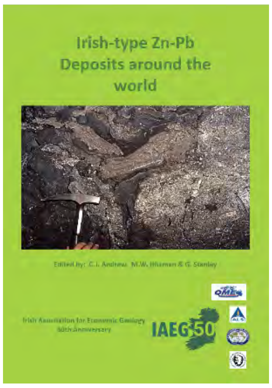

Irish-type Zn-Pb Deposits around the world

Ore depositional processes at the carbonate-hosted Tara Deep Zn-Pb deposit, Navan, Ireland

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Ore depositional processes at the carbonate-hosted Tara Deep Zn-Pb deposit, Navan, Ireland

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Abstract: The Tara Deep Zn-Pb deposit (currently 26.2 Mt @ 8.4% Zn, 1.6% Pb) is the latest major discovery by Boliden Tara Mines (first announced in 2016) which significantly adds to the existing world-class Navan deposit. Located 2 km south of the Navan deposit in Co. Meath, Ireland, economic mineralization is hosted by upper Tournaisian carbonates (Pale Beds; 87% of the total economic resource), within a degraded footwall of a major south-dipping normal fault, and also within lower Visean sedimentary breccias ('S Fault' Conglomerates; SFC). Sphalerite and galena are the dominant sulphides, with massive, cavity fill and brecciated textures dominating. These textures attest complex, subsurface, episodic mineralization events that display considerable reworking, fracturing, dolomitization, open-space infill and selective replacement. Lower Visean syn-rift sliding, erosion, and deposition of thick debrites and calc-turbidites at Tara Deep record basin margin processes near extensional faulting associated with formation of the Dublin Basin. These debrites host detrital sulphide-rich clasts and offer unambiguous evidence that the onset of mineralization occurred during the upper Tournaisian. δ^{34}S values of base metal sulphides have a bimodal distribution suggesting both bacteriogenic (-13.5 to -3.6‰) and hydrothermal sulphur sources (+3.4 to +16.2‰). Both textural and sulphur isotope data reveal the dynamic nature of mineralization at Tara Deep and infer fluid mixing. Lead isotope analyses display remarkably homogeneous ^{206}Pb/^{204}Pb of 18.23 ±0.006 (2σ, n=25), which is coincident with Pb isotope data across the Navan deposit. Subsequently, Tara Deep and Navan are isotopically similar, showing both a statistically identical Pb isotopic signature and a bimodal sulphide S isotopic distribution and homogeneous sulphate signature. In particular, the Pb isotopes and the hydrothermal S signature, correlate with Navan and support the view that base-metals were leached from the underlying Lower Palaeozoic basement, and suggest that similar deep, circulating metalliferous fluids were also involved at Tara Deep. However, despite these similarities, key differences can be recognized within the S isotope data; around 5‰ shifts to higher δ^{34}S in the surface-derived S isotope signatures (both bacteriogenic sulphide and sulphate) indicate that Tara Deep's sulphur was sourced from a distinct seawater/connate fluid signature. The Tara Deep deposit has many similarities with the neighbouring Navan deposit reflecting comparable controls on the mineralizing processes in terms of host rocks, Pb and S sources, and tectonic environment. Mineralization initiated during an early phase of the developing Dublin Basin (syn-diagenetically) and kept pace with rifting and subsequently an evolving basin.

Keywords: Zn-Pb Mineralization, Tara Deep, Irish-Type, Navan, Petrogenesis, S Isotopes, Pb Isotopes.

Introduction

The Navan deposit is a world-class carbonate-hosted Zn–Pb orebody, hosted in upper Tournaisian carbonates, and mined by Boliden Tara Mines, with total production and remaining resources (excluding Tara Deep), exceeding 125Mt at end 2020. Following a seismic survey in late 2012, first drilling in the Tara Deep region, 2 km SE of the existing mine's Southwest Extension (SWEX, Fig. 1), intersected 32.5m of mineralization at 11.1% Zn and 3.0% Pb at a depth of 1.6km (Ashton *et al.* 2018). Hosted in the footwall of a large south-dipping basin margin fault, Tara Deep occurs at depths of between 1.2

and 1.9km. The current inferred resource at this new discovery is 26.2Mt @ 8.4% Zn and 1.6% Pb (Boliden Summary Report, 2020), and the deposit remains open to the south and west.

Navan is by far the largest Zn+Pb deposit yet discovered in the Irish Zn+Pb(±Ag±Ba) orefield and has dominated European zinc production for over 40 years. It is a type example of an Irish-type carbonate-hosted base-metal deposit (Singer, 1995; Wilkinson, 2010; Wilkinson & Hitzman, 2015). These deposits are typically limestone/dolomite-hosted, with sphalerite dominating galena, typically by a ratio of 5:1 or greater. Variable but locally major pyrite, marcasite, barite and anhydrite occur, with minor sulfosalts and rare Cu-sulphides. They have features in common with both SedEx and MVT deposits, such as MacArthur River, Red Dog, the Alpine-type deposits and deposits in the Selwyn Basin (Wilkinson, 2014). This cross-over between the two styles, characterizes the deposits as a distinct style - Irish-type - and has also led to controversies in their genetic understanding (Peace & Wallace, 2000). What is agreed, are that these deposits have formed by mixing of two fluids –1) a deep, basement derived, metal-bearing hydrothermal fluid of moderate salinity with temperatures reaching at least 250° C; 2) a highly saline groundwater, or subsurface brine, derived from evaporation of Mississippian seawater (Boast *et al.*, 1981a; Samson & Russell, 1987; Banks & Russell, 1992; Banks *et al*., 2002, Wilkinson, 2010; Ashton *et al*., 2015). Major Caledonian fault systems, reactivated during Mississippian extension, likely related to crustal thinning (Russell, 1968; Boyce *et al,*, 1983a; Davidheiser- Kroll *et al*, 2014), exerted key structural controls on focusing fluid flow (Russell, 1978, 1986; Wilkinson & Hitzman, 2015). Pb isotopic evidence indicates that metals were sourced from the underlying basement, particularly the Lower Palaeozoic package of sediments and volcanic rocks, rather than regional or trans-continental fluid flow through the Tournaisian Red Beds of the Munster Basin or the Irish Midland Basin (LeHuray *et al*., 1987; Everett *et al*., 2003; Walshaw & Menuge, 2006; Fallick *et al*., 2001).

A dominance of bacteriogenic sulphide is also an essential ingredient of the economic Irish-type deposits (Fallick *et al*., 2001), a feature shared, for example, with Alpine-type deposits (Schroll & Rantisch, 2005; Henjes-Kunst *et al*., 2017). An association with Mississippian volcanic diatremes and extrusive rocks at Pallas Green, Co. Limerick, has added a new element to the complex nature of these deposits (Elliot *et al*., 2019), although He isotopes had already identified a mantle contribution to the genetic system for all economic Irish-type deposits (Davidheiser-Kroll *et al*, 2014).

In this context, this research presents the first detailed examination of the new Tara Deep discovery with focus on the stratigraphy, mineralogy, textures, and S and Pb isotope geochemistry. The relationship to the Navan deposit (see Anderson *et al*., 1998, and Ashton *et al*., 2015) is explored to help constrain a genetic model and widen our understanding of Irish-type deposits. The Tara Deep deposit has many similarities with the existing Navan deposit, reflecting comparable controls on the mineralizing processes in terms of host rocks, Pb and S sources, and tectonic environment. Tara Deep thus offers exciting potential for future expansion of resources.

Geological Context

Regionally, Zn–Pb mineralization in the Irish Orefield is hosted by Mississippian (upper Tournaisian) rocks, within both the Waulsortian Limestone Formation and the Navan Group (Hitzman & Beatty, 1996; Wilkinson & Hitzman, 2015; Phillips & Sevastopulo, 1986; Hitzman *et al*., 2002; Hitzman *et al*., 1995; Lee & Wilkinson, 2002). The Navan deposit, including Tara Deep and some smaller deposits in the north-eastern Irish Midlands e.g., Clogherboy and Tatestown, are hosted mainly by micrites of the basal Tournaisian limestone sequence (Pale Beds; see Strogen *et al*., 1996; Ashton *et al*., 2015). These rocks were deposited in tropical, typically photic to sub-photic seas and associated with sedimentary basin development during crustal extension (Boyce *et al.*, 1983a; Philcox, 1989). Further south and west in the Irish Orefield, the Lisheen, Galmoy, Tynagh, Silvermines and Pallas Green deposits are hosted in dolomitized Waulsortian limestones (Hitzman & Beatty, 1996). Irish-type carbonate-hosted deposits are typically concentrated near normal, syn-sedimentary faults, which in the Navan area are associated with the northern margins of the Dublin Basin (Russell, 1986; Wilkinson & Hitzman, 2015; Ashton *et al*., 2015). The morphology of these orebodies are broadly stratabound and occur as single or multiple lenses hosted by permeable and/or reactive horizons within the host rocks (Ashton *et al*., 2015). There is significant evidence for syn-diagenetic deposition of some of these ores e.g. mineralized clasts in debris flow breccias (Boyce *et al.*, 1983a; Ford, 1996; Anderson *et al*., 1998; Blakeman *et al*., 2002), hydrothermal vent phenomena (Boyce *et al.*, 1983b, 2003; Banks & Russell, 1992), and for purely epigenetic subsurface replacement and open-space textures (Boyce *et al.*, 1983a,1983b; Taylor, 1984; Blakeman *et al.,* 2002; Anderson *et al*., 1998; Everett *et al*, 1999) intimately associated with dolomitization of the host sequence (e.g. Braithwaite & Rizzi, 1997; Gregg *et al*., 2001; Lee & Wilkinson, 2002). The bulk of the Zn-Pb mineralization appears to have been deposited epigenetically, but very early in the diagenetic history of the host rocks and basin evolution.

Navan Geology

Navan is located immediately south of the Longford Down Lower Palaeozoic Inlier, within a major NE to ENE-trending structural corridor approximately coincident with the underlying Iapetus Suture (Vaughan & Johnston, 1992). To the south and west are Mississippian platformal carbonates and calcturbidites of the developing Dublin Basin.

The Navan local stratigraphy records an overall marine transgression during the upper Tournaisian-lower Visean and contains pre-, syn-, and post-rift elements. These rocks lie on a regional unconformity overlying Ordovician and Silurian volcano-sedimentary and igneous rocks, originally deposited on the Laurentian and Avalonian margins of the Iapetus Ocean (Romano, 1980; O'Keeffe, 1986, Murphy *et al.*, 1991 ; Fritschle *et al.,* 2018). The Tournaisian Old Red Sandstone (ORS) of the Irish Midlands represents the oldest of the local Early Mississippian units and marks the start of the transition from subaerial to submarine deposition (locally termed Red Beds).

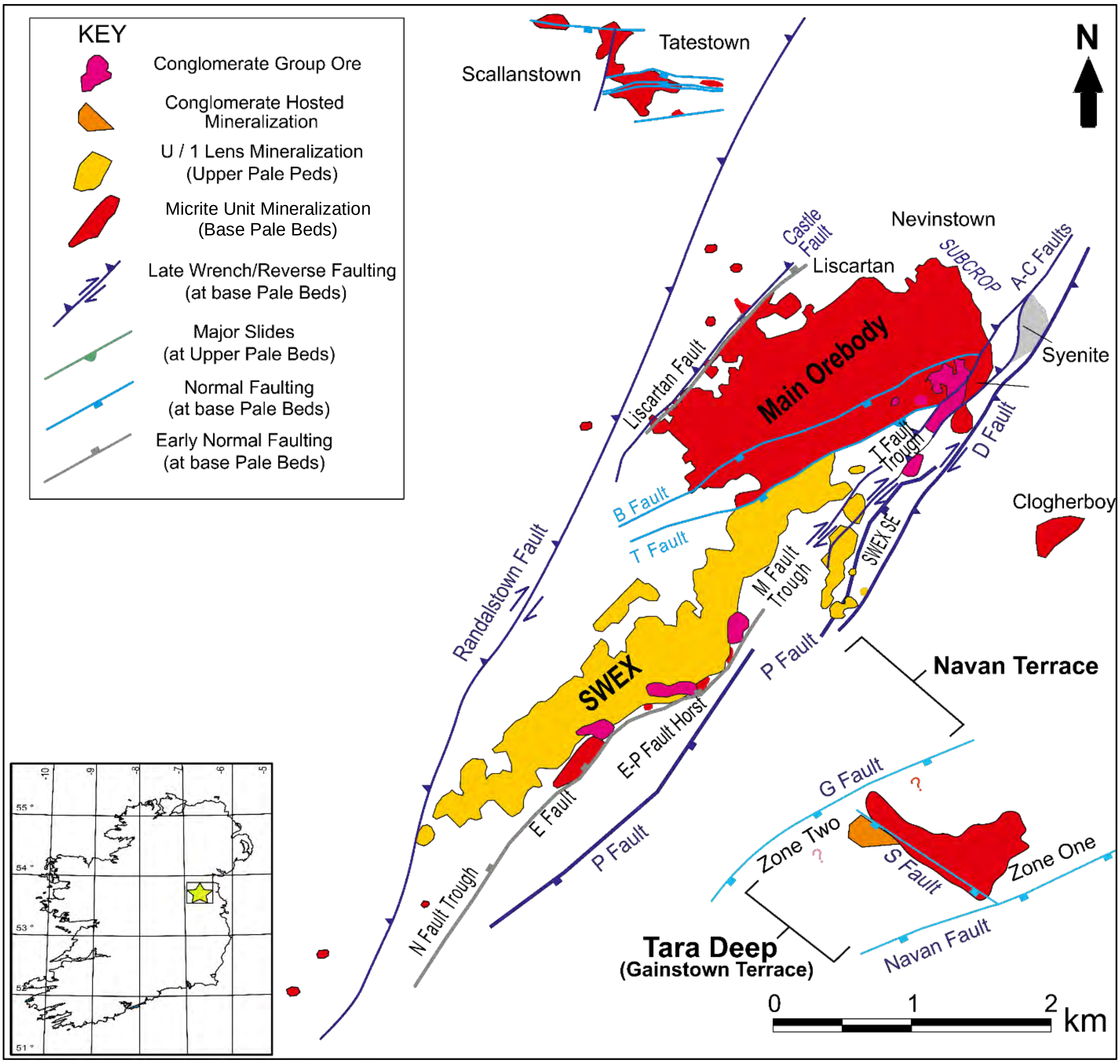

Figure 1: *Structural plan showing the positioning of Tara Deep relative to the Navan Orebody, and the distribution of principal ore lenses and faults, adapted from Ashton et al., (2015). Note the faults are shown as plan projections from their intersections with the ore lenses, not as outcrop positions. SWEX is an abbreviation of Southwest Extension.*

Stratigraphic and palaeogeographical settings of the Mississippian sequences are described in detail by Phillips & Sevastopulo (1986) and Philcox (1989). The Tournaisian/lower Visean (pre-rift) stratigraphy at Navan records shallow water carbonate deposition within a developing peritidal environment (Ashton *et al.*, 2015), followed by gradually deepening sea levels and the accumulation of ~200 m of micrites, bioclastic calcarenites, oolites, calcareous sandstones and siltstones. In local nomenclature, these 'Pale Beds' (Fig. 2) are the principal (but not the exclusive) host for mineralization, particularly within the Micrite Unit sub-group. This Micrite Unit is a fenestral limestone, exhibiting birds-eye features and representing deposition in a dominantly intertidal environment (Strogen *et al.*, 1996; McNestry & Rees, 1992). Overlying this unit, the remaining Pale Beds at Navan comprise shallow marine oolitic grainstones and calcarenites with N-S trending channels recorded in the northern regions of the deposit (Rizzi, 1992; Anderson, 1990). Increasing water-depth led to the deposition of the Shaley Pales and Argillaceous Bioclastic Limestones (ABL), followed by the deep-water Waulsortian mudbank limestones, which unlike some other deposits across Ireland, are poorly developed and unmineralized at Navan (Boyce *et al.*, 1983a; Caulfield *et al.*, 1986; Wilkinson *et al.*, 2005; Barrie *et al.*, 2009; Ashton *et al.*, 2015; Wilkinson & Hitzman, 2015). Two-dimension seismic surveys, conducted in 2012, in the Navan area demonstrates that the rates of extension accelerated during the deposition of the ABL, such that marked changes in the thickness of this unit can be seen across extensional structures (Andrew, 1993; Ashton *et al.*, 2018). In the Navan region, the timing of rifting is difficult to constrain, despite the preceding thickening of the ABL on the hanging wall of faults, but the main phase of rifting has generally been

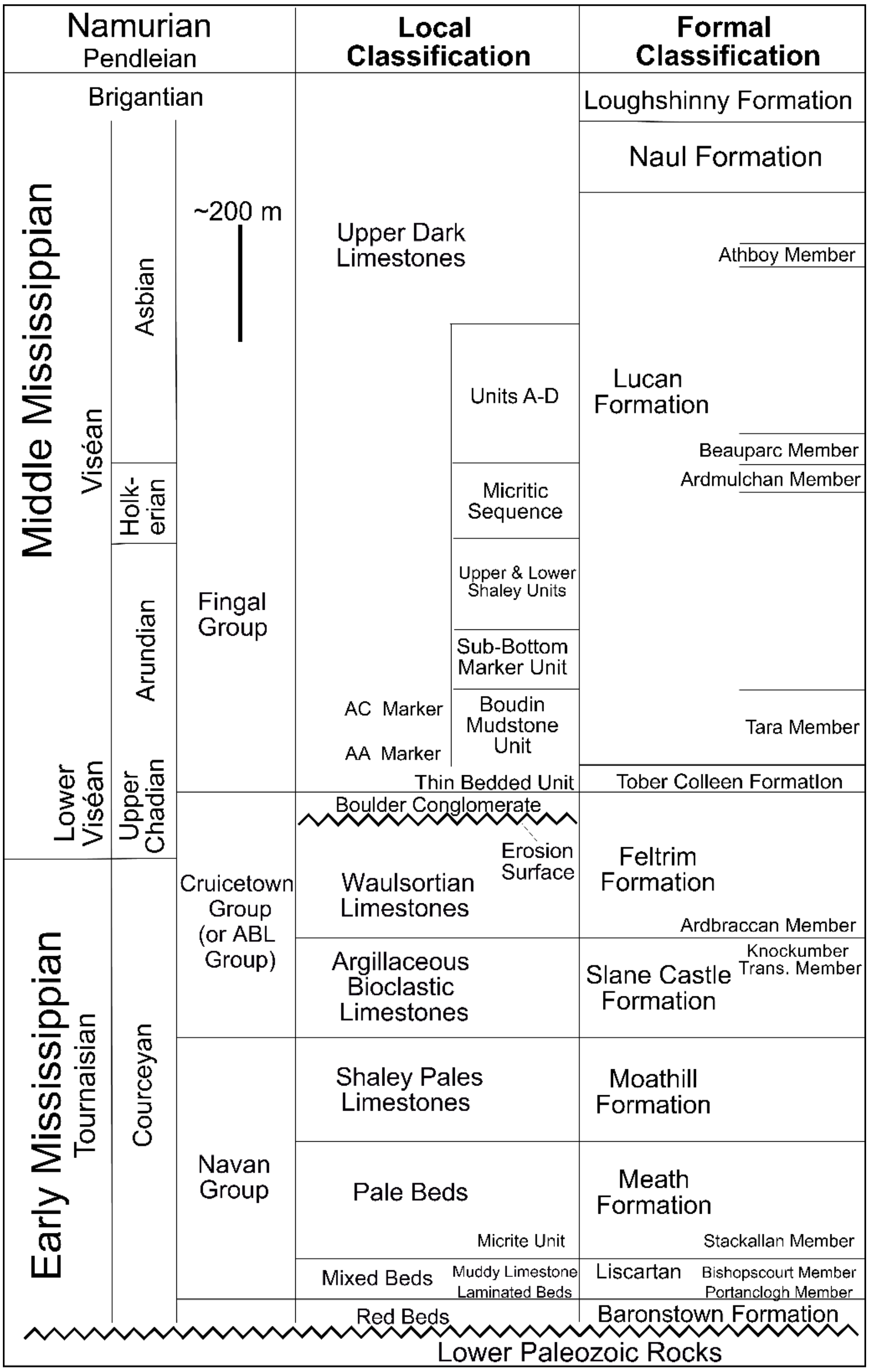

Figure 2: *Formal and informal stratigraphy table of Mississippian rocks in the Navan and Tara Deep area (after Philcox, 1984, 1989; Strogen et al., 1990, 1996 and Ashton et al., 2015).*

accepted by the generation of the catastrophic Boulder Conglomerate (BC). The Boulder Conglomerate is a laterally extensive series of debrites, and a key expression of the main rift event in the lower Visean (Ford, 1996), where rapid subsidence resulted in gravitational instability that has truncated much of the upper Tournaisian stratigraphy. Ultimately large collapse events led to the reworking and re-deposition of material as large allochthonous blocks and submarine sedimentary breccias (Figs. 2 & 3); Philcox, 1989; Andrew, 1993; Boyce *et al.*, 1983a; Ford, 1996). These syn-rift deposits thicken markedly to the south, particularly south of the large Navan fault (Fig. 1) especially with regards to the basal parts of the Upper Dark Limestone (locally termed the Thin Bedded Unit).

Although the Boulder Conglomerate at Navan is a unit, it is likely composed of many individual sedimentary breccias related to multiple extension events (Ford, 1996). Thick accumulations of Arundian-Holkerian calc-turbidites and minor conglomerates formed the infill to the Dublin Basin, known locally as the Upper Dark Limestone (Nolan, 1989;

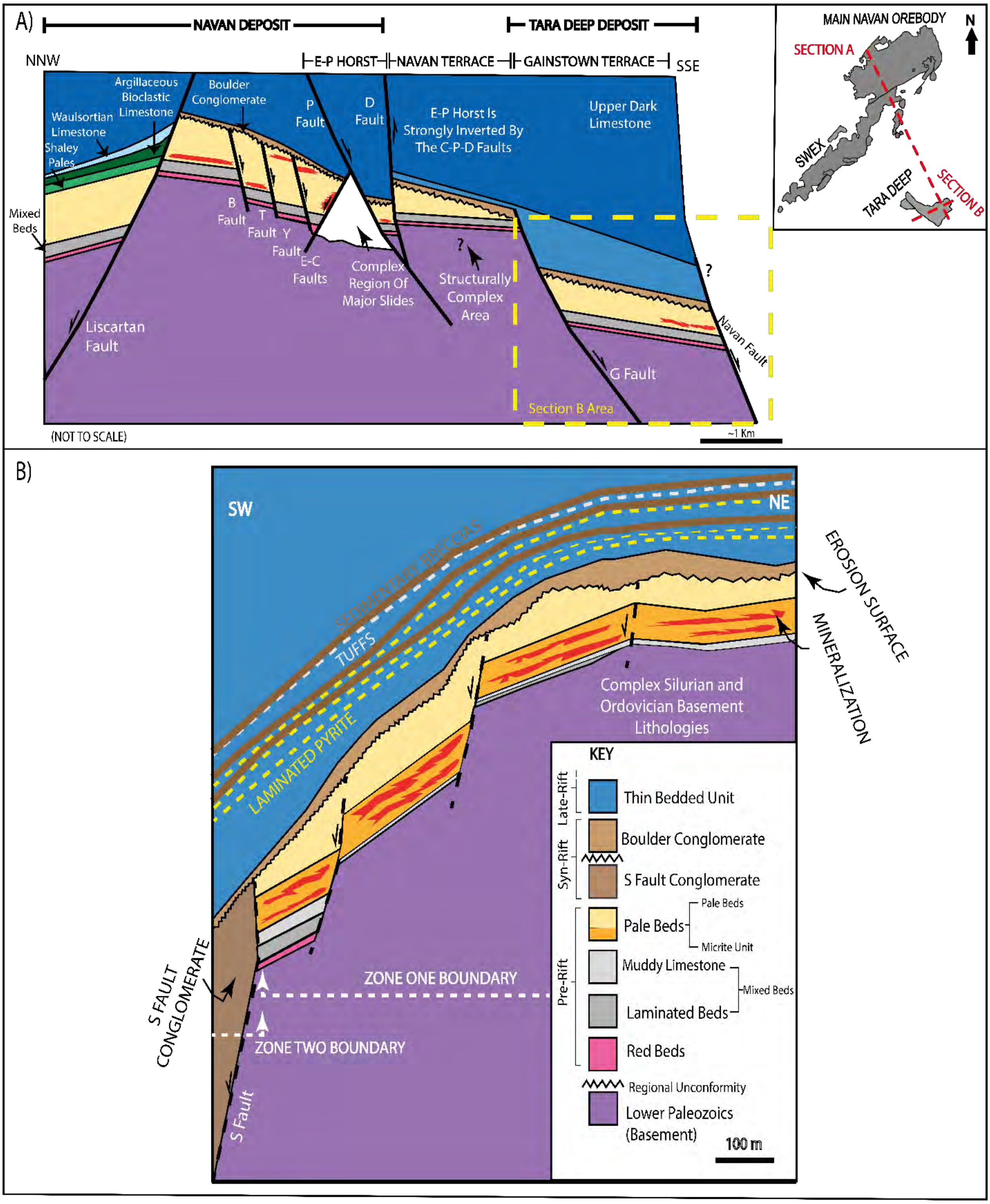

Figure 3: *A)* *Highly schematic (NNW-SSE) post inversion cross section across the Navan to Tara Deep region, highlighting the principal controlling faults. A full review of the complex Navan structure can be found in Ashton et al., (2015).* ***B)*** *SW-NE schematic section highlighting the setting of the Tara Deep deposit (post-inversion) within the Gainstown Terrace (Fig. 1); a region consisting of a series of fault-controlled terraces, often faulting out much of the Mixed Beds and Red Beds. The S Fault divides the deposit into Zone One and Zone Two. The Micrite Unit is a subgroup of the Pale Beds, but a stronger demarcation is adopted here.*

Philcox, 1989; Ashton *et al.,* 2015). A detailed review of fault evolution at Navan is described within Ashton *et al.,* (2015). Finally, later Variscan compression led to inversion, and a local dip of 15-20° SW was also probably imparted (Ashton *et al.* 2018).

Methods

Drill Core Analysis and Sampling

Detailed logging of Tara Deep core was undertaken during the exploration drilling campaign. Representative samples were collected that outlined different stratigraphical units and mineralization styles and textures. One hundred seventy polished thin sections were created. Petrographic analyses were carried out using standard transmitted and reflected light microscopy at the Scottish Universities Environmental Research Centre (SUERC) and at the Grant Institute, University of Edinburgh. Detailed scanning electron microscopy (SEM) was completed at the University of Glasgow, using a Quanta 200F Environmental SEM with EDAX microanalysis.

Sulphur Isotope Analyses

Sulphides were prepared for conventional isotopic analyses by diamond micro-drilling techniques using samples collected from Tara Deep's mineralized units (n=163). Standard techniques for sulphides (Robinson & Kusakabe, 1975) and sulphates (Coleman & Moore, 1978) were used. Liberated SO_2 gases were analyzed on a VG Isotech SIRA II mass spectrometer, and standard corrections applied to raw $\delta^{66}SO_2$ values to produce true $\delta^{34}S$. Data are reported in $\delta^{34}S$ notation as per mil (‰) variations from the Vienna Canon Diablo Troilite (V-CDT) standard. The standards used were the international standards NBS-123 and IAEA-S-3, and SUERC standard CP-1. Repeat analyses of these standards gave $\delta^{34}S$ values of +17.1‰, -32‰ and -4.6‰ respectively, with a standard error of reproducibility around ±0.3‰ during the processing of these samples.

Lead Isotope Analyses

Powdered samples of sulphides from mineralized drill core were dissolved using 1 ml 2% HNO_3 at the British Geological Survey in Nottingham. Dissolved samples were converted to bromide using 2 ml of concentrated HBr. Pb was separated using columns containing 100 ml of Dowex AG1x8 anion exchange resin using standard bromide separation methods. Prior to Pb isotope analyses each sample was spiked with a thallium solution, which was added to allow for the correction of instrument-induced mass bias. Samples were then introduced into a Nu Plasma HR multicollector ICP-MS (inductively coupled plasma-mass spectrometer). For each sample, five ratios were simultaneously measured ($^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$). Each individual acquisition consisted of 75 sets of ratios, collected at 5-second integrations, following a 60 second de-focused baseline. The precision and accuracy of the method was assessed through repeat analyses of an NBS 981 Pb reference solution (also spiked with thallium). The average values obtained for each of the measured NBS 981 ratios were then compared to the known values for this reference material (Thirlwall, 2002). All sample data were subsequently normalised, according to the relative daily deviation of the measured reference value from the true, with the aim to cancel out the slight daily variations in instrumental accuracy. Internal uncertainties (the reproducibility of the measured ratio) were propagated relative to the external uncertainty.

Results

Structure of the Tara Deep Deposit

Tara Deep is fault-bounded by structures that formed part of the northern margin of the Dublin Basin during the lower Visean. Broadly N-S extension led to several major faults trending generally ENE and defining a series of fault bound terraces (Fig. 3). The southern margin of the Navan/SWEX deposit, is defined by a major horst bounded by the NW dipping 'E Fault' (>500m normal throw) and the SE dipping 'P Fault' (>800m apparent normal throw; see Ashton *et al*., 2018; Fig.1). Southwards (~1.5 km), the SE dipping 'G Fault' is developed (>500m normal throw) with the intervening area termed the 'Navan Terrace'. Both the 'E-P Horst' and the Navan Terrace are poorly understood due to low resolution drilling and southwards-directed sliding and erosion (Ashton *et al*., 2015). The Navan Terrace is also strongly dislocated by a complex zone of later major SE dipping post-mineral faulting termed the 'D-Q Fault' Zone. This complex zone of late inversion, like other late dextral-reverse faults at Navan, complicates the reconstruction of pre-inversion relationships between Navan and Tara Deep (a significant dextral offset is suspected).

Stepping down to Tara Deep (Fig. 3), a further ~1.5km south of the 'G Fault' lies the SE dipping Navan Fault, which is the largest structure in the area and displays a normal displacement of at least 3km, as estimated from seismic data (Ashton *et al.*, 2018). Tara Deep occurs in the Gainstown Terrace, lying between the 'G' and Navan Faults, where strongly mineralized host rocks have been subject to several episodes of faulting (Fig. 3B). The terrace is dissected by several SW-dipping, low-angle listric normal faults with vertical displacements of <50m, striking broadly perpendicular to the 'G' and Navan faults. Of most importance, in the western parts of the Tara Deep deposit, is a large complex zone of shearing cutting obliquely through the Gainstown Terrace, with the principal fault termed the 'S Fault', which trends NNW-SSE and dips steeply WSW with a normal throw of >600m. Preliminary structural interpretation suggests that this may be an inverted early slide fault. Seismic and drilling data indicate that the 'G', Navan and 'S' Faults (Fig. 1) do not significantly displace the lower Visean debrites and basal units of the Upper Dark Limestone that overlie the truncated Pale Beds (Fig. 2 and Fig. 3).

The 'S Fault' separates Tara Deep into Zone One ('S Fault' footwall) and Zone Two ('S Fault' hanging wall), which will be discussed separately. Zone One displays the Navan deposit's lower Pale Beds stratigraphy almost intact. However, to the west, Zone Two shows a complex series of sedimentary breccias and large rotated blocks of Tournaisian stratigraphy in the S Fault hanging-wall, where it gives rise to a complex, sheared and west-facing monoclinical geometry. The description of the Mississippian stratigraphy within both zones is separated into pre-, syn- and late-rift sections (Fig. 3B), with the Tournaisian units below the Boulder Conglomerate categorized as pre-rift, whereas the Boulder Conglomerate is categorized as syn-rift, and the Thin Bedded Unit of the Upper Dark Limestone is deemed late-rift.

Local Stratigraphy at Tara Deep Zone One: Pre- and Syn-Rift Stratigraphy

Situated east of the 'S Fault' and north of the Navan fault, Zone One hosts a similar upper Tournaisian sequence to that observed at the Navan deposit. These upper Tournaisian sequences progressively steepen westward towards the S Fault from 15 to 40 degrees (Figs. 1 & 3B). The basal early Mississippian Red Beds of terrestrial/fluvial origin are overlain by a shallow-water sequence of thinly laminated siltstones, sandstones, limestones and shales termed the Laminated Beds. A distinctive opaline quartz horizon, which is similar to that seen under the Navan deposit (Rizzi, 1992), being a diagenetic replacement of anhydrite, suggests at least localized peritidal conditions. As a result of the NNW trending low-angle faults that dissect Tara Deep (Fig. 3B), a complete intersection of this Tournaisian Mixed Beds package has not yet been made. The unit most affected by faulting is a succession of finely bedded sandstones (mm to cm scale), siltstones, minor carbonates and muds termed the Laminated Beds. Thus, there is likely structural contacts cutting the Tournaisian units (Fig. 3B).

The principal host for mineralization within this zone is the lower parts of the Pale Beds (~50m in thickness; Fig.1), locally termed the Micrite Unit in the Navan deposit. At Tara Deep this unit is characteristically fine-grained, organic-rich, navy/dark grey in colour and fractured, showing no evidence of soft sediment deformation, suggesting it was fully lithified at the time of ore deposition. It also exhibits abundant birdseye (fenestral) textures, which are typically associated with an intertidal depositional setting (Grover & Read, 1978). This package is a distinct manifestation of the same intertidal processes that developed the Micrite Unit in the Navan deposit (Rizzi, 1992, Anderson *et al.*, 1998; Ashton *et al.*, 2015). However, at Navan it consists of a sequence of heterogeneous and variably dolomitized micrites, oolites and calcarenites (including channels in the northern part of the mine; Anderson *et al.*, 1998; Rizzi, 1992), whereas at Tara Deep this interval is far more consistent, with no current evidence for channelling. Oolitic grainstone horizons are often interbedded within the micrite (typically three), these are preferentially dolomitized, whereas the surrounding rock is variably dolomitized. An Upper and Lower Micrite can be distinguished on either side of a ~9m laterally continuous central dolomitized oolitic grainstone horizon across the entire Zone One. An equivalent dolomitized horizon is found in the Navan deposit, termed the 5-lens Dolomite. This, together with a consistency of thickness in the Micrite Unit (around 50m) across the Navan and Tara Deep deposits, suggests a strong similarity in depositional environment across the entire area.

Directly above the Micrite Unit, a succession of dominantly oolitic grainstones display a distinctive texture, locally-termed the 'Healed Conglomerates', which are succeeded by a series of emergent surfaces. Initial observations of this 'Healed Conglomerate' texture suggests it represents a diagenetic overprint of a nodular limestone, with pervasive pressure solution occurring through a partially lithified host rock, so called stylo-nodular textures or non-seam solution (see Wanless, 1979). The key characteristic of this texture is typified by undolomitized 'ghost' nodules that have diffuse margins, sitting within a dolomitized stylo-cumulate matrix. Stylo-cumulate herein refers to insoluble residue accumulated along a pressure-solution surface. Subsequently, the matrix hosts numerous pressure solution seams and dissolution has removed much of the pre-existing calcite, leaving behind heavy detrital mineral relics (albite, apatite, jadeite, lucite, quartz, zircon) and it is associated with burial dolomitization. Although the occurrence of the 'Healed Conglomerates' within the Navan deposit is unclear (Anderson, 1990; Rizzi, 1992), at Tara Deep the lithology is widespread (1.5km^2). Its true thickness is also unclear because it is superimposed by the Boulder Conglomerate. Mineralization in this lithology is patchy and typically uneconomic at Tara Deep.

Much of the pre-rift stratigraphy has been wholly or partly removed by a series of slides and debrites of lower Visean age, termed collectively as the Boulder Conglomerate (BC), that cut through the succession from the north and north-east. The preserved debris flows are generally polymict and matrix supported, with clast sizes ranging from 1 cm to >10m. The matrix is a dark, almost black, highly fossiliferous argillite. The clasts in the lower sedimentary breccias are dominated by Waulsortian limestone but the abundance of Pale Beds increases in the upper breccias. In rare occurrences clasts of Lower Palaeozoics are preserved. A major unconformity now exists between the BC and the underlying upper Tournaisian facies, and these debrites have superimposed early faulting (Fig. 2.3). This has been interpreted by several authors (Boyce *et al.*, 1983a; Philcox, 1989; Cook & Mullins, 1983; Ashton *et al.*, 1992; 2003; 2015; Ford, 1996) as the result of gravitational sliding, submarine debris flows and fault talus breccia formation, representing syn-rifting brought about by major extension and growth faulting during the upper Tournaisian/lower Visean. This erosion has resulted in the removal of >500m of pre-rift stratigraphy. On the footwall crest of the Navan Fault, the Boulder Conglomerate cuts down to the Lower Palaeozoic basement. Subsequently, Tara Deep preserves a much more complex syn-rift sequence of events than the main Navan deposit and the SWEX deposit.

Zone Two: Pre- and Syn-Rift Stratigraphy

Zone Two occurs west of the S fault (Fig. 3), as a steeply dipping (>75°), structurally complex region of syn-rift origin that dissects the Gainstown Terrace (Fig. 1). Overlying the common hanging-wall of the 'G' and 'S' faults, is a distinct sedimentary breccia, termed the S Fault Conglomerate (SFC), composed almost exclusively of Pale Beds clasts, with only very minor Waulsortian limestone towards the base. This unit also hosts clasts of detrital sulphide and rafts of displaced Micrite Unit mineralization. This mineralization is similar to that found at the base of the Boulder Conglomerate in the Navan Deposit in the hanging-wall of the 'T Fault' (Ashton *et al.*, 2015). The nature of these breccias again indicates a fault talus origin due to their polymict and angular nature. The SFC contains areas of very high Zn+Pb grades. Other distinctive minor sedimentary breccias occur in the 'S Fault' hanging-wall, and these appear to pre-date the S Fault Conglomerate. Towards the south-eastern end of the 'S Fault' hanging-wall, the 'S Fault' Conglomerate gives way to an apparently extensive series of debrites of intermixed blocks of ABL and Shaley Pales that in places appears to overlie more orderly Middle and Lower Shaley Pales and in one area a raft of Pale Beds.

Zone One and Two: Late- to Post-Rift Stratigraphy

The Erosion Surface at the Tara Deep deposit is overlain by the basal unit of the Upper Dark Limestone (UDL) termed the Thin Bedded Unit (TBU; Fig. 3). The Thin Bedded Unit at the Navan deposit barely exceeds 20m in thickness. Seismic interpretation, drilling and detailed stratigraphic correlation studies indicate that the TBU at Tara Deep thickens dramatically across the 'P' and 'G' faults, reaching thicknesses of 120m in the east of Zone One and >600m in the west of Zone Two (Ashton *et al.*, 2018). The TBU can be broken down into several sub-units, each of which host abundant iron sulphide laminations, separated by sedimentary breccias (see Yesares *et al.*, 2022). From oldest to youngest, they are termed the TBU-4, TBU-3, TBU-2 and TBU-1. The Thin Bedded Unit is also host to several tuff horizons of which the uppermost is the best preserved just beneath SB-1. These tuffs are missing at Navan, likely removed by later debris flow(s) during the formation of the Boulder Conglomerate. Overlying the TBU the Upper Dark Limestones comprise generally similar limestone turbidites to those elsewhere in the area (Philcox, 1989). Extensional activity in the area continued into the mid-Mississippian as polymict conglomerate horizons occur sporadically throughout the Upper Dark Limestones (Ashton *et al.*, 2015, Ashton *et al.*, 2018).

Mineralization

Mineralization at Tara Deep occurs primarily within three principal lithologies; A) the Pale Beds, in particular the Micrite Unit subgroup (Fig. 4A-E), B) 'S Fault' Conglomerate (SFC; Fig. 5A-B), and C) microcrystalline (typically bedding parallel) pyrite-rich mineralization in the TBU (Fig. 5C). Based on the most recent estimation, the Pale Beds hosts 87% of the total economic resource, primarily within the Micrite Unit, whereas the SFC hosts 13% of the total resource. The TBU is sub-economic. The dominant ore minerals comprise sphalerite and galena, at a ratio of ~7:1. Other minerals in decreasing order of abundance include calcite, dolomite, pyrite, marcasite, barite, and much less commonly, anhydrite and chalcopyrite. A series of complicated sulphosalts also occur as inclusions within galena, dominantly bournonite and boulangerite. A variety of textures exist within each of these hosts, which are controlled by open-space infill, replacement, and dissolution within a subsurface environment.

A) Pale Beds (Zone One)

Pale Beds mineralization, almost entirely hosted in the Micrite Unit subgroup (Fig. 4A), dominates in Zone One, occurring in blocks bounded and displaced by low-angled listric faults that dip SW (Ashton *et al.*, 2018). Mineralization within these blocks are typically stratabound, and gains in intensity as the footwall crest of the Navan Fault is approached. This interval is equivalent to the lowest lens - the 5- lens - of the Navan Deposit which hosts roughly 70% of the Main Orebody resource (Figs. 1 & 3; Ashton *et al.*, 2015). The mineralization most frequently presents as massive, disrupted cavity fill, brecciated and massive mineralization textures, which are dominated by multistage infill and replacement mineralization processes. Late marcasite and barite are observed infilling and cross cutting many of these textures. Finally, late phase burial and associated pressure solution exploits these textures. Directly above the Micrite Unit, the remaining Pale Beds are typically poorly mineralized.

Mineralized textures found in the Pale Beds occur as follows, in order of relative abundance:

Cavity fill textures (Fig. 4B) can occur on various scales (5-40 mm) and is the most common texture associated with the Micrite Unit. They occur within both undolomitized and dolomitized regions of the Micrite Unit. These mineralized textures consist of layered/colloform yellow-burgundy coloured sphalerite that nucleate on the cavity walls. Galena commonly forms isolated, dendritic or coarse crystals (5 - 60 mm), nucleating within or on cavity walls. Colloform sphalerite can be accompanied by variable concentrations of minor trace elements (Fe, Mn, Cu, Ga, Ge, Ag, Cd, As and Hg). This is consistent with the Navan deposit (Gagnevin *et al.*, 2014). Colloform regions can be observed nucleating around host calcarenites, or as disrupted, isolated textures. Weaknesses between individual colloform layers are often exploited by late phase barite and/or calcite.

Brecciated mineralization (Fig. 4C) occurs as hydraulic fracturing and collapse brecciation within the Micrite Unit. Fracture fill and brecciated textures tend to dominate regions where complete dolomitization of the Micrite Unit has occurred. Ultimately, expansion of cavities through mineralization occurs over time, generating wider cavities and often allowing cavity bridging to take place. Sometimes when cavity collapse occurs, brecciated textures can develop. Thus, a continuum in processes likely exists, where convergence of cavity fill textures results in brecciated mineralization.

Massive mineralization (Fig. 4D) occurs where replacement and infill mineralization has completely obliterated the original fabric of the intertidal carbonate mud, leaving behind only reworked dolomite and undissolved host rock components (e.g., jadeite, apatite, quartz, albite and mica). Examples exist where numerous cavity fill textures have been reworked, packed, and amalgamated together, creating regions of massive mineralization and highlighting the complexity and cyclicity of the mineralizing system (Fig. 4E).

B) 'S Fault' Conglomerate (SFC; Zone Two)

Mineralization in the SFC is concentrated near the hanging walls of the 'G' and 'S' faults in Zone Two of Tara Deep. Mineralization in the SFC takes three forms: 1) isolated allochthonous clasts of sulphide (> 10mm), similar to the Conglomerate Group Ore in the Main Navan Orebody, detrital clasts of mineralization are often embedded by late matrix replacement mineralization. The margins of these allochthonous clasts can be angular or sub-rounded, and range in size from <1mm to 50mm across (Fig. 5A). 2) A raft of Micrite Unit mineralization (~50m) hosted between complex sedimentary breccias.

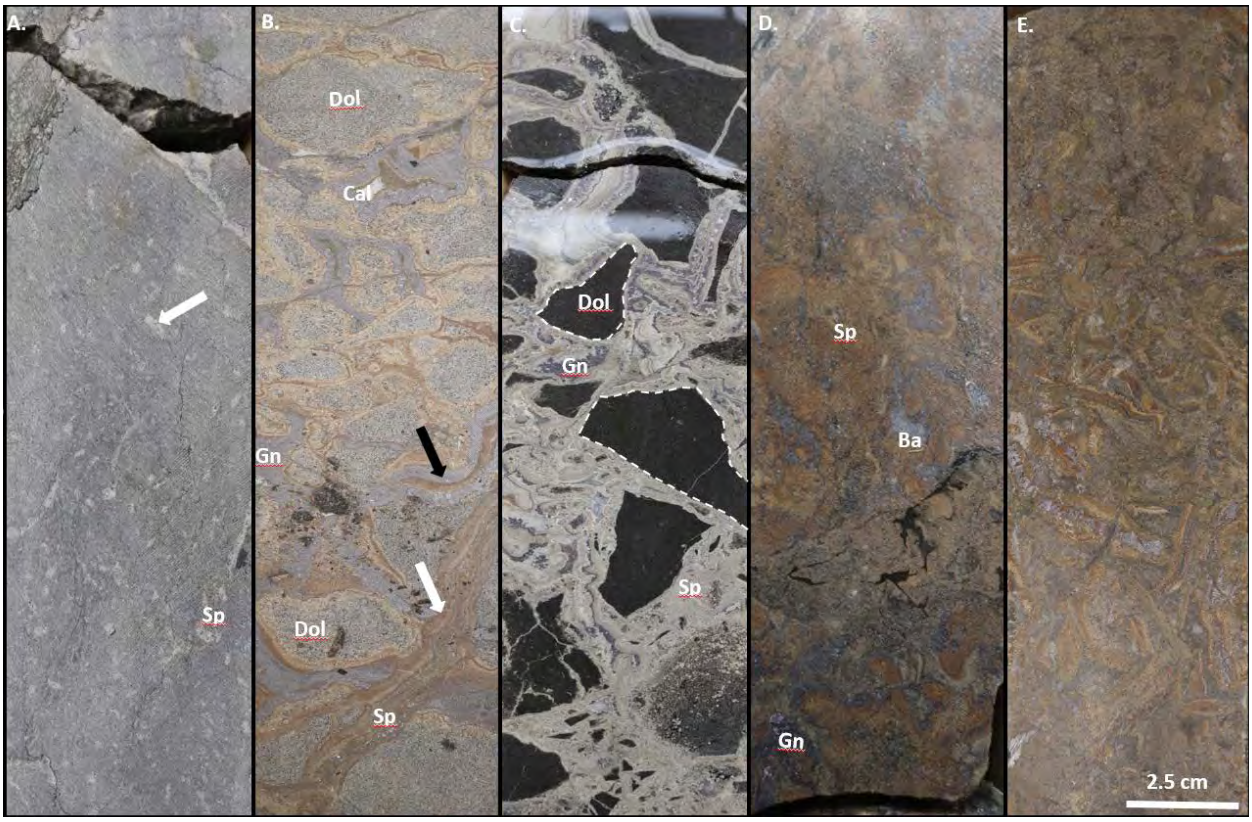

***Figure 4**: Drillcore (NQ) images outlining common mineralization textures within Zone One's Micrite Unit. **A)** Largely undolomitized Micrite Unit with characteristic birds-eye textures (fenestral; white arrow) with minor disseminated sphalerite (N02334/19; 1786.5 m) **B)** Coarse, intensely mineralized cavity fill within the Micrite Unit, consisting of classic colloform sphalerite (Sp; white arrow) nucleating on the cavity walls. These cavities have also been exploited by coarse galena (Gn; black arrow). Host rock has been replaced by dolomite (dol) prior subsurface mineralization, leading to a complete occlusion of the original fenestral fabric. Metalliferous fluids exploit and expand fractures in the Micrite Unit (N02499; 1786.2 m). **(C)** Brecciated mineralization with subrounded to angular clasts of dolomitized micrite (dashed lines) encased by high grade sphalerite mineralization, with subordinate coarse galena (N02334; 1815.3 m; wet). **(D)** Massive mineralization with a complete replacement of the host rock, and the original fabric, with dominantly sphalerite (Sp) mineralization with minor galena (Gn) and barite (Ba) (N02334; 1775.3 m; wet**).** **E)** Numerus disrupted cavity fill textures consisting of dominantly sphalerite with minor galena, with later barite infill between textures (N02445, 1780.05 m).*

This large raft of allochthonous Micrite Unit mineralization rest on the hanging wall of the 'S Fault' (Fig. 3). 3) As matrix replacement and infill, dominated by late phase marcasite and barite. Bioclast replacement is common within the high-grade SFC matrix (Fig. 5B). A zone of intense, replacive mineralization of up to 90m vertical thickness, with grades in excess of 50% Zn+Pb, can be found towards the top of the S Fault Conglomerate.

The SFC is characterized by bioclast replacement textures, which help to differentiate the SFC mineralization from allochthonous clasts of Pale Beds mineralization. At Tara Deep the abundance of iron sulphide within the SFC is typically 2-5%, whereas intersections of 30-40% iron sulphide can be made within the Conglomerate Group at the Navan Mine.

C) Laminated Iron Sulphides in the TBU

The overlying TBU comprises 5 mm to >3 m thick bedding-parallel layers of dominantly framboidal and microcrystalline pyrite hosted in a fine grained, organic-rich carbonate shale. This mineralization extends over a region of ~2 km^2. Minor remobilized sphalerite and galena are found within these laminae, again highlighting the multiphase nature to mineralization. The pyrite framboids are abundant and show a high degree of preservation, with recrystallization being poorly developed and constrained to regions that are more massive in texture. Regions of massive framboidal pyrite (~ 5m in thickness) can be intersected in the 'G Fault' hanging wall, typically proximal to underlying normal faulting (Fig. 5C). Mineralization is often associated with hydrothermal chert and MnO staining in drill-core (Yesares *et al.,* 2019; Yesares *et al.*, 2022). Rare, late phase barite veins crosscut the TBU Fe-sulphide laminations. Microscale textures in the TBU iron laminations at Tara Deep suggest they have been displaced by late compressional deformation, suggesting they predate Variscan compression. Similar iron sulphide laminated textures have also been recorded at Navan but they are less abundant (Ford, 1996; Anderson *et al.*, 1998).

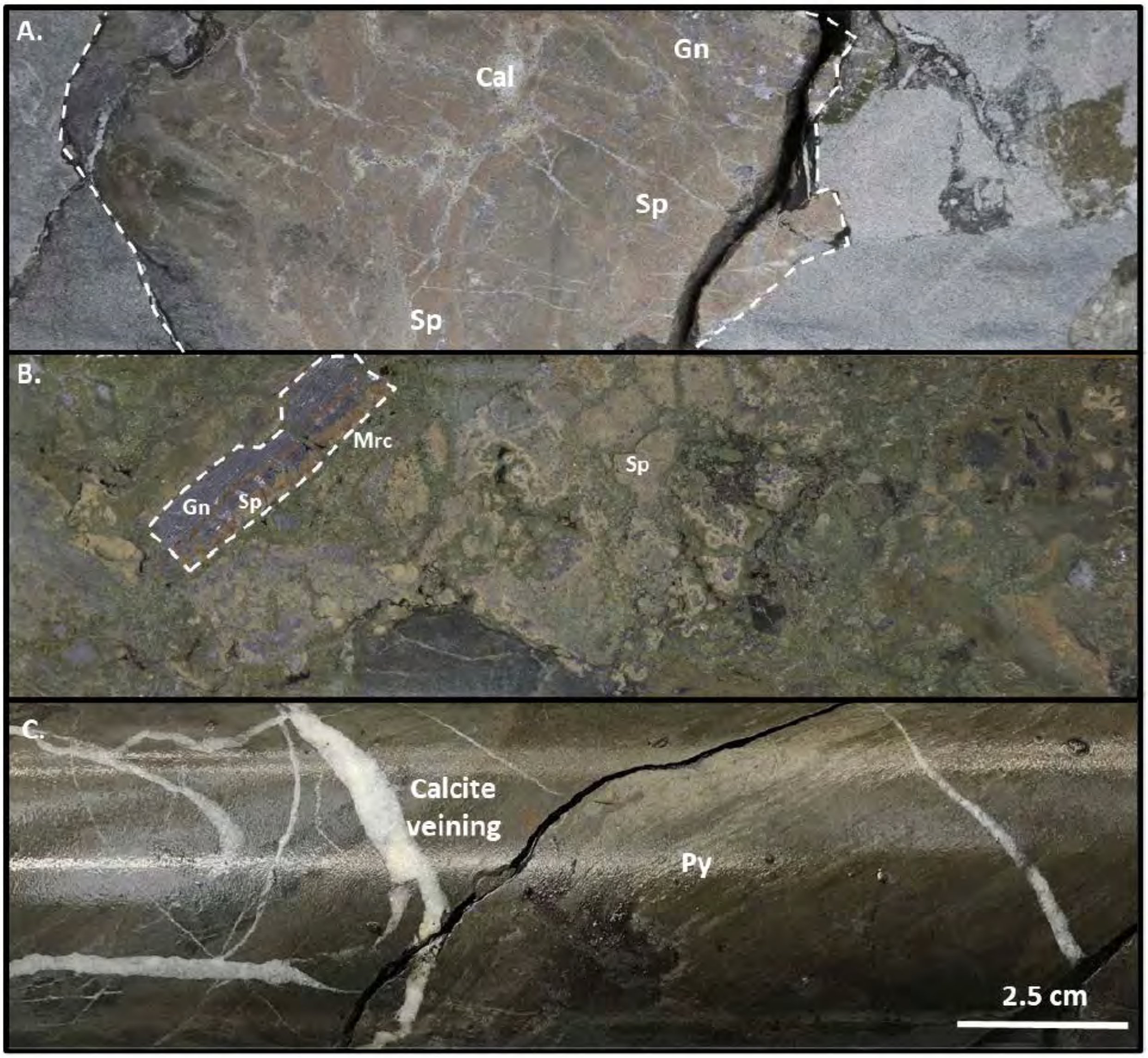

Figure 5: *Drillcore (NQ) images outlining common mineralization textures within the S Fault Conglomerate (SFC).* ***(A)*** *Allochthonous clasts of early sphalerite (Sp) mineralization, with minor coarse galena (Gn), hosted within the S Fault Conglomerate at Tara Deep (N02466; 1728.2m)* ***(B)*** *Mineralized S Fault Conglomerate (SFC) with an allochthonous clast of cavity fill mineralization (indicative of the Micrite Unit) encased by later phase marcasite and sphalerite which replaces the debrite matrix (N02427; 1776.7 m)* ***(C)*** *Massive microcrystalline pyrite within the TBU, overlying SFC mineralization, consisting of dominantly framboidal pyrite within an organic rich lutite (N02439; 1653.6 m).*

Paragenetic Sequence

The paragenetic sequence at Tara Deep is extremely complex, especially in high grade zones, and it is very likely that hydrothermal activity, tectonism, and burial have resulted in this complexity. The paragenetic sequence has been broken down into early-rift to late-rift phases which coincide with changing depositional environments and subsequently an evolving basin (Fig. 3B). All of these phases pre-date Variscan compression.

Early-rift phase mineralization: The majority of replacement dolomitization predates mineralization (Fig. 6A). Sphalerite and galena dominate the early phases of the paragenetic sequence and reveal a synchronous precipitation relationship. Dendritic galena and colloform/layered sphalerite textures are common within cavities of the Micrite Unit. These textures denote rapid, supersaturated precipitation, with sphalerite and galena precipitating at the same time. This is epitomized by dendritic galena infilling colloform sphalerite that encases it (Fig. 6B). Sphalerite also exists as zoned microcrystalline globules (~20 um). Abundant Sb- and occasional Cu- sulfosalts (bournonite and boulangerite, respectively) occur as micro-inclusions within galena (Fig. 6C-D).

Main-rift mineralization: Marcasite and barite are later phases that do not co-precipitate with early Zn-Pb textures. Marcasite replaces pre-existing textures, and often veins across pre-existing Micrite Unit textures. It is most abundant within the SFC

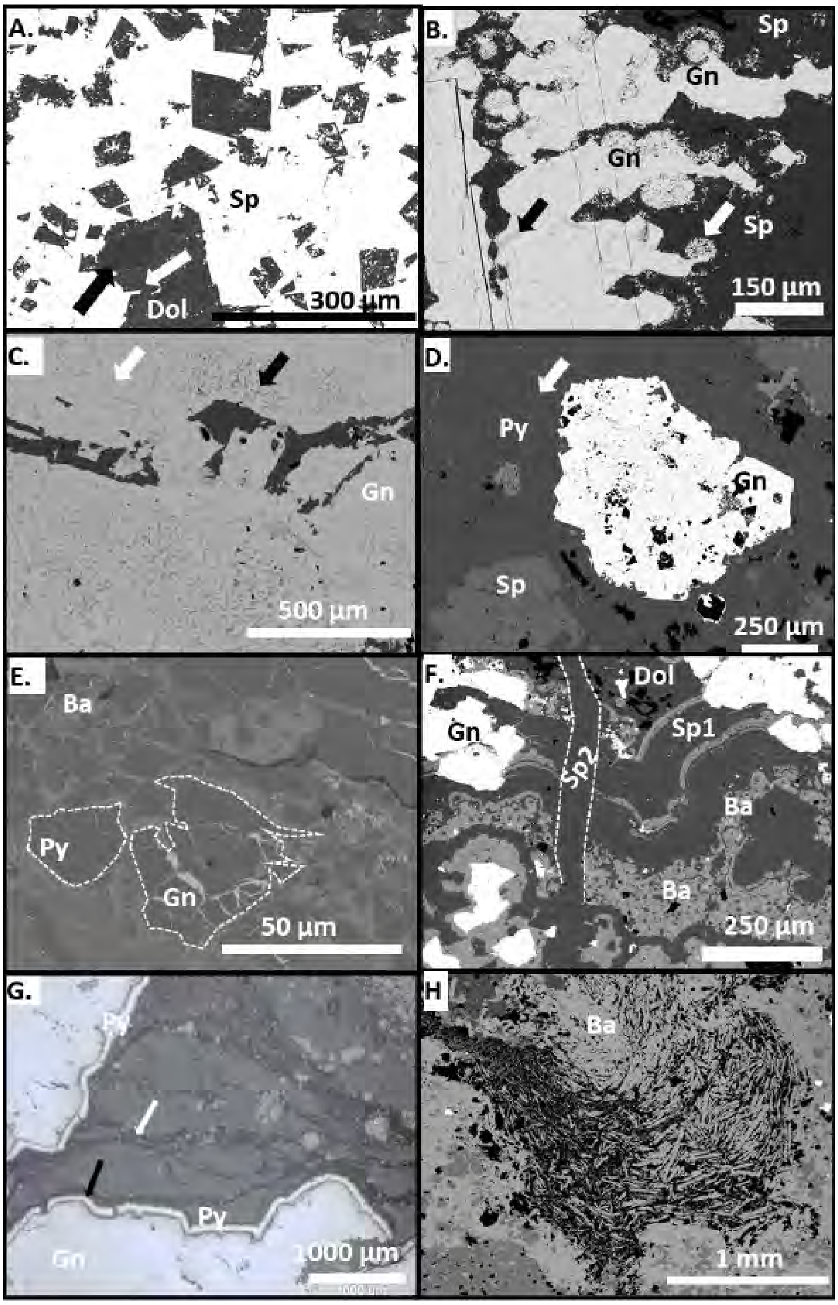

Figure 6: *Standard petrology and backscattered electron (BSE) images from mineralized textures in the Micrite Unit.* ***(A)*** *Dolomitization predates sphalerite mineralization. Note the corroded edges to the dolomite. Dolomitization comprises an early Mn and Fe replacement phase with an iron rich coating (black arrow), with a later Fe-rich dolomite infill (white arrow; N02445; 1788.1 m)* ***(B)*** *Dendritic galena with inclusions of Sb-sulphosalts (typically bournonite; black arrow). Sphalerite and galena precipitated at the same time highlighted by dendritic galena infilling microcrystalline sphalerite that encases it, generating zoned infill structures (white arrow; N02499; 1781.3m).* ***(C)*** *Globular Cu-sulfosalts (typically boulangerite; black arrow) and bladed Sb-sulfosalts (largely bournonite, white arrow) inclusions in hydrothermal galena (N02445;1788.1 m).* ***(D)*** *Coarse galena with Sb- and Cu-sulphosalts, encased by hydrothermal pyrite that displays faint arsenic zonations (white arrow; N02428;1473.6 m).* ***(E)*** *BSE image with galena crosscutting pyrite (dashed line) which is subsequently brecciated by barite (N02437/02; 1678.3)* ***(F)*** *BSE image showing a complex relationship where colloform sphalerite (Sp1) has been infilled and exploited by late phase barite. A final phase of coarse honeyblende sphalerite (Sp2) crosscuts all of these textures (N02418/03; 1589.6 m)* ***(G)*** *Pressure dissolution postdates mineralization, horsetail stylolites (white arrow) associated with abundant microcrystalline pyrite. Microcrystalline pyrite from pressure solution seams nucleates on the margins of pre-existing hydrothermal galena (black arrow; N02445; 1788.1 m)* ***(H)*** *Laths of bladed barite are 'splintered' by pressure solution (N02334;1765.1 m). Mineral abbreviations; barite (Ba) boulangerite (Boul), bournonite (Bour), dolomite (Dol), galena (Gn), pyrite (Py) sphalerite (Sp).*

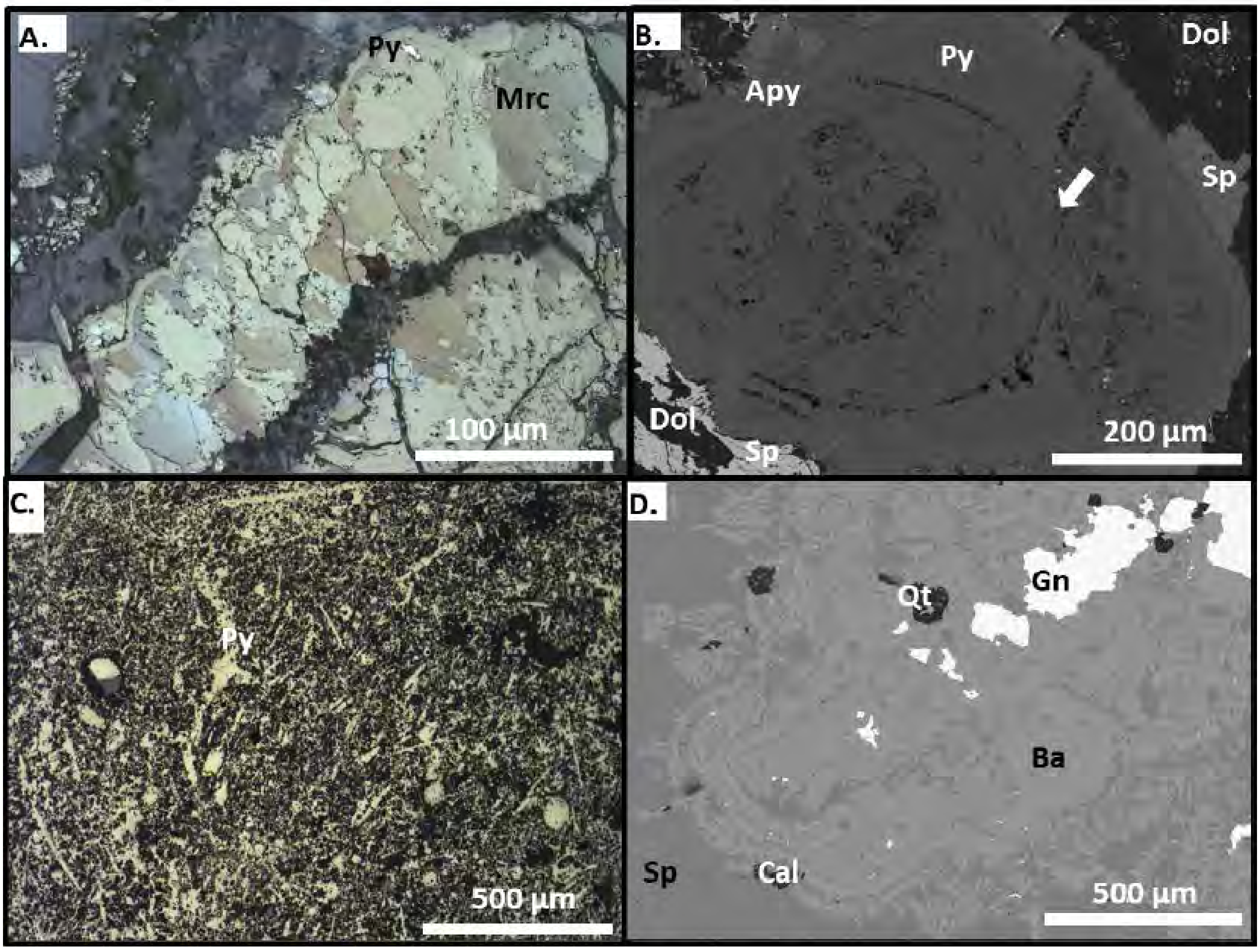

Figure 7: *Reflected Light (RL) and Backscattered Electron (BSE) images of textures associated with the S Fault Conglomerate of Zone Two. Mineralization pre- and post-dates the formation of this submarine debrite, and the system becomes progressively more iron rich over time.* ***(A)*** *Cross- Polarized Reflected Light (XRL) image displaying marcasite replacing pyrite mineralization (N02439/06).* ***(B)*** *BSE image shows pyrite replacing ooids. Ooids reveal evidence of compaction and still retain their isopachous marine cements (white arrow; N02477/01; 1748.6m).* ***(C)*** *Complete replacement, by dominantly pyrite, of a diverse variety of bioclasts (N02439/03; 1693.2 m).* ***(D)*** *Layers within a colloform sphalerite are being exploited by late phase barite (N02427/04; 1792.5m). Mineral abbreviations; arsenopyrite (Apy), barite (Ba), calcite (Cal), dolomite (Dol), galena (Gn), marcasite (Mrc), pyrite (Py) sphalerite (Sp), quartz (Qt).*

where it replaces the matrix around earlier Zn+Pb clasts (Figs. 5B & 7A). The matrix of the SFC is dominated by bioclast replacement typically by pyrite and marcasite (Fig. 7B-C), these textures often encase early mineralized clasts (Fig. 5 B). Bladed, porous, barite postdates marcasite, and can be observed infilling interstitial space, veining and exploiting weaknesses between colloform sphalerite layers within the Micrite Unit (Fig. 6E) and SFC (Fig. 7D). Within the TBU, rare barite veins cross cuts microcrystalline pyrite laminations. Minor, late phase, coarse, honeyblende sphalerite postdates marcasite, but it is poorly understood, it is often synchronous with late calcite and barite (Fig. 6F).

Late-rift mineralization: The TBU is dominated by iron sulfides. Sphalerite, galena, marcasite and barite precipitation still occurs, but as minor typically disseminated and potentially remobilized phases (see Yesares *et al.*, 2022). Burial of the entire Tara Deep deposit has resulted in extensive pressure solution within every unit. Pressure dissolution subsequently postdates the Micrite Unit mineralization, with examples observed where stylolites cross-cut earlier base-metal sulphides and barite (Fig. 6G-H). Each of these pressure solution seams are associated with framboidal and microcrystalline pyrite, which nucleate on pre-existing base metal sulphides.

In summary, crosscutting relationships reveal a dynamic and evolving paragenetic sequence (Fig. 8). Firstly, Zn-Pb dominates during the early phases of mineralization. Secondly, Ba+Fe ±Sp±Gn dominates during the main rifting event and the formation of the SFC. Finally, late in the paragenetic sequence, during the late phases of basin rifting, the system appears dominated by pyrite, with only minor Zn, Pb and Ba input, but overall, the system is clearly waning. These observations are consistent across hundreds of complex samples but have been summarized (Fig. 9). The presence of barite and marcasite as an intermediate phase suggest a shift to metals being transported in reduced, acidic brines, which may have remobilised other base metal sulphides and facilitated the precipitation of honeyblende sphalerite (Cooke *et al.*, 2000). Overall, the mineralizing system is dynamic and despite the

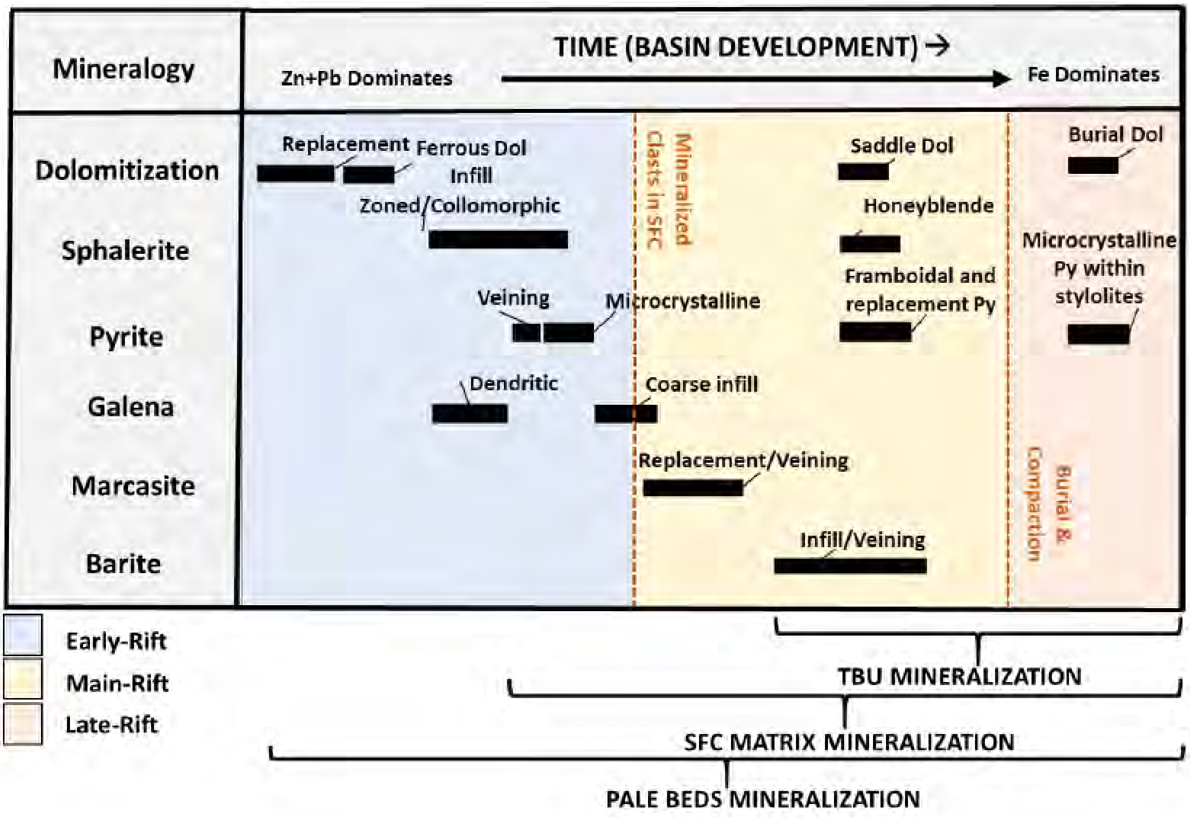

Figure 8: *Paragenetic sequence for Tara Deep mineralization showing the general trend and the evolving mineral assemblages through time.*

evolving depositional and tectonic environment, mineralization is prolonged and responds to basin development.

Sulphur Isotope Analyses

Cavity fill brecciated and massive mineralization textures of the Pale Beds displays a dominant bimodal distribution of $\delta^{34}S$ in sphalerite and galena ranging between -13.5 to -3.6 ‰ (average= -8.5‰, σ= ±2.4) and +3.4 to +16.2 ‰ (average= 9.6‰, σ=± 2.9), suggesting two different S sources (Fig. 10A&B). The lowest values (-13.5 ‰ to -3.6‰) are interpreted as the product of bacterial reduction of seawater sulphate (BSR) during the Mississippian (Altinok, 2005, Anderson *et al.*, 1998; Anderson, 1990; Barrie *et al.*, 2009; Blakeman *et al.*, 2002; Boyce *et al.*, 1983b; Caulfield *et al.*, 1986; Coomer & Robinson, 1976; Fallick *et al.*, 2001; Ford, 1996; Wilkinson & Hitzman, 2015; Wilkinson *et al.*, 2005). The heavier values (+3.4‰ to +16.2 ‰), are considered to represent hydrothermal sulphide which enters the orebody with the metalliferous hydrothermal fluids, sourced dominantly from the Lower Palaeozoic basement (Anderson *et al.*, 1998; Fallick *et al.*, 2001).

Within the S Fault Conglomerate, a light signature dominates -16 to -5.9 ‰ in both allochthonous clasts and matrix replacement mineralization, with only two minor heavy hydrothermal S isotope signatures recorded (+7.7 to +8 ‰; Fig. 10B).

Barite and anhydrite from the Pale Beds have an average $\delta^{34}S$ of 26 ±1.7‰ (n= 17); one value from the SFC gives 29‰.

Lead Isotopes

An extremely homogeneous lead isotope dataset exists for Tara Deep, with analyses completed on drilled out galena samples, ($^{206}Pb/^{204}Pb=18.23\pm0.006$, 2σ, n=26), revealing that lead (and by association, zinc) are sourced from the underlying Lower Palaeozoic basement (Boast *et al.*, 1981b; Caulfield *et al.*, 1986; O'Keeffe, 1986; LeHuray *et al.*, 1987; Mills *et al.*, 1987; Dixon *et al.*, 1990; Fallick *et al.*, 2001; Everett *et al.*, 2003).

Discussion

Controls on Ore Development

Certain factors including timing of mineralization and the location of fluid migration pathways are still highly debated within Irish-type models (e.g., Hitzman & Beaty; 1996 ; Gleeson *et al.*, 1999; Wilkinson *et al.*, 2003; Wilkinson *et al.*, 2005; Johnson *et al.*, 2009; Torremans *et al.*, 2018). There are no clear, single fault structures which can currently be identified as distinct feeder zones at Navan, as opposed to other Irish-type deposits such as Silvermines (Taylor, 1984). Instead, multiple faults of varying size, ranging down to minor fractures in the Navan Orebody, even those with very limited throws (<1m), were conduits for ore fluid movement (Blakeman *et al.,* 2002). Yesares *et al.,* (2019) argues that the high abundance of copper and antimony sulfosalts in galena from Tara Deep suggest proximity to a feeder system. However, at this stage, determining that exact feeder is extremely ambig-

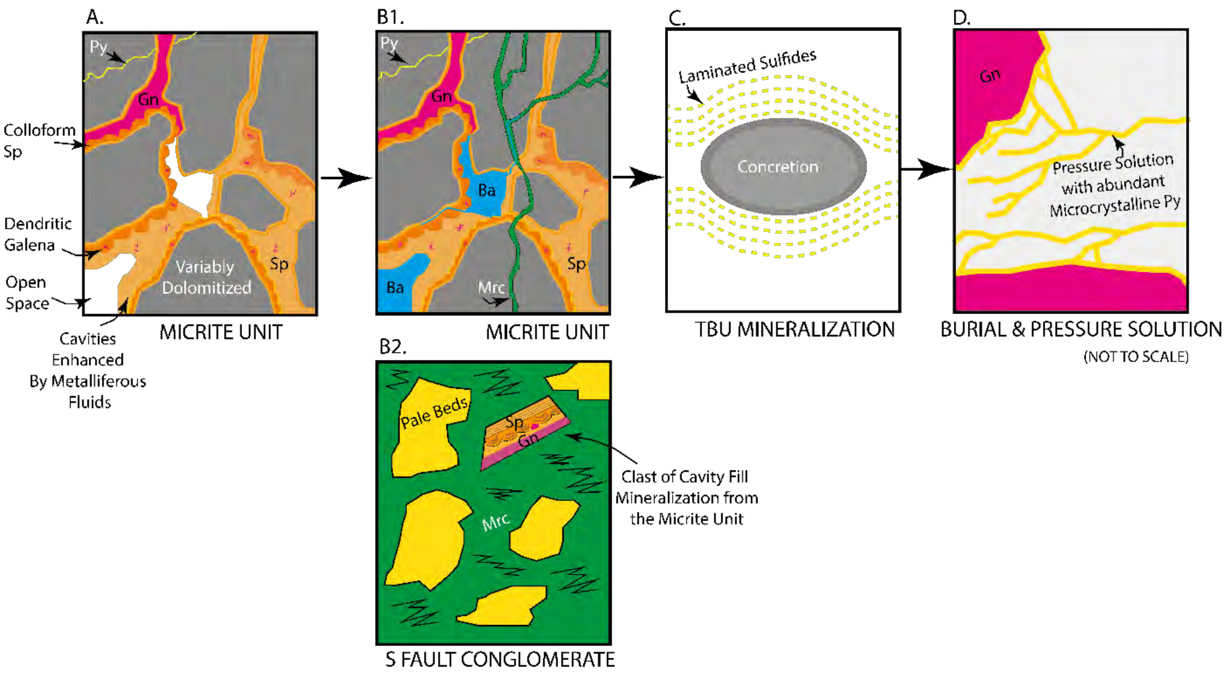

***Figure 9**: Schematic summary of the key textural relationships, which explain the timing of phases of mineralization within the Tara Deep deposit. It is worth noting that the ore is extremely complex and difficult to interpret, especially in high-grade zones, but these trends hold true across all samples and at various scales. **(A)** Cavity fill mineralization in the dolomitized Micrite Unit (similar example see Fig. 4B), showing early colloform and dendritic textures (similar example in 6B). Metalliferous fluids enhance cavities and rapid precipitation textures are likely generated through fluid mixing. **(B1)** Later phase Micrite Unit mineralization is exploited by marcasite veining and infilled by barite. Note the barite exploits weaknesses within colloform sphalerite (see Figs. 6E&F &7D) and crosscuts marcasite, it is often associated with coarse honeyblende sphalerite and late calcite veining. **(B2)** Cavity fill textures from the Micrite Unit can be found encased by marcasite in the S Fault Conglomerate (SFC; see Fig. 5B). Clasts of Micrite Unit mineralization in the SFC offer unambiguous evidence that the onset of mineralization occurred prior to or during the upper Tournaisian. **(C)** Laminated sulphide encases concretions within the Thin Bedded Unit, suggesting subsurface mineralization after a phase of early diagenesis. **(D)** Pressure solution in the Micrite Unit and Thin Bedded Unit host abundant microcrystalline pyrite that nucleate on pre-existing textures (see Fig. 6G). Mineral abbreviations; barite Ba), galena (Gn), marcasite (Mrc), pyrite (Py) sphalerite (Sp).*

uous, especially considering the structural complexity, and because similar Cu-bearing sulphosalts have been recorded at the Navan deposit (Steed, 1980). However, at Tara Deep the predominance of massive lenses of iron sulphide overlying the S Fault hanging wall, highlights the important role of these early NNW-SSE faults.

The diversity of textures at Tara Deep reveal a dynamic mineralizing environment within the subsurface (Fig.8). Most of these textures contain evidence of disruption and reworking of the original units. Within the Micrite Unit of the Pale Beds, mineralization is associated with replacement and open-space textures ultimately leading to the development of complex cavity fill, brecciated and massive mineralization. A continuum exists between these textures with cavity fill textures amalgamating and forming brecciated mineralization, and in regions where complete replacement occurs, massive mineralization dominates. Open-space textures are epitomized by dendritic-skeletal galena and colloform sphalerite. Whereas matrix replacement textures are dominantly destructive and often leave behind little evidence of the pre-existing unit, detailed petrographic examination reveals delicately replaced bioclasts, partially replaced dolomites and detrital heavy mineral relics. Similar complex textures to those at Tara Deep have been outlined at other Irish-type deposits (see Anderson *et al.*, 1998; Ashton *et al.*, 1986; Boast *et al.*, 1981a; Fusciardi *et al.* 2003, Doran *et al.*, 2017).

The Micrite Unit was an effective trap for precipitation of sulphides due to its organic content, porosity (both fenestral textures and fractures), and finally its fully lithified nature. These factors have provided ideal conditions for fluid mixing, and a substrate for base metal sulphides to nucleate and replace. It was also an organic rich environment where anaerobic sulphuretum thrived and replacement mineralization processes dominated (Fallick *et al.*, 2001; Wilkinson et al., 2005). Within the SFC of Zone Two, allochthonous clasts of cavity fill textures (originally Pale Beds) are found engulfed by later matrix replacement mineralization (Fig. 6 B). This indicates that ore deposition was prolonged, initiating during early phases of rifting and thus pre-Boulder Conglomerate. In addition, large rafts of allochthonous Pale Beds mineralization rest on the hanging wall of the ‘S Fault’, which are subsequently overlain by matrix replaced SFC mineralization; highlighting that rifting and footwall failure occurred pre-Boulder Conglomerate, and also providing time constraints for upper Tournaisian mineralization. Despite the regional debrites that occur, mineralization continues during TBU deposition, with extensive deposition of laminated iron sulphides. Currently no significant evidence exists, apart from minor fractured and displaced laminated sulphides in the TBU, to highlight when mineralization ceased, however mineralization was still able to exploit pressure solution seams associated with burial (Fig. 6G-H). Regionally, there is significant geologic evidence that ore at Lisheen (Carboni *et al.*, 2003) and at Navan (Ashton *et al.*, 1986) are cut by thrusts related to Variscan tectonic inversion, implying that mineralization had ceased prior to Variscan deformation at ~300 Ma (Johnston *et al.*, 1996; Wartho *et al.*, 2006).

The paragenetic sequence agrees with a period of prolonged mineralization (Figs. 8 & 9), which evolved with basin development.. The Micrite Unit is the oldest host rock to be mineralized, and subsequently it has been exposed to all mineralizing events and records the entire paragenetic sequence for the Tara Deep system. Zn+Pb dominated during early phases of mineralization, with abundant dendritic galena and colloform sphalerite textures identified within cavities of the Micrite Unit; suggesting rapid, supersaturated conditions in an environment where there has been a sudden change in conditions brought about by fluid mixing (Fig. 6B). Barite and marcasite are preserved as intermediate phases, particularly replacing the matrix of the SFC (Fig. 5B) and infilling any remaining porosity in the Micrite Unit. The preservation of late phase barite and marcasite suggests that during syn-rifting there was a shift to more acidic conditions, facilitating the transfer of barium in an ascending, reduced, fluid which subsequently mixed with a subsurface brine/connate fluid (see Cooke *et al.*, 2000). This shift to more acidic conditions likely remobilised other base metal sulphides, in particular late coarse honeyblende sphalerite (Fig. 6F). The late timing of barite and marcasite within the paragenetic sequence is crucial as it highlights an evolving mineralization relationship, and despite the abundance of barite within mineralized regions, it did not coprecipitate with early base metal sulphides. It is also important to note that the size and morphology of barite crystals formed by different precipitation modes are distinct (see Paytan *et al.*, 2002). Barite at Tara Deep often reveals a platy, highly porous fabric, with triangular pits, and internal crystal zonation (variations in concentrations of Sr). This crystal habit agrees with Ba-rich pore fluids being expelled and meeting sulphate-rich seas (diagenetic origin). Finally, pyrite dominates the last phases of the paragenetic sequence and subsequently late-rifting, it is highlighted by the abundance of laminated pyrite preserved in the TBU (Fig. 5C) and within pressure dissolution textures (Fig. 6G-H), suggesting the system is waning as it becomes Fe-rich and Zn+Pb deficient.

A broad statement is often made in Irish economic geology that mineralization occurs in the lowest, non-argillaceous, clean carbonate unit (Hitzman & Beaty, 1996), however this study stress extreme caution with this statement. Detailed petrography at Tara Deep reveals that mineralization exploits and precipitates in a range of carbonate depositional environments within the Micrite Unit, SFC and TBU. In each of these host rocks mineralization has exploited every available porosity; from fenestral textures, interparticle porosity, argillaceous matrix in debris flows, fractures, cavities and even pressure solution seams. This research proposes that fluid mixing was a greater control on the location of metalliferous fluids. Locations where seawater brines/connate fluids pooled within the subsurface ultimately provided traps for deep ascending metalliferous fluids. The heterogeneity brought about by emergent surfaces in the overlying Pale Beds (see Rizzi, 1992) likely facilitated brine percolation into the subsurface. Whereas dolomitized stratabound units within the Micrite Unit, possibly provided a suitable seal for these dense subsurface bacteriogenic rich brines/connate fluids, eventually interacting and mixing with hot, buoyant hydrothermal fluids, carrying metals from the basement during rifting.

Isotopic Constraints

Sulphur Isotopes

Existing Navan Data: An extensive S isotope database exists for Navan (Anderson, 1990; Ford, 1996; Anderson *et al.*, 1998; Fallick *et al.*, 2001; Blakeman *et al.*, 2002; Altinok, 2005, Yesares *et al.*, 2019) and other Irish-type deposits (Boyce *et al.*, 1983b; Caulfield *et al.*, 1986; Wilkinson *et al.*, 2005; Barrie *et al.*, 2009; Wilkinson & Hitzman, 2015), but comparatively little work has been undertaken on Tara Deep (Yesares *et al.*, 2019). Studies in the Main Navan Orebody have outlined two principal populations of δ^{34}S in ore sulphides, -26 to -4 ‰ and -4 to 16 ‰. The lightest δ^{34}S subgroup is interpreted as the product of contemporaneous bacterial reduction of seawater sulphate (BSR) during the Mississippian (Coomer & Robinson, 1976), with an average bacteriogenic isotopic fractionation $\Delta^{34}S_{SO4-H2S}$ around 35‰ being typical for ore sulphides. The heavier sub-group likely represents hydrothermal sulphur which enters the orebody as metalliferous hydrothermal fluids, sourced dominantly from the Lower Palaeozoic basement (Anderson *et al.*, 1989; Boyce *et al*, 1993, 1994, O'Keeffe, 1986). Local sulphates (largely barite, and minor anhydrite) throughout the Navan deposit, have an average δ^{34}S of +21 ± 2‰ (n = 23; Andrew & Ashton, 1985; Boyce *et al.*, 1983b; Caulfield *et al.*, 1986) which is consistent with the range of δ^{34}S of Mississippian seawater sulphate (Claypool *et al*, 1980; Kampschulte *et al.*, 2001).

Mixing of a deep, basement-derived hydrothermal fluid, carrying metals and limited reduced sulphide, with a surface fluid containing bacteriogenic sulphide, was critical to ore deposition at Navan, and in all other economic ore deposits in Ireland (Coomer & Robinson, 1976; Boyce *et al.*, 1983b; Caulfield *et al.*, 1986; Anderson *et al.*, 1998; Anderson, 1990; Ford, 1996; Blakeman *et al.*, 2002; Altinok, 2005, Wilkinson *et al.*, 2005; Barrie *et al.*, 2009; Wilkinson & Hitzman, 2015). This interpretation is also supported by fluid inclusion studies and radiogenic isotopes (Banks & Russell, 1992; Eyre, 1998; Everett *et al.,* 1999; Samson & Russell, 1987 and see below). Fallick *et al.* (2001) quantified the importance of BSR at the Main Navan Orebody using the δ^{34}S of mine concentrates, taken from the Navan deposit's principal ore lens, the 5-lens (and representing up to 1Mt of ore per sample). Zn and Pb concentrates gave an isotopically homogeneous mean value of -13.6 ±2‰ (varying from -17.5 to -10‰), in contrast to the wide range (-25 to +15‰) obtained from laser and conventional sulphur isotope techniques on individual ore sulphide samples

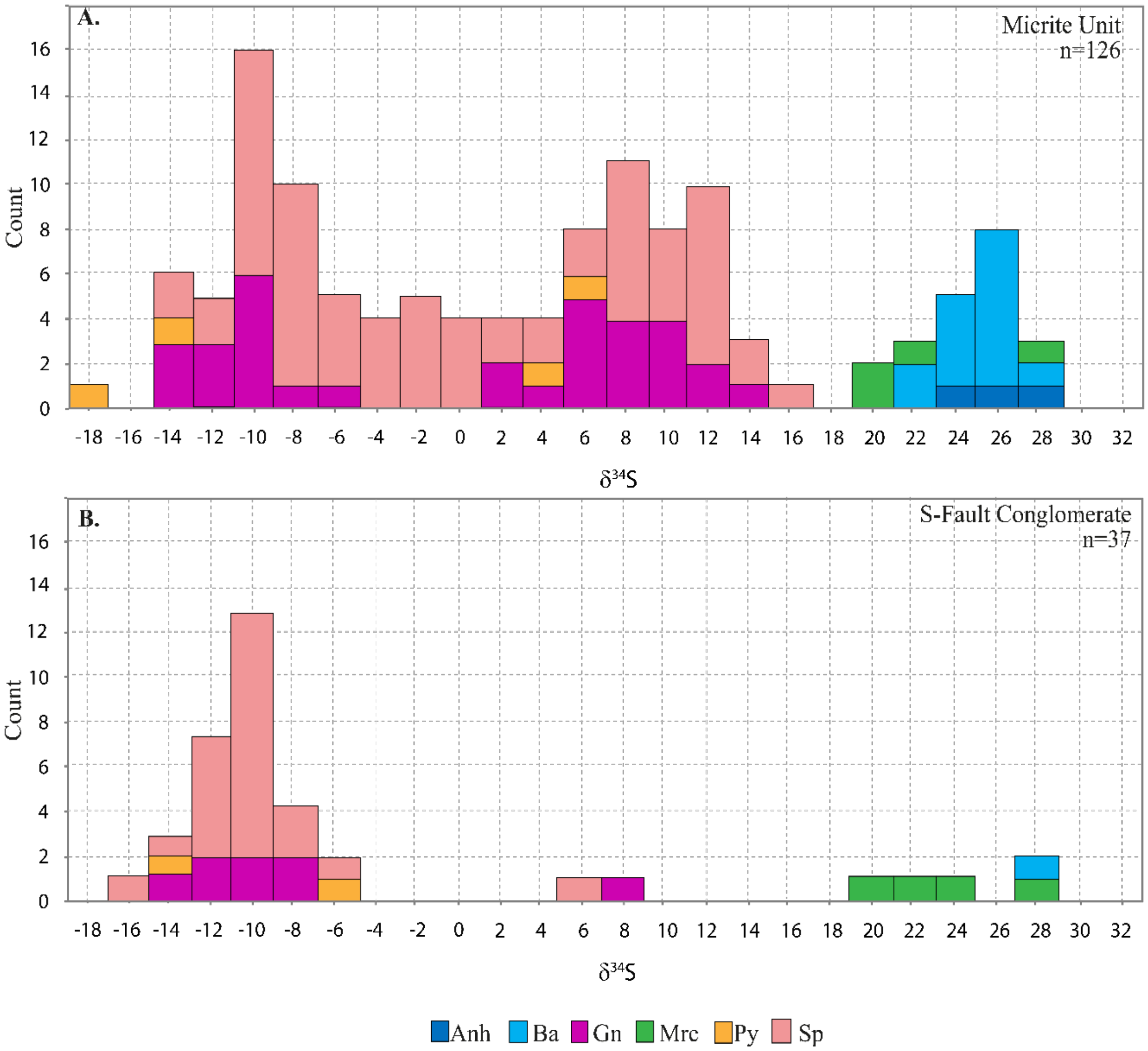

Figure 10: *S isotope analyses of base metal sulphides from Tara Deep. A) Micrite Unit values outline a bimodal distribution bacteriogenic (-13.5 to -3.6 ‰) and hydrothermal sulphur source (+3.4 to +16.2 ‰) B) S-Fault Conglomerate (SFC) revealing a similar bacteriogenic involvement (-5.9 to -16‰) but with a minor hydrothermal component. Contemporaneous Mississippian seawater signature is recorded for barite and anhydrite in both regions (average=26.2‰).*

(Anderson *et al.,* 1998), indicating that more than 90% of Navan sulphide was bacteriogenic. This dominance is reflected in other mines in Ireland, creating a clear message: bacteriogenic sulphide dominance is a critical factor in development of economically viable mines in Ireland (Coomer & Robinson, 1976; Boast *et al.*, 1981a; Thamdrup *et al.*, 1993; Boyce *et al.*, 1983b; Caulfield *et al.*, 1986; Anderson, 1990; Ford, 1996; Anderson *et al.*, 1998; Fallick *et al.*, 2001; Banks *et al.*, 2002; Blakeman, 2002, Blakeman *et al.*, 2002; Weber & Jorgensen, 2002; Altinok, 2005, Wilkinson *et al.*, 2005; Barrie *et al.*, 2009; Anderson *et al.*, 1998 and Yesares *et al.*, 2019).

Tara Deep sulphates: Barite at Tara Deep is paragenetically distinct, and open-space infill and veining suggest that fluid mixing was occurring between a reduced, Ba-bearing fluid and an oxidised seawater (Cooke *et al.*, 2000). δ^{34}S of barite at Tara Deep have a mean value of 26.2 ± 1.8‰ (n=18; Fig.10A & B), with a range of 22.7 to 29 ‰. These values are noticeably higher than the Irish Waulsortian-hosted deposits, which have a mean value of δ^{34}S of 18.2 ± 2 ‰ (n=48; data from Boast *et al.*, 1981a; Boyce 1990; Wilkinson *et al.*, 2005). Similarly, the values are 5‰ heavier, and distinct from, the mean δ^{34}S of the Navan deposit at 21 ± 2‰. Nonetheless, it is reasonably assumed that the homogeneous δ^{34}S from the barites are a close reflection of contemporaneous seawater sulphate in the dynamic environment of Tara Deep, which are distinct from the sulphate signal from the Navan deposit. The higher δ^{34}S in Navan deposits' sulphates, compared to other Irish ores, was suggested by Anderson *et al* (1998) to reflect a distinction in age and/or setting between the deposits. Indeed, the N-S transgression, and existing ages for the sequences in the Irish Orefield indicate that the Navan and Tara Deep deposits are likely younger than the Waulsortian-hosted deposits (Andrew, 1986, 1993; Schneider *et al.*, 2007; Creaser *et al.*, 2009, Symons *et al.*, 2007). No matter the reason for this increased δ^{34}S at the Navan deposit, the mean values at Tara Deep differ and are clearly distinct. Thus, the mineralizing systems at Tara Deep and Navan were unlikely to be directly connected at the time of ore deposition, and it is implausible that Tara Deep represents an allochthonous slice of the Navan deposit.

Tara Deep sulphides: At Tara Deep, galena and sphalerite from Pale Beds-hosted mineralization reveal a bimodal distribution of -13.5 ‰ to -3.6 ‰ and +3.4‰ to +16.2 ‰ (Fig. 10A), reflective of the Navan deposit's similar bimodal distribution. This bimodal pattern also occurs in the 'S Fault' Conglomerate-hosted ores with BSR values of -16‰ to -5.9‰, but with a much-reduced minor hydrothermal component of +7.7‰ to +8‰ revealed to date (Fig. 10B). However, whilst this bimodal distribution is consistent with the same sources as interpreted for the Navan deposit, and other Irish-type deposits (BSR and hydrothermal sulphur) there is a clear distinction from the Navan deposit.

At Tara Deep, the bacteriogenic sub-group distribution is shifted to less negative values, and their mean δ^{34}S is ~5 ‰ heavier than the Navan deposit (a mean of -13.6 ± 2‰ for 5-lens, Fallick *et al.*, 2001; versus -8.5 ± 2.4‰ and -9.7 ± 2.1‰ for Tara Deep's Micrite Unit and SFC, respectively). This resonates with the distinction in sulphate δ^{34}S as discussed above (with an overall mean of 26.2 ± 1.8‰). Taken as a whole, the average extent of fractionation of bacteriogenic ore sulphide from the marine sulphate signal ($\Delta^{34}S_{SO4-H2S}$) is relatively constant at around 35‰ on average in both systems. This ~35‰ average extent of fractionation is also seen between contemporary marine sulphate and bacteriogenic ore sulphide at Lisheen, Silvermines and Tynagh (Wilkinson *et al.*, 2005; Boyce *et al.*, 2003; Boast *et al.,* 1981a). In contrast, the hydrothermal end-member mean and distribution closely match that of the Navan deposit, averaging around 9‰ at Tara Deep.

Together, these data suggest that Tara Deep received a similar hydrothermal fluid input as the Main Orebody, but that the location (in space and time) of the two ore bodies were distinct. It is speculated that there may have been a time gap and/or physical separation in the sub-basins in which bacteriogenic sulphide reduction was taking place. Whatever, the cause of the variation in seawater sulphate δ^{34}S, the bacterial communities were likely similar in both cases – and more broadly in Ireland - when hydrothermal metals were being precipitated in a dynamic environment using bacteriogenic sulphide. Weber & Jorgensen (2002) note a dramatic increase in intensity of BSR activity and sulphide production in active hydrothermal centres in the Guaymas Basin, compared to off-mound production rates. We speculate that the extent of fractionation – and perhaps the intensity - seen in the Irish deposits is a reflection of such a hydrothermally stimulated bacterial community in the Mississippian sea of this region during ore deposition.

In contrast to Anderson *et al.,* (1998), no simple correlation is observed between sphalerite and galena textures and the S isotope signature, a feature which they noted in the Navan deposit. At Tara Deep this may reflect the dynamic nature of the depositing system, typically associated with fluid mixing, and with textures revealing an intimate relationship between hydrothermal and bacteriogenic signatures (Figs. 6C & 10). At Tara Deep, cavity fill, coarse galena, brecciated textures, and massive mineralization can possess both hydrothermal and bacteriogenic values. Thus, we argue that rapidly changing conditions, brought about by dynamic fluid mixing and thus modifying local physio-chemical conditions, were more important than the overall available S source for generating these textures (Fig.11), the metals using whichever source was available at a given moment.

Coarse-grained galena with a hydrothermal δ^{34}S signature always have abundant Sb-sulphosalts and sporadic Cu-sulphosalt inclusions (Fig. 6C), in contrast to coarse-grained galena with a bacteriogenic δ^{34}S signature which only hosts minor Sb sulfosalt inclusions. This allows an accurate representation of the sulphur source at the petrographic scale. The occurrence of the abundant Cu and Sb sulphosalts reflects the ability for metalliferous fluids to mobilise copper, suggesting a temperature regime that is on the upper end of the spectrum (>250°C) of fluid inclusions recorded at the Navan deposit (Lydon, 1988; Wilkinson, 2014).

Yesares *et al.*, (2022) outlines that the TBU at Tara Deep displays a distinct S isotope pattern. In addition to the bimodal distribution in ore minerals similar to the Pale Bed and SFC counterparts, an extremely negative signature is noted in pyrite of the TBU (<-20‰). This is also seen in the TBU37 equivalent levels at the Navan deposit (Anderson *et al.*, 1998). Blakeman *et al.,* (2002) cogently argue that this reflects a bacterial consortium operating in more oxidizing conditions during "quieter" periods when the main mineralization is not taking place (instead, solely pyrite deposition), allowing increased disproportionation cycles during dissimilatory bacterial reduction of sulphate (Thamdrup *et al.*, 1993; Canfield & Thamdrup, 1994; Finster, *et al.*, 1998). As Blakeman *et al.,* (2002) point out, a corollary of this observation is that the sulphide in remobilized pyrite cannot be the source of this base-metal sulphide, as remobilized pyrite would simply retain its original δ^{34}S signature (see also Boyce *et al.*, 1983b; Anderson *et al.*, 1998).

Lead Isotopes

Data from Tara Deep display remarkably homogeneous ^{206}Pb/^{204}Pb of 18.2 ± 0.006 (2σ, n=25), which is coincident with Pb isotope data across the Navan deposits (Caulfield *et al.*, 1986; O'Keeffe, 1986; Fallick *et al.*, 2001). Fallick *et al.,* (2001) analysed bulk mine concentrates across all lenses at Navan (^{206}Pb/^{204}Pb=18.19 ± 0.03, 2σ), and agreed with earlier and subsequent interpretations of Pb isotope data from across the Irish Orefield (LeHuray *et al.,* 1987; Mills *et al.*, 1987; Dixon *et al.*, 1990; Everett *et al.*, 2003) that the Pb, and thus ore metals, were derived from leaching of the underlying Lower Palaeozoic basement.

Across Ireland, there is a systematic variation in lead isotope ratios from northwest to southeast Ireland, following the Caledonide inherited grain, which is seen in both Mississippian-hosted and basement-hosted mineralization. This variation across the Irish orebodies are interpreted to reflect mixing of lead extracted from Ordovician and Silurian volcanic and sedimentary rocks during Caledonian accretion, derived from different crustal reservoirs north and south of the Iapetus suture (Boast *et al.*, 1981b; Caulfield *et al.*, 1986; O'Keeffe, 1986; LeHuray *et al.,* 1987; Mills *et al.*, 1987; Dixon *et al.*, 1990; Fallick *et al.*, 2001; Everett *et al.*, 2003). A potential alternative

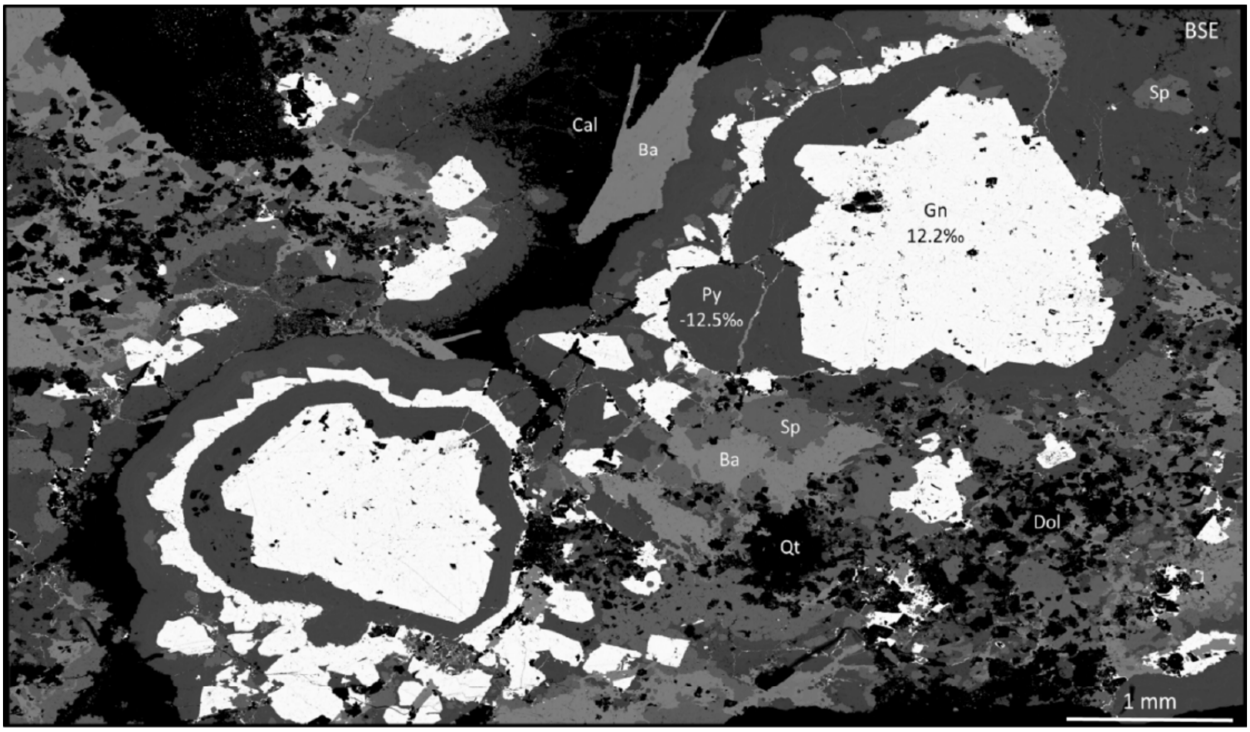

Figure 11: *Back Scattered Electron (BSE) image of Pale Bed mineralization displaying the complex textures present at Tara Deep and the close relationship between bacteriogenic and hydrothermal base metal sulphides. Sphalerite is encased by colloform bacteriogenic pyrite which displays arsenic zonations (Py; -12.5‰), this is infilled by hydrothermal galena (12.2‰) with inclusions of Sb- and Cu sulphosalts (N02428; 1473.6m). Mineral abbreviations; Barite (Ba), Calcite (Cal) Dolomite (Dol), Galena (Gn), Sphalerite (Sp) and Quartz (Qt).*

source of lead from the Old Red Sandstone has been almost certainly ruled out based on the experimental work of Everett *et al.*, (2003).

Summary of Isotopic Constraints

Tara Deep and Navan show broadly similar Pb and S isotope characteristics, with both exhibiting a statistically identical Pb isotopic signature and a bimodal ore sulphide S isotopic distribution and homogeneous sulphate signature. An average isotopic fractionation between the contemporaneous marine sulphate and ore sulphide around 35‰ is found in both deposits, and is found in all other economic Irish ore deposits. However, whilst they appear to be horses of the same colour, the shades are slightly different. Around 5‰ shifts to higher $\delta^{34}S$ in the subsurface-derived S isotope signatures (both sulphide and sulphate) indicate that Tara Deep's sulphur was sourced from a distinct seawater signature. In contrast, the Pb isotopes and the hydrothermal S isotopic signature show a similar hydrothermal influence, with derivation of both most likely from the Lower Palaeozoic basement.

Differences Between Tara Deep and Navan

A series of additional mineralized lenses exist within the upper Pale Beds at the Main Navan Orebody; whilst for Tara Deep, the sedimentary sequence above the lower Pale Beds are principally lost or missing, and marker horizons within the Pale Beds are not preserved (Fig. 3A&B). Deciphering separate debris flows with the Navan deposit's Conglomerate Group Ore (CGO) is difficult (Ford, 1996), and so the unit is generally lumped as a homogenous package. At Tara Deep, particularly in Zone One, several distinct sedimentary breccias are clearly recognised in the TBU, with intervening thinly bedded limestones and shales that have consistent characteristics and are laterally persistent- highlighting that numerous slope instability events occurred in this region. Finally, seismic interpretation and initial drilling have revealed that the TBU has dramatically thickened over the Tara Deep region, and is interbedded with a series of slides, tuffaceous horizons, hydrothermal cherts and laminated iron sulphide mineralization. These features clearly highlight instability during rift-related basin margin sedimentation during the lower Visean and have led to deposition of ~600m of TBU in the Tara Deep region (which has a thickness of 20m at the Navan Orebody). The increased thickness of TBU units in this area appears to reflect renewed peripheral faulting, potentially to the north (Ashton *et al.*, 2018).

In summary, discrepancies exist between Tara Deep and Navan, but most of these differences can be explained by considering the variation in differential subsidence, sea-level variations, debrites/erosion, and subsequent removal of stratigraphy.

Genetic Implications

How Tara Deep formed has significant implications for the genesis of Irish-type base-metal deposits and facilitates our understanding of the evolution of the Navan and Tara Deep

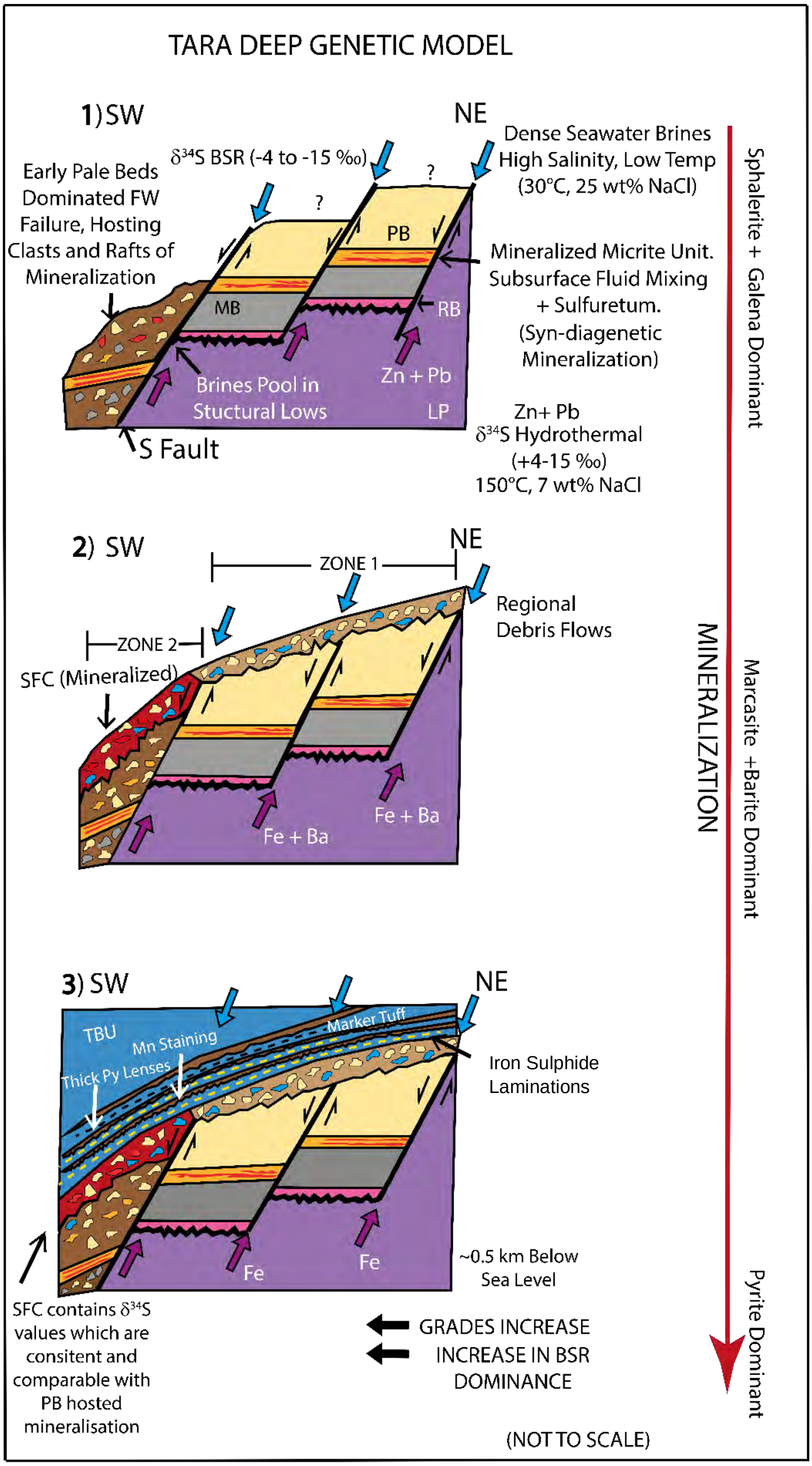

Figure 12: Tara Deep cartoon schematic model outlining the evolution of the deposit and showing the relationship between mineralization and the 'S Fault'. Model highlights the close association between basin development, evolving carbonate depositional environments, and mineralization. A series of low angle faults likely exist which complicate this reconstruction. Abbreviations are, LP- Lower Palaeozoic, MB- Mixed Beds, PB- Pale Beds, RB- Red Beds, SFC- 'S Fault' Conglomerate, TBU- Thin Bedded Unit.

systems. A schematic genetic model for the formation of Tara Deep is presented in Fig. 12. This model splits the broadly syn-rift mineralization relationships into three stages, early-rift, syn-rift and late-rift:

Stage 1 (early-rift): Basin rifting initiates, subsequently generating fault conduits for hot, buoyant metalliferous fluids from the basement. Structural lows developed where dense brines/connate fluids became trapped within the subsurface. In the Tara Deep region, NE trending faults ('G' and potentially the Navan fault) and the 'S Fault' were important conduits, especially at the junctions between these faults. The onset of early-rift mineralization pre-dates the significant lower Visean debris flows. Allochthonous clasts and rafts of Micrite Unit mineralization within the SFC support early extensional faulting, mineralization, and footwall failure pre-Boulder Conglomerate.

Stage 2 (syn-rift): Brines continued to pool within structural/topographic lows within the subsurface. The Pale Beds mineralization and the SFC mineralization are geographically and temporally distinct. The SFC likely represents a debrite in a region where mineralization was already occurring. The SFC records an evolving mineralization story, more acidic and reducing conditions, highlighted through the dominance of late phase marcasite and barite within the SFC matrix. There was a gradual shift to more Fe-dominant conditions with time. Exploration criteria at a regional scale should strongly favour highly productive, extensional basin margins, with focus on structural lows where debrites have occurred. These regions are insights into areas where faulting generated structural lows and locations where brines/connate fluids pooled. These structures also provided active conduits for metalliferous fluids to rise from the basement, and eventually generated footwall instability and collapse.

Stage 3 (late rift): Basin subsidence continued, with differential subsidence occurring between Tara Deep and Navan. This is highlighted by a remarkable thickening of the TBU stratigraphy between Tara Deep and Navan (Fig. 3). Late-rift debrites and turbidity currents dominated in the Tara Deep region. Fault conduits remained active, with the 'G Fault' likely having a more crucial role. The system waned and became iron dominated with extensive iron sulphide lamination in the TBU, with only minor sphalerite and galena. Subsequently, the TBU provides a visual vector to potential underlying mineralization.

Conclusions

The Tara Deep deposit is hosted by Mississippian carbonates within complex fault-controlled terraces on the degrading footwall of a major normal fault system. These terraces have resulted from basin margin activity during the upper Tournaisian. The Tara Deep deposit has many similarities with the neighbouring Navan deposit that reflect comparable controls on the mineralizing process such as host rocks, base-metal and sulphur sources, and tectonic environment. Of crucial importance is the presence of eroded, transported and abraded clasts and rafts of sulphide entrained within syn-rift conglomerates in both the Navan (Conglomerate Group Ore) and Tara Deep ('S Fault' Conglomerate) deposits. This observation demonstrates that the onset of mineralization occurred during the upper Tournaisian, and relative to the stratigraphy, the timing of mineralization at Tara Deep is similar to Navan. Tara Deep and Navan are isotopically similar, showing both a statistically identical Pb isotopic signature and a bimodal sulphide S isotopic distribution and homogeneous sulphate signature. However, around 5‰ shifts to higher δ^{34}S in the subsurface-derived S isotope signatures (both bacteriogenic sulphide and sulphate) indicate that Tara Deep's sulphur was sourced from a distinct seawater signature. Close similarities with the Navan deposit allows Tara Deep to adopt a similar genetic model as Ashton *et al.*, (2015). However, this research demonstrates that mineralization initiated during an early phase of the developing Dublin Basin and kept pace with rifting and subsequently an evolving basin. It develops the existing model to highlight the evolving basin and mineralization relationships, and also to outline that the Pale Beds mineralization is temporally distinct from the 'S Fault' Conglomerate-hosted ore. Upper Tournaisian extensional faulting allowed dense brines to pool in structural lows, and also provided fault conduits for hot, metalliferous fluids from the basement to access the carbonate host rocks.

To discover more deposits like Tara Deep, it is vital to understand the basin margin architecture and to model existing debrites and structural lows where mineralization once occurred. Correlations with Navan are important encouragement for continuing exploration in the Tara Deep region and indeed in the areas to the south and west of Navan.

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