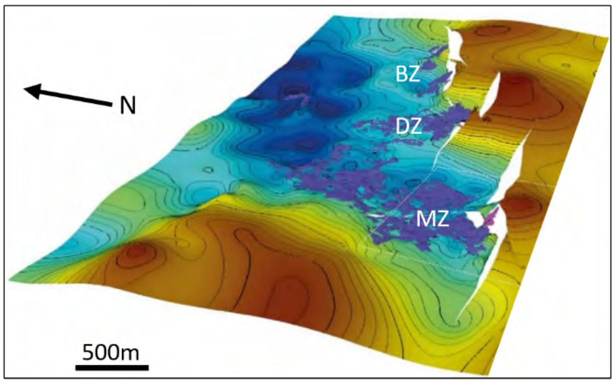


Figure 18: *View looking east of contoured top Ballysteen surface showing ramp-relay fault geometry and orebody zones in purple: Main-MZ, Derryville-DZ and Bog-BZ. In all cases ore is in the topographic lows in fault hanging-walls, (after Kyne et al., 2019)*

Figure 19: *A typical interval through ore in the structural hanging-wall proximal to ore-controlling faults. Pyritic, black matrix breccias pass quickly into massive pyrite. This is often barren of zinc, as in this case, and forms a 'pyrite cap' above the economic ore. Zinc grades typically increase towards the bottom, (grades in % to right). The footwall contact and the Ballysteen beneath is commonly tectonized. (LK-1784, Bog-Zone East, Lisheen, box length 1.5m).*

Figure 20: *Black matrix breccia with various clast morphologies and minor pyrite (Py). The bottom run is significantly replaced by pale, tan-brown sphalerite, (Sp) and galena (Gn). From hole 4513-12, R-Zone, Galmoy.*

73, adjacent to the Rapla Fault, where it is present in vughs over a 110m interval of core above the Ballysteen contact.

Lisduff Oolite mineralization

At Lisheen, the Lisduff Oolite is host to c.300kt, of ore. Although this is only a small proportion of the total resource, its presence provides many insights into the mineralization processes operating along the Rathdowney Trend. Mineralized Lisduff Oolite is also known from drilling at Galmoy' G-Zone and at the small Baunmore Pod but here intersections are intermittent or sub-economic and were never extensively investigated. It is from Lisheen where oolite mineralization was extensively drilled and mined that most of our understanding is derived.

Lisduff Oolite mineralization is largely located on the structural footwall of the main orebody-controlling faults, in and adjacent to the faults themselves and related structures (Fig. 6 and Fig. 24; Kyne *et al.*, 2019). As there has been significant

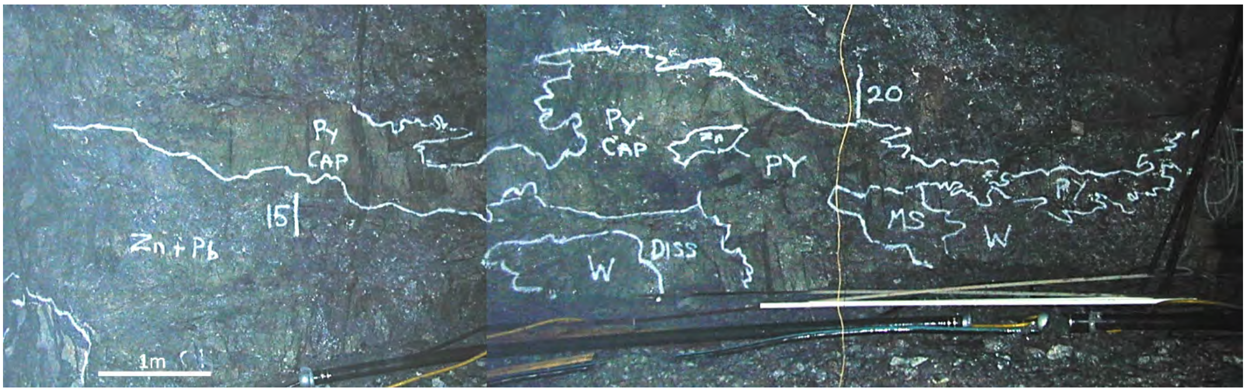


Figure 21: *Underground side-wall grade mapping, Main North, Lisheen. Ore grade variability and distribution can be extreme where mineralizing fluids do not have well defined conduits to access the host rock. This is typically the case in upper ore lens developments, off the contact and peripheral from structures. (W-barren dolostone and hydrothermal breccia, Diss-disseminated sulphide, MS- massive sulphide).*

reactivation of these structures during Variscan compression the orebodies can be structurally complex and current fault juxtapositions, particularly with Waulsortian hosted ore in the hanging-wall, may not be as they were during mineralization (Fig. 24). This is indeed the case at Main Zone, Lisheen.

Lisduff Oolite hosted ore is the most complex mineralization at Lisheen exhibiting a complex paragenesis that is described in detail by Doran (2021). A range of styles and textures are present (Fig. 25), however brecciated sulphide textures are especially common. The mineralogy is largely similar to Waulsortian-hosted sulphides but their appearance and proportions are significantly different. A number of pyrite generations are recognised (Doran, 2021). Some pyrite is clearly replacive with ooids being replaced progressively to produce massive pyrite. Much of the massive pyrite however is colloform and brecciated being cemented, together with other fragmental sulphide phases, by additional colloform growth. A coarse botryoidal pyrite appears to be the latest sulphide phase and commonly cements and overgrows broken blocks of other Zn, Pb, Cu and As sulphide phases. Sphalerite in the Lisduff Oolite ore is generally darker, being commonly brown-red, dark grey or black. Both it and the galena are often extremely fine-grained and have locally co-precipitated by replacement (Doran, 2021) The resulting massive sulphide has a dull grey lustre and was termed ‘steel ore’ by the mine geologists. Its fine grain size presented significant metallurgical problems in sufficiently separating both mineral phases. Similar material also forms sedimentary layers of dark, finely-laminated massive sulphides infilling cavities and breccias generated by dissolution processes. Nickel and copper grades are higher, and the nickel mineralogy is more varied, including bravoite and gersdorffite. The tennantite typically contains higher silver grades.

Figure 22: *Banded sulphide, principally sphalerite and galena, developed by replacement of black matrix breccia. Within the breccia is a large slab of Waulsortian dolostone that is not replaced, (Main East, Lisheen).*

At Lisheen Main zone, up to 30m of Lisduff Oolite stratigraphy above the mineralization is missing, presumably dissolved (Fig. 24B). This dissolution would explain the geometries of faults that displace the top Lisduff Oolite contact but do not propagate through the lower contact. Bedding beneath the oolite mineralization is largely intact, its contact with the massive mineralization above being relatively sharp but undulous (Fig. 25G). Above this, by contrast, a breccia is developed with rounded and angular clasts and blocks with a matrix that is composed of dark dolomite and argillite (Fig. 25B). Locally this contains laminated beds of disaggregated carbonate grains and argillite and are often deformed by well-rounded dropstones (Fig. 25H). These breccias form a wedge above the oolite orebody which can be interpreted to result from collapse gradually propagating upwards. They are not developed on hanging-wall side of the bounding fault to the north, but some mineralization occurs within the fault zone in faulted Upper Ballysteen and Lisduff Oolite blocks (Fig. 24B).

To the west this fault intersects with another related structure and their combined displacement brings the Lisduff Oolite into contact with the Waulsortian (Fig. 24; Kyne *et al.*, 2019). This juncture is where the main feeder into the Waulsortian is situated. At this location a massive niccolite body is developed within fractured oolite and a resource of 3kt @ 10% Ni was estimated. Its location is likely due to mixing of fluids and a rapid change in Ni solubility. The corresponding Waulsortian ore in the hanging-wall, characterised by massive tennantite, has been subsequently displaced dextrally to the east by inversion (Fig. 24A). Sulphur isotope data of various oolite-hosted sulphide phases, shows a mix of $\delta^{34}S$ isotopic signatures ref-

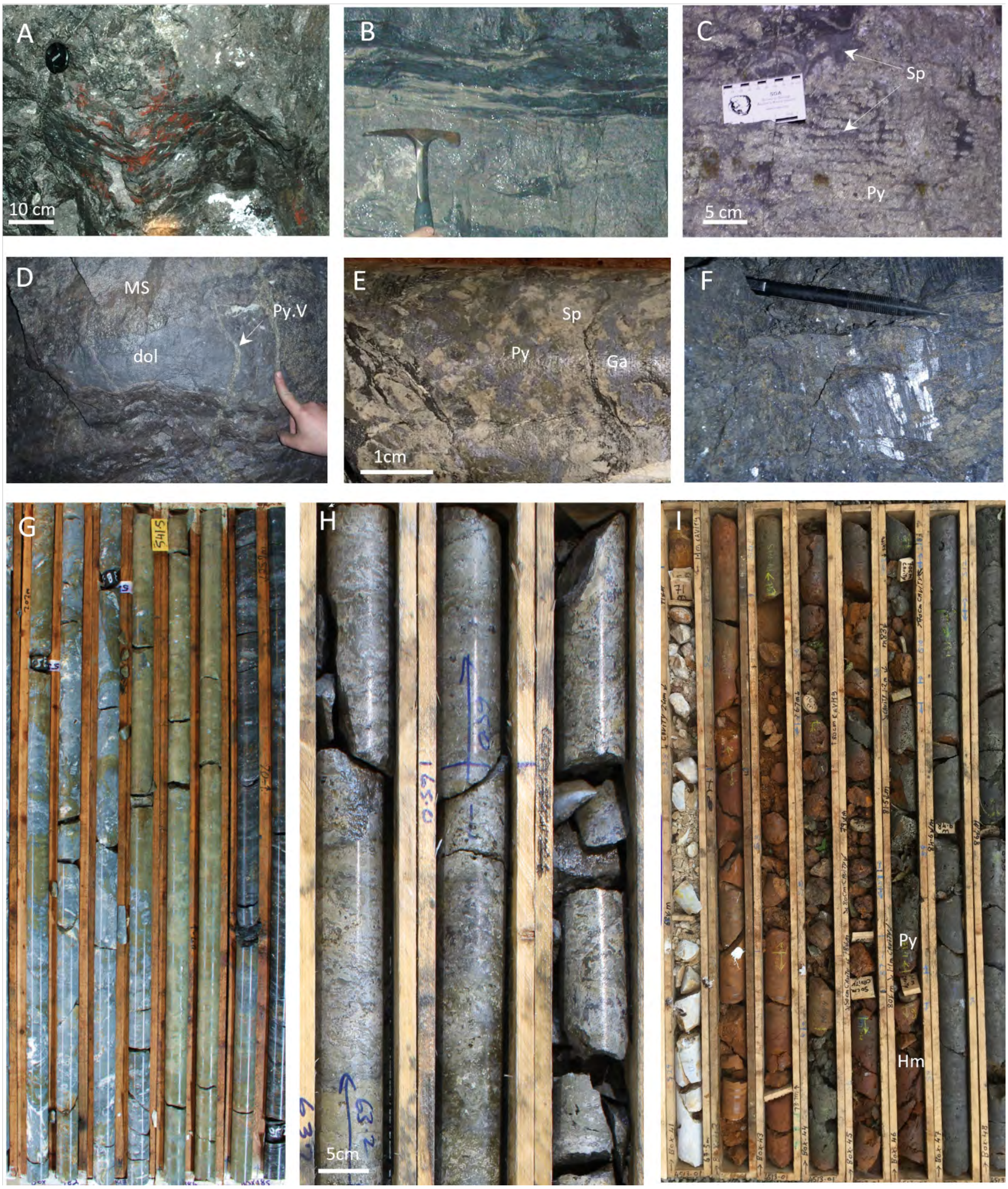


Figure 23: *(**A**): Silicified haematite and chert within massive sulphides, central Derryville, Lisheen. (**B**): Ballysteen calcarenite and shaley beds beneath massive sulphides commonly host moderate grades of pale replacement sphalerite, Main East, Lisheen. (**C**): Very, fine-grained, grey sphalerite replacing banded pyrite, Main North, Lisheen. (**D**): Dolostone Clast, (dol), within massive sulphide, (MS). Both cut by late pyrite vein, (Py.V), Derryville South Lisheen. (**E**): Massive sulphide, sphalerite, galena and pyrite from Rapla. (**F**): Very coarse galena growth by replacement of black matrix breccia, Main North, Lisheen. (**G**): Massive pyritic sulphide intersection from Rapla displacing many of the same features seen at Lisheen and Galmoy. It is largely barren but for the bottom 30cm which hosts 20% Zn (hole 3312-58, box length 1.5m). (**H**): Almost total replacement of massive pyrite by sphalerite and galena, G-Zone, Galmoy. (**I**): Oxidation of top 6m of massive pyrite cap, Py, to massive hematite, Hm, G-Zone, Galmoy, (box length 1.5m).*

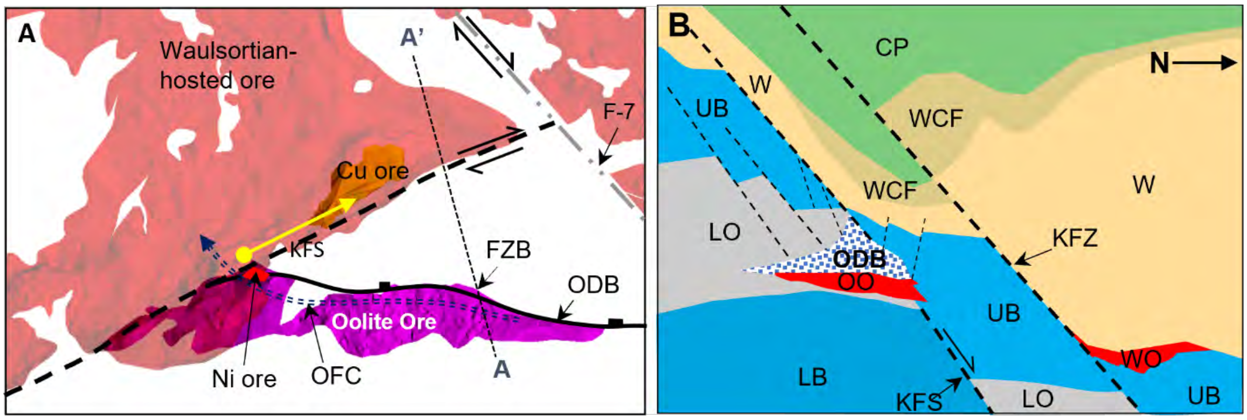


Figure 24. *(**A**): Oolite feeder conduit, (OFC) in fault and oolite dissolution breccias, (ODB) developed on the structural footwall of a Kiloran fault segment, (KFS). Fault zone breccias, (FZB) host minor ore. 3kt Ni ore in oolite occurs where the oolite feeder conduit intersects Waulsortian in the structural hanging-wall where a 40kt @7% Cu body was also developed. This Cu ore has been displaced (yellow arrow) by later inversion. (**B**): Section A-A' looking west. Dissolution of oolite above the ODB is significant. The oolite orebody, (OO) is developed at the base of the ODB above relatively undeformed oolite beds. Minor mineralization occurs within fault breccias associated with a bounding Kiloran Fault segment, (KFS), to the north. Most inversion is concentrated on the main Kiloran Fault Zone branch, (KFZ), to the north. (LB-lower Ballysteen, LO-Lisduff Oolite, UB-Upper Ballysteen, W-Waulsortian, WCF-Waulsortian cover facies, CP-Crosspatrick, WO-Waulsortian-hosted ore)*

lecting both bacteriogenic and hydrothermal sulphur input but with a stronger hydrothermal component than in Waulsortian hosted ore (Yesares *et al.*, 2019; Doran, 2022).

A somewhat different style of mineralization also occurs within the Lisduff Oolite on the structural footwall of the Kiloran fault. It is characterised by thick massive sulphide developments that are almost exclusively composed of fine, dark sphalerite and galena. Based on very limited mining that was conducted within them they occupy irregular, brittle and

irregular fault related fractures that can be up to 3m thick. The mineralization has a sharp contact with fractured oolite wall-rock which is undolomitized, completely unmineralized and separated from the sulphide by a thin 2mm layer of white calcite. It is highly irregular - sometimes steeply dipping and sometimes following bedding and can be intersected at any level within the Lisduff Oolite. It is poorly defined by drilling but have been encountered in a number of drill intersections, one over 150m south of the Kiloran Fault. Little is understood of its origin, but it is likely related to the same zinc and lead phase of the main mineralization, possibly accessing faults that developed by oolite dissolution and unavailable to earlier mineralization stages.

The Derryville Zone oolite mineralization is not as extensive as its Main Zone counterpart but from the limited mining conducted there it appears genetically quite similar. The Bog Zone West oolite orebody however is very different. Mineralization is developed within fractured footwall rocks associated with the Bog West Fault that are best developed within the Lisduff Oolite (Fig. 25F). The fractures are up to 2m thick and filled with massive fine-grained galena. There is minor replacement of wall rock oolites usually by pale sphalerite. Very minor chalcopyrite is present with the galena but there is no tennantite. The Waulsortian hosted Bog Zone West, orebody is relatively depleted in Pb for an orebody in this structural position (*cf.* Torremans *et al*., 2018). This may indicate that much of the Pb precipitated within the fault zone feeder before reaching the Waulsortian, leading to Pb mineralization on the fault plane, similar to that seen at the Silvermines G-Zone (Andrew, 1986). This would require that the fault zones had access to reduced sulphur bearing fluids (Torremans *et al*.,2018), implying that the faults were at least temporarily relatively conducive to downward fluid flow (Childs *et al*., 2009; Walsh *et al*., 2018). The Bog Zone East Waulsortian hosted ore is similarly depleted in Pb suggesting that a similar style of mineralization might exist there also. This possibility was however, not extensively investigated.

The Lisduff Oolite is the first clean carbonate that would have been encountered by metal-bearing fluids as they moved up through fault conduits. It is not considered to have been deeply buried at the time of mineralization and so was likely relatively permeable. That it is not extensively mineralized therefore might seem surprising, given many genetic models emphasize the importance of clean, reactive carbonates for mineralization (e.g., Wilkinson & Hitzman, 2014). Drilling intercepts of oolite further out in the structural hanging-wall and footwall confirm the absence of any mineralization.

This absence can be explained by the requirement for reduced sulphur to permit the precipitation of metal sulphides, with the ascending metal-rich fluids typically not sulphur rich, and in situ seawater derived brines typically sulphur rich (e.g., Hitzman *et al*., 2002; Wilkinson *et al*., 2005, 2009; Barrie *et al*., 2009). It is likely that fluids containing sulphur were segregated and unable to access the Lisduff Oolite through the impermeable Upper Ballysteen Formation above. Consequently, the metal-bearing fluids would have continued to migrate up without precipitating sulphides. Limited mineralization would have occurred utilizing any hydrothermally reduced sulphur that may have been present in the ascending fluids. Indeed, the Lisduff Oolite has commonly weak or trace mineralization

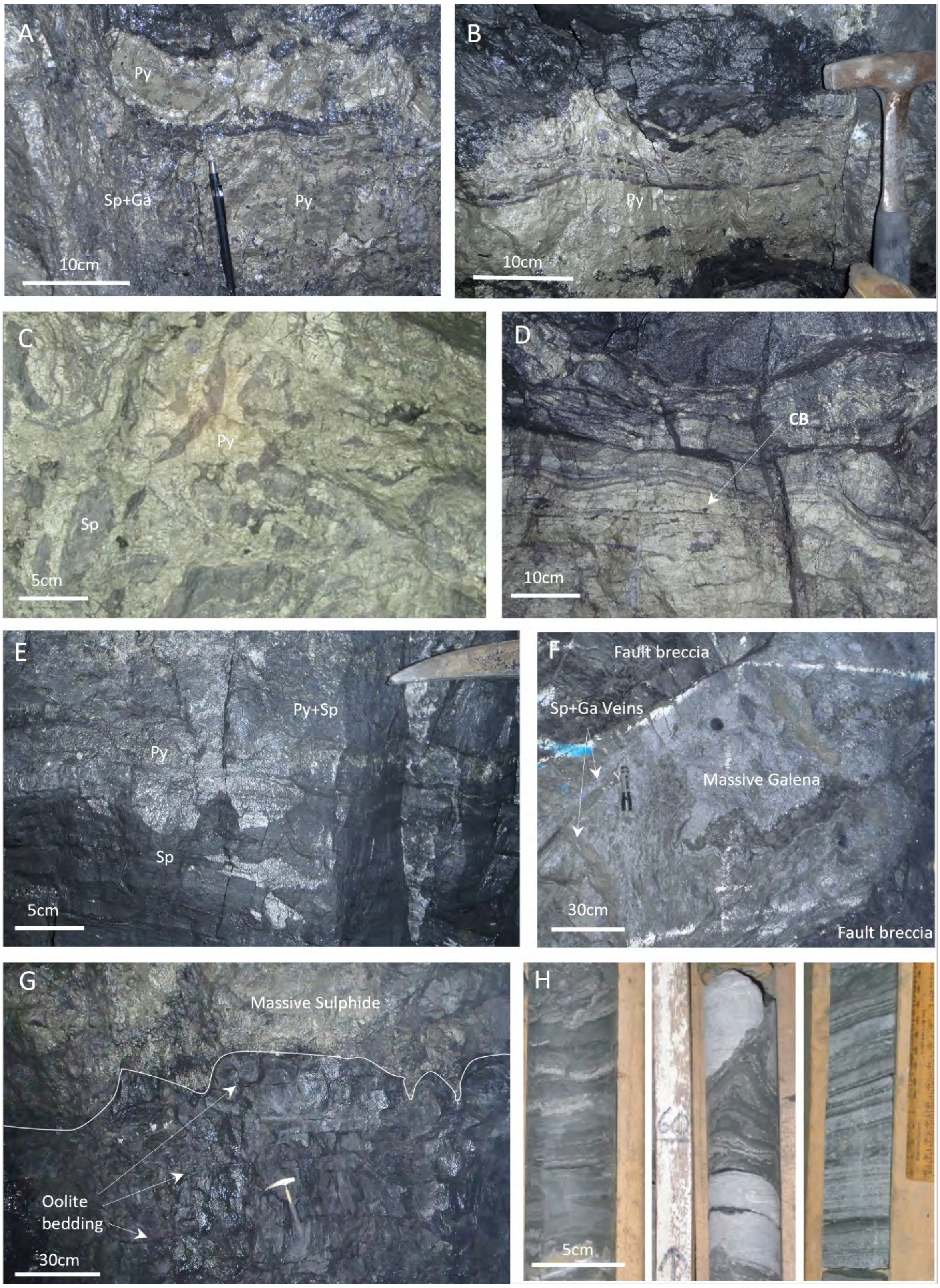


*Figure 25: Oolite ore textures: (**A**): Massive colloform pyrite clasts in matric largely replaced by sphalerite and galena. (**B**): Banded pyrite clast within oolite breccia. (**C**): Massive colloform pyrite with sphalerite replacement of finer grained cores. (**D**): Delicate replacement of oolite preserving possible crossbedding, CB. **€:** Massive, dark-grey, fine-grained sphalerite replacing pyrite in D above, while still preserving oolitic texture. (**F**): Massive, mainly fine-grained galena replacement of oolite within the Bog West Fault Zone that is cut by later compound, sphalerite and galena veins. (**G**): Sharp contact between base of massive oolite sulphide and relatively undeformed bedded oolite below. (**H**): Laminated resistates with 'dropstones' within the oolite breccia. All images Main South Oolite, Lisheen except F Bog Zone West, Lisheen.*

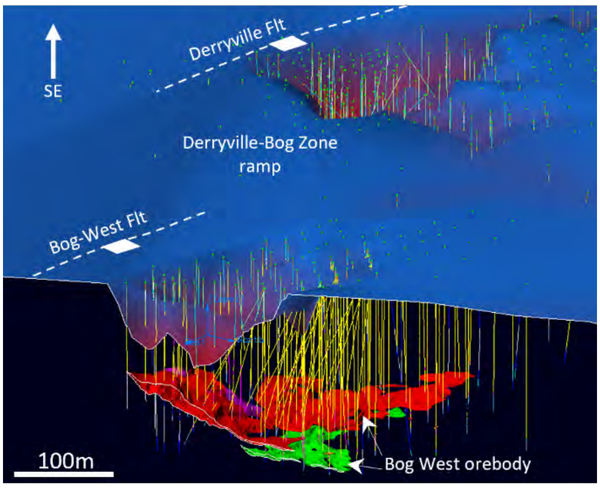


Figure 26: *Cut through a 3D model at Bog Zone West Zone, Lisheen, with base of the upper wavy-laminated, 'cover facies' surface (blue). The facies is best developed above the thickest ore in the hanging-wall of the ore controlling faults.*

where faulted by structures related to the main controlling structures.

The overall view is that oolite mineralization involved multiple pulses each working through that which went before. As a feeder conduit (Torremans *et al*., 2018), the oolite was likely the focus of many more fluid pulses compared to the Waulsortian. The hydrothermal fluids that produced the black matrix breccias likely accessed the Waulsortian via this conduit. The hydrothermal fluid that caused dissolution during black matrix breccia development likely had a similar or even greater effect on the oolite fault breccias given that here it was likely hotter and more confined.

It is likely that Lisduff Oolite fault breccias, related to the main ore controlling faults, would have provided a more permeable conduit for fluids migrating from depth than would other faulted, more argillaceous lithologies. Once accessed, fluids would then likely migrate along the fault plane following these breccias (Kyne *et al*., 2019). The geometry of the Main South oolite orebody at Lisheen is consistent with this path of fluid migration. It is an elongate, E-W trending body on the footwall of an extensional fault that parallels and bounds it to the north by juxtaposition with the argillaceous and impermeable Upper Ballysteen formation on the hanging-wall (Fig. 24). The ore is developed on the bottom contact of the Lisduff Oolite where the fluid was bound beneath by the more argillaceous Lower Ballysteen Formation. Despite the passage of hydrothermal fluids through this conduit however, it is unlikely, without the availability of sulphur, that there could have been any large-scale metal mineralization occurring.

Faulted oolites in juxtaposition with Waulsortian would certainly provide a good conduit for ascending fluids and a direct contact with the Waulsortian would promote access to the ultimate host lithology. However, it is worth noting that not all orebodies have oolite juxtapositions, including even some of the larger ones such as the R-Zone at Galmoy. Additionally, the Baunmore Pod, between Lisheen and Galmoy has mineralized oolite in the structural footwall but this is among the smallest mineralized bodies on the trend.

Dissolution related to mineralization

Dissolution related to the passage of hydrothermal fluids through the Lisduff Oolite is also recognised in other mineralized lithologies. Irregular argillaceous developments up to 20cm thick are often present between massive sulphides and truncated Ballysteen beds beneath are likely to be restitic (residual) in origin. In addition, encrinites and other typical transitional contact facies are poorly represented beneath massive sulphides compared to non-mineralized areas. The most significant dissolution, however, is related to black matrix breccia and sulphide mineralization within the Waulsortian. At Lisheen, where there is upper contact control, there is a notable thinning of the Waulsortian over thick developments of both, but particularly above massive sulphides. The preservation of Crosspatrick Formation above the Main Zone and parts of the Derryville Zone and its absence in the unmineralized areas between these orebodies is a direct consequence of this.

This relationship is best seen over the thick massive sulphide developed in the immediate hanging-wall of the major structures where the Waulsortian has been greatly thinned. Here dissolution is so intense that the Crosspatrick Formation has been drawn down in large fault-controlled blocks by dissolution of basal Waulsortian facies beneath (Fig. 26). Breccias that may be related to this collapse locally occur that are very different to black or white matrix breccias.

Based on drilling at higher levels within the Waulsortian above the Derryville orebody the breccias are polymictic containing both Waulsortian and Crosspatrick clasts, the latter being often well-rounded. The matrix is composed of Crosspatrick detritus liberated by dissolution and possibly also a Crosspatrick sediment washed down from above. Drilling intercepts above the Bog-Zone West orebody suggests that they form steeply-dipping irregular fractures of variable thickness. From observations in mining exposures in the orebody beneath they form very coarse breccias with large clasts of Waulsortian up to a few metres across in a matrix of dark dolomite and argillite (Fig. 27). Clasts include massive sulphides and the matrix is locally mineralized with fine-grained, cream-coloured sphalerite. This would suggest that they are contemporaneous with mineralization. This style of breccia is not encountered away from the main controlling faults and even here their abundance would appear insufficient to account for all the dissolution observed. Their occurrences may be localized to areas where breaching faults developed, linking early extensional faults segments and where the main fluid feeders into the Waulsortian ultimately developed.

Interpretation of the geological evolution

Five evolutionary summary diagrams of the Zn-Pb mineralized systems in the Rathdowney Trend are shown in Figure 28. They include the key observations described above from stratigraphic and structural observations, diagenetic and authigenic cement phases, as well as mineralization. The geometries on these diagrams are based on the well-constrained Lisheen deposit, but the key observations apply to the trend as a whole. The following sections should be read in conjunction with these diagrammes.

Figure 27: *Collapse breccia at the base of a thick massive sulphide development in Bog Zone West, Lisheen (**A, B,**). The breccia consists of blocks of mineralized black matrix breccia and barren Waulsortian dolostone in an argillaceous and dark dolomite matrix. Although much of the mineralization appears to pre-date brecciation, the matrix is locally replaced with pale sphalerite. (**C**): Very fine-grained, pale sphalerite forms the matrix in a breccia that includes earlier breccia clasts. The sphalerite is slightly deformed and appears to have precipitated during breccia development, during which pyrite was also deposited and fragmented. (dol.st. Dolostone, bx, Breccia, Sp, sphalerite, Ga, galena, Py, pyrite, bmb, black matrix breccia).*

Tectonic setting of sedimentation

Sedimentation along the Rathdowney Trend predates and continues through and after the development of the extensional fault array that controls the location of the trend's deposits. Differences between stratigraphic thicknesses and facies of the various formations on the structural footwall and hanging wall provides evidence for when faulting initiated and likely ceased (Sevastopulo & Redmond, 1999; Doyle, 2022).

The earliest indication from the stratigraphy that there might be some activity is in the Upper Ballysteen (Fig. 28A). At Lisheen, the footwall thickness (south of faults and ramp zones), from the base of Waulsortian to the top of the Lisduff Oolite, is c. 80-90m. This is c. 30-40m thinner than those typically drilled in the hanging wall. While many of the holes that indicate reduced thickness are close to the fault zone and could have been structurally thinned, minor structures present in the cores appear too small to account for the magnitude of stratigraphic loss involved. Although the hanging-wall sequence is sometimes structurally thickened by subsequent inversion, the thicker sections are not just confined to the immediate hanging-wall but more generally within the structural hanging-wall. It is worth emphasising that the transition from Ballysteen to Waulsortian is complex and diachronous. This appears unlikely and if true coincidental. No appropriate recognisable tuff horizons were seen in either lithology from any of the holes drilled.

Establishing evidence of syn-rift deposition during growth of the Waulsortian Formation based on footwall and hanging-wall thickness differences is difficult as its thickness is very variable to begin with. In two footwall locations 7km apart and 3km to the southwest and southeast of Lisheen, it is 260m and 130m thick respectively. In the structural hanging-wall at Lisheen it is typically in the order of 200m. Due to this inherent variability and the absence of the upper contact control in the immediate structural footwall it is not possible to definitively establish if there is difference in thickness directly across the fault. At Rapla where there is more proximal footwall control the Waulsortian is marginally thinner, c.150m, than in the immediate hanging-wall where it is marginally thicker c.160-180m. This difference is probably not significant given inherent thickness variability and uncertainties in the actual structural configuration.

At Lisheen, the presence of a greatly thickened wavy laminated, cover facies in the immediate hanging-wall of all the major fault strands has been previously interpreted to suggest that faulting had initiated at this time (Fig. 28B & 28C; Kelly, 1993). The absence however, of a corresponding displacement of the Ballysteen contact beneath, necessary to accommodate this thickening, is problematic (Figs. 24 & 26). One would have to advocate inversion of the extensional fault geometry of a greater magnitude than what is currently envisaged. At Rapla, a cover facies is also widely developed but shows no significant thickening next to similarly scaled faults. At Galmoy the upper Waulsortian is not preserved.

There is good evidence of syn-rift deposition of the Crosspatrick (Fig. 28D) from thickness variations at Rapla where there is control on thicknesses in both structural hanging-wall and footwall sections. Here in the footwall, it is c.50-60m thick whereas in the hanging-wall it is c.150-160m. The chert nodules that are typically abundant in the Crosspatrick are largely absent in the immediate footwall of the normal faults. At Lisheen, the lowermost Crosspatrick preserved in the immediate hanging wall commonly appears disturbed, possibly by slumping which may indicate sedimentation in an active tectonic environment.

The upper age of the faulting in the Rathdowney trend is currently not well constrained.

Timing of mineralization

Evidence from thickened Waulsortian cover facies in the hanging-wall of faults

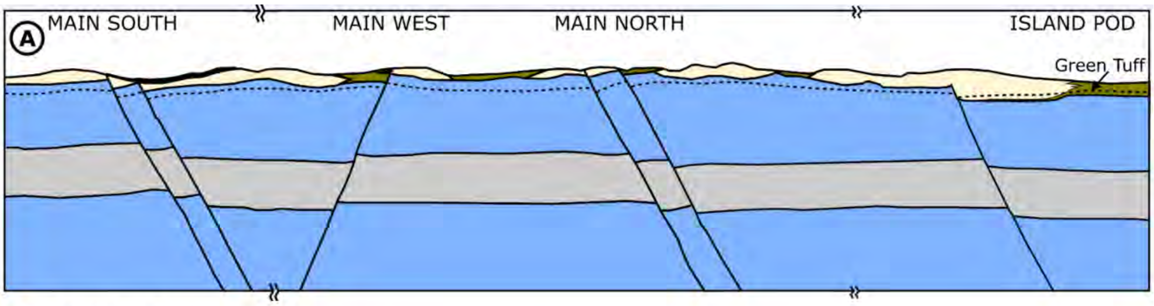
Wilkinson *et al.* (2011) interpreted that the dissolution related to mineralization might have also caused the depressions necessary to facilitate the deposition of thickened wavy-laminated, cover facies at these locations (Fig. 28C). This is consistent with the location of its development – namely above the most heavily mineralized faults of the largest orebodies (Figs. 24 and 26). It implies that mineralization commenced during late Waulsortian development (Fig. 28C). Although many mineral parageneses related to regional dolomite development interpret the regional dolomite to exclusively pre-date the black matrix breccia (Redmond, 1997; Sevastopulo & Redmond, 1999; Hitzman *et al*., 2002; Doran, 2021), which would imply regional dolomitization was likely to be later than the Crosspatrick Formation, thereby suggesting that a dissolution generating black matrix is impossible at this time. If, however, the regional dolomite is a longer-lived event, spanning the upper Waulsortian and early Crosspatrick development then timing constraints related to the Crosspatrick are removed.

Evidence from juxtaposition of Waulsortian and Lisduff Oolitic-hosted ores

The juxtaposition of mineralized Lisduff Oolite in the structural footwall of the main ore-controlling faults with Waulsortian hosted ore in the hanging-wall has often been cited as evidence that the mineralization post-dated extensional faulting (e.g., Shearley *et al*., 1996; Sevastopulo & Redmond, 1999; Hitzman *et al.*, 2002). The mixing of bacteriogenic reduced and hydrothermal sulphur in oolite-hosted ores (Yesares *et al*., 2019; Doran, 2022) would certainly suggest that both were at least in close proximity during mineralization. This does not preclude, however, the possibility that hydrothermal fluids were passing through the oolite during fault development generating dissolution breccias and minor mineralization utilising hydrothermal sulphur. The geometry of the oolite dissolution breccia bodies which terminate at the extensional fault contact suggests continued movement after their generation and that collapse breccias developed on the structural hanging-wall were progressively displaced down-dip (Figs. 28B to 28D).

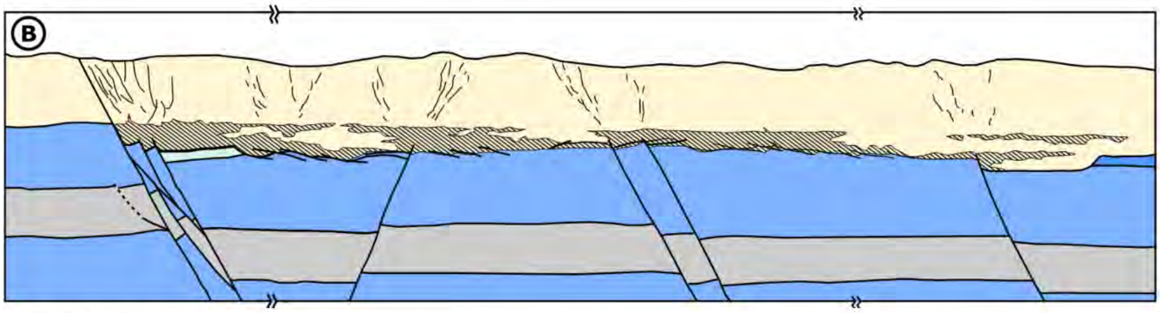
Evidence from metal distributions

Although the distribution of the early pyrite and main Zn-Pb metal mineralization stages largely overlap there are distinct trends within the deposits that appear to have only been mineralized by the later Zn-Pb phases (Figs. 28C and 28D). This suggests an evolving structural control during mineralization (Torremans *et al*., 2018). These trends are associated with the northwest-southeast extensional fault arrays described earlier.



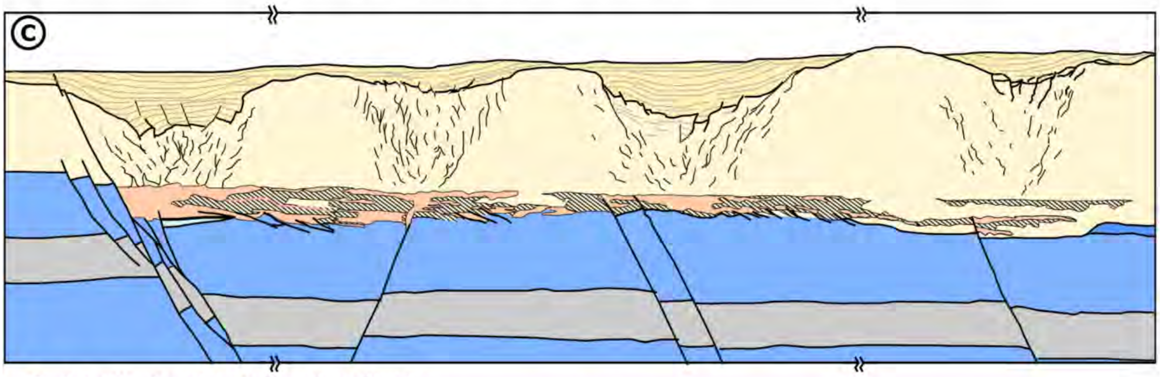
A. Early fault development

- Extension initiates during late-Ballysteen to early Waulsortian development with many small displacement faults.
- Diachroneity of the contact. Bioherm development synchronous with Ballysteen, nodular micrite facies.
- Earliest Waulsortian development at Island Pod where the Green tuff is within inter-mound facies.
- Shale band developments locally in the Waulsortian possibly in HW of structures.



B. Early hydrothermal Phase

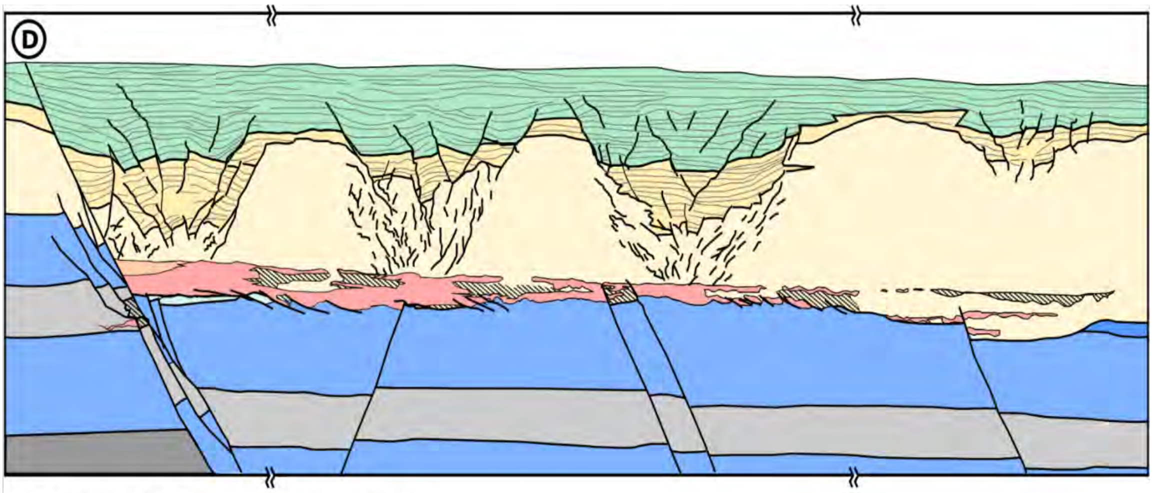
- Regional dolomitization soon after lithification. Preservation of Waulsortian limestone beneath shale bands.
- Continued extension resulting in development of low-angle faults at contact.
- Fault death: Most displacement on just a few structures. Smaller structures cease development.
- Breaching between fault segments on larger structures provides good conduits for fluid flow. Faulted Oolite becomes an important conduit and focus for dissolution.
- Hydrothermal dolomitization and dissolution at base of Waulsortian generating black matrix breccias. Fluids access faults at contact and are contained by impermeable Ballysteen beneath and in fault juxtaposition to south.
- Despite their high temperature, the hydrothermal fluids are stratified at the base of the Waulsortian.
- Extension and dissolution promotes development of white dolomitic breccias in Waulsortian above.
- Mineralization at Island Pod largely off the base Waulsortian contact.



C. Late Waulsortian, Pyrite mineralization

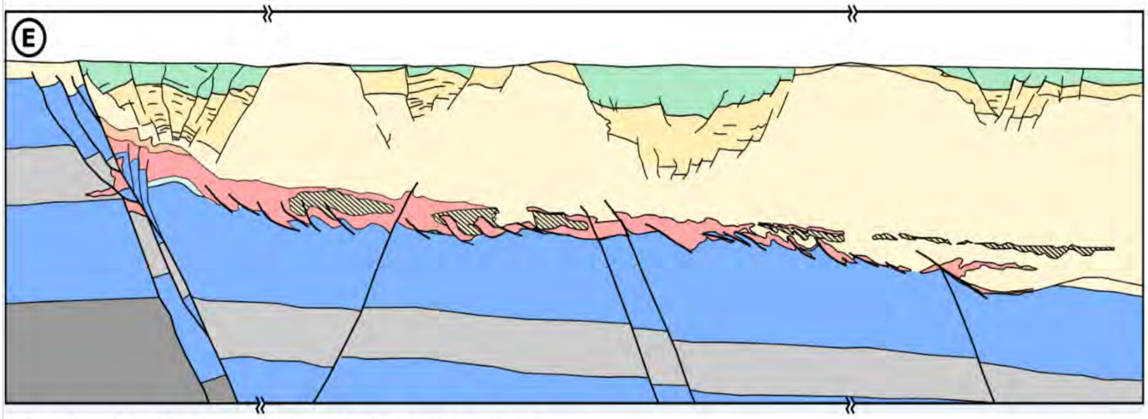
- Massive pyritic bodies develop largely by replacement of black matrix breccias. This is strongest in the hanging-walls of structures where fluid flow is most intense. Stratiform pyrite lenses also develop out into breccias from controlling fault conduits. Hydrothermal dolomitization continues.
- Intense dissolution of Waulsortian in areas of most intense mineralization creating depocenters for increased thicknesses of cover facies developing above. These are also the sites of intense white matrix breccia development.
- All displacement now on ore-controlling structures to south.
- Dissolution in the Lisduff Oolite initiates collapse and fault development above.

Figure 28 (Part 1): *Development of the Lisheen, Main-Zone orebody. The section highlights areas of structural and mineralization interest at Main Zone: South, West and North and at the Island Pod. The line of section is indicated on Figure 6, (solid line). The dashed line portion of the section has been omitted at locations indicated on the margins of each section.*



D. Crosspatrick, base metal mineralization

- *Last Waulsortian bioherm gives way to Crosspatrick development.*
- *Continued extension on main ore-controlling structures*
- *Zn-Pb mineralization replaces mainly massive pyrite bodies and hydrothermal breccias but also certain permeable dolomitized Waulsortian facies. Synchronous ongoing going hydrothermal dolomitization and breccia development.*
- *Strongest fluid flow and consequently replacement and grade at base contact of pyrite bodies.*
- *Development of new, northwest – southeast trending extensional fault arrays that provide additional conduits for base metal fluids.*
- *Associated dissolution affects Crosspatrick sedimentation.*
- *Replacement of oolite pyrites and dissolution breccias. Now in close juxtaposition with Waulsortian in hanging-wall.*



E. Cessation of extension, mineralization and post ore events

- *Full displacement approx. 180m.*
- *Mineralization likely continues to end of extensional tectonic phase.*
- *Waulsortian thickness greatly reduced in areas of most intense mineralization.*
- *Late-stage Ni and Cu minerals develop in the oolite breccias and adjacent Waulsortian, now juxtaposed in the structural hanging-wall.*
- *Later inversion reactivates the extensional structures. Contact low-angle extensional structures are folded and the orebody is deformed up against ore-controlling faults as old fault segments are reactivated.*

Stratigraphic Units

Crosspatrick
Waulsortian cover facies
Waulsortian Fm
Waulsortian Lst.
Ballysteen Fm
Lisduff Oolite
Lower Limestone Shales

Alteration / Mineralization

Black matrix breccia
Massive Sulphide (pyrite)
Massive Sulphide (pyrite & base metals)

Figure 28 (Part 2): *Development of the Lisheen, Main-Zone orebody. The section highlights areas of structural and mineralization interest at Main Zone: South, West and North and at the Island Pod. The line of section is indicated on Figure 6, (solid line). The dashed line portion of the section has been omitted at locations indicated on the margins of each section.*

They are typically Zn/Pb rich relative to Fe and do not appear to have been present during the early pyrite mineralization. Their development appears to have opened new conduits for base metal mineralization and cut off flow to areas of early pyritic mineralization. On the western margin of the G-Zone at Galmoy the development of one such trend directed base metal mineralization along the K23 fault to the K and K2 orebodies. This development diverted fluids from thick early pyrite developments in the G-Zone that are much closer to the source feeder on the G-Fault. Similar trends are present but less obvious at Lisheen as they largely overlap existing mineralization. A thick E-W trending, pyritic body associated with the Main-North Fault, hosts its highest-grade base metal mineralization on its eastern flank associated with a northwest-southeast extensional fault that intersects it. If all the mineralization at Lisheen and Galmoy post-dated extension it is difficult to explain how these structural trends would not have been extensively exploited by paragenetically earlier pyrites and why large bodies of pyrite, adjacent to the main ore-controlling faults and their associated feeders, would have been overlooked by paragenetically later base metal sulphides.

Direct isotopic evidence

Re-Os geochronology conducted by Hnatyshin *et al*. (2015; 2020) on ore-stage pyrite from the Lisduff Oolite at the Lisheen deposit provides an age of 346.6 ± 3.0 Ma. This overlaps with the probable depositional age range of the Waulsortian at Lisheen (353–347 Ma; Sevastopulo & Redmond, 1999; Waters *et al*., 2011; Somerville *et al*., 2012) and is consistent with mineralization during the late Waulsortian when the cover facies was being deposited (Figs. 28C and 28D). The massive sulphide sample used in the analysis by Hnatyshin *et al*. (2015) was assumed to be early pyrite but given the abundance of late-stage, post base-metal, massive pyrite in the oolite, it is hard to be certain of its exact place in the broader deposit paragenesis. If it is a late-stage pyrite it would place the commencement of mineralization even earlier in the Waulsortian.

Mineralization related to inversion?

The orebodies of the Rathdowney have all been deformed by later inversion and there is no question that the vast majority, if not all, of the mineralization pre-dates this event (Fig. 28E). Most sulphide occurrences that are developed higher in the Waulsortian are likely related to the main mineralization and possibly related to the rare escape of base metal fluids out through white matrix breccia fractures associated with normal faults. However, a number of these mineral occurrences are adjacent to or up-dip of structures that are known to be significantly inverted at the orebody level. This includes vuggy-hosted honey-blend sphalerite at Rapla, previously mentioned, and an extensive buck-shot lead development within white dolomitic breccias at the Island Pod. Although insignificant economically, if these occurrences are related to inversion, it would suggest that inverted structures could be anomalously elevated in metals. They could therefore present a geochemical target at the surface regardless of if this is in post-rift stratigraphy. A very tight soil geochemical anomaly is present above the inverted, Kiloran Fault at Lisheen, (M. Hitzman, *pers. comm*. 2017), and above the inverted Rapla fault, where its surface expression is in rocks much higher in the stratigraphic sequence (A. Milner *pers. comm.*, 2014).

Controls on mineralizing processes and original deposit geometry

Importance of base Waulsortian extensional structures

Just as with black matrix breccias, faulting exerts a major control on ore thickness and distribution of metals. The larger structures provided a conduit for hot metal-bearing fluids from basement lithologies to enter the Waulsortian at discrete feeder zones (Torremans *et al*., 2018). Metal distributions (Zn:Pb ratios, Cu, Ni) indicate that the fluids progressed northwards from the feeder zones along the Ballysteen-Waulsortian contact replacing black matrix breccias and previous pyrite-marcasite mineralization (Torremans et al., 2018). An important conduit for this flow was the network of small-displacement, low-angle extensional structures that were previously accessed by hydrothermal fluids to generate black matrix breccias, as illustrated in Fig. 7 and Fig. 8. Distal from feeders, the fluid's potential for carbonate replacement is much reduced and consequently mineralization becomes increasingly patchy and tightly restricted to fault conduits.

Extension through normal faulting is often associated with and kinematically linked to bedding-parallel slip (Ferrill *et al*., 1998; Delogkos *et al.*, 2022). We interpret the development of early low-angle structures at the Ballysteen - Waulsortian contact to have provided a critical initial conduit for hydrothermal fluids migrating northwards, out along the contact from the main east-west ore-controlling faults. They are a common feature of the mineralization at Galmoy and Lisheen and away from the main ore-controlling faults host the thickest and highest-grade ore. It is possible that these structures also occur at Rapla. Based on existing drilling at Rapla they appear to be less developed and here the lithological contact often appears unfaulted and structurally benign, although drilling density is insufficient to adequately elucidate their full distribution. Instead, much of the mineralization at Rapla appears to be adjacent to the east-west controlling fault zones themselves. The reasons for this are unclear despite a similar lithological and structural setting to Lisheen and Galmoy.

Mineralizing processes and controls on fluid flow

Mineralization within Irish-type Zn-Pb deposits occurs by replacement of Lower Carboniferous marine carbonates resulting from fluid mixing of high-temperature, high salinity, reducing metal-bearing fluids and low-temperature, medium-salinity seawater-derived fluids (Banks *et al.*, 2002; Wilkinson *et al.*, 2005, 2009; Barrie *et al*., 2009; Wilkinson, 2010). Based on textural, isotopic, and geochemical signatures of layered sphalerite at Galmoy and Navan, the fundamental trigger for rapid sphalerite precipitation at these deposits is interpreted to be the influx of deep sulphur-poor hydrothermal fluids into a shallow reservoir of bacteriogenic sulphur-rich fluids (Barrie *et al*., 2009; Gagnevin *et al.*, 2012, 2014), similar to many Zn-Pb deposits worldwide (Muchez *et al*., 2005).

An important observation which is not yet understood is the occurrence of flat-lying, stratified geometries of sulphide mineralization and to a lesser extent the black matrix breccia (Figs. 17 and 28). This mineralization is relatively flat-lying despite significant variability in the elevation of units below, for example resulting from extensional faulting, signifying these bathymetries likely developed prior to ingress of the fluids generating the flat-lying mineralization (e.g. Fig. 17). At mine exposure scale, horizontal, thinly banded sulphides of varying mineralogy are developed which are often individually monomineralic (Fig. 25). These have developed by replacement across the fabric of the heterogeneous black matrix breccias that host them (Figs. 23 and 25). They therefore possibly represent mineralization due to mixing at the contact between two fluids with different densities. This may indicate stratification of fluids in significant secondary permeability, or in significantly permeable connected pore-space within the Waulsortian rock mass, bounded below by the impermeable Ballysteen Limestone (Figs. 28B to 28C). The absence of hydrothermal dolomite, sulphides or any litho-geochemical indicator at the same contact in the structural footwall would suggest that, at the onset of hydrothermal activity, faulting must already have been initiated and sufficient to contain fluid progress north of the north-dipping faults where it would be juxtaposed against the Ballysteen formation (Fig. 28).

The paucity of mineralization within the Waulsortian above the orebody at Lisheen and the absence of any substantial geochemical anomaly in soils that rest directly on it suggests that metals must have been very efficiently removed from the hydrothermal fluids before they progressed further up through the Waulsortian. Limited clumped C-O data from white matrix breccia dolomites indicates high but falling temperatures up section (Hollis *et al*., 2017), suggesting a hot fluid mixing with a colder fluid or thermally equilibrating, as it rises through the Waulsortian. In mineralized areas it is possible therefore that the white matrix breccia cements were, at least in part, precipitated from remnant hydrothermal fluids (Hollis *et al*., 2017; Yesares *et al.*, 2019). Although containing and depositing minor metals in white matrix breccias proximal to the orebodies (e.g., Fig. 14), these fluids were largely stripped of their metals at the ore horizon.

Controls on fertility and size

The deposits of the Rathdowney Trend share a common lithological and structural setting and yet they exhibit very different sizes. As in many mineral systems, a major factor that controls the size of these deposits is most probably the quantum of hydrothermal fluids that accessed the controlling fault segment, and equally importantly, how they are focused (Corbella *et al*., 2004; Muchez *et al.*, 2005; Walsh *et al.*, 2018; Palmowski *et al*., 2023). The exact mechanism by which fluids reach and interact with basement rocks and bring metals to higher stratigraphic levels is not entirely understood.

Despite the seeming lack of connectivity of individual fault segments at the stratigraphic level of the orebodies, it is thought that they connect at depth, likely controlled by basement irregularities (Kyne *et al*., 2019). Given the broad coincidence of gravity lineaments (Johnston *et al.*, 1996; O'Reilly *et al.*, 1999) with magnetic lineaments (Fig. 3), it is likely that all fault arrays on the Rathdowney Trend are connected to the same, or similar, underlying basement trend(s) and it is therefore possible that they are also all fundamentally hydraulically connected, at least transiently so.

Recent high precision measurements of lead isotope ratios reveal systematic changes moving north-eastwards from Main Zone at Lisheen along the orebodies of the Rathdowney Trend to Rapla (Steve Hollis, *pers. comm*, 2020; Yesares *et al.*, 2019; Doran *et al*., 2022). The lowest average Pb isotope ratios coincide with Main Zone, where the generally left-stepping, extensional Rathdowney Trend fault array suddenly steps to the right, onto the Barnalisheen Fault (Figs. 2 and 3). If these changing signatures are related to crustal contamination during fluid migration this would certainly suggest fluid connectivity at depth, and it can possibly explain why deposit clusters become smaller north-eastwards. Such inherent basement complexities or changes in basement geology would be critical to controlling fluid flow at depth and may well be why the largest known mineralization along the whole trend is located at Main Zone (Walsh *et al*., 2018).

Our evolutionary compilation (Fig. 28) shows that fault growth coincides with the generation of black matrix breccias and both early iron and main stage Zn-Pb mineralization. This co-evolving structural-stratigraphic architecture provides an explanation for (a) the mechanisms required for driving thousands of fluid pulses to generate deposits of economic size, whether co-seismic or otherwise, (b) the changing fluid flow pathways seen from metal distributions and paragenetic sequences, and (c) the gradual intensification of the hydrothermal systems over time, as the fault networks developed and became increasingly connected at depth into basement. It is worth highlighting that seismic pumping typically generates the greatest fluid flow along faults following seismic activity (Walsh *et al.*, 2018), and it may well be a key, if not the most applicable mechanism to the deposits of the Rathdowney Trend.

Conclusions

Lisheen and Galmoy are the quintessential Irish-type deposits. Faults provided conduits for very hot fluids to access Waulsortian host-rock from the basement and to migrate along its base contact with the Ballysteen. Permeability at the contact was enhanced by dissolution and dolomitization of the Waulsortian. This together with faulting promoted fracture development above to higher levels in the Waulsortian. These fluids were contained within developing breccias at the base of the Waulsortian by impermeable Ballysteen beds beneath and in fault juxtaposition to the south. A cooler, more saline fluid, derived from Carboniferous seawater, accessed the base of the Waulsortian via faults and fractures. These solutions contained dissolved bacteriogenic reduced sulphur that resulted in the precipitation of sulphides when metals were eventually carried in with the hydrothermal fluid. Lithological development, metal distributions and direct isotopic dating of sulphides all suggest that mineralization is likely contemporaneous with fault growth and had initiated shortly after faulting commenced during deposition of upper Waulsortian facies. Mineral paragenesis is likely linked to fault development with increasing displacement permitting access to a greater volume of source-rock.

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