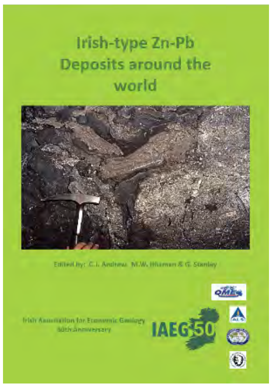

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Irish-type Zn-Pb deposits - What are they and can we find more?

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To cite this article: Ashton, J.H., Andrew, C.J. & Hitzman, M.W. (2023) Irish-type Zn-Pb deposits - What are they a more? *In:* Andrew, C.J., Hitzman, M.W. & Stanley, G. '*Irish-type Deposits around the world*', Irish Association for Economic Geology, Dublin. 95-146. DOI: https://doi.org/10.61153/DODR7609

To link to this article: https://doi.org/10.61153/DODR7609

Irish-type Zn-Pb deposits - What are they and can we find more?

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Abstract: Seven carbonate hosted Zn-Pb (+/-Ag, Ba) or Cu deposits have been mined in Lower Carboniferous limestones in Ireland since 1960 - representing a resource base of ca. 22 Mt of metal (Tynagh, Gortdrum, Magcobar, Silvermines, Navan, Galmoy and Lisheen). The orebodies are amenable to modern mining and metallurgical processes and exploration for further deposits continues. Several significant prospects remain unexploited with numerous smaller prospects and mineralized localities attesting to the metal endowment of the country (Pallas Green, Stonepark, Ballinalack, Kilbricken and Keel). These deposits share sufficient characteristics to be termed Irish-type Base Metal Deposits and define a metallogenic province of worldwide significance known as the Central Irish Orefield. Early discoveries resulted from shallow soil geochemistry, Induced Polarization surveys, and follow-up of legacy mining or mineralized outcrops. More expensive, deeper penetration methods including deep drilling, airborne geophysics and seismic methods have been utilized extensively in more recent years - but thus far with variable success. Large amounts of ground remain unexplored at depth, but further discovery is extremely challenging. Following over 60 years of discovery and mining this contribution summarizes our knowledge of Irish-type deposits and their exploration with a view to generating new ideas for future discovery.

The Tynagh, Silvermines, Lisheen and Galmoy deposits, all hosted in the Waulsortian Limestone, occur in a distinct area in the SW of the Orefield. Silvermines, Lisheen and Galmoy are remarkably similar, comprising several, tabular, stratabound, lenses containing locally massive and high-grade sphalerite-galena with substantial pyrite +/- barite. These deposits are hosted in the first clean limestone above basement in Lower Carboniferous limestones and dolomites and exhibit fine grained, replacive sulphides with significant breccia and crosscutting mineralization. Structurally all these deposits abut major syn-sedimentary faults usually trending NE or ENE. The Navan deposit occurs on the NE side of the Orefield and is hosted in stratigraphically lower, Pale Bed limestones, that are roughly age equivalent to the Waulsortian Limestone in the SW of the Orefield. Navan is much larger and more complex than the deposits in the SW Orefield but shares several of their key characteristics.

A review of the characteristics of Irish-type deposits and exploration results suggests some important areas for future exploration and research. For example, most observers relate the location of Irish-type deposits to the regional distribution of host rocks and structures of a certain age. It is suggested that the spatial location of these deposits is more fundamentally controlled by deep structural heterogeneities related to the collisional zone between basement rock terranes termed the Iapetus Suture. Understanding the timing of fault development is likely key to further discovery at depth as the mineralizing feeder structures are located on faults that did not necessarily extend through post-Waulsortian aged strata. Several promising fields for research and development to help enable further discovery are discussed.

Keywords: Central Irish Orefield, exploration, carbonate-hosted Zn-Pb, Irish-type.

Introduction

Background

Since 1960 over 300Mt of economic to potentially economic Zn/Pb/(Cu, Ag, Ba) mineralized carbonate rock has been discovered in Central Ireland within the Lower Carboniferous carbonate sequence (Fig. 1, Table 1, Plate 1). Exploitation of these deposits, termed 'Irish-type' ('IT' in this paper for brevity), has had a major positive effect on the Irish economy, paralleling Irelands growth within the European Union (EU) and they constitute an important asset for the EU (INDECON, 2013, AECOM, 2020). Ireland is a major European producer of Zn, which though not currently designated as a critical raw material (CRM) by the EU (European Commission, 2023) but has been so designated by the United States. The Irish Orefield has also historically been a major producer of barite (an EU designated critical raw material) and has contributed to European copper production with copper currently designated as a strategic critical raw material by the EU. In addition, the Irish Orefield has potential to contribute both germanium and nickel to the EU; both of these metals are EU designated strategic raw materials.

The growth of Irish mining, exploration and support companies and consultants has been remarkable; many have been successful worldwide with positive effects on entrepreneurship, technology, training, research and development in Ireland. The IAEG, the leading society for economic geologists in Ireland, has been at the forefront of these developments. This 50-year anniversary is the perfect time to assess the accumulated technical knowledge on IT deposits and consider how we might enhance further discovery for the betterment of the Irish and EU economies.

Historical

In comparison with the UK, where historical Zn/Pb mining was widespread in Carboniferous limestones, (North & South Pennines, Minera-Maeshafn, Somerset etc.) Ireland had relatively little history of Zn/Pb mining (OBrien, 1959). Notable exceptions being the centuries old Silvermines district where mining was still active in the 1950s, and Abbeytown during the same period - though these were then quite small operations. This apparent dearth of base-metal mineralization combined with the flat lying topography of the Irish Midlands suggested to many observers that if mineralization was present, then it would be deeply covered by peat and glacial deposits and probably sub-economic - however this perception was false!

Prompted by financial incentives brought in by the Irish Government and the successful efforts of returning expatriates from Canada (e.g., *see* Clavin, 2017), exploration in the late 50s and early 60s was rewarded with the discovery of the Tynagh deposit in 1962 (Plates 1A & 1B. later estimated to contain over 10Mt of Zn, Pb, Cu and Ag ore (Derry *et al.,* 1965, Morrissey *et al.,* 1971; Table 1). There followed increased exploration activity which resulted in the discovery of a major stratiform orebody at Silvermines within a few metres of historical base-metal and silver mine workings and close to an existing barite open pit at Ballynoe ('Magcobar') (Plate 1C & 1D; Grennan & Andrew, 2022). This success coupled with the discovery of the Gortdrum Cu-Ag-Hg deposit (Plate 1E. Steed, 1986; Cordiero *et al*., 2023; Dunleavy *et al.,* this volume) and several other prospects, proved that Irish base-metal discovery potential was extremely high, measurable in tens of millions of tonnes and in orebodies quite different to anything in the UK or indeed Europe. This was confirmed by the discovery of the Navan deposit, initially 67Mt, located 120km NE of the then known deposits and significantly larger in size, effectively widening the search space to most of central Ireland and making it exploration 'elephant country' (Plate 1F; OBrien & Romer, 1971; Libby *et al*., 1985).

The Tynagh, Silvermines and Navan discoveries, together with smaller prospects at Keel and Ballinalack, identified multi-million tonne deposits of carbonate hosted Zn-Pb ores that shared several characteristics. They comprised shallow dipping stratiform to stratabound deposits hosted by Lower Carboniferous limestones and dolomites generally on the downthrown sides of major NE trending normal faults. Mineralized zones usually formed several closely situated but separate lenses, the larger of which proved to be readily amenable to modern mining and milling methods leading to potentially excellent economics. These deposits clearly constituted a newly discovered metallogenetic province and attracted considerable interest as to ore genesis (Derry *et al.,* 1965; Morrissey *et al.,* 1971; Russell, 1968, 1978). Geological details gradually emerged from publications by company geologists and academics proposing that the deposits were the product of early mineralization during syn-sedimentary faulting and shallow sub-surface replacement (Derry *et al*., 1965; Russell, 1968, 1986; Coomer & Robinson, 1976; Boast *et al.,* 1971; Boyce *et al.,* 1983a; Andrew & Ashton, 1985; Taylor & Andrew,1978). Russell (1978, 1986) proposed an innovative mechanism involving downward convecting hydrothermal cells as a process for leaching metals from the Lower Palaeozoic basement (e.g., Bischoff *et al*., 1981).

Discoveries slowed in the 70s and the amount of published research on the IT deposits was quite limited. In the early 80s the IAEG organized a major international conference to present knowledge on all metallic mineral deposits in Ireland for better understanding and to promote further discovery. "*Geology and Genesis of Mineral Deposits in Ireland*" (Andrew *et al.,* 1986) was held in Trinity College in 1984 and attracted a worldwide audience from industry and academia, with presentations on most mineral deposits in Ireland, drill-core and poster displays, and extensive field visits. This successful conference had at least three effects. Firstly, the genesis of the larger IT deposits became increasingly controversial with many workers questioning a strictly syn-sedimentary origin (e.g., Hitzman & Large, 1986). This led, secondly, to more focused research into IT deposits by a larger cohort of research workers. In particular, several North American economic geologists questioned whether IT deposits should be re-classified as Mississippi Valley Type Deposits (MVTs). Thirdly and most importantly, exploration within Ireland was stimulated and over the following six years the Galmoy and Lisheen deposits were discovered – producing a major boost to the industry and indicating that more IT deposits could be found under cover (Plates 1G+H. Doyle *et al*., 1992; Hitzman *et al.,* 1992; Shearley *et al*., 1996). Both deposits showed close similarities with existing mines - again reinforcing the concept that Central Ireland comprised a globally important metallogenic district.

Over the following years the IAEG continued to promote the industry with major conferences and publications each decade - including its participation in the worldwide field meetings, conference and publications organized by the Society of Economic Geologists in 1995 (Anderson *et al.,* 1995; Sangster, 1997). Opinions amongst some observers on the genesis of IT deposits at this time changed from essentially 'syn-diagenetic' mechanisms to later epigenetic models influenced by the near worldwide adoption of Garven's topographic and density driven models for derivation and transport of MVT metal transporting brines (Garven, 1995; Garven *et al*., 1999; Johnston, 1999; Nagy *et al*., 2003; Sevastopulo & Redmond, 1999). Considerable further detailed research on IT Deposits since the 90s has seen many workers swing back in favour of the 'syn-diagenetic' model where mineralization is seen as epigenetically emplaced but at shallow burial levels co-eval with early growth faulting in the Lower Carboniferous, with hydrothermal fluids derived from deep convection in the basement (Everett *et al.,* 1999; Lewis & Couples, 1999; Everett *et al*., 2003; Hitzman & Beaty, 2003; Murphy *et al*., 2008; Wilkinson *et al.,* 2005c; Wilkinson, 2010; Wilkinson *et al*., 2011; Wilkinson & Hitzman, 2015; Shelton *et al.,* 2019).

Lisheen, discovered in 1990, was the most recently developed mine in Ireland (Hitzman *et al*., 1992). However, in the 00s extensive mineralization was found at Pallas Green and later at Stonepark at the edge of the Limerick Lower Carboniferous volcanic centre (Blaney *et al*.; 2003; Redmond, 2010; Blaney & Redmond, 2015). These deposits while of economic size presently remain undeveloped. Interestingly these deposits, while hosted at the same (basal Waulsortian) stratigraphic level as nearby IT deposits, have a spatial association with intrusives (dykes and diatremes) (Elliot *et al.,* 2019) however a connection with large normal faults is not, yet, evident. The discovery of Kilbricken in east County Clare in 2008 is also of note especially since it also displays strong similarities to IT deposits in that it occurs in the hanging-wall of a normal fault in the Waulsortian Limestone but is rich in Cu in the Fort Zone where Cu as disseminated bornite and chalcopyrite attains levels of up to 0.3% (Colthurst & Reid, 2019; Murphy, this volume). In recent years two major extensions to the Navan deposit, the South West Extension (SWEX) (Ashton *et al*., 2003) and Tara Deep (Ashton *et al*., 2018), have shown the massive potential in Ireland for discovery beneath deep cover and the potential of seismic surveying for target definition.

In conclusion, the Irish Orefield is young in comparison to most Zn-Pb districts worldwide and its discovery was unexpected, as indeed, was the size of the giant Navan deposit – so surely further discoveries are possible?

Discovery Methodology – What is state of the art?

A number of techniques have been responsible for the discovery of IT deposits (Table 1). Most were discovered using shallow soil geochemical surveys often in areas where there was small scale mining activity or at least some sign of mineralization in outcrops or float. In the case of Silvermines there was a long history of extensive mining before the 1963 discovery although there had been recent Pb mining and barite extraction within 1-2 km of the discovery. Drill siting in these discoveries was often guided by Induced Polarization (IP) geophysical surveys. Early discoveries were of sub-outcropping mineralization, and with intensive exploration throughout Central Ireland in the 70s having only limited success, the industry started to employ more expensive methods with notionally deeper penetration to aid discovery. These involved ‘direct’ detection methods such as deep overburden geochemistry, litho-geochemistry and mobile-ion geochemistry (and similar methods) for soils, IP and EM (electromagnetic) surveys, and the deep drilling of geologically defined targets. Several ‘indirect’ techniques aimed at defining favourable geological features (faults, antiforms, suitable host-rocks etc.) were extensively used including satellite image analysis, ground and airborne geophysics, including gravity, magnetics, and EM methods. The results were not strikingly effective and highlighted the need for diamond drilling as a key tool. Most recent successes are, arguably, the result of a mix of analysis of legacy data, geological insight, local geophysics and diamond drilling, and by no means omitting good fortune! Problems include the glacial drift cover, lack of geophysical parameter contrast between rock types and mineralized zones, the low conductivity of the main target mineral – sphalerite, the small size of many licence holdings, and lastly cultural interference with geophysical techniques and geochemical surveys in a countryside that is increasingly infrastructurally ‘urbanized’ (modern farming, new houses, new roads etc.).

Following recent regional surveys (de Morton *et al.,* 2015) and success with near-mine exploration at Navan (Ashton *et al*., 2018) exploration has increasingly utilized 2D and locally 3D seismic surveying (Murphy, *this volume*) as a tool to define subsurface geology in terms of faults, suitable host-rocks and to identify and direct (and exclude) exploration to areas that are effectively too deep to target. These techniques, whilst capable of producing structural profiles that are easier to interpret than many potential field or electrical geophysical methods, ideally require petrophysical data on lithologies that are only now becoming available. Such methods are also very expensive and need drilling for calibration and then of course more drilling to test targets. As yet, no new ‘green-fields’ discovery has been made using seismic methods - so what of the future?

Leveraging Discovery

The Irish Government has historically been supportive of discovery by public release of Geological Survey records and embarking on the recent Tellus programme of regional airborne (magnetics, EM and radiometrics) and geochemical surveys. Furthermore, all legacy exploration data is freely available on ‘Open File’. After >60 years of exploration this constitutes a massive amount of data, whose quality is extremely variable and can be difficult to capture, assemble and interpret. Over this time as well large amounts of data have been released at IAEG meetings and via numerous University PhD theses and published articles. There is now also a growing data base of drill holes, intersecting most of the Courceyan and Chadian aged lithologies and significant portions of the younger stratigraphy, and many regional 2D seismic profiles. An obvious prime recommendation for the future is employing data analytical methods on these databases to allow fast, intelligent AI-type query to assemble, evaluate quality, and present data collations in novel, useful and timely fashions. As this material becomes available via ‘Open File’ and freely available there will be an unrivalled opportunity for academia and industry to understand the geology and evolution of the Central Irish Orefield in considerably greater detail than at present – however such studies, to be useful, need to be funded and coordinated to provide regionally sound interpretations.

The Central Irish Orefield must now be considered a mature exploration area, at least in terms of the near-surface search space. Any exploration company embarking on a new programme in Ireland not only has this wealth of data to assimilate but has to apply considerable geological ‘nous’ to proceed with area and target selection - likely involving a ‘Mineral System Analysis’ approach or similar (e.g., Hagemann, 2016).

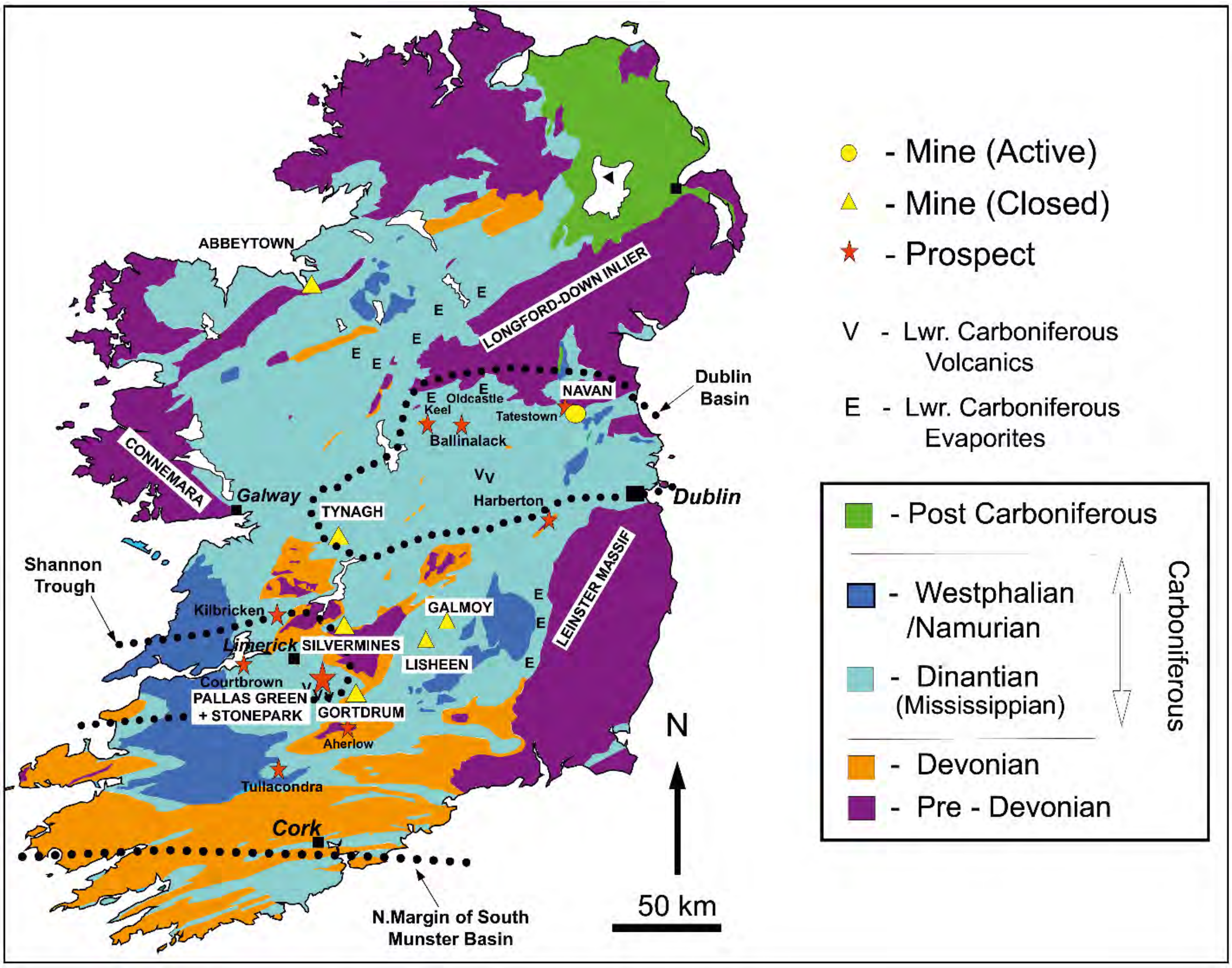

Figure 1. Geological map of Ireland showing distribution of principal Zn, Pb (Cu,Ag,Ba) deposits in lower Carboniferous limestones (after the Geological Survey of Ireland). Approximate Carboniferous basin locations after Strogen et al. (1996).

However, many Irish exploration geologists have considerable valuable knowledge, experience and ideas, much of it unpublished, to contribute towards discovery. Our focus here is to encourage exploration by providing a questioning summary of IT deposits and experts opinions to date to consider whether the Orefield can be expanded both laterally and at depth.

Geological Setting

The geology of the Central Irish Orefield has been described in various levels of detail by many authors (Phillips & Sevastopulo, 1986; Hitzman & Beaty, 2003; Holland, 2009; Wilkinson & Hitzman, 2015). IT deposits occur in lower Carboniferous (Courceyan to Chadian-aged) carbonate rocks that unconformably overlie a locally heterogenous basement of variably deformed and metamorphosed Silurian and Ordovician sediments and lesser extrusive and intrusive rocks (Fig. 1). In the southern part of the Orefield the lowest Carboniferous rocks conformably overlie Devonian Old Red Sandstones that thicken southwards into the Munster Basin which has a thickness of *ca*. 6 kms of these rocks (McCarthy, 1995). Most of Central Ireland comprises Carboniferous carbonate rocks with topographically pronounced inliers of Devonian and Lower Palaeozoic rocks (Fig. 1). These inliers are mostly the result of Variscan folding but in part reflect earlier faulting and stable areas inherited from the basement geology. Larger areas of basement outcrop are present to the SE in County Wicklow, cored by the Leinster granite batholith, to the NE in the Longford Down inlier, and to the West in Connemara. To the south, outcrop patterns reflect the thickening of Devonian rocks into the major Munster Basin and increasing E-W folding resulting from the Hercynian orogeny with a distinct geological and topographic margin at the Variscan front. Lower Carboniferous rocks are largely carbonate rocks of Courceyan to Brigantian age with Namurian sandstones and shales preserved in local outliers. Precambrian rocks are not exposed in Central Ireland but xenoliths of Grenvillian-aged gneiss in Lower Carboniferous volcanic diatremes in the Midlands indicates that Precambrian crystalline basement extends beneath central Ireland (Strogen, 1974; Van den Berg *et al.*, 2005).

Lower Palaeozoic Basement

The basement exposed below the Devonian-Carboniferous unconformity is composed primarily of a heterogeneous group of Silurian and Ordovician sedimentary rocks including mudstones, siltstones, greywackes and volcanic rocks that have been strongly folded and cleaved but only weakly metam-

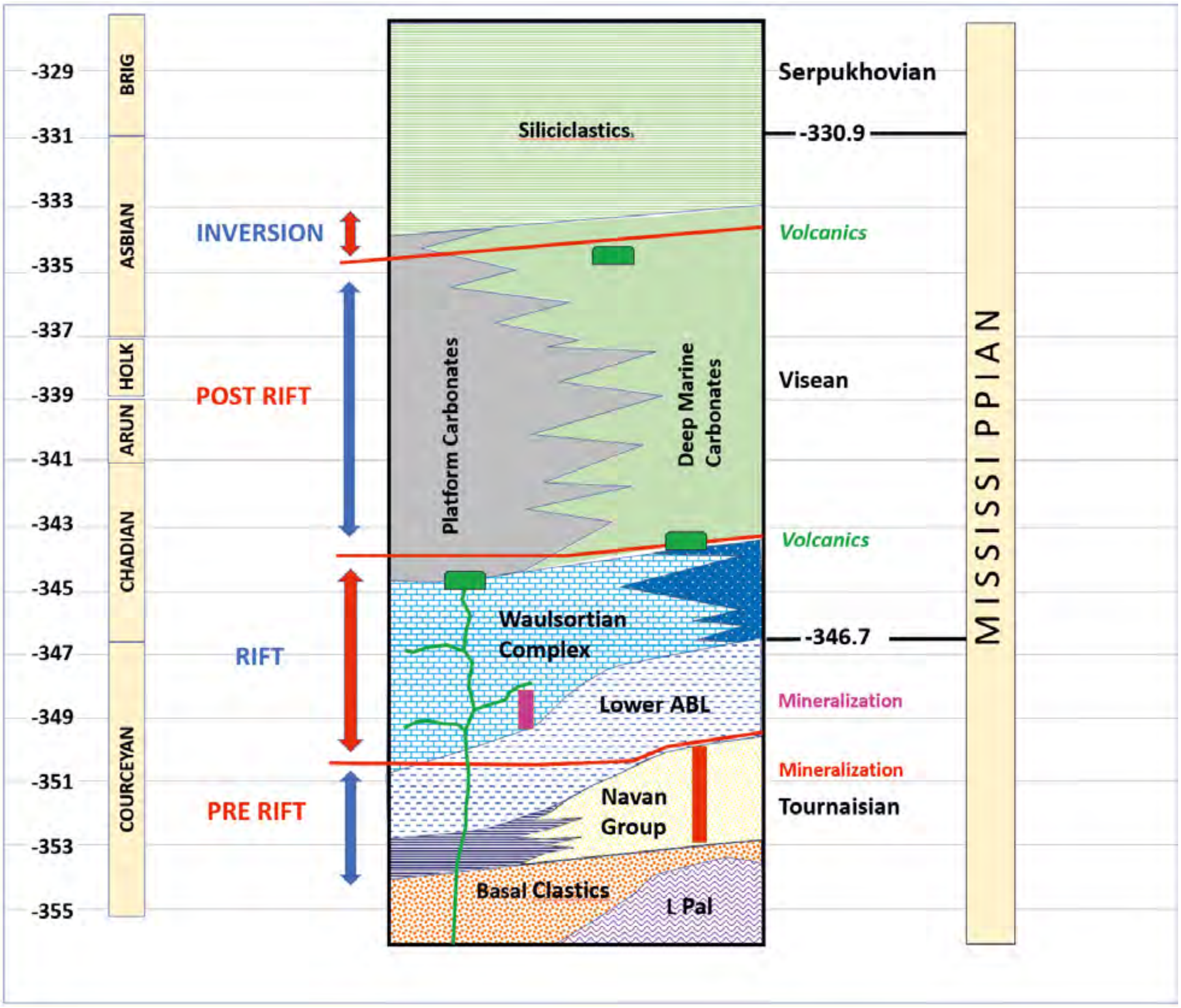

Figure 2. *Diagrammatic stratigraphic column through the Lower Carboniferous of Central Ireland (after Andrew, this volume).*

orphosed. These rocks are locally intruded by dominantly granitic intrusive rocks that are less deformed and were intruded by late Caledonian granites at roughly 400Ma (Chew & Stillman, 2009).

The disposition of these rocks is highly complex and reflects a number of juxtaposed terranes resulting from oblique plate collision during the Caledonian orogen between Laurentia and Avalonia from Ordovician to Silurian times (Hauser *et al*., 2008; Holland & Sanders, 2009; Chew & Strachan 2014; McConnell *et al*., 2021). There has been very extensive publication and discussion in the literature over the exact mechanisms for collision and subsequent complex terrane superimposition but there is general agreement, based on a combination of geophysical, faunal and geological data, that the former collision zone, known as the Iapetus Suture ("IS"), runs in a NE to SW direction under Central Ireland (Fig. 4) (Phillips *et al*., 1976; Beamish & Smythe, 1986; McKerrow, 1987; Freeman *et al.,* 1988; Harper & Parkes, 1989; Chadwick & Holliday, 1991; Todd *et al*., 1991; Vaughan, 1991; Owen *et al*., 1992; Vaughan & Johnston, 1992; Chew & Stillman, 2009; McConnell, 2020). This feature is widely mis-named the Navan-Silvermines Fault in the literature and there is no evidence of an outcropping individual fault cutting the Carboniferous sequence. The Iapetus Suture is better thought of as a broad, deformational zone several tens of kilometres wide comprised of a complex of juxtaposed basement terranes. Near the surface the suture zone is likely disrupted by faulting and thrusting but at greater depth it comprises a gently northwards dipping feature (Vaughan & Johnston, 1992; Klemperer *et al*., 1993). An alternate location is favored by some workers comprising lineaments running on a sub-parallel course but located a few tens of km to the south (e.g., Murphy *et al*., 1999; Rao *et al.,* 2014).

Lower Carboniferous Stratigraphy & Structures

Following peneplanation of the Caledonian mountains, Devonian Old Red Sandstone rocks were deposited in the Munster Basin, thinning northwards and absent in the northern and eastern part of Central Ireland, where red sandstones and conglomerates of basal Carboniferous (Courceyan) age rest unconformably on Lower Palaeozoic rocks. The general stratigraphy of Central Ireland is shown in Figure 2 to briefly discuss the host rocks for the IT deposits. The sequence is capable of sub-

Name	Status	Principal Metals	Host Rock	Discovery	Method	Mt	Zn %	Pb%	Cu%	Ag ppm	Main Reference
Navan	Active Mine	Zn, Pb, (Ag)	PB + BC	1970	Soil geochem.	159.3	7.4	1.6		15	Boliden, 2022
Lisheen	Mine (closed)	Zn, Pb, (Ag)	WAL	1990	Soil geochem. IP. Gravity.	22.2	11.5	1.9		26	Shearley et al., 1995
Silvermines	Mine (closed)	Zn, Pb, (Ag) Ba	WAL (ABL/BAS)	1963	Near old mine. Geophysics.	17.7	6.4	2.5		23	Andrew, 1986a
Magcobar	Mine (closed)	Ba	WAL	1950	Near old mine.	4.6					Grennan & Andrew, 2022
Galmoy	Mine (closed)	Zn, Pb, (Ag)	WAL	1986	IP/resistivity. Soil geochem.	10.9	12.4	1.6			Lowther et al., 2003
Tynagh	Mine (closed)	Zn, Pb, (Ag) Ba	WAL	1961	Near old mine. Soil geochem.	12.3	4.5	4.9	0.4	52	Morrissey et al., 1971
Gortdrum	Mine (closed)	Cu Ag, Hg	WAL/BCL	1963	Stream/soil geochem. IP.	3.8	0.0	0.0	1.2	25	Steed, 1986
Pallas Green	Major Prospect	Zn, Pb, (Ag)	WAL	2002	Mixed methods, drilling.	45.0	7.2	1.0			Glencore, 2022
Harberton	Major Prospect	Zn, Pb, (Ag)	WAL	1975	Soil geochem. IP. Gravity.	11.3	7.8	1.2			ZMI, 2022
Aherlow	Major Prospect	Cu Ag	sub-WAL	1965	Outcrop, Soil geochem. IP.	6.0	0.0	0.0	0.9	33	Romer, 1986
Ballinalack	Major Prospect	Zn, Pb, (Ag)	WAL	1970	Soil geochem.	5.4	7.6	1.1		9	Gordon et al., 2019
Stonepark	Major Prospect	Zn, Pb, (Ag)	WAL	2007	Soil geochem. IP. Gravity.	5.1	8.7	2.6			Gordon et al., 2018
Kilbricken	Major Prospect	Cu, Zn, Pb, Ag	WAL	2008	Drilling below old mine.	4.3	4.6	2.9	0.3	47	Colthurst & Reed, 2019
Tullacondra	Minor Prospect	Cu Ag	sub-WAL	1973	Geochem/Geophys. Anoms.	4.2	0.0	0.0	0.7	45	Wilbur & Carter, 1986
Keel	Minor Prospect	Zn, Pb, (Ag)	BCL	1962	Stream geochem.	1.9	7.7	1.0		40	Slowey et al., 1995
Garrycam	Minor Prospect	Ba (Zn,Pb)	WAL	1976	Drilling	1.4	2.7	0.2			Slowey et al., 1995
Tatestown	Minor Prospect	Zn, Pb, (Ag)	PB	1972	Soil Geochem.	1.7	6.0	3.2			Ashton & McDermott, 1996
Courtbrown	Minor Prospect	Zn,Pb	WAL	1962	Soil geochem. IP. Gravity.	1.0	3.5	2.0		14	Grennan, 1986
Drumlerry	Minor Prospect	Zn,Pb	PB	1977	Quarry, soil geochem. IP.	1.5	4.5	0.7			Open File Reports
Moyvoughly	Minor Prospect	Zn,Pb	PB	1968	Soil geochem.	0.1	6.5	1.0			Andrew, 1993

Table 1. *Approximate total sizes of Lower Carboniferous hosted base metal deposits in Ireland. (Diverse sources, sizes and grades are approximate and where possible include ore extracted to give a geological indication of total size, consequently this data should not be regarded as JORC or NI43-101 compliant). Navan figure comprises total production plus resources at end 2022 and includes Tara Deep. Abbreviations: WAL- Waulsortian limestones, PB, Pale Beds, BC - Boulder Conglomerate, ABL - Argillaceous Bioclastic Limestones, BAS/BCL - Basal Clastics.*

division into separate provinces and many units display significant facies changes that are by no means fully documented or understood; these likely reflect localized changes in sedimentation and are at least partly related to active tectonism during the Lower Carboniferous (Philcox; 1984 in preparation), especially during the latest Courceyan to early Arundian and again in the Asbian. Full formal stratigraphic nomenclature for the Lower Carboniferous has been developed for many areas but is not easy to summarize (Strogen *et al.*, 1990; Strogen *et al*., 1996; Sevastopulo & Wyse-Jackson, 2009). Figure 3 shows a highly simplified cartoon showing the relationships of the principal units, location of the Dublin Basin, and the main ore deposits.

Broadly, the Lower Carboniferous reflects a northward directed marine transgression through the Courceyan (Andrew, 1986; Andrew, 1992; Andrew, this volume) during and after which active extension resulted in differential subsidence in Central Ireland, roughly centered along the IS and probably reflecting reactivation of favourably oriented pre-existing basement structures. Major depocentres formed in east Central Ireland (Dublin Basin) and to the west (Shannon Trough), both of which contain deep-water limestones; subsidence continued through into Asbian times (Strogen *et al.*, 1996).

Basal Courceyan rocks in south central Ireland comprise the Lower Limestone Shale Formation while further northwards the Navan Group developed comprising a heterogenous suite of shallow water calcarenites, oolites, micrites and shalier limestones with local sandstones. A distinct group of clean pale micrites and overlying grainstones, termed the Pale Beds represents the principal host-rocks to the Navan deposit and several peripheral prospects (Plates 2A to 2D). Subsequent deepening of the depositional environments led to sedimentation of more argillaceous units such as the Shaley Pales and Argillaceous Bioclastic Limestones (ABL). This appears to represent a switch from regional northwards transgression to somewhat more localized subsidence in Central Ireland, aided by growth faulting, with larger thicknesses of ABL accumulating in the proto-Dublin Basin (Nolan, 1989; Strogen *et al.*, 1996; de Morton *et al*., 2015). Continued deepening, perhaps accompanied by a lessening of the influx of terrigenous (clay-rich) material, caused a switch to Waulsortian mud-mound growth (deep water clean micrites; Plates 2E to 2H) and ancillary facies (Lees & Miller, 1995). Mud-mound growth led to large accumulations (>1km) of the Waulsortian Limestone (sometimes referred to as "reef") in central basinal areas. In places, possibly resulting from the formation of local tilt blocks and variations in sediment supply versus depth, the Waulsortian developed with more complex 'reef equivalent' lithologies varying from shaley mudstones to clean higher energy oolites such as the Allenwood Beds. On cessation of Waulsortian Limestone deposition in approximately early Chadian times, basin development accelerated particularly towards the east with deposition of large thicknesses of shaley limestones and limestone turbidites known as 'Calp' or 'Upper Dark Limestones' in the Navan area. Peripheral to these areas shallower shelf conditions prevailed reflecting the importance of basin-margin faulting and tilt block creation (Pickard *et al.*, 1994).

Basin development was clearly assisted by contemporaneous faulting of Chadian to post Arundian age, best recorded by extensive drilling and mine openings in Navan where *ca.* 500m of Lower Carboniferous section was removed by complex sliding that reflects footwall degradation on a major basin margin-type fault (Philcox, 1989; Ford 1996; Ashton *et al*., 1992; 2015; 2018). The sliding affected the mineralized section of the Navan Group, ABL and Waulsortian Limestone and locally cut down to Lower Palaeozoic basement with clasts of these lithologies preserved in variable debris flow type deposits termed the Boulder Conglomerate ('BC') (Philcox, 1989). Broadly similar features have been recorded elsewhere around the margins of the Dublin basin (Nolan, 1989; Andrew 1993; Philcox *et al*., 1995).

The more poorly understood Holkerian, Asbian and Brigantian

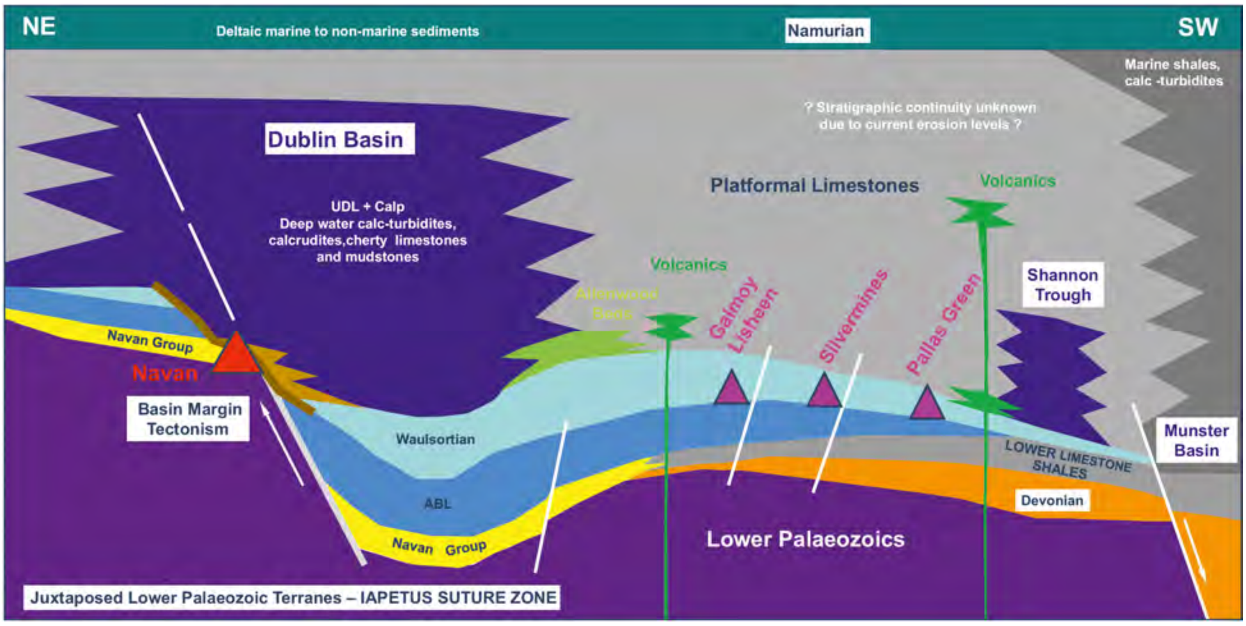

Figure 3: *Cartoon section from NE to SW through the Central Irish Orefield showing stratigraphical relations and location of mineralization. The stratigraphic relationships are greatly simplified and diagrammatic.*

rocks of the Dublin Basin are locally overlain by Namurian shales and sandstones of presumed deltaic origin (Sevastopulo, 2009).

Igneous activity in the Lower Carboniferous comprises widespread occurrence of thin tuffs and the presence of two significant volcanic centres in County Limerick and at Croghan Hill in County Offaly. (Sevastopulo & Wyse Jackson, 2009; Koch, 2021; Slezak *et al.*, 2023; Slezak *et al.*, this volume). This volcanic and related intrusive activity comprising alkaline basalts, trachytes and ankaramites occurs over two periods (Chadian to early Arundian and Asbian). Wilkinson & Hitzman (2015) interpret this igneous activity to indicate: "….*intermittent surface expression of a deep-sourced, relatively low volume, magmatic system that was episodically active throughout the 30 Ma period of Lower Carboniferous basin development and imply moderate degrees of crustal extension*". Sm-Nd garnet dating of these basement rocks shows that the lower crust remained hot or was re-heated to ~600ºC at ~345Ma associated with extension and this volcanism (Daly *et al.*, 2016). The ages suggest that enhanced basement heat flows may have been temporally related to formation of the IT deposits (Slezak *et al.*, 2023). Intrusive Tertiary dykes related to the Tertiary Atlantic opening are known at Navan and Ballinalack and are clearly post ore (Turner *et al.*, 1972).

What is an Irish-type Deposit?

Deposit Location, Size and Metal Content

The characteristics of most of the Irish deposits have been extensively documented (Morrissey *et al.*, 1971; Boyce *et al.*, 1983a; McArdle, 1990; Hitzman & Large, 1986; Andrew, 1993; Hitzman & Beaty, 1996; Wilkinson, 2014). Wilkinson & Hitzman (2015) provided a succinct summary of genetic thinking. Regionally the deposits occupy a broadly NE trending area of Central Ireland centered on a zone drawn between Navan and the Shannon estuary which neatly mirrors the axis of the IS zone and reflects the current known limits of the Central Irish Orefield (Fig. 4). The majority of these deposits occur near the base of the Waulsortian Limestone which is strongly dolomitized in several of the deposits. Of these the former mines at Silvermines, Galmoy, Lisheen and to a lesser extent Tynagh, show strong similarities - sufficient to demand a co-genetic interpretation (Wilkinson & Hitzman, 2015). The Navan deposit, still an active mine, is different in some respects. It is much larger, having passed 100Mt of production in 2021, and is mostly hosted in the stratigraphically lower (but time equivalent) Pale Beds of the Navan Group (Figs. 2, 3). These five deposits represent nearly 80% of metal in the Orefield and most clearly define the 'IT' classification. Recently discovered major prospects at Pallas Green and Stonepark, portions of the same mineralizing system, are of great interest due to their size and association with the Limerick volcanic centre. They too share several characteristics with the other Waulsortian-hosted deposits - but much less is known about them as there is no underground or surficial exposure. Figure 5 shows the footprints of the more important deposits to emphasize the relative areal extent of mineralization.

Apart from these deposits there are numerous smaller prospects and showings (Figs. 4, 5); only those with published resources or at least a reasonable tonnage/grade estimate are tabulated in Table 1. Most of these deposits share some characteristics with the principal IT deposits but are not discussed in detail here. These include several Cu-Ag – rich deposits in the SW of the Orefield, including the now depleted Gortdrum (Cu, Ag, Hg) mine (Steed, 1986; Cordeiro *et al.*, 2023; Dunlevy *et al.*, this volume) and the unmined deposits at Aherlow (Romer, 1986) and Tullacondra (Mallow) (Silva *et al.*, 2021). These deposits are mostly hosted in the Lower Limestone Shale Formation and to a lesser extent the overlying ABL rather than in Waulsortian Limestone. We can speculate

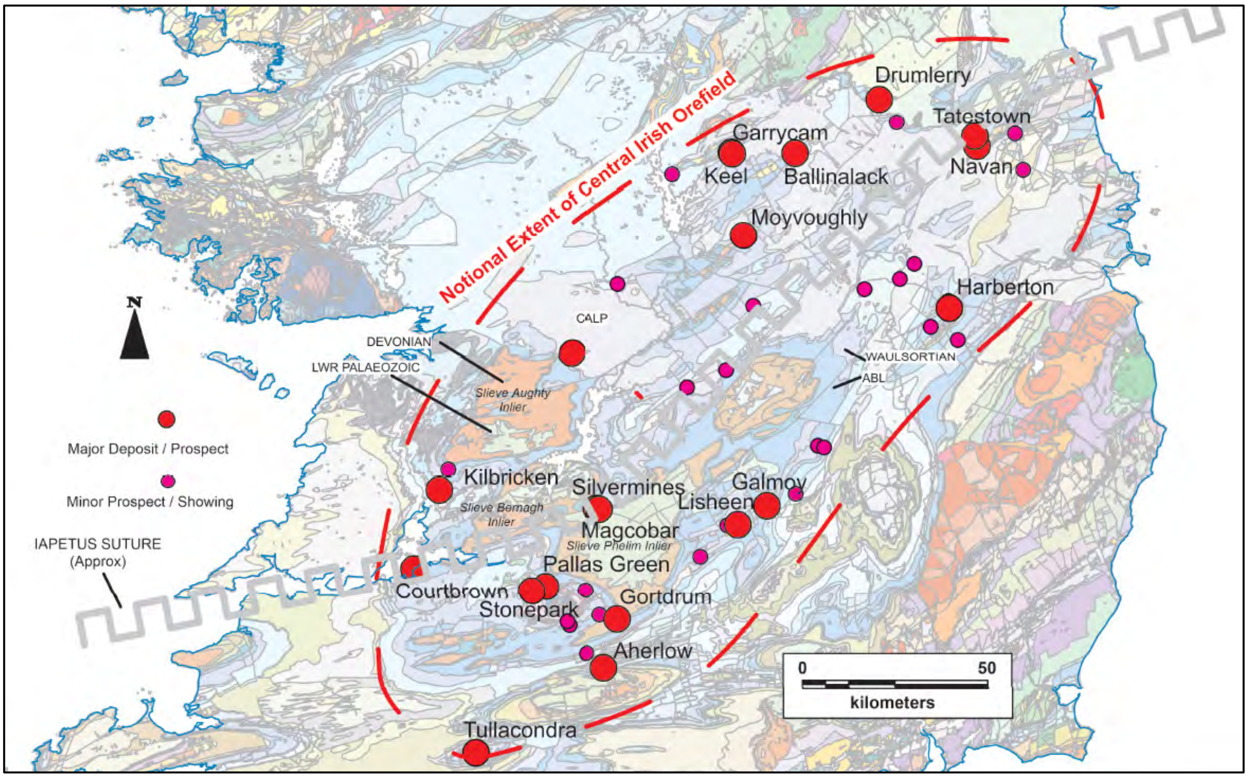

Figure 4: *Central Irish Orefield with deposits showing notional outline of Orefield, mines, major and minor prospects, and the location of the Iapetus Suture. Note that Abbeytown is further north and off the diagram (see Fig. 1). The background geological map is after the Geological Survey of Ireland.*

that the Gortdrum deposit might have formed a "feeder" zone for a now eroded Zn-Pb deposit in the Waulsortian Limestone (Dunlevy *et al*., this volume).

In the SE portion of the Orefield near Kildare, the Harberton and Allenwood areas contain extensive, but as yet sub-economic mineralization within Waulsortian Limestone and younger rocks and have frequently been classified as MVT deposits (Andrew 1993; Trude & Wilkinson, 2001). They bear strong similarities to Pine Point and other MVT districts but do not share many diagnostic characteristics of IT deposits (Andrew & Stanley, this volume).

Briefly, it is worth noting that residual and supergene mineralization is sometimes an important facet of IT deposits (Boni *et al.,* 2015). At Tynagh this constituted *ca*. 4Mt of 'secondary ore' and was an important factor in economics comprising early open-pitable material (Morrissey, 1970; Clifford *et al*., 1986). At Silvermines zinc oxide mineralization was historically mined and further tonnages were discovered by more recent exploration (Rhoden, 1959; Boland *et al.,* 1992). Smaller quantities of oxidized and residual material have also been reported from Harberton (Emo *et al.*, 1986), and Galmoy (Lowther *et al.,* 2003).

Prime questions for future exploration are whether economic deposits exist outside the strictly notional outline of the Orefield (Fig. 4), and where to look for more deposits within the Orefield as recognized. Historically, the lateral extent of the Orefield has been continually increased, particularly with the discovery of Navan (OBrien & Romer, 1971), more recently by the discovery of Pallas Green – Stonepark (Blaney *et al.,* 2003; Minco, 2005; Redmond, 2010) and Kilbricken (Colthurst & Reed, 2019) so further enlargement of the Orefield certainly has precedents. The outline of the Orefield (Fig. 4) is reflected broadly by the massive amount of exploration conducted over this area as shown by Open File reports, geochemical and geophysical surveys, and drilling: areas outside the Orefield have undergone much less investigation. However, an analysis of the mineral deposits using total metal tonnes reveals two markedly enriched areas and questions our understanding of the extent of the Orefield (Figs. 6, 7). These two areas comprise Navan in the NE and a 'SW Area' defined by: Tynagh, Silvermines, Lisheen and Galmoy (also containing Pallas Green, Stonepark, Kilbricken and Courtbrown). This poses several questions, principally:

- How prospective is the Orefield outside these two high metal tonnage areas?
- Is this bipartite grouping of deposits real and due to source (fluid/fertility) and transport mechanisms or other factors?

Clearly, answers to these questions have the potential to improve both exploration models and methods; they will be addressed in later sections where we review the differing IT deposits and particularly the similarities and differences between the SW Area and Navan.

In terms of metal ratios, the areas are similar with the exception that the SW area contains Cu, albeit fairly minor and variable between the various deposits; it is very low at Navan. Metal ratios indicate a slight tendency for the SW area to have higher

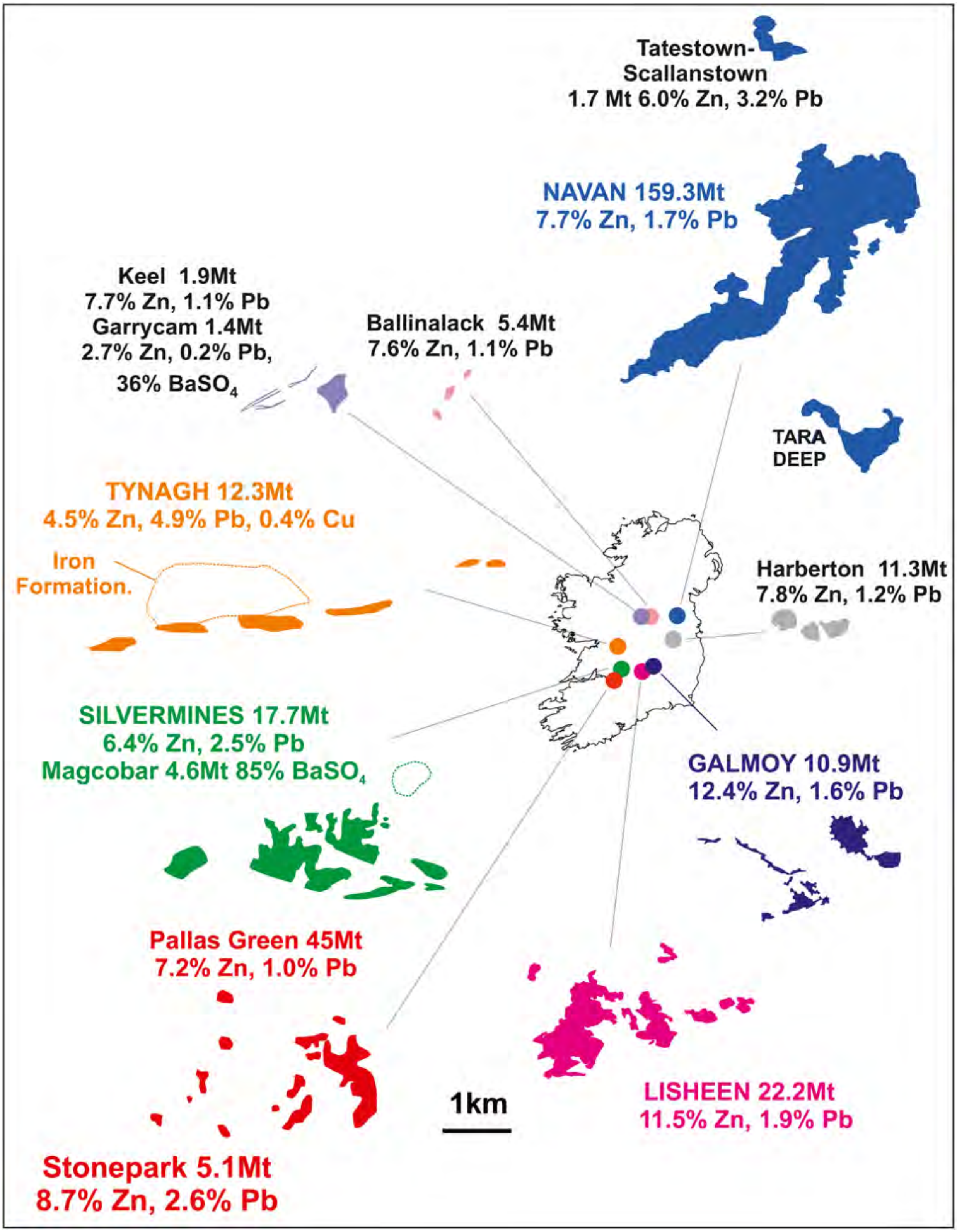

Figure 5: *Footprints and approximate sizes of the larger IT deposits. The deposits are shown in their approximate relative geographical positions (unscaled) with 1km scale bar applying to each deposit (data sources as outlined in Table 1).*

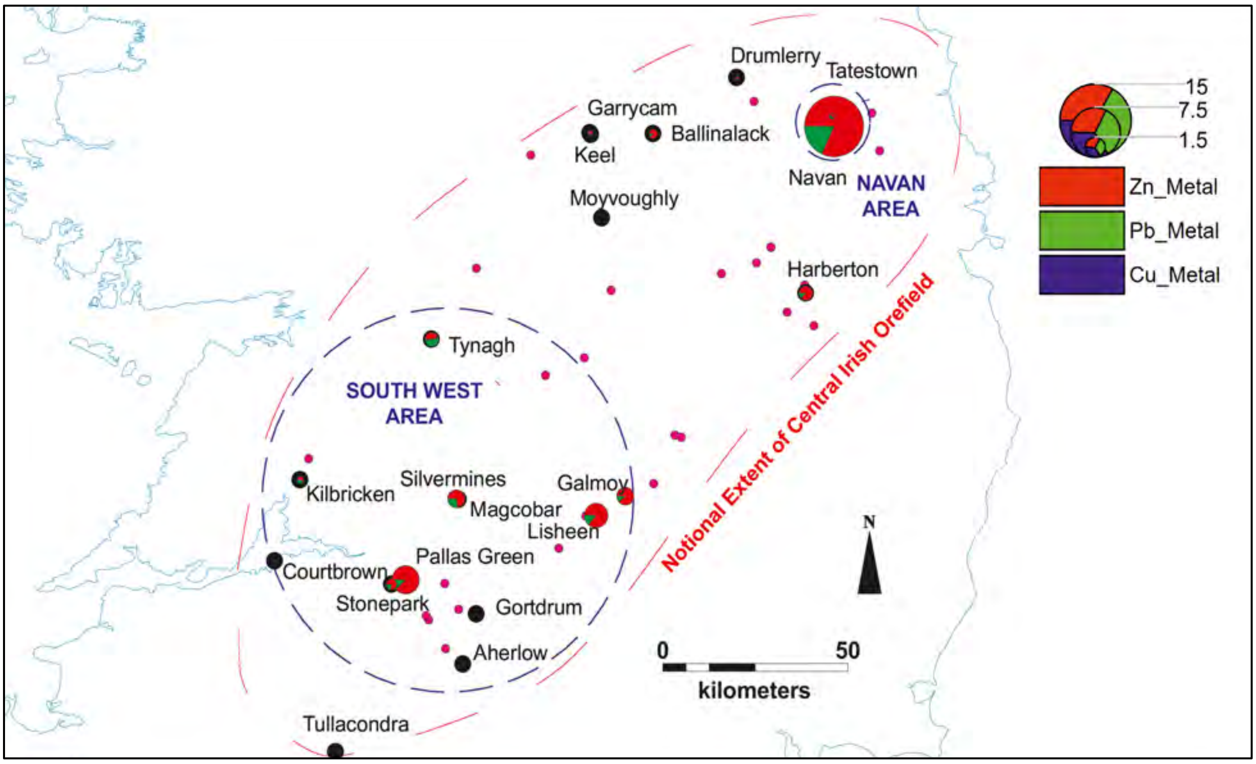

Figure 6: *Central Irish Orefield showing deposits but with graphical representation of total Zn, Pb, Cu metal tonnes (Mt) as pies. (based on data in Table 1).*

Pb (Zn/Pb=4.0) than Navan (Zn/Pb=4.4. Fig. 7). Silver data is insufficient to quantify, however it seems likely from very incomplete data that Ag would be somewhat higher in the SW area (Table 1). Barite is even more difficult to quantify. Economically extracted barite (Magcobar plus minor extraction from Tynagh) is certainly higher in the SW and there is no discrete barite lens at Navan, nor has one been discovered along the Rathdowney Trend. However, barite forms a common gangue in the Navan orebody, so the amount of barite is significant, but unquantified. Unfortunately, Fe values are not available for many of these deposits but since we know that many of the SW orebodies are very pyritic and Navan is not (overall Fe content of ca. 2.8%), then the SW area is relatively iron rich. There is a caveat here however in that several deposits have iron formation (haematite+/-magnetite+/-siderite +/- silica) and/or barren pyrite outside mined or resource outlines that complicates attempts at global Fe comparisons. For example, the Navan deposit is mostly low in Fe but there are very large amounts of framboidal pyrite above the deposit in a hanging-wall halo, particularly at Tara Deep.

Structural Control

Regional Structural Control

Several considerations indicate that mineralization in the Central Irish Orefield was primarily controlled by Caledonian basement geology:

- Regional interpretation of basement terranes and the Iapetus Suture (‘IS’) run below the axis of the Orefield (Figures 4 & 10).
- Regional Caledonide (NE-ENE) trends of major structures in the basement have been interpreted as running below IT deposits and some have been named in the literature as the Navan-Silvermines, Rathdowney and the Tynagh-Ballinalack trends (O’Reilly *et al.*, 1999; Wilkinson & Hitzman, 2015) (Figures 8 & 9). It appears clear that the trans-tensional stress regime that developed in the early Carboniferous interacted with the pre-existing structural grain of the basement to configure fault development in the Carboniferous cover.
- Brown & Williams (1985) noted a correlation of some deposits with edges of NE to ENE trending ridges interpreted from contoured residual gravity data. They interpreted these buried faulted horst/graben and basin margin type structures, following the Caledonide structural grain (also Williams & Brown, 1986. Fig. 8).
- Several studies have demonstrated that the Pb isotopic signature of galena in the orebodies, forms regional trends (termed “isoplumbs”) orientated essentially parallel to the Caledonide structural grain and mirrors Pb isotopic values from galena in rocks from the underlying basement rocks (Caulfield *et al*., 1986; O’Keeffe, 1986; Le Huray *et al*., 1987; Dixon *et al*., 1990; Everett *et al*. 2003). These data strongly suggest the lead in the deposits was leached from proximally underlying Lower Palaeozoic and Pre Cambrian rocks.

These large-scale regional trends have been widely used in the literature to convey the high significance of mineralization

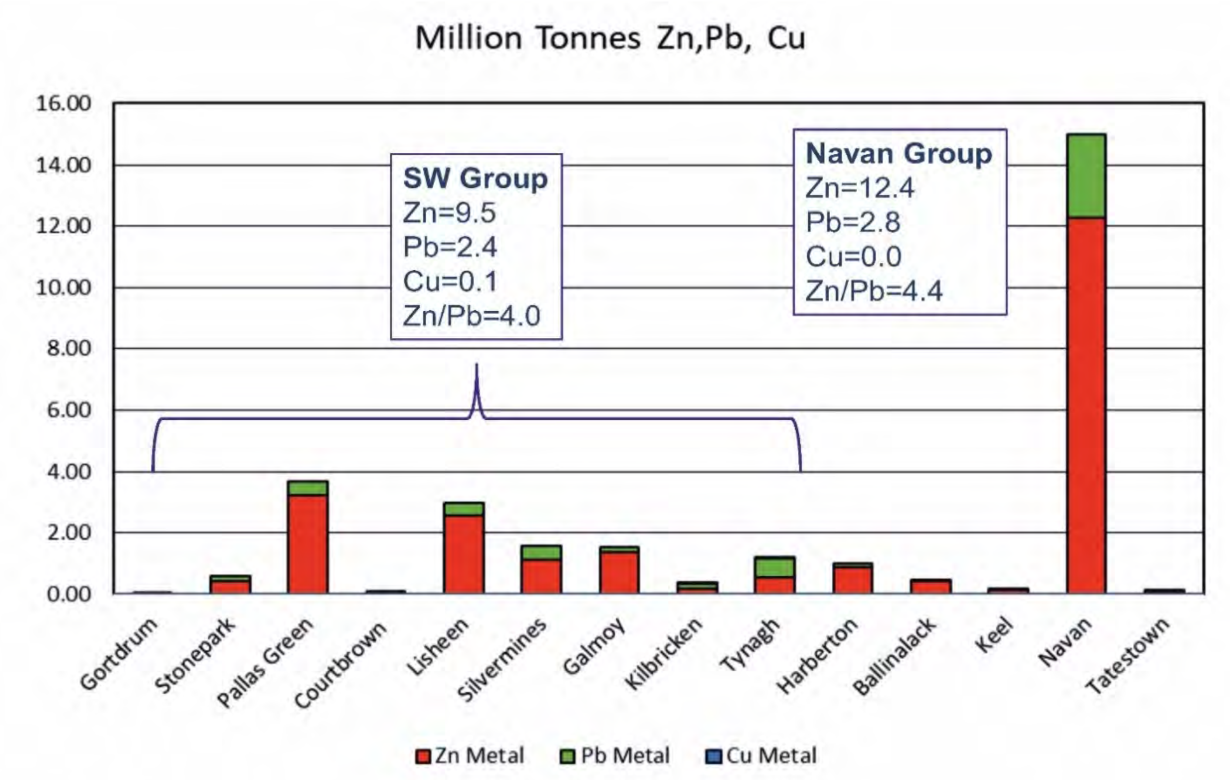

Figure 7: *Bar chart showing metal contents in the principal deposits and in SW and NE groupings (data from Table 1)*

control by NE trending basement structures, however they do not explain the concentration of metals in deposits to the SW and NE of the Orefield. Geologically the intervening area, commonly regarded as a fundamental part of the Orefield, is very similar to the higher metal areas and logically should be regarded as exploration '*elephant country*'. However, with 60 years of exploration - much of it between the two metal-rich areas - this appraisal now requires more critical evaluation. There are two possibilities, firstly that the NE and SW areas have some fundamental geological control that has not been fully recognized, or that the intervening area, occupying much of the Central Midlands, contains barriers to successful exploration. For instance, parts of this area are covered by extensive bogs that have stymied exploration or are too deep to explore; in places maybe the thicker shalier ABL underlying the Waulsortian may have acted as a barrier for uprising hydrothermal fluids. Additionally, perhaps the supply of reduced sulphur was constrained in these areas. If fundamental geologic reasons prohibited establishment of significant mineralizing systems in this area, they would downgrade the area for targeting. While further discussion will hopefully ensue, we now prefer to focus on the significant metal enrichment in the SW and NE areas.

Early workers proposed that lineaments or fault zones oblique to the Caledonide trend have provided regional structural ore deposit controls. Russell (1968) proposed the existence of several N-S geo-fractures. These geo-fractures have little support from high level mapped structures in Carboniferous rocks or regional geophysical data and it is difficult to explain how they could transect regional terrane boundaries. However, Russell's (1968) geofractures 1 and 3 do run through the centre of both the SW and NE high metal areas. Horne (1975) proposed a denser system of >20 NW-SW transverse faults and more recently Blaney *et al*., (2003) proposed a WNW-ESE structure influencing the Pallas Green area. Other features have been highlighted in several Open File reports and media feeds (e.g., Minco, 2005). Morris & Max (1995) also identified a strong magnetic trend running NW through the Limerick area (the Aran-Waterford line) that they proposed was an important dextral offset to the Iapetus suture (Fig. 10). Although elements of these linear trends may exist and could be important locally, evidence for truly regional extent and metallogenetic control by oblique structures (i.e., not paralleling the Caledonide trends) remains debatable.

The likely location of the suture can perhaps be best visualized from plotting the position of the IS from a number of previous studies (Fig. 10). The broad zone outlined by all these "suture lines" correlates well with the medial axis of the Orefield (Klemperer *et al.,* 1991; Todd *et al.,* 1991; Everett *et al.;* 2003). In detail all interpretations are debatable as the suture is more correctly a complex collision zone at depth, but almost all interpretations show a sigmoidal outline with an anticlockwise strike change going east from the west coast near Limerick and a clockwise strike swing going east from Navan to the east coast. These strike swings are close to areas of high metal deposition and suggest the possibility that enhanced fracturing and resultant permeability in the crust in these areas was generated during the Carboniferous extensional events that promoted mineralizing processes.

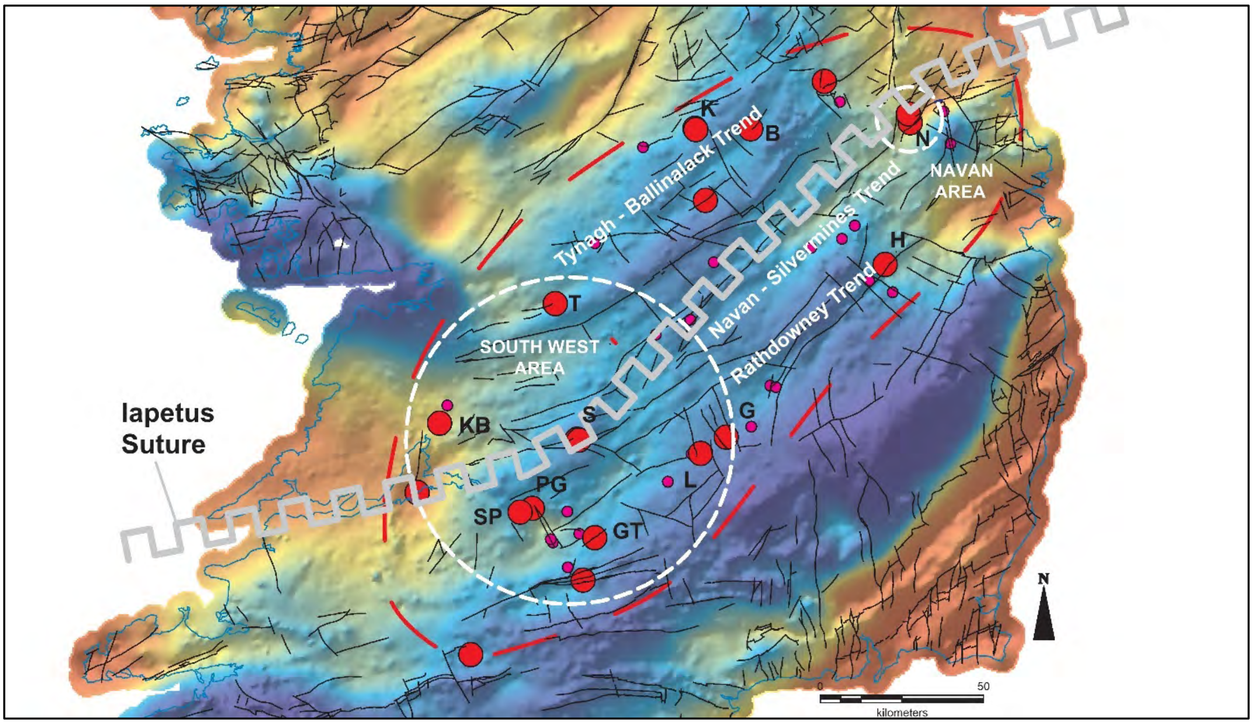

Figure 8: *Central Ireland processed gravity image (residual) overlaid with deposit locations, principal NE trends and Iapetus Suture. Data courtesy of Dublin Institute of Advanced Studies and re-processed by B.O'Donovan. Red and magenta circles are as per Figs. 4, 5 and 6 with some deposit names abbreviated (T-Tynagh, S-Silvermines, N–Navan, G-Galmoy, L-Lisheen, GT-Gortdrum, P-Pallas Green, SP-Stonepark, H-Harberton, K–Keel, B-Ballinalack, KB-Kilbricken).*

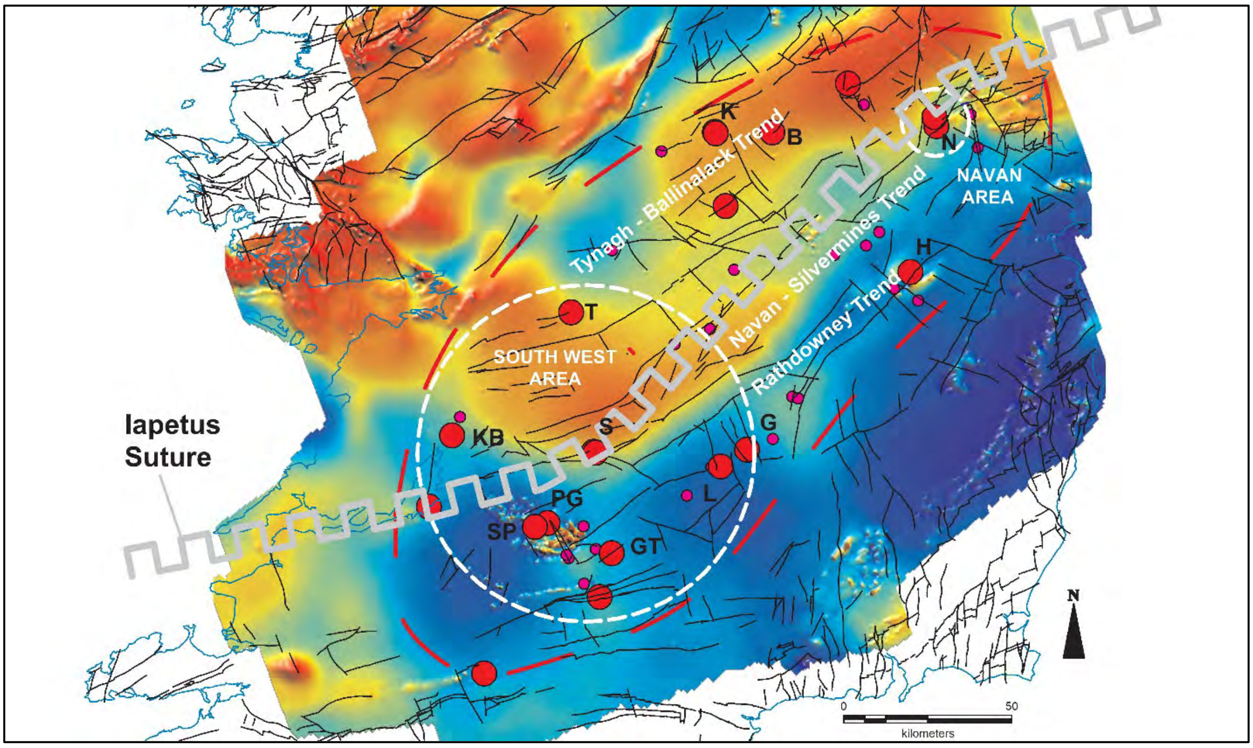

Figure 9: *As Figure 8 but showing RTP magnetics. Huntings aeromagnetic data set courtesy of Geological Survey of Ireland and re-processed by B.O'Donovan. The 1;500.000 fault data set of the Geological Survey of Ireland is also included. Red and magenta circles are as per Figs. 4, 5 and 6 with deposit names abbreviated.*

The strike swings may relate to lateral changes in terrane composition and deep structure along the suture. Evidence to support this contention is present in both areas.

In the SW Area:

- Compilations of galena Pb isotope ratio data (Everett *et al.,* 2003; Hollis *et al.,* 2019) show a perturbation correlating generally well with the SW area (Fig. 11).
- Rao *et al* (2014) analysed five major magneto-telluric profiles-oriented NNW-SSE across the IS in western and central Ireland confirming the anti-clockwise strike swing in the IS going eastwards and noted deep compositional variations along strike near the IS.
- Wilkinson & Hitzman (2015) suggest that the deep structure of the IS and contemporaneous Lower Carboniferous igneous activity at depth may have triggered fluid flow and heating but did not discuss its lateral extent (see also Slezak *et al*., 2023).
- The diminution in size of deposits going to NE from Lisheen to Galmoy and then to Rapla along the Rathdowney Trend.
- Exploration company Group Eleven (2020) referring to structural work by F. Murphy have suggested that tectonism induced in the IS was an element in defining the 'Limerick Basin' mineralizing system.
- The SW area is loosely correlated with several pre-Carboniferous inliers (Slieve Aughty, Phelim and Bernagh. Fig. 4) loosely centered on this area. Could this have been a developing high during the Courceyan/Chadian that helped focus fluids from depth?

In the NW Area*:*

- The Navan deposit is located in a faulted antiform directly above where Ordovician sediments and volcanics of the Grangegeeth terrane (Romano, 1980), plunge SW at the south-western tip of the Longford-Down inlier, below the Carboniferous (Ashton *et al*., 2015). This terrane represents the southern part of the Laurentian basement according to Owen *et al*., (1992) and McConnell *et al.* (2010, 2019, 2020). Major faulting in the eastern part of the mine at Navan and in the inlier eastwards has a strong NE to ENE trend (Vaughan, 1991; Vaughan & Johnston, 1992).

- To the SE of Navan the Balbriggan Lower Palaeozoic inlier contains the Bellewstown terrane, interpreted as lying south of the IS (McConnell *et al*., 2015) and is characterized by a strong E-W aeromagnetic fabric arising from partly outcropping Ordovician volcanics. This terrane encroaches obliquely on the major NE fault trend in the Navan area and constitutes a major lateral change along the IS (illustrated in Waldron *et al*., 2014).

- A buried late Caledonian granite lies ca. 10km SE of Navan at Kentstown (O'Reilly *et al*., 1997; Fritschle *et al.,* 2015) and exhibits a circular bouguer gravity anomaly and a likely footprint of the order of 5x5 km (Brian Williams, unpublished data). Phillips *et al*. (1988) and Andrew & Ashton (1985) proposed that the granite and related weakly mineralized syenitic apophyses near Navan could have controlled mineralization by providing fracture-controlled permeability.

- Seismic surveying has confirmed that the Navan antiform represents part of a footwall uplift complex on the northern side of a regional-scale major normal fault (the Navan Fault) that occurs SW of the mine (unpublished reports D. Coller and A. Beach; Ashton *et al*., 2018). This structure has *ca*. 4km of displacement and defined a basin margin in the Chadian-Arundian in which >500m of Courceyan/Chadian rocks were removed by low angle slides on the flank of the fault. The Navan deposit is located in the footwall degradation area of this fault which appears to take a clockwise swing south of Navan, possibly following a line of weakness west of the buried Kentstown granite and Bellewstown inlier.

Deposit Scale Structural Control

In the SW area each Waulsortian-hosted deposit comprises several distinct zones of mineralization that have an overall easterly to NE trend and are located in the hanging-walls of normal fault zones that trend broadly east to ENE and dip steeply northwards with throws of up to several hundred metres (Figs. 12, 13). At Silvermines and Lisheen the constituent ore zones are spatially strongly localized to the hanging-walls of several *en-echelon* faults generally trending E-W (Lisheen) or WNW-ESE (Silvermines) (Taylor & Andrew, 1976; Andrew, 1986; Kyne *et al*., 2019). These faults are orientated clockwise to the main deposit trend. Individual faults dip north and are interpreted to have an overall element of north to NNE extension (Kyne, 2019). At Tynagh (600m throw) and Galmoy (200m throw) the main faults trend east to ENE and show less obvious segmentation but in detail also consist of complex and potentially originally similar bifurcations, and form part of larger ENE trending en-echelon structures (Clifford, 1986; Bonson, *et al.,* 2005; Lowther *et al*., 2003). The orebodies are mostly sited at points of maximum throw on the controlling faults. Johnston *et al.* (1996) interpreted the faults to have formed following dextral movement on underlying basement faults with a Caledonian trend. Kyne *et al.* (2019) consider the faulting at Silvermines and Lisheen as resulting from N-S extension on pre-existing basement Caledonide faults and stress the importance of breaching of relay ramps between the faults as possible mechanism to generate permeable channels for upflowing fluids (see also Walsh *et al*., 2018).

Mineralization was clearly strongly controlled by the faults in that the highest grade and thickest mineralized zones are often near the point of maximum throw and subsidiary structural deformation has been noted in hanging-wall areas bordering the faults comprised of minor faulting, fracturing and folding (Moore, 1975; Clifford *et al.,* 1986; Lowther *et al*., 2003). Several of the deposits show subsidiary ore zones located some distance from the nearest fault and these have been interpreted as the result of ancillary faulting and fracturing diverting some metal-bearing fluids upwards and laterally from the main faults

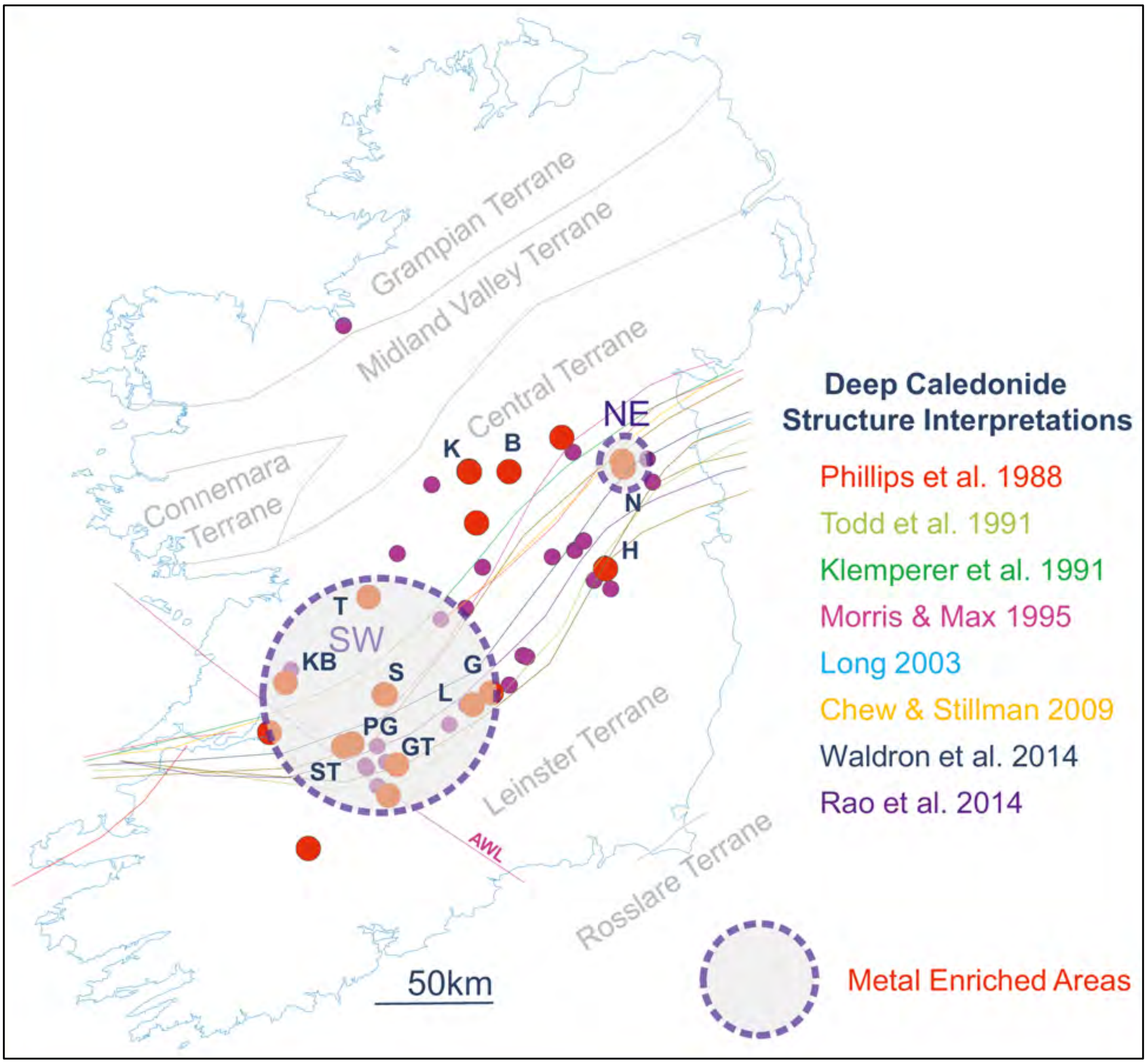

Figure 10: *Proposed Iapetus Suture location from a variety of authors in relation to IT deposits and showings and the SW and NE high metal areas. Note some workers stress the suture zone could be 10s of kms wide. Note both SW and NE high metal clusters are at swings in most interpreted IS locations. Figures 4 and 9 show a median position. Terrane locations after Chew and Stillman, (2009) and Long (2003). Morris and Max et al. (1995) consider that the IS was dextrally offset along the NW-SE trending Aran-Waterford line ("AWL").*

the faults comprising of minor faulting, fracturing and folding (Taylor, 1984; Lowther *et al*., 2003; Kyne *et al.*, 2019; Yesares *et al*., 2019; Doran *et al.,* 2022). Despite the strong association of mineralized zones and faults, the principal fault planes are often unmineralized gouge filled shears. Drilling below the ore zones and into the faults and fault foot-wall areas has been remarkably sparse at most deposits with the exceptions of Silvermines and Lisheen so the nature of any underlying feeder systems is poorly known.

At Silvermines economic mineralization occurred below the main G zone orebody in the Lower Dolomite hosted Lower G Zone ore (*ca*. 2.0Mt) adjacent to the G Zone Fault. Elsewhere at Silvermines, breccia and vein hosted mineralization occurred close to faults in the Lower Dolomite, Basal Clastics and Devonian rocks in the K, P and C Zones and at Shallee (Rhoden, 1959; Andrew, 1986). Cross-cutting and fault-controlled mineralized zones clearly represent feeders to the stratigraphically overlying Waulsortian-hosted deposits, and in the case of the Lower G to Upper G Zone transition the so-called "throat zone" contains a range of unusual soft sediment replacive textures (Graham, 1970).

At Lisheen mineralization occurred within an oolite member of the ABL adjacent to the Killoran fault that controlled the location of the Main Zone at the base of the Waulsortian Limestone. Drill holes penetrating the fault itself displayed clay-rich ouge with sparse, highly disrupted sphalerite-dolomite veins (Hitzman *et al*., 2002), suggesting late, post-mineralization Variscan age fault reactivation.

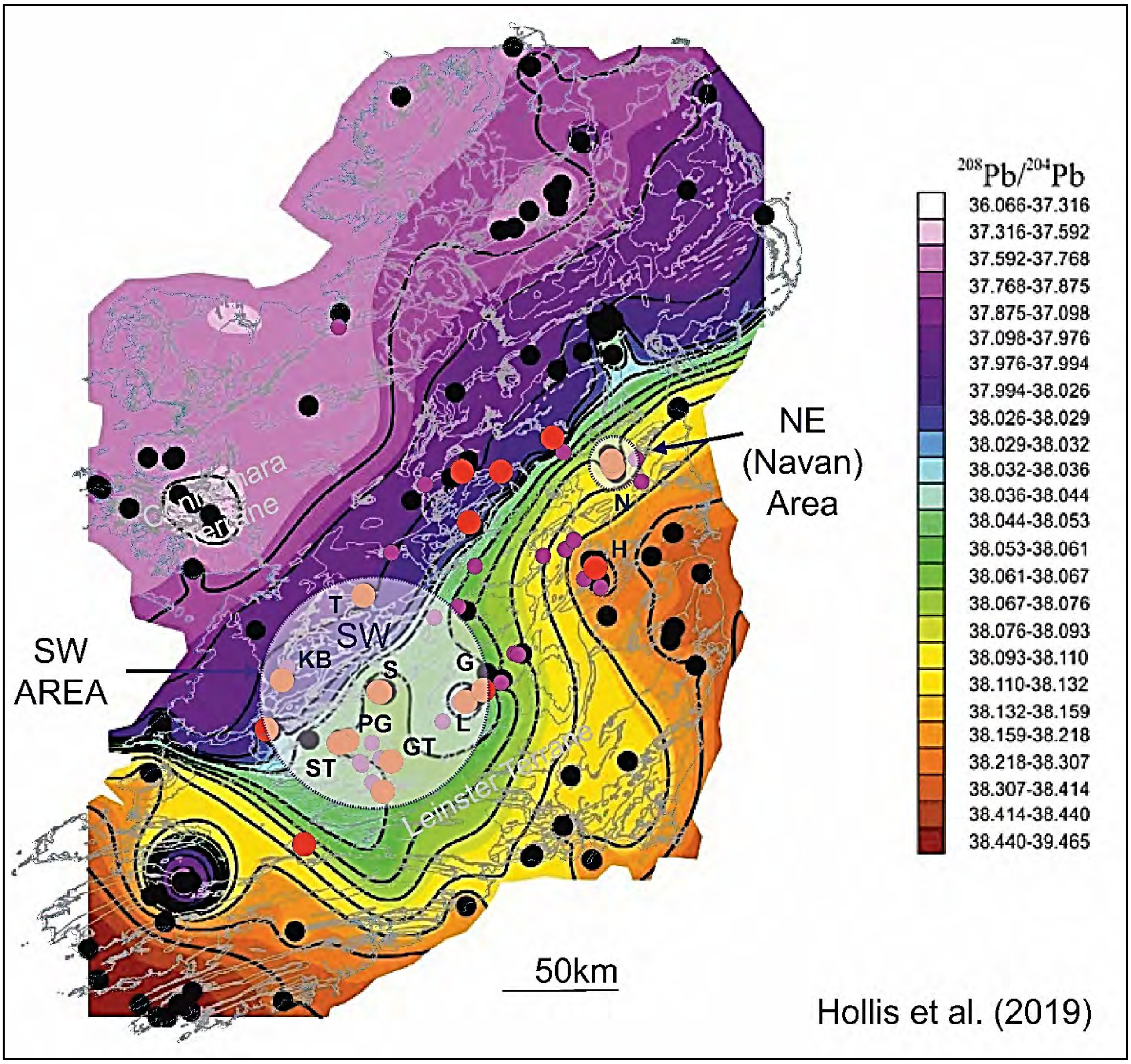

Figure 11: *IT Deposits, prospects and showings and high metal areas superimposed on Pb isotope ratio ($Pb^{208/}Pb^{204}$) from Hollis et al. (2019). Pb sampled from galenas in wide range of deposits (black). Values range from ca. 36 in NW to 39 in SE. The blue-green patch of ratio values extending SE is approximately coincident with the high metal area.*

At Navan the fault system is more complex (A. Beach and D. Coller unpublished reports, Coller *et al.,* 2005; Ashton *et al.*, 2015, 2018) and represents a progressive sequence of extensional faulting ranging between late Courceyan to early Chadian in age, formed on the uplifted margin of the developing Dublin Basin to the south. The faulting was inverted after mineralization, probably at end Carboniferous (Variscan) times (Fig. 14).

The early 'E' and 'L' north dipping faults at Navan trend ENE with throws of several hundred metres are very similar to those in the SW deposits (Figs. 12, 13). The remaining normal faults at Navan all dip southwards and while they may have been initially synchronous with the north dipping faults, they become dominant and are accompanied by major low angle south-dipping gravity slides. During this phase the 'B' and 'T' normal faults developed, both trending ENE, dipping at around 50-70° south and with throws of up to 150m. Both faults display listric profiles and show a clockwise rotation in strike, eastwards. Further faults comprise the low angle south-dipping 'N' and 'M' slides overlain by allochthonous rafts and complex sheared-wedges of (in decreasing abundance) Shaley Pales, ABL, Pale Beds and Waulsortian Limestone (Philcox, 1989; Ashton *et al*., 2015). These slides represent a major extensional tectonic event which removed all of the older Carboniferous stratigraphy in places. The sliding event was succeeded by deposition of debris flow and fault talus breccia-conglomerates, termed the Boulder Conglomerate ('BC'), over the area affected by the sliding which extends roughly as far north as the northern extent of the deposit. The base of the BC, locally termed the 'Erosion Surface', represents cessation of major slide block wastage and its replacement by more local debris flow and fault talus development at fault scarps formed where earlier structures such as the 'B' and 'T', 'N' and 'M' faults

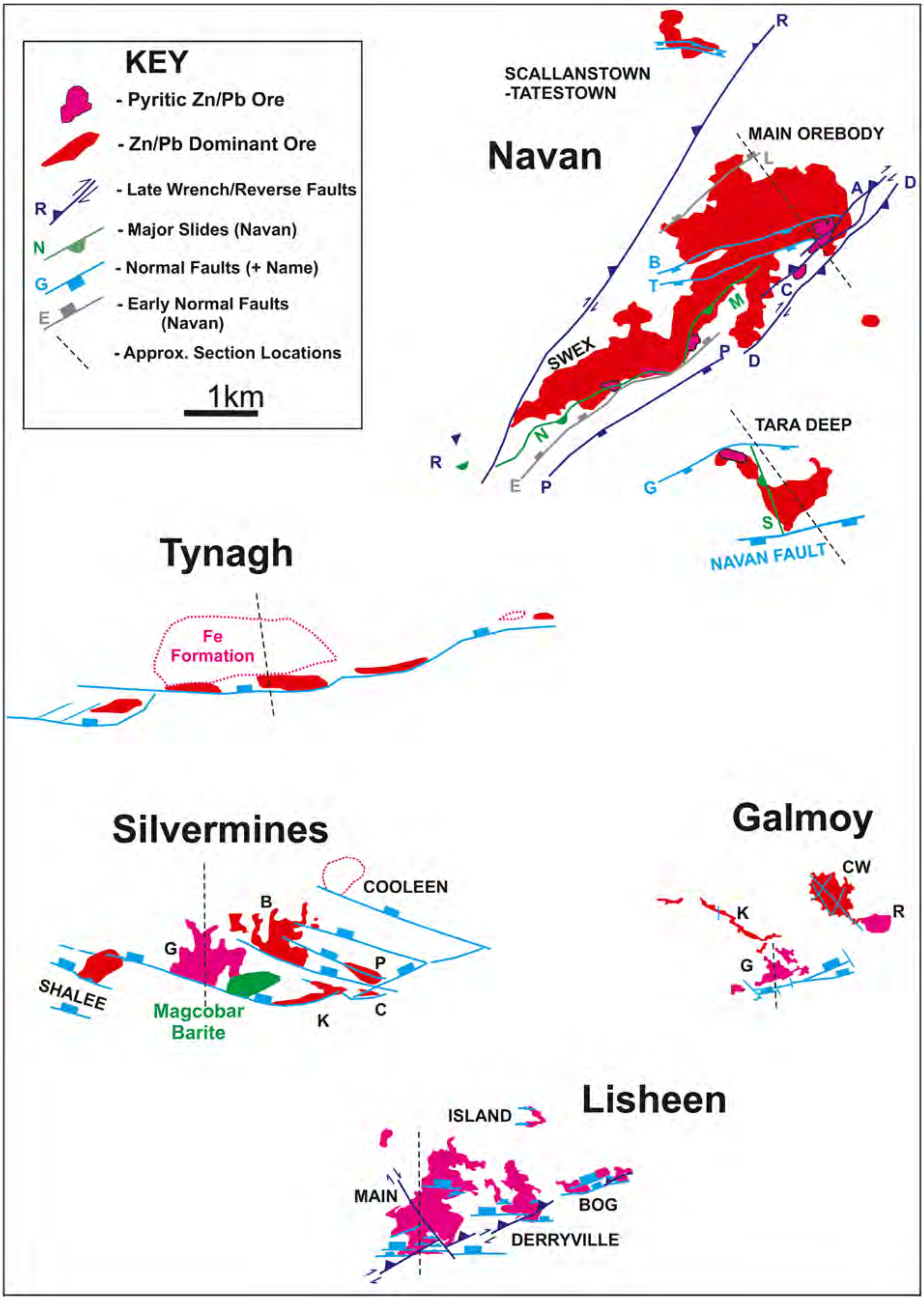

Figure 12: *Summary plans of main deposits showing principal ore zones and faults. Data sources: Tynagh - Clifford et al. (1986); Silvermines – Andrew (1986), Kyne et al. (2018); Navan - Ashton et al. (2015) and Ashton et al. (2018); Galmoy - Lowther et al. (2003); Lisheen – Hitzman et al. (2002); and Kyne et al. (2018).*

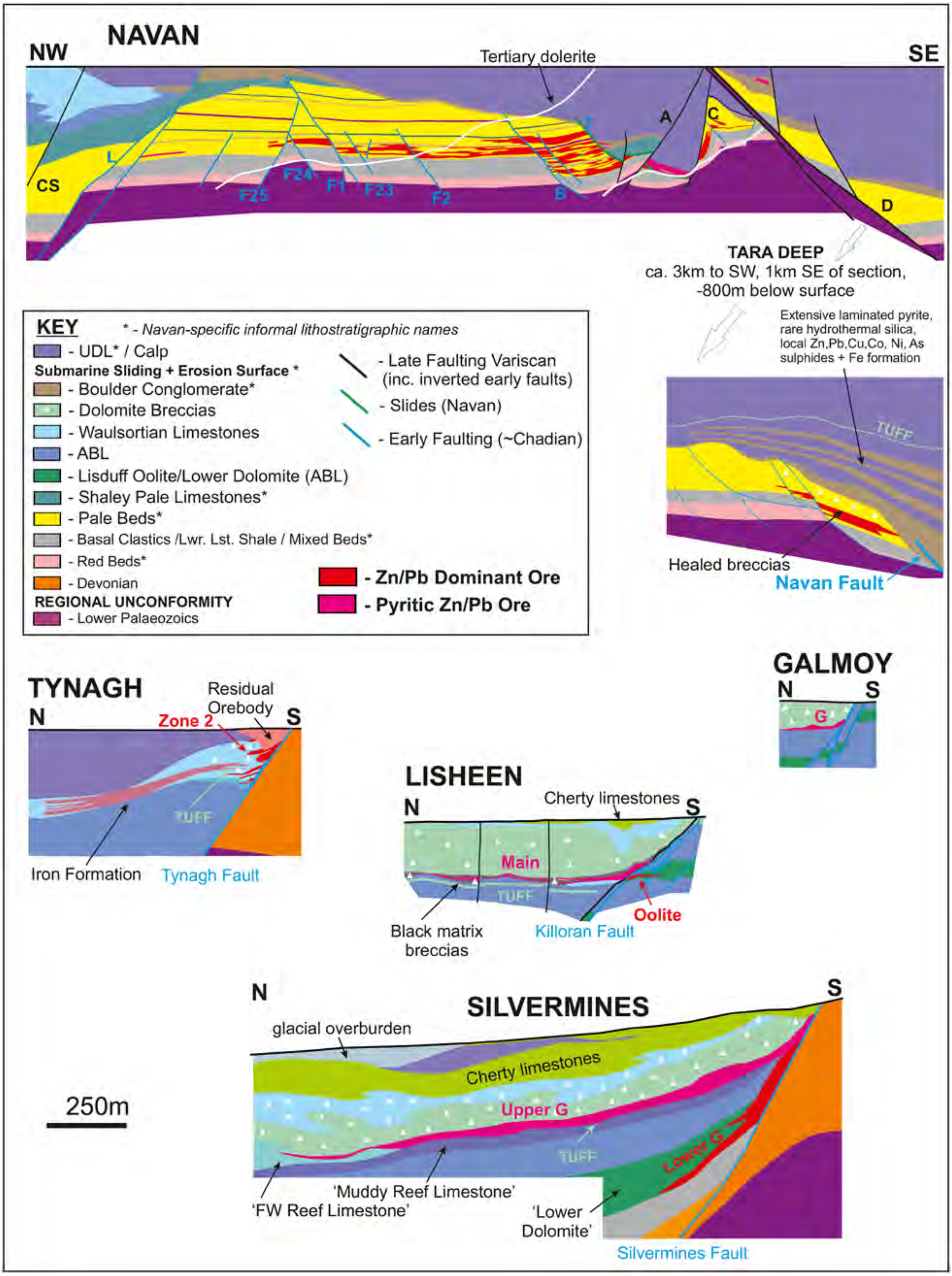

Figure 13: *Compilation of sections across IT deposits at same scale, looking eastwards. Litho-stratigraphic names and colour codes have been amalgamated and simplified in an attempt to show comparative geology between the five areas. Data sources as per Figure 12.*

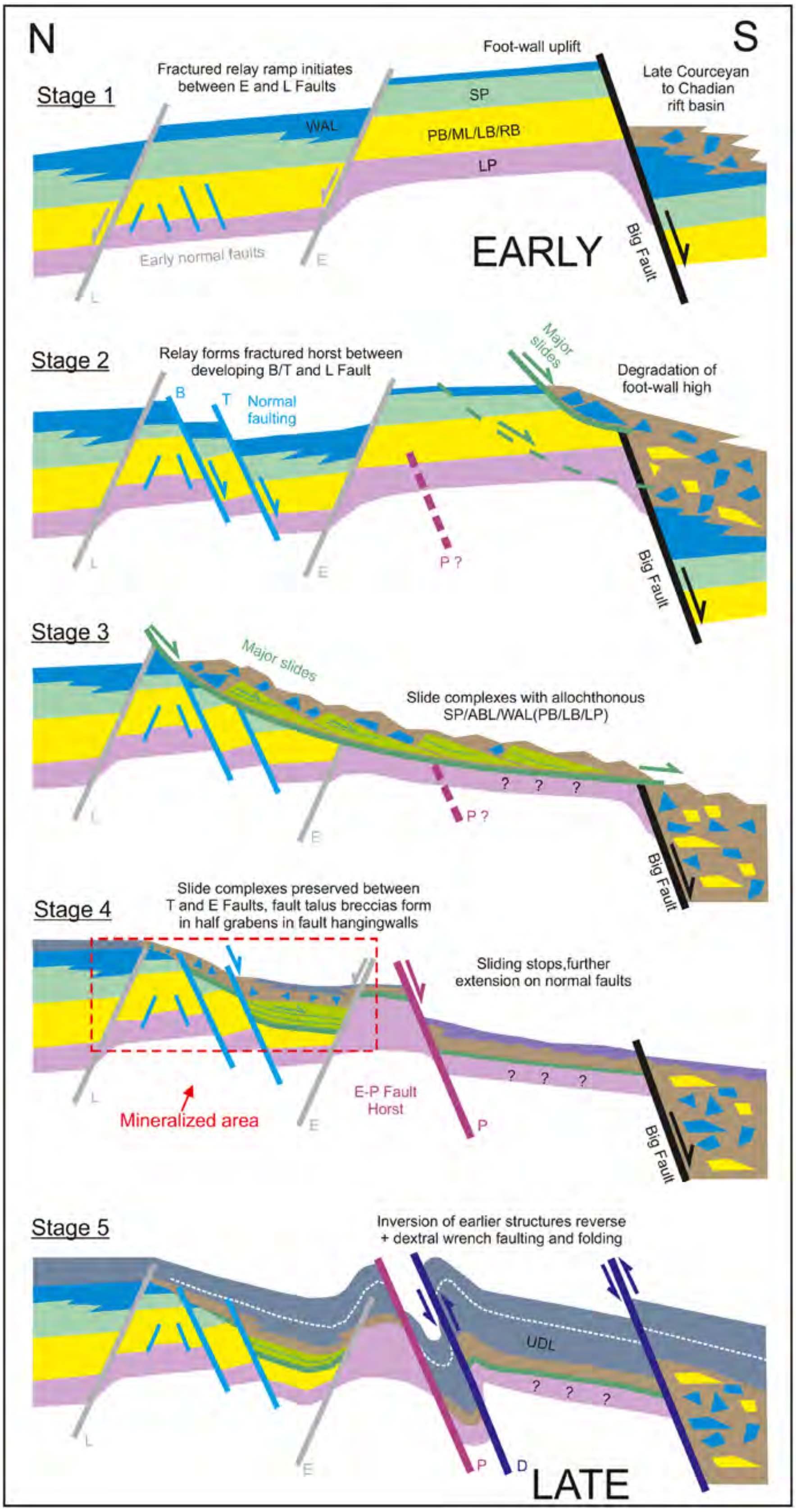

Figure 14: *Idealized N-S sketch sections showing the progressive development of the extensional fault system at Navan and later inversion. Stages 1 to 4 are arbitrary depictions of the progressive extensional faulting at Navan during the Lower Carboniferous while Stage 5 depicts the final and much later (Variscan?) inversion phase. The subset rectangle shown in Phase 4 approximates to the best mineralized area. Mineralization may well have commenced during Stages 1 to 3. Not scaled but sections are approximately 6 km long. (After Ashton et al. (2015). Tara Deep is not shown but is in the foot-wall area of the Big (Navan) Fault.*

continued minor movement. In these half grabens and above south dipping slopes in the BC, pyritic massive sulphides termed Conglomerate Group Ore (CGO) were developed (Figs. 12 & 13). The south-dipping faulting, sliding and debris flow activity record a period of footwall uplift on a major normal fault located at least 2km southeast of the mine with all the degraded material being directed southwards into the developing Dublin Basin (Philcox, 1989; Nolan, 1989; Hesthammer & Fossen**,** 1999; McLeod & Underhill, 1999). Seismic surveys have confirmed this scenario which is indicative of active faulting at a basin margin (Cook & Mullins, 1983; Ashton *et al*., 2015). However, the precise relationship of the major Navan Fault to major slide development has yet to be fully delineated by drilling and is still under investigation.

The Tara Deep deposit is located between the Navan deposit and the Navan Fault where several complex terraces are developed between the 'P', 'G' and Navan faults (Ashton *et al*., 2018). All of these faults are normal, have a southerly dip, trend ENE and have large throws - "P" (600m), "G" (500m), Navan (3-4km). The Tara Deep deposit occurs between the "G" and Navan Fault where a NNW-trending, steeply west dipping normal fault (the "S" Fault) cuts across the terrace and has been interpreted as an inverted slide (Coller, unpublished reports; Ashton *et al.,* 2018. Figs. 12 and 13).

In Navan's Main Orebody, mineralization in the Pale Beds is seen associated with swarms of small offset normal faults and mineralized extension veins centered on and parallel to zones of bulk Zn/Pb enrichment (Andrew & Ashton, 1985; Ashton *et al.,* 2015). The mineralized fractures lie between the 'L' and 'E' faults and, together with other faults, define a NE trending faulted asymmetric antiform trending through the northern part of the orebody in which the SE limb is most pronounced and has the most fracturing (unpublished reports; Coller *et al.,* 2005). Coller has interpreted the area between the 'L' and 'E' faults as a relay ramp related to the early faults and has noted that the 'polarity switch' from north to south dipping faults likely resulted in enhanced development of fracture permeability. Mineralization was also enhanced close to some of the larger faults and slides. However, these major faults, even those bordering massively mineralized zones, are typically unmineralized, contain gouge and appear to cut the ore. This is, at least partly, the result of reactivation of these structures during later Variscan compressive tectonism.

The relationship between Lower Carboniferous faults and sedimentation

Available evidence indicates that faulting at all the main deposits was active during Courceyan to Chadian sedimentation:

- At Tynagh the thickness and dip of the Waulsortian Limestone changes close to the Tynagh fault and the sequence also contains 'slump' breccias (Derry *et al.*, 1965; Moore, 1975; Boast *et al.,* 1981; Clifford *et al.*, 1986; Cruise 2000).
- At Silvermines similar changes in thickness of host units are observed coupled with formation of thick debris flow and slump breccias and folds close to major faults (Ashton, 1974; Taylor & Andrew, 1978; Taylor, 1984; Andrew, 1986; Lee & Wilkinson, 2002).
- At Lisheen, the normal faults are considered to have been active through deposition of the Waulsortian limestones and overlying Crosspatrick Formation (late Courceyan to Chadian), but the faults were not directly involved in the formation of the majority of the dolomite breccias associated with the mineralization (Hitzman *et al.,* 2002; Carboni *et al.,* 2003; Fusciardi *et al*., 2003).
- At Galmoy evidence of local contemporaneous fault activity is lacking largely due to erosion of supra-Waulsortian rocks but Lowther *et al*., 2003 note: "*The entire area straddles a significant strike parallel sea-floor flexure that was active in the late Courceyan to Chadian and was significant enough to have affected sedimentary thicknesses*".
- At Navan early extensional faults clearly pre-date the Chadian erosion surface and the BC and are part of an extensional sequence active at least into the Arundian and possibly later. The faults formed on the basin margin during the rift phase of the Dublin Basin (D. Coller and A. Beach, unpublished reports; Philcox, 1989; Ashton *et al*., 2015). Evidence of syn-sedimentary fault movement includes growth of Waulsortian Limestone in the hanging-wall of the early 'L' Fault (Philcox, unpublished reports; Ashton *et al*., 2015); truncation of several normal faults by the Chadian erosion surface and Boulder Conglomerate and growth in the basal UDL recorded by seismic surveys and drilling (Figs 12,13), (Ashton *et al*., 2018). Increased extensional activity probably commenced around the time of ABL and Waulsortian sedimentation and continued during the deposition of the BC and into the time of UDL deposition (Boyce *et al.,* 1983a; Andrew, 1986b; Andrew, 1993). Local conglomerate horizons in the UDL suggest that faulting remained active until Asbian and Brigantian times (Philcox, 1989; Nolan, 1989; Ashton *et al*., 2015).

Thus, it seems that while development of normal faults was widespread in the Courceyan to Chadian, and locally, continued until the Asbian, the magnitude and exact timing and interplay of fault emergence on to the sea floor versus sedimentation was variable. It is remarkable that not only do the deposits all show evidence of syn-sedimentary faulting at and later than Waulsortian Limestone deposition but also that breccia development is a feature of each deposit. At Navan an indistinct monomict healed breccia-conglomerate, preceding the Boulder Conglomerate, is variably developed in the Pale Beds and is well-developed at Tara Deep (Philcox, unpublished reports; Ashton *et al*., 2018): could this indicate a similar event to that forming some of the dolomite breccias in the Waulsortian-hosted deposits?

The relationship between faulting, mineralization, and metal distribution

Comprehensive metal distribution studies are available for most of the SW deposits and strongly confirm the increase in grade and thickness of mineralized zones towards the principal deposit-scale faults (Taylor & Andrew, 1976; Taylor, 1984; Lowther *et al.*, 2003; Fusciardi *et al.*, 2004; Torremans *et al.*, 2018). These studies also confirm that Zn/Pb ratios decrease towards the faults and in the case of Lisheen additionally demonstrate higher temperature type mineralization comprising Ag, Ni, Co, Sb, and As enrichments close to faults.

Extensive studies of metal distribution patterns at Navan are also available (Andrew & Ashton, 1985; Ashton *et al*., 1992; Blakeman, 2002; Blakeman *et al*., 2002; Barnicoat *et al*., 2004; Davidheiser-Kroll *et al*., 2013; Davidheiser-Kroll, 2014; Ashton *et al*., 2015). In the Main Orebody, distinct elongate areas of high Zn/Pb trend NE-SW and are coincident with major faults or localized zones of minor mineralized extensional fracturing (Andrew & Ashton, 1985; Blakeman *et al.*, 2002). There is a strong tendency for the Zn/Pb ratio to decrease westwards, with depth and in stratigraphically lower host rocks, and for Fe to increase to the NE and up-section. The highest Fe concentrations occur in the stratigraphically highest 2-1 lens, and in the strongly pyritic Conglomerate Group Ore hosted by the Boulder Conglomerate (Ashton *et al.*, 1992). The SWEX 3-U Lens metal distribution shows different patterns. There is a gross correlation between high Zn and Pb areas running northeast to east-northeast and trending parallel to the 'Y', 'M', 'N' and 'E' Faults; these clearly parallel and extend the northeast to east-northeast trends evident in the Main Orebody. However, several quite distinct areas of Zn/Pb enrichment tend to be less linear than the Main Orebody and more equant in shape (Davidheiser-Kroll, 2014; Davidheiser-Kroll *et al*., 2015). Taking these elongate and equant shapes together they may indicate near-vertical up-flow of metal bearing fluids near some SWEX faults with subsequent lateral flow along smaller faults and fractures through the Main Orebody. This would accord with the view that the northern part of the main orebody represents a strongly fractured relay ramp (Coller *et al*., 2005, unpublished reports). The lenses of CGO over the Main Orebody and the SWEX tend to show distinct patterns with Zn/Pb highest adjacent to faults, widespread enrichment of Fe, and a tendency for the Zn/Pb ratio to decrease to the southeast. Metal distribution has not yet been studied at Tara Deep in any detail but does not appear to differ substantively from other parts of the Navan system.

Variscan tectonism

The Lower Carboniferous extensional faults at all deposits have been variably, and locally strongly, inverted by later reverse and dextral compressive events of suspected, but unconstrained, Variscan age either along existing faults or 'new' faults usually with a more NE-trend (Moore, 1975; Hitzman, 1999; Kyne *et al*, 2019). The extent of this inversion is quite variable and appears to be mostly on NW-dipping structures. At Navan there are several large NE-trending dextral-reverse faults that mostly dip NW with throws of several hundred metres; however, the largest of these structures, the 'D' Fault, dips SE, has a reverse throw of over 600m and an unconstrained wrench component (Coller, unpublished reports; Ashton *et al.*, 2015). These compressional structures are unmineralized and clearly cut and displace ore; they are frequently associated with considerable minor folding, shearing and carbonate veining. Later NNW-trending jointing and fracturing is common and has been responsible for significant groundwater ingress at several deposits. Apparent remobilization of sphalerite into late carbonate veins carrying coarse honeyblende has been noted at Navan and elsewhere (Andrew, 1993; Marks, 2015). Torremans *et al*., (2019) document later post-Variscan movement on NNW-trending faults at Lisheen. At Harberton Bridge the breccias hosting the zinc-lead mineralization are compartmentalized within "corridors" constrained by NNW-SSE faults that transect and displace the Variscan aged Kildare Inlier Thrust. In addition, the highest-grade mineralization occurs with these mineralized fault zones and on their immediate hangingwalls (ZMI, 2021; Andrew & Stanley, this volume).

Host Rock Control, Geometry of Ore Zones and Mineralogy

Host Rock Control and Geometry

The deposits in the SW and at Navan all show a very close host-rock control on where mineralization occurred. Those in the SW are usually developed at and near the base of, usually dolomitized, Waulsortian Limestone while the Navan deposit is largely developed in partially dolomitized Pale Beds, both in the basal micrites and overlying grainstones with a variable degree of brecciation (Plates 2 and 3). Thus, the host-rocks comprise the first clean carbonates (micrites, grainstones, dolostones) in the host Carboniferous sequence, a factor recognized as important by many workers since they represent the first chemically reactive rocks encountered by uprising hydrothermal fluids (Wilkinson & Hitzman, 2015). At Navan the Waulsortian Limestone has largely been removed by submarine sliding in the area of the deposit but where preserved, in peripheral areas, these rocks show little or no dolomitization or mineralization.

An interesting caveat to this stratigraphic control is that deposits hosted by the Waulsortian Limestone north of the SW area, such as Tynagh and Ballinalack, display mineralized zones that are not restricted to the basal portion of this unit. The reason for this difference is not readily apparent but may relate to the lower degree of dolomitization at these deposits, which may have allowed less restricted fluid flow to higher levels.

All the deposits have multiple mineralized zones separated by weakly mineralized host rock and generally show irregular lateral outlines of ore zones away from the controlling faults. The geometry of the ore zones varies substantially but they are usually locally stratiform to stratabound lenses showing parallelism with the host stratigraphy. In general, the lenses have an overall tabular shape and display thicknesses ranging from less than a metre to tens of metres and areal extents of several hundred metres to well over a kilometer. Ore-waste contacts vary from locally sharp to exceedingly irregular both in section and plan. High density drilling and/or sampling and/or mapping is often needed to establish economic ore limits. In general, the ore zones are elongated either as a group or individually in a NE to ENE direction, but where controlling faults are oblique to this trend then the individual ore zones may be partially aligned parallel to the faults (e.g., Silvermines, Lisheen, Galmoy). At most deposits there is usually a single lens or perhaps several sub-lenses separated by small layers of sub-grade material. Some important parts of the Navan deposit exhibit remarkable stacked tabular lenses separated by metres or tens of metres of waste or weakly mineralized material and in the richest, eastern section of the Main Orebody these lenses amalgamated giving a total thickness of mineralized material approaching 120m, with local sections amenable to provide stoping thicknesses up to 80m.

The ore lenses vary compositionally. At Tynagh, Silvermines, Galmoy and Lisheen, (and Pallas Green) the dominant ore simplistically, comprises massive and semi-massive pyritic sulphides inter-mixed with dolomitized Waulsortian breccias (Plates 3, 4, 5 & 6). The degree of pyrite development varies however, and, in some deposits, different carbonate gangue mineralogy is evident, generally dolomite but siderite in portions of the Silvermines deposit and calcite in portions of Pallas Green. At Navan the bulk of the ore hosted by the Pale Beds is relatively low in iron apart from subsidiary mineralization in the BC (Plates 7 & 8).

The ore zones at Tynagh, as noted above, are less stratabound and form a series of bodies in Waulsortian Limestones and flanking debris flow breccias (locally weakly dolomitized) restricted to ca <100m from the fault (Plate 4), however a large stratiform, silica-haematite-magnetite body, the Tynagh Iron Formation, occurs at the same stratigraphic level at the base of the Waulsortian Limestone and extends for ca. 1-2km north of the fault in “off reef” argillaceous carbonate rocks. (Figs. 12, 13. Plates 9A to 9C). Boast *et al*. (1981) recognized four major stages of mineralization that span the diagenetic and post-lithification history of the host Waulsortian limestones: (1) growth of colloform pyrite clots during early diagenesis; (2) rapid geopetal precipitation of microcrystalline sulphides, largely sphalerite, within a dilatant fracture system developed in response to tectonism in the Tynagh fault zone; (3) epigenetic mineralization dominated by tennantite, galena and barite and, (4) precipitation of calcite within veinlets and cavities, and dolomitization of large bodies of Waulsortian limestones.

The principal gangue mineralogy of the lenses at Silvermines varies enormously with barite being dominant at Magcobar and massive pale siderite forming a significant part of the B Zone (Andrew, 1986; Kucha, 1989). Massive pyrite is the dominant constituent of the large G zone, which is a fine-grained massive sulphide orebody (Graham, 1970), and is also an important constituent of parts of the B Zone, where it tends to occur at slightly higher stratigraphic levels (Plates 5A to 5C). The northern and down-dip part of the B Zone is dominated by a large lens of pale-buff siderite containing sphalerite and galena (Plate 5E).

The massive pyrite at Silvermines comprises a range of textures and fabrics ranging from laminated fine-grained sulphide with textures indicating graded bedding and slump fabrics (Plates 5A to 5C). These fine grained sulphidite sediments pass up dip into coarser often highly polymictic breccias comprising angular clasts of sulphides, which, in turn, flank mounds of colloform iron sulphides. The presence of pyritized fossil polychaete worms, similar to *Paravinella* type worms and hydrothermal chimneys also strongly suggests near or at surface phenomena (Larter *et al*., 1981; Boyce *et al*., 1983). These textural features have been interpreted as strongly resembling a sinter mound with flanking talus breccias and a piedmont of finer detritus (Andrew, 1986) or, alternatively, as well as geopetal infills of large cavities (Reed and Wallace, 2004). Massive pyrite typically shows macro to micro textures of banded botryoidal pyrite/marcasite/oxysulphides (“BPMO”) showing complex crustiform, resedimented detrital, framboids and laminated textures (Andrew, 1986). At Silvermines Kucha (1989, 2016) identified peloid agglomerations either forming thin films on breccias of clasts of pre-existing older sulphides or lithoclasts. These peloid films, formed from zinciferous calcite, dolomite and siderite as are seen under high-resolution SEM comprise a complex porous fabric containing nanometric specks of sphalerite, and also contain filamentous sulphides similar to those produced by sulphate reducing bacteria. These micro and nano textures suggest direct involvement of sulphate reducing bacteria in the formation of at least portions of the Silvermines massive pyrite facies.

Overlying and laterally the ore is enclosed by dolomite breccias with variable amounts of disseminated pyrite and then pale dolomite breccias with spectacular clasts of dolomite in a grey dolomite matrix (Plates 3A to 3E). Barite at Magcobar has a very variable thickness from 0m in the southwestern corner of the pit to a maximum of 31m (Plate 5F). The barite is accompanied by varying amounts of pyrite, minor galena, sphalerite, and haematite (Plate 9D). The barite orebody immediately overlies a footwall of a 1-cm thick, finely laminated lime-green shale and is discontinuously overlain by a sulphide 'cap', locally up to 2-m thick, consisting of massive pyrite with minor galena, chalcopyrite, pyrrhotite and other sulphides. Pyrite occurs as both disseminations and collomorphic veins cutting the barite. Textures in the orebody have been interpreted in differing ways. Barrett (1975) and Mullane & Kinnaird (1998) describe sedimentary features of the mineralization including bedding, syn-depositional breccias, load and slump structures, debris flow and rip-up clasts of barite within the basal hanging-wall breccias. Alternatively, Hitzman and Beaty (1996); Reed and Wallace (2001, 2004) consider these features as arising from hydrothermal brecciation and/or deposition of geopetal sediment within subsurface hydrothermally produced cavities.

At Silvermines the base of the orebodies is near the transition zone between the Waulsortian and ABL, known locally as the Muddy Reef Limestone. The orebodies display a strong local stratiform to stratabound morphology – often termed ‘concordant’. In greater detail the underlying limestones may be silicified and contain pale sphalerite, barite and more rarely silica-haematite (Plates 9E & 9F). Silica-haematite is also common along the base of the Magcobar barite body. Moving outwards from the faults and thickest ore, the base of the mineralized zones become stratigraphically slightly higher and are underlain by un-dolomitized Waulsortian limestones termed locally ‘FW Reef’. The ore is strongly associated with dolomite breccias and these form the hanging-wall of the mineralized zones. Some of these breccias have been interpreted as early debris flow and fault talus type features controlled by active faulting during growth of Waulsortian mounds, supported by company profiles across the B zone fault showing slumping and overfolding (Ashton, 1975; Barrett, 1975; Taylor & Andrew, 1978; Taylor, 1984; Andrew, 1986; Lee & Wilkinson, 2002. Plates 3A & 3B, Plates 5D & 5E). In part they may also be related to hydrothermal brecciation and dolomitization of Waulsortian mudstones in a fashion resembling the development of 'Black Matrix Breccias' (BMBs) at Lisheen and Galmoy (Wilkinson & Earls, 2000; Hitzman *et al*., 2002. Plates 3F to 3H). However, it is important to note that the term "BMB" has been used somewhat arbitrarily at various deposits in the Irish Orefield as a basket term to cover breccias of various genetic affinities.

At Silvermines all workers have noted the remarkable variation in gangue mineralogy - pyrite, siderite, barite - at the base of the G, B and Magcobar orebodies respectively. This change in mineralogy has been suggested to have been controlled by palaeo-bathymetric depressions in the Waulsortian limestones and breccias and has been interpreted as representing a redox control on or near the Carboniferous seafloor (Taylor & Andrew, 1976; Taylor, 1984). Globally siderite and barite are important constituents of IT affinity deposits such as Kremikovtsi (Bulgaria) and Vares (Serbia) (Marinova & Damyanov, 2016; Palinkas *et al.,* 2016).

Mineralization at Silvermines also occurred stratigraphically below the Waulsortian Limestone in dolomitized ABL equivalent rocks and within the Devonian Old Red Sandstone (Lower G, K, P, C Zones, and Shallee). While such mineralized zones are stratabound to a degree, they are spatially related to faults and zones of veining and brecciation; such zones are better described as 'discordant'. Sulphides occur in veins, disseminations and as replacement of dolomite host rock and compositionally this mineralized material rarely contains Fe or Ba gangue minerals (Plate 5G to 5I).

Mineralization at Galmoy formed the CW, G, K and R zones (Fig. 12. Lowther *et al*., 2005; Sullivan *et al*., 2002. Plates 6A & 6B) which are described as tabular lenses of semi-massive to massive sulphide, generally bounded on the footwall by the underlying ABL and with disseminated halos forming upwards towards the (assay) hanging wall. The G orebody was associated with a massive pyrite while the CW, K and R zones carried less pyrite. The geometry of mineralized lenses appears to have been controlled locally by thin shaley bands within the ore horizons, either sedimentary in origin or representing traces of low angle normal faults (Lowther *et al.*, 2003). In all the zones apart from the R Zone, sub-economic mineralization occurs in the upper 4-5m of the ABL as steeply dipping veins, commonly of stockwork style, and in thin beds parallel to the footwall. In the southern part of the R Zone, massive bands of sphalerite and galena are found in the ABL, often with copper in the form of tennantite-tetrahedrite, typically as replacement of dolomitised limestone units. (Sullivan *et al*., 2005).

Sulphide bodies at Lisheen occur within 30m of the base of the Waulsortian, forming single and multiple stratiform zones (Hitzman *et al*., 2002). The massive orebodies commonly display sharp contacts with adjacent dolostones. Pyrite, sphalerite, and galena display a complex range of textures ranging from replacement of carbonate rocks with initial sulphides in intragranular porosity and progressively replacing wall rocks to veinlets to geopetal fabrics with layered sulphides formed by internal sedimentation within apparently hydrothermally produced karstic cavities to massive bodies with typical colloform textures (Plates 6C to 6F). Chalcopyrite, arsenopyrite, tennantite and barite are most abundant near the Killoran and Derryville faults, especially within the Lisduff Oolite in the upper portion of the footwall ABL. A general sequence of deposition is: (1) pre-sulphide dolomite; (2) locally present replacive silica-hematite replacement of generally the uppermost ABL; (3) early sphalerite and pyrite; (4) extensive iron sulphide precipitation with minor sphalerite, galena, and gangue; (5) mixed sulphide assemblage, including ore-stage sphalerite and galena; (6) late sphalerite and galena, and (7) late carbonate, occasionally with minor honeyblende or chalcopyrite.

Pallas Green and Stonepark appear to comprise many small to medium size lenses of pyritic sulphides in un-dolomitized to dolomitized Waulsortian limestones (Plates 6G & 6H). As noted above, there appears to be a less obvious relationship of mineralized zones to faults, at least those that can be discerned from surface drill holes. Some of the mineralized bodies are spatially adjacent to Chadian-aged maar diatremes (McCusker & Reed, 2014; Elliot *et al*., 2019; Blaney, this volume). The base of mineralized zones at Pallas Green and Stonepark is frequently some tens of metres above the base of Waulsortian Limestone and combined mineralization/alteration packages frequently reach over 100m (and locally >200m) in thickness. The bulk of the high-grade zinc-lead mineralized zones at Stonepark occur as sub-horizontal, stratiform (1.0 to ca.7.5m thick) lenses of massive and semi-massive sphalerite, galena, and pyrite hosted within thick (10 to ca.75m) hydrothermal dissolution bodies of breccia that display some similarities to the BMB within the Waulsortian Limestone in Galmoy-Lisheen and Silvermines. However, these breccias are not uniformly dolomitized and display abundant evidence of hydrothermal karstification with internal sedimentation within the resulting cavities. Colloform textures are common in the sulphides with alternating bands of dark to light-brown sphalerite, galena and pyrite. Disseminated pyrite (1 to 5%) frequently occurs in the breccia matrix of the dissolution breccias with trace sphalerite and galena occurring locally, particularly above zones of high-grade massive sulphide (Kerr, 2013).

At Navan the Zn-Pb sulphides occur in several lenses and complex sub-lenses as massive, semi-massive and more minor texturally complex replacements in dolomitized or partly dolomitized grainstones and un-dolomitized micrites. Around 97% of the ore is located in several, locally superimposed stratabound lenses in the Pale Beds (PBO) (Anderson *et al.*, 1998; Ashton *et al.*, 2015. Plate 7). The remainder of the ore is located in several smaller lenses of pyritic massive sulphides termed Conglomerate Group Ore (CGO) in the BC generally on the hanging-wall side of half grabens where south dipping faults have preserved BC (Ashton *et al*., 1992; Ford, 1996; Ashton *et al*., 2015. Plate 8). The PBO is present as stratabound lenses in several stratigraphic layers in the Pale Beds. The most laterally extensive and lowest lens (5 Lens) is developed within pale grey micrites and interlayered and/or overlying pale dolomitized calcarenites. The micrites are overlain by nearly 200m of variably oolitic, bioclastic and sandy grainstones containing siltstone, shale and sandstone layers. In the main orebody, the more calcareous horizons are replaced with several tabular sulphide lenses. In the SWEX, apart from some structurally controlled 5 Lens ore near the 'E' fault, mineralization was most pronounced in the Upper Pale Beds along several bioclastic grainstone horizons (U-Lens) (Peace, 1999; Peace *et al*., 2003).

Sphalerite and galena are the principal ore minerals at Navan; minor silver-bearing (~10-15 g/t in mill feed) and antimonide sulphosalts also occur. The main gangue minerals are calcite, dolomite and barite. Pyrite and marcasite are present in subordinate amounts in the Pale Beds ore (~1-3% Fe), but locally increases in the upper lenses, particularly the 1 Lens (>6% Fe: Andrew & Ashton, 1985) and the overlying Conglomerate Group Ore (>20%; Ashton *et al*., 1992; Ford, 1996; Altinok, 2005; Barker & Menuge, 2010; Barker *et al*., 2011, 2012).

Sulphide layers are often developed below silty and/or dolomitic horizons that appear to have acted as impermeable barriers (Plates 2C & 7B). The bases of the sulphide layers are approximately stratiform locally but can display significant irregularity and the ore disposition is best considered as a stratabound replacement (Plates 7A & 7G). Some of the sulphide veins present in mineralized zones display a distinctive crumpled, concertina-like appearance suggesting that compaction and host rock lithification were incomplete during mineralization (Anderson *et al*., 1992; Ashton *et al*., 2003. Plate 7D). In areas of intense mineralization, evidence for open-space growth of sulphides is common and includes coarse-grained galena, geopetal fabrics with layered sphalerite in internal sediment, sulphide stalactites and, usually minor, late gangue-filled cavities containing barite, rare gypsum and/or carbonates (Anderson, 1992; Anderson *et al*., 1998. Plates 7A, 7C & 7H). The ore characteristically contains complex and chaotic assemblages of usually fine- to medium-, but locally coarse-grained sulphides, host-rock and gangue minerals (Ashton, 1995; Anderson *et al*., 1998; Ashton *et al.,* 2003). Ore textures are often complex, comprising varying proportions of disseminated, replacement, fracture-fill, breccia and massive styles that exhibit repetitive disruption, replacement, cyclic sulphide deposition and open space fill processes (Anderson *et al*., 1998. Plate 7). The texturally varied nature in the mineralized zones implies several strongly episodic mechanisms for ore deposition. Textural styles include bedding-parallel to cross-cutting extensional brecciation and veining (Plates 7C & 7G), delicate to massive replacement of host rock (Plates 7A, 7E, & 7F), and dissolution of limestones to form open spaces that were subsequently completely filled with sulphides (Plate 7H).

Although all these textures occur throughout the Pale Beds-hosted ore lenses, there is significant variation, largely due to the differing nature of the host limestones. It is a highly complex intermixture of lenses, sub-lenses, pods, mineralized breccias and veins that appear to have developed preferentially in the micrites, grainstones and dolomitized grainstones of the Lower Pale Beds (Anderson *et al*., 1998). Ore morphology tends to vary between host-rock types. Contacts between sulphides and micrites are often sharp and indicate that the limestones were extensively dissolved by the hydrothermal fluids. In grainstones and dolomitized grainstones, the contacts are generally more diffuse and larger amounts of disseminated sphalerite occur (Plates 7E & 7F). Disseminated granular sphalerite is characteristically very well developed in the sandy grainstones of the Upper Pale Beds U Lens in SWEX (Plate 7F). Where mineralization was particularly intense, fracture fill and breccia-hosted sulphides cut the dolomitized horizons and are interpreted as areas where mineralizing fluids breached an impermeable seal (Plate 7C).

Conglomerate Group Ore ('CGO') consists of irregular massive iron-sulphide-rich layers with local bedding-parallel morphologies and layering (Plate 8). The proportion of iron to zinc-lead sulphides is variable as are grain size and textures. The iron sulphides occur in several forms; as laminae of fine-grained framboidal pyrite associated with dark argillites regarded as being early diagenetic (Barker *et al*., 2012), as a coarser grained matrix to the conglomerate, in bands with a speckled appearance associated with medium-grained white calcite, and as thicker layers of massive pyrite often accompanied by high-grades of zinc-lead (Ashton *et al.*, 1992; Ford, 1996. Plates 8A & 8B). Early pyrite in the CGO is strongly arsenian, compared to Pale Beds pyrite (Barker *et al*., 2012). Rotated clasts of pyritic massive sulphides and rip-up clasts of pyritic argillite are commonly intercalated in the mineralized conglomerates (Ashton *et al*., 1992; Ford, 1996). Sphalerite and galena occur with iron sulphides as massive bands, disseminations and in crosscutting veins. The textures indicate that a substantial amount of the Zn/Pb sulphide precipitation post-dated precipitation of Fe sulphides. Near the base of the Boulder Conglomerate, SW of the main CGO Lens, ore layers consisting of sphalerite, lesser galena and only minor pyrite are developed. These appear to have formed by infill of pore spaces between clasts and by replacement of limestone conglomerate fragments. Rare clasts of iron-deficient sulphides, comparable to Pale Beds-hosted ore and showing truncation of layering at clast margins, are also present (Ashton *et al*., 1992; Ashton *et al.,* 2015; Ford, 1996; Blakeman *et al.,* 2002. Plates 8C & 8D). In the SWEX the lower BC contains large irregular blocks of upper Pale Beds sandy dolomitic grainstone with abundant disseminated sphalerite (Plates 8E & 8F). These are interpreted as slide blocks derived from a palaeo-scarp on the 'M' Fault and also suggest that some mineralization occurred earlier and/or was synchronous with formation of the Boulder Conglomerate.

The CGO provides unequivocal evidence that mineralization was in place in the Pale Beds before the incisive erosion surface unroofed the stratigraphy. It thus provides accurate dating of at least some of the mineralization event at Navan. Locally, often at stratigraphically high locations in the Boulder Conglomerate and overlying Thin Bedded Unit, fine grained zinc-lead sulphides form thin stratiform layers (Ashton *et al.*, 1992; Ashton *et al.,* 2002; Ashton *et al.,* 2015) (Plates 8G & 8H). Laminae of fine-grained framboidal pyrite are common in the lowest *ca.* 20m thick Thin Bedded Mudstone (TBU) unit of the Upper Dark Limestones and persist for at least 50m in shaley layers above in the Main Orebody and in the SWEX.

Tara Deep mineralization is similar to 5 Lens in the main orebody and occurs in thick micrites and pale dolostones. The mineralized zone east of the 'S' fault is approximately tabular while west of the S Fault mineralized zones become steeply dipping and thicker and are locally overlain by sub-economic massive CGO-type pyrite. Only the lowest part of the Pale Beds stratigraphy is preserved in the Tara Deep area and the basal micrites pass upwards into complex, un-dolomitized or partially dolomitized breccias that have a healed appearance and whose origin is unclear. They are overlain by the Erosion Surface and a succession of thick debris flow breccias and thin bedded limestones representing a more complex expression of the BC in this area. Overlying the breccias the basal Upper

Dark Limestone is dissimilar to that present above the main orebody and SWEX areas in that ca. 500m of thinly bedded (TBU) material are developed which contain large amounts of laminated framboidal pyrite with striking similarities to some classic SEDEX type deposits. Yesares *et al*. (2022) have described the occurrence of apparently syn-depositional hydrothermal silica with disseminated sphalerite in a distinct layer in this unit and recorded minor amounts of chalcopyrite, galena, siegenite, stibnite and Co-pentlandite.

In summary the host rocks to IT deposits comprise micrites and variably dolomitized micrites and grainstones often displaying substantial brecciation. Not only are the Waulsortian Limestones and the Pale Beds chemically pure limestones but they also contain internal heterogeneities that facilitated brecciation, fracturing and permeability. In the case of the Waulsortian Limestones these include the complex non-stratiform mud-mound facies with irregular fenestral porosity and stromotactis cavities (Lees & Miller, 1995). The Pale Beds exhibit lateral and vertical facies changes and channeling reflecting the switch from quiet supratidal conditions (micrite) to high energy shallow shelf sedimentation and development of cyclic emersion surfaces in the micrite unit (Rizzi, 1992; Rizzi & Braithwaite, 1996). The presence of local weak shale and siltstone layers in both these rock units may also have promoted mechanical disaggregation during fault movements.

Alteration and Lithogeochemical Halos

Silica-Haematite ('Iron Formation')

At Tynagh a major lens of silica-haematite-magnetite is present to the north of the fault as a distal extension to the base metal orebody (Derry *et al.,* 1965; Schultz, 1966; Russell, 1975. Plate 9A to 9C). Smaller examples of similar 'Iron Formation', most lacking significant magnetite, have been described from Silvermines (Plates 9D & 9F), Lisheen (Plate 9G) and Navan (Plate 9H) as well as some of the smaller prospects at Keel (Garrycam) and Crinkill (Andrew, 1986a; Clifford *et al*., 1986; Hitzman *et al.,* 1992; 1995; Cruise *et al.,* 1999; Cruise, 2000; Byrne *et al.,* 2014; Ashton *et al.,* 2015). The well laminated 'Iron Formation' at Tynagh comprising jasperoidal collomorphic haematite, maghemite, stilpnomelane and minnesotaite typically show convoluted micro-botryoidal colloform fabrics strongly reminiscent of algal lamination and also contain interbeds of graded calcareous turbidites (Cruise, 2000). Towards the Tynagh Fault the banded iron formation passes laterally into haematitic flank Waulsortian talus breccias before terminating against the Waulsortian knolls developed on the fault which hosts the base-metal mineralization.

Cruise, (2000) and Byrne *et al.,* (2014) interpreted the 'Iron Formation' to be of early diagenetic origin in very shallow carbonate sediments pre-dating sulphides and hydrothermal dolomite and considered that significant quantities of this material may have been overprinted during sulphide mineralization. At Silvermines it forms clasts within the barite body in the B Zone (Plate 9E) and at Magcobar is locally present along the base of the barite zone (Plate 9D & 9F) but it is not necessarily a distal expression of the mineralizing system. At Lisheen this alteration is relatively rare and occurs from distal to the deposit (Hitzman *et al*., 1992) to immediately adjacent to the main controlling faults. It generally occurs near the Waulsortian-ABL contact (Fusciardi *et al*. 2003) and may be present in either the basal Waulsortian Limestone or the uppermost ABL. Clasts of this type of material are found within BMB and massive sulphide indicating it predates those events at least locally (Plate 9G). At Navan small quantities have been noted (also with minor silicified goethite/limonite) distal to the CGO in the BC and UDL on the SE side of the Main Orebody (Plate 9H) and on the SE side of Tara Deep (Ashton *et al*., 2015). The observed relationships suggest silica-haematite generally preceded sulphide mineralization and formed at various positions within the overall mineralizing system, presumably at sites of early hydrothermal discharge.

Cherty limestones occur *ca*. 100m above the Silvermines orebodies (Andrew, 1986; Plate 3E) and the silica in these limestones have oxygen isotopic values indicative of hydrothermal rather than diagenetic derivation (Hitzman *et al*., 1995). Potentially similar cherty limestones are present above the Main Zone at Lisheen (Hitzman *et al*., 2002) and in portions of the Stonepark system (M. Holdstock, *pers. comm*., 2023). Minor hydrothermal chert and sulphides associated with Mn rich mudstone has been described from the New TBU unit *ca.* 200m above the Tara Deep deposit at Navan (Yesares *et al.,* 2022). It is possible that other cherty limestones above the IT deposits have a hydrothermal origin; studies are currently underway examining this hypothesis (e.g., research by E. Burton at iCRAG).

Dolomitization

Dolomitization comprises the most widespread, highly complex and variable type of alteration seen in all the IT deposits; its timing and relationship to the mineralizing system is complex. Dolomitization of the Waulsortian limestone is the main alteration product observed in all the SW deposits and dolomite breccias form the host and hanging-wall rocks at Silvermines, Galmoy and Lisheen (Plate 3). At Pallas Green-Stonepark, Tynagh, and Navan dolomitization is patchier but is also spatially strongly correlated with many mineralized zones. It is likely that the process that caused mineralization was also capable of causing dolomitization, though there is evidence that dolomitization preceded, accompanied and post-dated the main sulphide depositional events.

In the SE of the Orefield, including Galmoy and Lisheen, massive grey crystalline dolomite occurs regionally and has partially to wholly replaced the Waulsortian limestones, and further SE, most of the Courceyan and Chadian rocks. These mineral deposits appear to lie within this zone of regional dolomitization but close to a complex dolomite front which lies to the NW of the Rathdowney Trend. Hitzman *et al.* (1992) noted that the regional dolomite itself comprises several sub-types and appears to pre-date the hydrothermal dolomite centered on the mineralized areas. They ascribed the regional dolomite to the palaeogeographical influence of the Anglo-Brabant massif during the Chadian-Arundian directing gravity driven hypersaline fluids westwards (see also Wright *et al*., 2004; Nagy *et al.,* 2004; Johnson *et al.,* 2009). Gregg *et al*. (2001) also noted there was a "*a complex, multistage, multiple fluid history for regional dolomitization*". Wilkinson (2003) for example, considers the regional dolomite while forming after the main stages of calcite cementation probably developed within tens of metres of the seafloor due to incorporation of clasts of dolomite in intraformational sedimentary breccias. Alternatively, Sevastopulo & Redmond (1999) have ascribed potentially younger (Arundian or later) dates for the regional dolomite and by implication the hydrothermal dolomites and mineralization. Models for regional dolomitization, whilst complex and incompletely understood, are important in that they ascribe this event to Lower Carboniferous mechanisms prior to sulphide mineralization.

At Tynagh Clifford *et al*. (1986), noted the presence of several stages of dolomitization that preceded, were coeval with, and post-dated the Zn-Pb mineralization event. At Silvermines spectacular massive dolomite breccias are intimately associated with and/or overly the Waulsortian-hosted ore zones which Andrew (1986) and Lee & Wilkinson (2002) consider to be related to early replacement of debris-flow breccias essentially spanning the mineralizing event. Alternatively, an interpretation of the same rocks by Hitzman & Beaty (1996) lead to the conclusion that these dolomite breccias formed dominantly by hydrothermal replacement and infill of hydrothermal karstic cavities by geopetal sediments including syn-sedimentary breccias.

However, and importantly, it should be noted that breccia bodies and equivalent stratigraphy are sometimes, as at Silvermines, thickened (often substantially) over the location of underlying mineralization rendering a collapse model difficult to reconcile at such locations. At Galmoy Doyle *et al*., (1992) and Lowther *et al.*, (2003) describe crystalline dolomite breccia and dolomitized rock matrix breccia (RMB) that occurs near the base of the Waulsortian Limestone in large lenticular bodies that they postulated were a pre-requisite for sulphide mineralization. With increasing distance north of the main fault, the RMB becomes less well developed and more sporadic in its distribution. Doyle *et al.,* (1992) considered the RMB to be formed *in-situ* due to early instability on the main fault and introduction of dolomitizing and mineralizing fluids, while the regional crystalline dolomite breccia was formed by volume reduction in the Waulsortian following development of the RMB.

At the simplest level hydrothermal dolomite breccias at Lisheen comprise Black Matrix Breccias (BMBs) and White Matrix Breccias (WMBs); in detail the dolomitization is capable of more complex subdivision (Hitzman *et al.,* 2002; Wilkinson *et al.,* 2005; Doran *et al*., 2022). The BMBs are similar to the RMBs at Galmoy and some breccias in the Pallas Green-Stonepark system and are considered to post-date the regional dolomization event (Fusciardi *et al*., 2003. Plates 3F to 3H). They comprise buff to grey dolomite clasts in a matrix of microcrystalline grey to black dolomite commonly with trace apatite (Vafeas *et al*., 2023). The WMBs comprise irregular stockworks of coarsely crystalline white, non-ferroan dolomite forming veins and breccia zones in the regionally dolomitized Waulsortian Limestone, generally above the zones of BMB (Redmond, 1997). Both the BMB and WMB are developed in a broad stratabound halo enclosing the mineralization, but the area affected by WMB alteration appears to be several times as large as the area of BMB, though it is commonly difficult to megascopically separate WMB dolomite from components of the regional dolomite. Wilkinson (2003) considers the BMB to originate from hydrothermal fluid mixing and sulphide deposition within permeable dolomite breccias. Dolomite breccias therefore are a key indicator of IT mineralization in the Waulsortian deposits and the term BMB has become widespread as a positive drill core indication amongst the exploration community.

At Navan dolomitization is less well developed than in the SW deposits and there is little or no evidence of regional dolomite or dolomitization of the Waulsortian Limestone, where present. It can be loosely divided into two occurrences (Anderson *et al*., 1998; Everett & Wilkinson, 2001; Rizzi, 1993; Braithwaite & Rizzi 1997). Firstly, a structurally controlled ‘plume’ of locally completely dolomitized Pale Beds trending roughly ENE through and above the northern part of the Main Orebody, loosely correlated with the similarly trending zone of mineralized fracturing and faults and metal distribution highs. This plume is interpreted to be hydrothermal in origin based on fluid inclusion and isotopic analyses; it is fabric destructive and occasionally porous but is only generally correlated with mineralized zones near the base of the Pale Beds; at higher levels in the Pale Beds, it is unmineralized. Secondly, as bedding-parallel dolomitization of oolitic grainstones, sandstones and siltstones in the Pale Beds, conceptually envisaged as branches in ‘Christmas tree’ fashion to the aforementioned plume. Importantly these dolomitized layers, unlike the regionally dolomitized Waulsortian Limestone in the SW portion of the Orefield, are not porous and locally form distinct hanging-walls to high grade stratiform ore layers; they appear to have acted as a permeability barriers. Limited fluid inclusion and isotopic evidence suggests that the stratiform dolomite is also of hydrothermal origin.

Importantly, it must be recognized that dolomitization was not a pre-requisite for mineralization at all deposits. In the deposits where mineralization occurred in late diagenetic lithified sediments, porosity and permeability enhancing dolomitization enabled and facilitated fluid movement as in the K Zone, P Zone and Lower G Zone at Silvermines, in the Lisduff Oolite mineralized zones at Lisheen, at Keel, and in Zone 3 at Tynagh.

Minor pink baroque ferroan dolomite with associated minor pyrite and chalcopyrite is observed at most deposits and throughout the Central Midland Orefield though it does appear to be more abundant in and above mineralized areas. Its formation is considered to be a separate event to IT deposit mineralization and is of likely Variscan age (Andrew, 1993; Fusciardi *et al*., 2003; Wilkinson, 2003). The association of pink baroque ferroan dolomite with corroded nail head calcite and minor late crystalline chalcopyrite is a worldwide phenomenon as a late-stage product of thermochemical sulphate reduction (Machel, 1987) and has been named the “copper-dolomite” association (Andrew, 1993).

On the basis of stable isotope evidence these dolomites in Ireland seem to represent a late-stage basin dewatering event possibly formed at the time of inversion in the early Variscan (late Asbian to Brigantian Stages).

Lithogeochemical Halos

Dolomitisation and pyritization form obvious, if irregular, halos for IT deposits. Several litho-geochemical studies on IT deposits have been completed to look for less visible geochemical indications that rocks hosting IT deposits could give a larger exploration target and provide vectors towards ore. Here we focus on what is known, utilisation of this knowledge is quite a different (and difficult) topic and is discussed later.

In the SW area most of the published work derives from Tynagh (Russell, 1974, 1975; Clifford *et al.,* 1986) where a significant litho-geochemical halo lying outboard and to the north of the orebody has been described as extending for several kms from the deposit with Zn, Pb, Mn, Ba and several other elements enriched in the host Waulsortian Limestone. At Silvermines Grey (1986) documented similar but less regular halos to Tynagh. There is little published work with regards potential litho-geochemical halos from Galmoy and Lisheen. Since the hydrothermal dolomite breccias, including BMBs, extend further than the economic limits of the deposits, geochemical anomalies may be restricted to these rocks.

Turner *et al*. (2019) have defined geochemical baseline levels for a range of metals, including rare earths, from a range of Lower Carboniferous rocks, including the Waulsortian Limestone, from the Rapla area, a prospect lying east of Galmoy. They recorded a spike in Ni/Co-V-Hf/Zr levels at the top of the late Chadian-aged Crosspatrick Formation thought to be a result of additional (mafic-intermediate) volcaniclastic input accompanying the detrital components in the sediment budget. This phase would temporally correlate with the spike in Ni/Co-V-Hf/Zr levels at the top of the Crosspatrick Formation (Turner *et al.*, 2019) suggesting an important thermal event potentially coeval with late-stage mineralization. De Brit (1989) noted the presence of a yttrium anomaly (*ca*. 1000pm) in brown late-stage sphalerite mineralization at the Ballinalack deposit which may also be temporally coeval.

At Navan it is well established that minor Zn, Pb, Fe, As, Mn, Sb, Cu, Tl, Ba and Mg occur in lithologies laterally equivalent to the orebody in Pale Beds and within the overlying BC and UDL (Finlay *et al*., 1984; Van Oyen & Viane, 1988; Gonzalez, unpublished; Walker, 2005; Blakeman, 2010; Walker, 2010; Marks, 2013, 2015). In the Pale Beds to the NW of the orebody there is a large area containing trace visible sulphides, dolomitisation and minor bleaching over 10s of km, with the best development of these features often related to faults and fractures. This epigenetic 'lateral' halo is extremely irregular and shows large variations in textural style and mineralogy. Blakeman *et al*., (2010) described this halo as defined by "*not necessarily strong or coincident enrichments in Zn/Pb, Ag, As, Sb, normative barite and normative dolomite*" extending laterally away from the main mineralized zones for at least 1km but for probably less than 4km. Unfortunately, on other sides of the orebody data on the nature of the lateral halo is unavailable due to faulting, lack of drilling, and/or erosion. Marks (2015) identified a proximal lateral area, within about 500m of the northern margin of the Navan orebody, as defined by a number of differing epigenetic sulphide textures and a more distal halo with more poorly developed sulphide occurrences. Based on isotopic studies, the intensity of the halos was related to a large area of fracture permeability and available sulphur, rather than lateral flow of fluid outwards from the main deposit (Marks, 2015). Marks (2015) also noted a 'secondary epigenetic halo' in Pale Beds near Variscan faults comprising visible coarse yellow honeyblende in late calcite veins. Such late-stage crystalline sphalerite has also been noted in drilling at other localities in the Orefield.

Lithogeochemical studies have also defined irregular halos in the Upper Dark Limestones above the orebody characterized by enrichments of Zn, Pb, Fe, As, Mn, Sb, Cd, Cu, Ni, Tl, Ba, Mg and P. (Walker, 2005; Walker, 2010; Marks *et al.*, 2013; Marks, 2015). Walker (2005) identified very distinct halos for Zn, Pb, Fe, Sb, Cd, Cu, Co, Ni, As, Tl, Mn and P for at least 100m in the UDL overlying the SWEX orebody and noted the presence of abundant pyrite. He ascribed these anomalous values as exhaust from hydrothermal fluids into basal UDL sediments near the sea floor and interpreted the fairly regular patterns to be evidence for essentially syngenetic metal deposition. Marks (2015) recorded similar but more vertically extensive results above Tara Deep concluding that higher values of the chalcophile elements were related to the extensive framboidal pyrite occurrences that formed a halo developed during sedimentation and early diagenesis. Marks (2015) also noted that the occasional orange coloration of UDL drill core, related to recent oxidation of siderite, ankerite and Mn enriched rocks, was a facet of this syngenetic halo, as is the presence of rare hydrothermal silica and fine-grained sulphides (Yesares, 2022).

Carter *et al.,* (1988) noted the presence of kilometre-scale light hydrocarbon gas anomalies at Silvermines and Navan and speculated that differences in the detailed nature of the anomalies, while not understood, reflected 'some fundamental change across the country'. Unpublished research by Chevron Mineral Corporation found a variable range of maturities of organic matter within the UDL above and adjacent to the Navan deposit that is probably fundamentally related to Carter *et al*.'s (1988) findings.

Paragenesis, Petrography, Timing

There are many studies documenting the petrography, mineralogy and paragenesis of ore and gangue minerals and enclosing host carbonates. Hitzman & Beaty (1996) provided a useful generalized paragenetic summary based on studies of several deposits (Fig. 15) and noted the general similarity between the main events over the Orefield. The main sequence of events at each deposit begins with hydrothermal calcite and dolomite (often Fe rich), silica+Fe oxide (iron formation), barite, pyrite-marcasite, then sphalerite and galena. However, excluding the generally early silica+Fe oxide, many of these phases comprise repetitive pulses, which also include carbonate dissolution events, intermixed with reversion to continued deposition of phases earlier in the sequence such as carbonate and/or pyrite.

Due to the textural complexity produced by the mineralization and alteration events, virtually all deposits display evidence of multiple cyclicity, carbonate precipitation and dissolution (including significant resulting brecciation) and rhythmic banding, making it difficult to derive a single paragenetic sequence of mineral precipitation and dissolution for the larger deposits

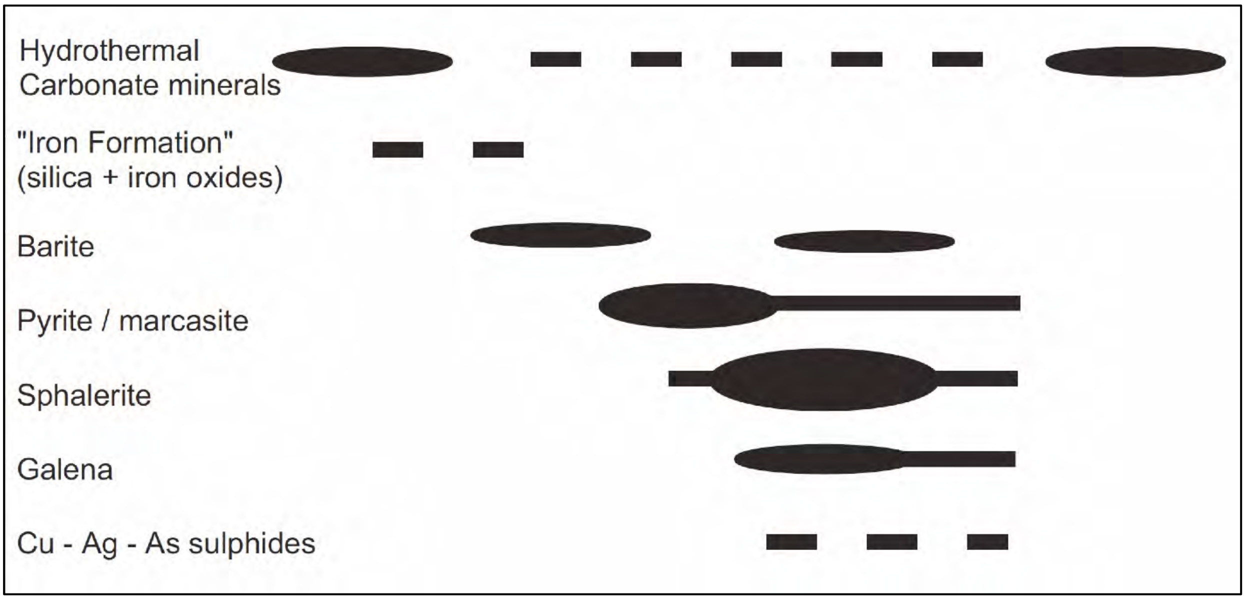

***Figure 15:** Simplified paragenesis of main minerals comprising IT deposits (after Hitzman & Beaty, 1996).*

(Anderson *et al*., 1998; Barrie *et al.,* 2009). At Navan for example mineralization in the Pale Beds likely involved a variety of complex cycles pre-dating mineralization in the CGO and UDL. Differences in mineralogy occur in zones in each deposit and between each deposit. It would be interesting to know if the degree of cyclic sulphide deposition was different between Navan and the SW deposits owing to the more complex faulting at Navan.

At some deposits it is evident that most Zn/Pb mineralization postdated initial marine cementation and dolomitization of the host rocks, however this is not always the case. At Ballinalack very early colloform sphalerite can be seen to line to fenestral porosity (stromatactis) prior to precipitation of diagenetic radiaxial marine calcite (Brand & Emo, 1986; Andrew, 1993). Petrological studies conducted by the Getty Oil Research Centre in the early 1980's clearly demonstrated that in some samples sphaleritization of some allochems (in particular ooliths) at Navan and Tatestown postdated radiaxial marine aragonite but predated blocky ferroan calcite infill cements (Caitlin & Danielli, 1983).

The interpretation of the timing of cementation and dolomitization varies, from near seafloor (Andrew & Ashton, 1985; Anderson *et al*., 1998; Everett & Wilkinson, 2001; Lee & Wilkinson, 2002) to greater than 800m burial depth and as late as the Asbian (Peace & Wallace, 2000; Reed &Wallace 2001; Reed & Wallace, 2004; Stacey *et al*., 2002). The precise age and duration of alteration and mineralization in the IT deposits remains unresolved and is largely centered on whether carbonate cementation was mostly completed during initial stages of burial or at significant depths. Peace (1999) and Peace *et al.,* (2003) note that mineralization in the upper Pale Beds in Navan is preferentially located in bioclastic grainstones that retained significant porosity in comparison to surrounding lithologies. Wilkinson (2003) noted that "*Mineralization clearly formed during diagenesis of the host-rock sequence; as such, it is accurately termed 'syn-diagenetic'. Since lithification occurred very early, near the seafloor, "epigenetic" textures do not imply that mineralization occurred a long period of time after host-rock deposition*".

In summary, while the nature and spread of paragenetic relationships is reasonably clear the timing of the Zn and Pb mineralization in relation to carbonate cementation and alteration is not fully understood (or agreed!). Opinions span a period ranging from shortly after sedimentation in the Courceyan to relatively deep burial in the Asbian and subsequent basin inversion – but there is agreement that the deposits are likely pre-Variscan with the possible exception of the Kildare deposits (Andrew & Stanley, this volume).

Geological and Geochronological Dating Studies

There has been debate, occasionally robust, over the last fifty years on the timing of emplacement of IT deposits. Most workers accept that the faults controlling the deposits were active during the Courceyan to Chadian, spanning sedimentation of the ABL, Waulsortian Limestone and later lithologies and the development of the Dublin Basin. Furthermore, several features of IT deposits have been widely interpreted as indicative of formation during or shortly after sedimentation. The paragenetically early Iron Formation at Tynagh and Silvermines and elsewhere is a minor but key component of several deposits representing an early record of the onset of hydrothermal activity (Cruise, 2000). Banks (1985, 1986) record what they interpret as pyrite chimneys and worms from pyrite at Tynagh. Similarly, at Silvermines the presence of framboidal pyrite of syn-diagenetic origin in the Upper G zone at Silvermines (Graham, 1970) and the deposition of cryptocrystalline barite mud as an apparent sediment at Magcobar (Barrett, 1975; Mullane & Kinnaird, 1998) potentially indicate mineralization in mini-basins controlled by palaeo-bathymetry (Taylor & Andrew, 1978; Taylor, 1984; Andrew 1986). Additionally, the presence of pyrite microbialites and the presence of sub-micron, filamentous hollow tubes of hematite cemented by quartz suggest fossil iron-oxidising bacteria, which could indicate the existence of a chemoautotrophic, near-seafloor habitat typical of both fossil and modern seafloor hydrothermal systems. The interpreted presence of fossil vent-related worm tubes suggests that sea-floor exhalative hydrothermal activity could have occurred at Silvermines and Tynagh around 350-360Ma (Larter *et al.*, 1981; Boyce *et al*., 1983b; Boyce *et al.,* 2003c; Kucha, 2017; Russell, this volume). Such an age is supported by a Rb-Sr age of 360±5 Ma on sphalerite from Silvermines (Schneider *et al*., 2007). More recent data, however, tends to indicate a slightly younger age of alteration and mineralization. Re-Os geochronology on pyrite from Silvermines gives a 334±6.1 Ma age (Hnatyshin *et al*., 2015) and recent U-Pb dating of apatite intergrown with the dolomite breccia (BMB) from above the Magcobar deposit yielded an age of 331+5.6 Ma (Vafeas *et al*., 2023), suggesting the possibility of a post-depositional age of dolomite breccia formation. These ages from the hangingwall rocks at Silvermines are in general agreement with Re-Os age of 346.6 Ma for sulphides from Lisheen. If real, they suggest alteration and mineralization in these systems was active from the Chadian into the Asbian. However, such dates also correspond to inversion of the Shannon Trough and could equally represent a late dolomitizing reflux enriched with P from phosphatic shales.

At Navan Anderson *et al.,* (1998), Ashton *et al*., (2015) note how some sulphide layers and veins in the Pale Beds have a deformed and folded appearance suggestive of formation in incompletely lithified grainstones. Furthermore, the occurrence of dislocated clasts of mineralization in the Boulder Conglomerate provide unequivocal evidence that some mineralization occurred no later than the Chadian. Blakeman *et al.* (2002) noted the presence of comminuted sulphides with faults in the northern part of the orebody that do not extend upwards through the Erosion Surface. These features imply a late-Courceyan to early Chadian age for some mineralization. CGO and the overlying TBU at Navan contains abundant fine grained laminated framboidal pyrite interpreted as sedimentary to extremely early diagenetic in age. However, it is clear that mineralization at Navan was also active in the late Chadian to at least the early Arundian due to the presence of Zn and Pb mineralization in the basal UDL above the Main Orebody, SWEX and particularly Tara Deep (Ashton *et al*. 1992; Ford, 1996; Altinok, 2005; Yesares *et al*., 2022).

A number of geochronological techniques have been attempted on IT deposits since the 70s but with little success (see Andrew, this volume). Boast (1978) and Boast *et al.,* 1981b reported that Tynagh galenas yielded a lead isotope model age for mineralization of about 348 Ma that agrees with the stratigraphic dating of the deposit but noted that lead isotopic ages from both Silvermines and Navan were unreliable. Variscan paleomagnetic dates of 277 Ma for Lisheen, 290Ma for Zn-Galmoy and 269Ma for the Ba mineralization at Silvermines are documented by Symons *et al*. (2007) and Pannalaal *et al*. (2008). Symons *et al*. (2002), based on comprehensive sampling and palaeomagnetic studies, estimated an older age of 334Ma (Asbian) for mineralization at Navan and noted that the palaeomagnetic data from mineralized and unmineralized rocks at Navan give a remarkably consistent orientation, interpreted as due to heating and recrystallization related to the hydrothermal event rather than by regional burial. Wilkinson *et al.,* (2017) considered that palaeomagnetic dates were unreliable and may have been 'reset' during Variscan orogenesis.

Schneider *et al*. (2007) reported a Rb-Sr isochron age of 360Ma on sphalerite samples from Silvermines. More recently, Re-Os dating of ore stage pyrite by Hnatyshin *et al*., (2015) from Lisheen gives a date of 346.6Ma, shortly after host rock deposition and agreeing with many geological estimates. They also report that pyrite from the Silvermines deposit returns an age of 334.0Ma. Such a discrepancy in the Re-Os data from the host-rock age has been interpreted in the Derryville Zone (322 ±11Ma) at Lisheen to potentially involve fluids associated with Variscan deformation (<310Ma) and that the Re-Os data does not reflect the timing of the iron sulphide mineralization due to mixing (Hnatyshin *et al.,* 2020).

In summary, geological and geochronological data has provided sometimes confusing and conflicting ages, highlighting the reasons for the lack of consensus on the age of IT deposits.

We suggest that mineralization occurred from close to the deposition of host sediments and into the Chadian-Arundian (and possibly the Asbian), and that there may have been resetting and potential re-mineralization during Variscan tectonism.

Igneous Activity

There are no contemporaneous igneous rocks known near Tynagh, Silvermines, Galmoy, Lisheen or Navan and indeed most minor prospects in the Central Midlands. Minor tuff horizons are recorded at most deposits, frequently logged as 'green shale' either at the base or above the level of mineralization (Koch, 2021; Yesares *et al*., 2022) typically in the upper ABL and near the base of the Waulsortian Limestone in the SW and in the upper Waulsortian Limestone and basal UDL at Navan.

There are two significant volcanic centres in the Lower Carboniferous of Central Ireland, at Croghan Hill (County Offaly) and Limerick (near Pallas Green). The effusive basalts at Croghan Hill in the Midlands (Haigh, 1914) are considered to be early Chadian on the basis of a 345 ± 3 Ma $^{40}Ar/^{39}Ar$ amphibole age (Timmerman, 2004) and have recently been dated to latest Tournaisian to early Chadian by U-Pb methods (Koch, 2021). The Limerick Igneous Suite ('LIS') contains two distinct basaltic igneous units: the Chadian-age Knockroe (Waulsortian and later) and Asbian-aged Knockseefin, which are expressed as hypabyssal intrusions, porphyritic dykes, diatremes, lava flows, agglomerates, and tuffs. These units make up two distinct evolutionary trends: the Knockroe igneous units which range from alkaline basalts to trachyandesites, and the Knockseefin igneous units which range from alkaline basalts to basanites. U–Pb dating of apatite establishes a primary crystallization age of *ca*. 350 Ma for the Knockroe units (Slezak *et al.,* 2023; *this volume*).

These igneous events were attributed to deep seated events related to 'consolidation of Laurussia and Gondwana' in the vicinity of the Iapetus suture. The Pallas Green, Stonepark and Gortdrum deposits are spatially related to the LIS.

Metal and Sulphur Sources, Nature of Mineralizing Fluids

A wealth of isotopic and fluid inclusion data is available for most of the IT deposits which is well summarized by Wilkinson & Hitzman (2015); only salient points are summarized here. This data has been invaluable in aiding development of ore genetic models for IT deposits. The results of these studies demonstrate that the metal and sulphur derivation, transportation and deposition was essentially similar in all IT deposits.

Extensive Pb isotopic studies reveal that the lead isotopic ratios in galena from the mineral deposits mirrors those of galena in the local basement. This strongly suggests that the Pb, and by implication other metals, have been leached from the local basement beneath the deposits and not derived from distal sources by lateral fluid migration (Caulfield *et al*., 1986; O'Keeffe, 1986; Le Huray *et al*., 1987; Dixon *et al*., 1990; Everett *et al*. 2003; Hollis *et al*., 2019).

Detailed S isotope ($\delta^{34}S$) studies by a number of workers utilizing extensive sampling from most IT deposits has indicated that the principal source of sulphur for the sulphides in the deposits was Lower Carboniferous seawater. This work consistently demonstrates a bimodal distribution of $\delta^{34}S$ that is interpreted to reflect a dominant component of light sulphur, derived from bacteriogenic reduction of Lower Carboniferous seawater sulphate, and a minor component of heavy sulphur introduced by hydrothermal fluids (Coomer & Robinson, 1976; Boast *et al*., 1981; Anderson *et al*., 1998; Hitzman & Beaty, 1996; Wilkinson *et al*., 2005; Wilkinson, 2014; Andrew, this volume; Boyce *et al*., this volume). In the SW deposits sulphur isotopic values indicate that the sulphides nearer the faults and feeders tends to be heavy while the sulphur in the larger and stratiform/stratabound ore is lighter. At Navan the situation is more complex in that the bimodal distribution of $\delta^{34}S$ isotopes occurs in samples taken throughout the main ore lenses but is skewed towards lighter values (Anderson, 1990; Anderson *et al*., 1998). Furthermore Anderson *et al*. (1990) have shown that sulphides with coarser textures indicative of slow crystallization tend to have heavier $\delta^{34}S$ values than both finer grained sulphides that presumably precipitated more quickly; the framboidal pyrite associated with the CGO and in the UDL displays distinctly light sulphur isotopic values (Ford, 1996; Altinok, 2005; Yesares, *et al.* 2019). Analysis of $\delta^{34}S$ in Zn and Pb concentrates from Navan confirm a dominant light signature and Fallick *et al*. (2001), consider that 90% of sulphides at Navan were derived from bacteriogenically reduced sea-water sulphate. Blakeman *et al*. (2002) noted that $\delta^{34}S$ increased in sulphides approaching interpreted feeder structures at Navan. Several more recent and quite detailed studies on Navan, Lisheen and Galmoy support the consensus of sulphide deposition resulting from availability of isotopically light reduced seawater-derived sulphur mixing with hydrothermal metal-carrying fluids carrying minor heavier sulphur (Barrie *et al*.,1999; Gagnevin *et al*., 2012; Davidheiser-Kroll, 2014; Marks, 2015; Doran *et al*. 2022; Yesares *et al*., 2019; Yesares *et al*., 2022). Application of this technique has now become almost '*de rigueur*' for academic studies on IT deposits. Importantly, Fallick *et al*. (2001), conclude: "*no bacteria, no giant ore deposit*" while Wilkinson & Hitzman (2015) state: "*this shallow sulphur reservoir (and/or the brines that mobilized it) is a primary control on whether economic mineralization developed or not*".

There is a large body of fluid inclusion, oxygen and carbon isotope studies available that Wilkinson (2010, 2014) and Wilkinson & Hitzman (2015) have used to constrain the nature of the ore forming fluids and depositional mechanisms in the Central Irish Orefield (see also Everett *et al*., 1999; Gleeson *et al*., 1999; Banks *et al*., 2002; Wilkinson *et al*., 2005b). In brief the data indicate that the deposits resulted from mixing of two distinct two fluids:

- <u>Metal - carrying hydrothermal fluid</u> ('Principal Ore Fluid'): This fluid is hypothesized to have formed from dense brines, perhaps from partially evaporated Lower Carboniferous seawater, that was circulated to depth, presumably during extension and resultant fracturing; these fluids were then heated enabling them to more effectively leach metals. Wilkinson (2010) considers that fluids in the north and west (salinities: 5-14 wt% NaCl eq.; temperatures: 100-190°C) were somewhat cooler and less saline than those in the south and east (11-19 wt% NaCl eq., 150-260°C). While the data is highly suggestive of this model, it is difficult geologically to demonstrate significant areas near the known deposits that were subjected to evaporitic conditions, especially at the end of the Courceyan, though such fluids may have formed on uplifted flanks of the IS zone lateral to the ultimate sites of the deposits. Such a scenario is possible for the Rathdowney Trend deposits (Galmoy and Lisheen) adjacent to the regional dolomite that is hypothesized to be due to reflux of evaporative fluids generated above the Wicklow massif. It may also be applicable to the Navan area where Chadian age evaporites are recognized tens of kilometers to the north.

- <u>Sulphur-carrying fluids</u> ('Sulphidic Brine'): Low temperature, high salinity brines, also hypothesized to have been initially sourced from shallow-evaporitic seawater, are invoked to be involved in the production of reduced sulphur in the near subsurface through biological (bacteriogenic) activity. A permissive scenario involves formation of oxygen deficient seawater in local depocentres with more limited water exchange such as syn-sedimentary half grabens. While this model works well at Navan where overlying rocks (above the erosion surface) are reduced basinal carbonates with abundant evidence for bacterial sulphate reduction (large amounts of framboidal pyrite), similar reduced rocks are not recognized above the IT deposits in the SW portion of the Orefield. This suggests that the majority of the biological activity probably took place in the shallow subsurface, with biological productivity enhanced significantly by leakage of heated hydrothermal fluids into unconsolidated or fractured rocks.

Lastly, a group of sub-economic deposits in the 'Kildare District' including Harberton and Allenwood in the SE part of the Orefield have long been considered to be MVT deposits based on textural and morphological grounds. The $\delta^{34}S$ in sulphides from these deposits is distinctly heavier and fluid inclusion temperatures are significantly lower (50°−100°C) than other Zn-Pb deposits in the Irish Orefield (Gallagher *et al*., 1992; Trude & Wilkinson 2001).

Genetic Synthesis

Genetic models for IT deposits have been widely discussed and are summarized by Wilkinson & Hitzman (2015) and for Navan by Ashton *et al.* (2015). All workers agree the deposits are pre-Variscan although this deformation may have resulted in local sulphide remobilization. Existing models invoke the mixing of deep sourced metal-carrying hydrothermal fluids and shallower-sourced fluids carrying reduced sulphur. It is clear that most IT deposits formed near or in the hanging-walls of normal faults and that many of these faults were active from at least the late Courceyan age of the Pale Beds and Waulsortian Limestone.

One controversy that appears to have been largely resolved is the ultimate source of the metals in the Central Midlands Orefield. The Pb isotopic studies provide fairly convincing evidence that the metals were sourced from basement rocks beneath the individual deposits. This probably also accounts for the distinctive trace element suite for a number of the deposits that is being revealed by high precision trace element studies (L. Zhou, pers comm., 2023). The highly fractured basement rocks that would be expected along the IS deformation zone probably provided the fracture permeability that enabled fluids to circulate and effectively leach metals. The apparent restriction of the most productive areas of the Orefield to the NE area (Navan) and the SW area (Tynagh/Silvermines/Galmoy/Lisheen/Pallas) may relate to major oroclinal bends in the IS. The position of the bends could have enabled enhanced fracturing of the basement relative to other stretches of the deformation zone and allowed heterogenous deformation in these areas during the focus of early Carboniferous trans-tension along the IS.

There is still uncertainty as to the exact age of mineralization in the Orefield and it is possible, if not probable, that it was not constrained to a single interval. The evidence at Navan is clear that mineralization was initiated in the late Courceyan and extended into the Arundian. In the deposits hosted by the Waulsortian Limestone exact age relationships remain more problematic. Several geological observations have been interpreted as favouring 'syn-diagenetic' models where mineralization occurred at relatively shallow burial depths while other geochronological evidence may suggest later Chadian to Arundian or even Asbian ages. Geological evidence indicates that both the Courceyan to Arundian and the Asbian were periods of extension, which locally resulted in major normal displacements such as in the Navan area.

From the exploration viewpoint the age of mineralization is important since clearly an Asbian age for mineralization, for example, might open up new potential host rocks in areas where the Pale Beds and Waulsortian occur at depth as well as focus exploration in areas where the first clean carbonates in the local sedimentary succession occur above the level of the Pale Beds and Waulsortian Limestone. Interestingly the Abbeytown deposit, to the northwest of the Orefield, occurs in such a location (Hitzman, 1986). Consequently, and bearing in mind that the authors have a healthy (?) range of views on this topic, we briefly examine the evidence for early and late mineralization and the consequences thereof.

Early Timing - 'The Syn-Diagenetic Model' (deposits form near seafloor, Courceyan to early Arundian)

There are numerous published interpretations of mineralizing fluids exhaling on or close to the penecontemporaneous seafloor at many of the IT deposits. Larter *et al*. (1981) reported the occurrence of fossil hydrothermal vents and a highly pyritic vent field at the Magcobar pit. These were among the first reported fossil vents in the world (Boyce *et al*., 1983). Fossil evidence of the presence of vent-related worm tubes provides evidence that sea-floor exhalative hydrothermal activity occurred at Silvermines around 352Ma. The development of "Iron Formation" at several deposits, preceding sulphides deposition, has been interpreted as an early feature (Cruise, 2000; Byrne, 2014) and as a likely indicator of exhalative Fe mineralization.

Other evidence for early mineralization includes the interpretation of cryptocrystalline barite at Magcobar as essentially sedimentary (Barrett, 1975; Mullane & Kinnaird, 1998; Taylor, 1982; Andrew, 1986) and the apparent palaeo-bathymetric redox control of major gangue mineralogy at Silvermines by early Waulsortian Mudbank distribution (barite-pyrite-siderite zones) (Taylor & Andrew, 1978; Taylor, 1984; Andrew 1986).

At Navan the presence of dislocated clasts of sulphides in the BC constrains at least some of the mineralization to no later than a Chadian age whilst the deformed soft-sediment appearance of sulphides layers in places in the underlying Pale Beds is also suggestive of mineralization preceding full lithification (Ashton *et al.*, 2015). At Tara Deep, within the basin margin sediments overlying the ore-hosting Pale Beds, Yesares *et al* (2022) describe similar associations of peloids and framboids, with minor replacive sulphides and sulphide-rich cherts that are interpreted as hydrothermal exhalates of Chadian age.

Late Timing - 'Burial Model' (significant burial, ca. Post Chadian to Asbian?)

Several workers favour a later age of mineralization for IT deposits based on their interpretation of relationships of carbonate cement histories and stylolitization with sulphides and some advocating mineralization after significant burial of the host lithologies (Peace & Wallace, 2000; Reed & Wallace, 2001, 2004; Stacey *et al.*, 2022). A number of workers invoke breccia and sulphides deposition in large cavity systems ('hydrothermal karsting') to explain the observed sedimentary textures involving both sulphides and gangue minerals (Hitzman & Beaty, 1996; Redmond, 1997; Sevastopulo & Redmond, 1999; Hitzman *et al*., 2000; Blaney *et al*., 2003; Fusciardi, *et al*., 2003; Kerr, 2013; Blaney & Redmond, 2015). Several of these workers also interpret the presumed pyritic fauna reported from Silvermines and Tynagh as representing complex colloform iron sulphides and pyritization of normal Lower Carboniferous fauna. With more geochronological studies have come additional evidence for post Courceyan and even Asbian age mineralization (Hnatyshin *et al*., 2015; Stacey *et al.*, 2022; Vafeas *et al.*, 2023). In the Limerick Syncline a new sulphide Re–Os isochron from the Ballywire prospect yielded an age of 340.9 ± 2.4 Ma (Slezak *et al*, *this volume*) and represents the first known mineralization age in this area and is contemporaneous with the Visean (Strogen, 1988; Sommerville *et al.*, 1992; McCusker & Reed, 2013; Blaney & Redmond, 2015; Elliott *et al*., 2019).

Discussion

Supporters of the syn-diagenetic model argue that early cementation in carbonates discounts a deep burial scenario and that post Chadian geochronological dates are related to post mineralization tectono-thermal events (Wilkinson and Lee, 2003; Wilkinson *et al*., 2017). Workers that favour a burial origin must discount the presence of early framboidal pyrite, 'Iron Formation' and apparently pyritized and baritized fauna by invoking their presence as being purely coincidental with later mineralization and that the association with contemporaneous faulting and brecciation reflects another coincidence of deep-seated fluids exploiting much earlier formed weaknesses. However, we lack evidence of the sedimentary successions above the Waulsortian hosted deposits (Tynagh, Silvemines, Galmoy, Lisheen) as they have been eroded so it is difficult to conclusively determine whether fault systems remained active into the Arundian and to later periods.

From an exploration standpoint the 'syn-diagenetic' model is easy to conceptualize and build into a testable model. Indeed, it could be argued that using the 'burial' model that similar geological exploration focus points could be generated. But could new targets in younger limestones be generated from consideration of the deep burial model? While it is highly likely that some sulphides were deposited later in portions of the Navan deposit, in the Kildare deposits, and at Abbeytown (Hitzman, 1986), exploration targeting rock younger than Arundian in age should be approached with caution.

Despite some differences, we regard the SW deposits and Navan as IT deposits and formed by similar mechanisms. In the SW the Waulsortian-hosted deposits are similar due to the nature of the pyritic and dolomite breccia hosted ores and Pallas Green even with its unique (?) relationship to volcanic diatremes can be included in this cohort. At Navan, the mineralization is associated with a more complex, longer period of extensional faulting in the degraded terrace of a major basin-margin normal fault. Consequently, despite the ongoing controversy regarding the exacts age(s) of mineralization in the Orefield, there is general agreement on the main aspects of an IT genetic model which is summarized using the source to trap stages on Figure 16.

This model invokes regional extension to create normal fault zones above pre-existing major basement structures (Wilkinson, 2010; Wilkinson & Hitzman, 2015; Ashton *et al.*, 2015). The development and episodic movement on basement structures underlying and controlling the faults in the overlying Devono-Carboniferous sedimentary carapace generated structural permeability in the basement that allowed ingress of surface waters, some apparently with enhanced salinity, that were heated and able to effectively leach metals in 'Collection Zones' (Fig. 16). The exact mechanism that favoured these areas for fluid focus and upward flow to higher levels and into the Carboniferous limestone 'Trap' environment is poorly understood but is likely a complex interplay of basement heterogeneity, heat supply and cyclical structural activity in the root zones of major faults. Exhaust of such hydrothermal metal-bearing fluids through the Carboniferous carbonate-succession and potentially to the seafloor allowed localized enhanced biological activity that resulted in reduction of seawater sulphate in Lower Carboniferous sediments. Episodic mixing of reduced sulphur with the metal rich hydrothermal fluids in the 'Trap' area, containing chemically reactive and permeable carbonates, allowed large tonnages of sulphides to be precipitated by replacement and open-space growth mechanisms. Thus, contemporaneous Lower Carboniferous faulting not only generated deep source areas for generation of metal-rich hydrothermal fluids, but also created channel ways to higher levels and was potentially directly involved in controlling sulphide-reducing areas in topographic depressions on the sea floor and/or in brecciated limestones (Fig. 16).

Future Zinc Exploration in Ireland

Can production from, and exploration for, Irish-type Zn/Pb deposits successfully continue for the next fifty years? Whilst both opportunities and challenges for the minerals industry exist arising from climate change related net zero targets and increasing social concerns about mineral extraction in Ireland could temper industry's interest in the country. The authors are very optimistic that further deposits are present and can be found. As an initial opinion we note that the connection between historic mines, prospects and mineral showings to the discovery of economic deposits whilst widely appreciated should not be ignored! We have previously noted that the push to find new discoveries at depth has led the industry to use increasingly expensive exploration methods: none of these methods has yet been outstandingly effective. What clues does our review of IT deposits provide towards future exploration to aid mineral exploration companies?

Almost all previous discoveries involved either mineralized zones that were exploited historically or shallow soil geochemical surveys (Table 1). Brownfields exploration in the shadow of known deposits has also been proven effective. The SWEX and Tara Deep discoveries at Navan are prime examples of better understanding of an existing orebody leading to increased resources. The expected re-opening of the Galmoy mine by Shanoon Resources is predicated on a plan to extract unmined reserves as well as newly defined resources.

The vast amount of soil geochemical data available in Ireland through public release of historic mineral exploration data and the nationwide Tellus geochemical data set has not been exploited to its fullest. This historic exploration data is of highly variable quality and were obtained from a wide variety of sampling protocols and analytical techniques. While it is now technically feasible to produce geochemical maps for at least zinc and lead for the entire Central Midlands Orefield as well as some adjoining areas, this has yet to be accomplished. To be practical and effective such work needs to employ advanced

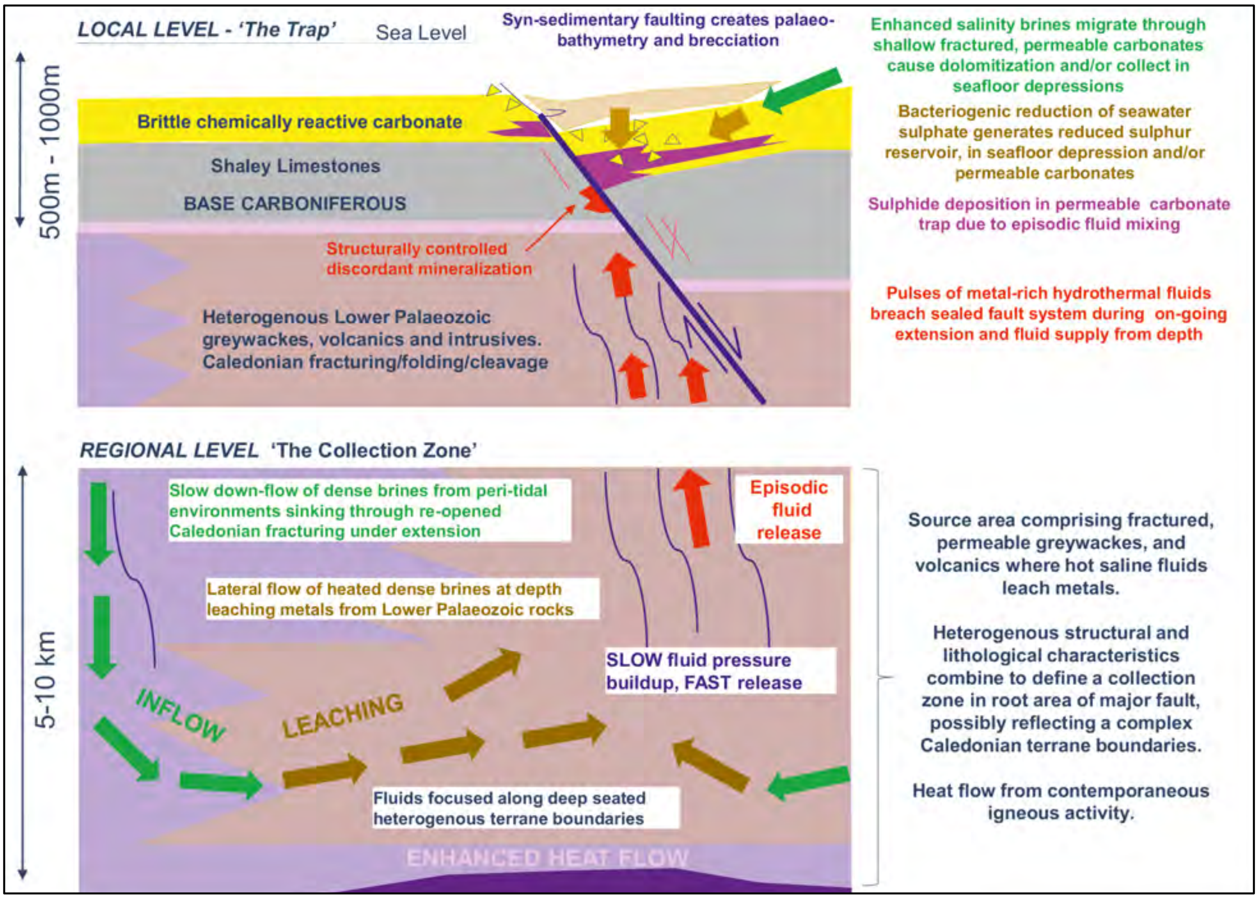

Figure 16: *Cartoon illustrating formation of an Irish-type base metal deposit with simplified representation of the relationship between fluid mixing and active faulting. The lower section denotes more regional-scale control on fluid leaching a deep Collection Zone in fractured basement.*

data-capture, analysis and presentation techniques that would allow, for example, data of varying quality to be identified and optionally used to the fullest possible extent. Examination of such a data set through filtering results by the expected underlying lithotype and stratigraphic unit as well as soil type (glacial drift, glacial lake sediments, modern sediments, etc.) could allow detection and possibly definition of distal geochemical halos to major mineral systems. Such an approach, conducted on a limited area, was largely responsible for the Lisheen deposit at the start of the 1990's (Hitzman *et al*., 1992). Given our better understanding of the geochemistry of the IT deposits and their individual geochemical characteristics, development of such a regional geochemical database could also highlight areas for shallow soil geochemical follow-up using a much wider suite of elements that could identify hidden mineral systems.

Litho-geochemistry has been widely used in Ireland and although there are several encouraging research studies it has been largely unsuccessful. It is a potentially powerful tool, but we note that legacy campaigns have been very inconsistent. For example, in the application of widely different sampling strategies (groove, chip, grab, split core etc.) to variable and restrictive parts of the geological succession (e.g., avoiding hanging-wall rocks, and/or taking a small grab sample every 5m for example) - and in focusing on differing element suites. Future studies need to have more consistent sampling and analytical guidelines, ideally high-quality multi-element geochemical analyses of full cores (stratigraphically above and below expected ore positions) at geologically reasonable intervals (≤ 1m). Although trace element and isotopic studies of individual minerals, primarily pyrite and potentially hydrothermal quartz, have yet to demonstrate their ability to provide convincing vectors to ore, ongoing research suggests the technique may yet hold promise (E. Burton and C. Geel, pers comm. 2023). Further research is certainly warranted.

Most IT deposits occur near faults that were active before, during and shortly after sedimentation. In many cases the faults appear to simply extend to surface above the (mostly shallow) orebodies. At Navan a wealth of drilling data, supported by seismic surveying shows that several critical faults do not extend to surface and are effectively blanketed by younger rocks. This raises the question of how far above the other deposits did the faults originally extend? (An answer to this question may help us resolve age of mineralization questions as well.) With increasing exploration depths key faults may not be present or detectable in younger rocks at surface via geological and geophysical mapping. This is one of several reasons that seismic methods hold the most promise for the immediate future in terms of exploration in the Central Midlands Orefield. The blind Tara Deep discovery in 2012 (Ashton *et al.*, 2018) was due to interpretation of traditional 2D seismic data. The interpretation of the data was key and was enabled by the very significant geological understanding of the regional geology by the Tara Mines geological exploration team. Since the discovery many kilometers of 2D seismic surveys have been undertaken in Ireland. Though no discoveries have yet been announced based on this work, much of the data is still in the process of being re-analysed and interpreted both by companies and academic research groups. Numerous structural targets mimicking those responsible for Waulsortian Limestone hosted deposits have been identified but few have been drilled. Zones containing evidence of major uplift and submarine degradation by slumping, similar to that present in the Navan area, would undoubtedly produce highly complex seismic responses (as does that at Navan) that may have thus far been misinterpreted. Nonetheless, the search through seismic exploration for a similar structural setting may currently represent our best means to discover a deeply buried, very large mineral systems.

There is also probably much more to be gained from better use of existing geophysical data and deployment of new geophysical techniques and technologies such as magneto-tellurics and passive seismic surveys to better define the lithologies and structures in the basement beneath the Central Midlands Orefield along the IS zone (and beyond). Major hydrothermal cells operating in the basement rocks should have caused wall rock alteration which may be discernable. Locating large areas of altered basement and then using more traditional 2D seismic to better image the overlying Carboniferous section could help focus future exploration.

The data presented in this paper suggests that major mineral systems may be concentrated at two loci within the Orefield, one in the NE in the Navan area where the IS exhibits a clockwise north-eastwards swing and another in the SW portion of the Orefield where the IS undergoes a similar but anticlockwise inflection also trending to the NE. These features are most likely related to as yet poorly understood lateral heterogeneities in the underlying Caledonian tectono-stratigraphic terranes. At Navan this likely includes the Caledonian Kentstown granite, the marked difference in orientation and composition of the Grangegeeth and Bellewstown terranes, straddling the IS and how these features affected development of the regionally important Navan Fault lying to the SW of Navan. In the SW area we see the continued expansion of the Pallas Green mineralized zone as confirmation of this exploration strategy. In this larger area, however the nature of any heterogeneity on the IS flexure is less clear though regional seismic, magnetic and magneto-telluric surveys can be interpreted to show some type of regional variation at depth. It is important to re-emphasize that the IS is not a line on a map but a wide, broadly distributed zone. Improved understanding of the nature of these inflections along the IS may provide new targets on similar terrane-boundary dislocations in Ireland and globally.

An openness to new ideas is a prerequisite for continued exploration. We know that economically mineralized zones exist in stratigraphic positions beneath those routinely tested (e.g., Gortdrum Cu deposit). Such mineralized zones could be sought in potentially favourable areas such as Pallas Green. Additionally, several of the former mines and prospects have attracted intense drilling targeted at the main host-rock, however deeper sections of the faulted stratigraphy have barely been examined. In the case of Silvermines it is worth noting that significant sulphide-mineralized zones are present in dolomitized ABL and underlying sandstones. These are known from legacy mining and drilling in an area where sulphides were near outcrop levels and easy to find as the area is mountainous. In several other, deeper deposits, where there is little topographic relief, and some of which display significant post-ore fault dislocation, it is valid to question whether any economically mineralized 'feeder' sections have avoided detection. Even at Silvermines for example, drillhole V-3 drilled in the late 1970s intersected significant copper mineralization within basal white sandstones adjacent to the B-Fault (0.6m @ 2.38% Cu and 18.2m @ 0.66% Cu) suggesting that a related, but different style of mineralization occurred at depth below the Courceyan/Chadian-aged, mineralized zones.

Recent geochronological work suggests that mineralization not only occurred in the late Courceyan to Arundian but possibly again in the Asbian. Facies models developed in the past several decades have rightly focused on identifying areas with rapid facies changes in the late Courceyan to Arundian, but such facies models are more poorly developed at the level of the Asbian for which we currently have much less well constrained data. Additionally, the examination for litho-geochemical halos has been much less rigorous in these stratigraphically higher units.

Drilling is what results in discovery. Thus, for exploration to move forward more drilling must be undertaken. Unlike in the past where a hole was drilled and then stored in the core shed or disposed of if it lacked significant mineralized zones, all holes drilled need to be rigorously interrogated. Drill cores should be carefully logged to capture the geological information contained in the rocks. This includes not only lithology, stratigraphic position (from micropalaeontology), and structure but also the chemical composition of the rocks derived from complete multi-element geochemical analysis as well as determination of the petrophysical properties of different units. Ideally wire-line geophysical logging of holes should also be conducted to better enable interpretation of historic and new geophysical data sets and enable more accurate hole to hole correlations.

Finally, while we are currently of the opinion the IS deformation zone represents the area with the highest chance of an economically significant discovery, the history of Irish Zn exploration demonstrates we could be wrong. Significant Zn mineralized zones are recognized outside this zone (e.g., Abbeytown –probably formed in the Asbian (Hitzman, 1986)) indicating that the mineralization process did operate more broadly in space and time. An openness to embracing new ideas and new technologies, along with luck, will probably be the winning combination going forward.

Acknowledgements

This paper assembles information from many of the published works on IT deposits and unpublished reports, university theses and myriad discussions between the authors and many in industry and academia. With a total of 140 years' experience in Ireland the authors cannot attempt to name all the geologists that have contributed to this paper, but we can say that many memorable discussions were held at IAEG, SEG, SGA, GSA, IMMM and MDSG meetings and field trips. In particular we recollect many stimulating discussions under-ground and in core sheds whether as participants - or as guides! One thing is sure, many geologists remain challenged by the exploration and science behind IT deposits – we are convinced that new discoveries will come, and we invite old and new, young and old explorationists to join us in the hunt!

Boliden Exploration is thanked for support and permission to publish several earlier papers from which some information for this contribution was drawn. This publication has emanated in part from research conducted with the financial support of Science Foundation Ireland (SFI) under grant number numbers 16/RP/3849 and 13/RC/2092_P2, awarded to Murray Hitzman.

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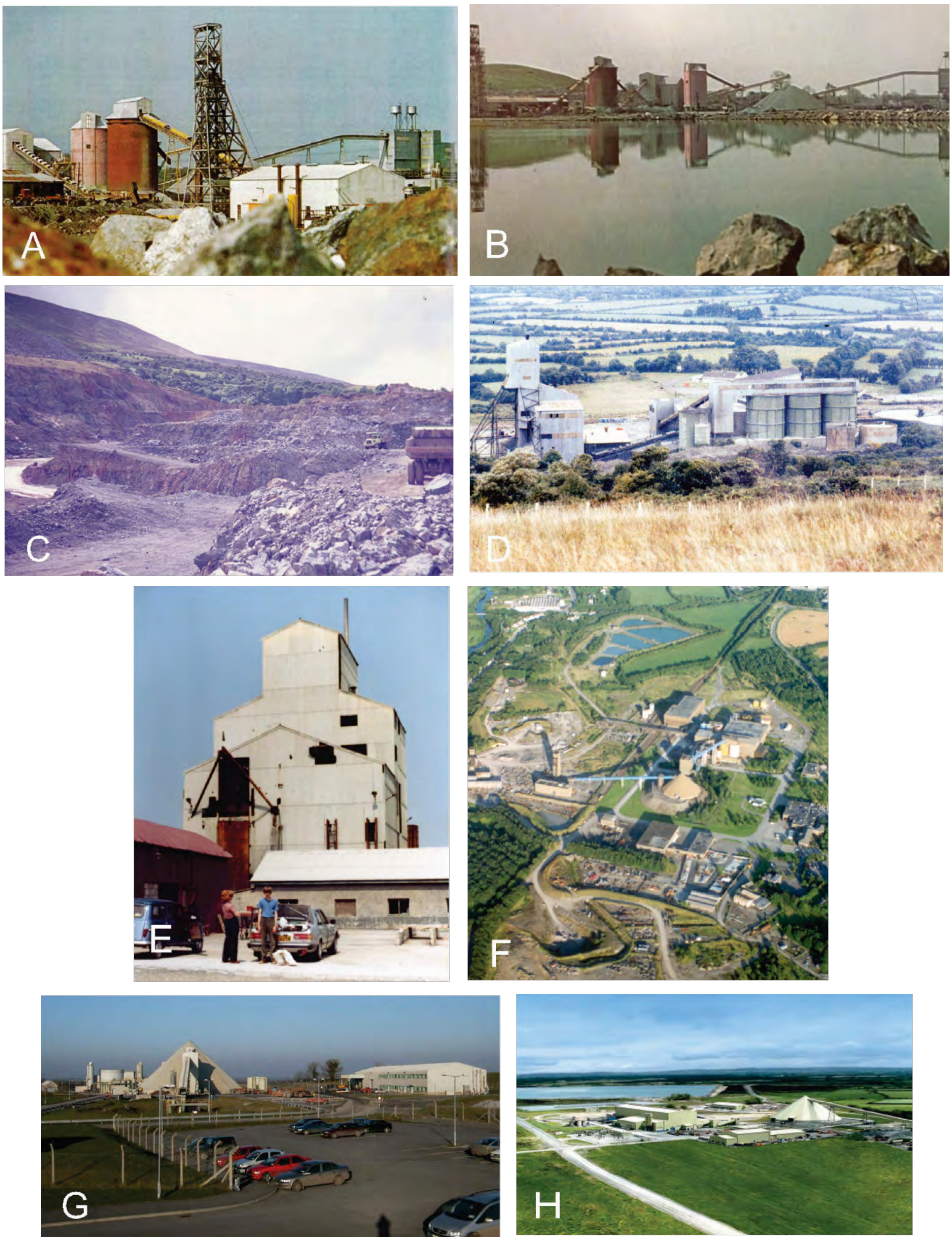

Plate 1 – Irish Mines

A. Tynagh – view of headframe (early 1970s).
B. Tynagh – view of processing plant (early 70s).
C. Magcobar barite open pit Ballynoe (*ca*. 1974). Silvermines.
D. Mogul of Ireland Mine complex, Silvermines (1976).
E. Gortdrum processing plant (1982).
F. Aerial view from north of Navan surface complex (*ca*. 1990).
G. Galmoy processing plant (*ca*. 2000).
H. Lisheen mine, processing plant and tailings management facility (late 00s).

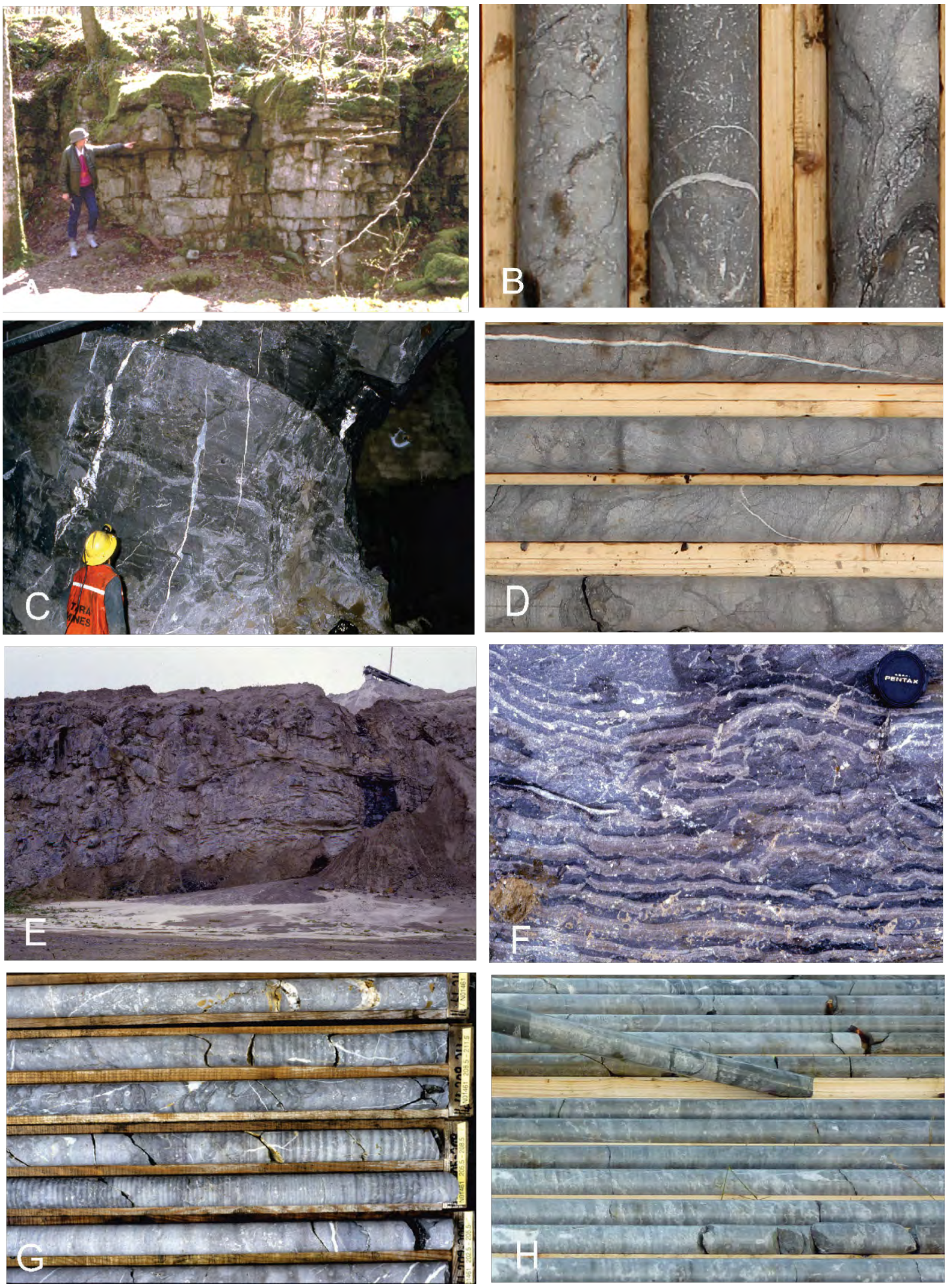

Plate 2.

A. Outcrop of Navan Group sandstone, Co Roscommon.
B. Micrite unit in core from Navan, showing birds-eye textures.
C. Underground photograph showing massive dolomitized Pale Beds 5 Lens grainstone overlain by dark calc-siltites of the Lower Dark Marker. The grainstone is heavily mineralized in the lower part of the photograph.
D. 'Healed breccia' in the 5 Lens grainstone from Tara Deep core at Navan.
E. Waulsortian Limestone, Bray Hill Quarry.
F. Waulsortian Limestone, Bray Hill Quarry. Detail of stromotactis textures.
G. Waulsortian Limestone core, Limerick.
H. Waulsortian Limestone core, Navan.

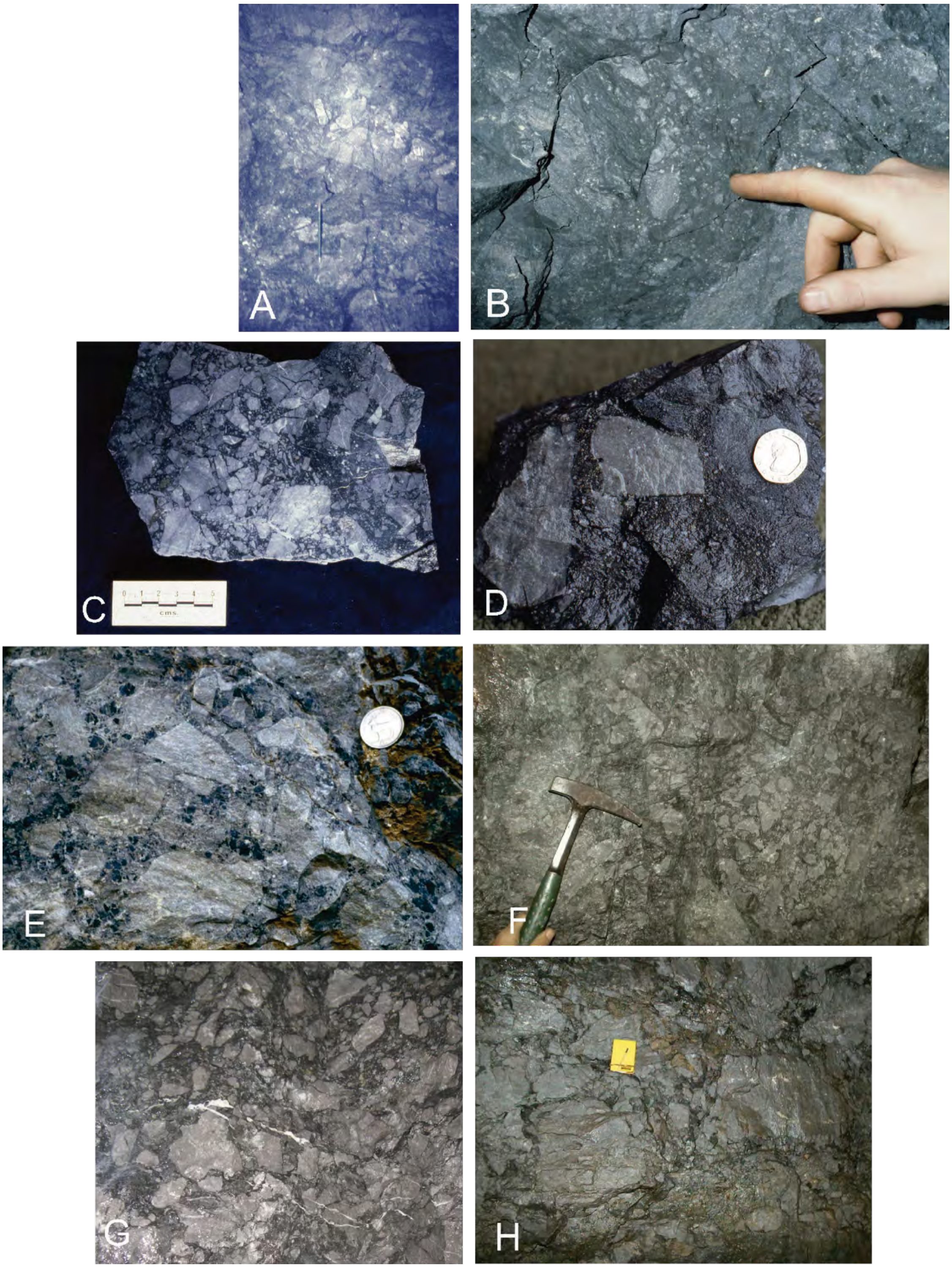

Plate 3. Dolomite Breccias

A. Debris flow breccias, B Zone, Silvermines. 4934 Room B Zone.
B. Debris flow breccias, Silvermines. 4400 Room B Zone.
C. Hand sample of dolomite breccia. Silvermines. Magcobar Pit.
D. Hand sample of dolomite breccia. Silvermines. 4403 Room B Zone.
E. Cherty dolomite breccia. Magcobar pit, Silvermines.
F. Dolomite breccia in sidewall, Galmoy.
G. Dolomite breccia in sidewall, Lisheen.
H. Dolomite breccia in sidewall, Lisheen.

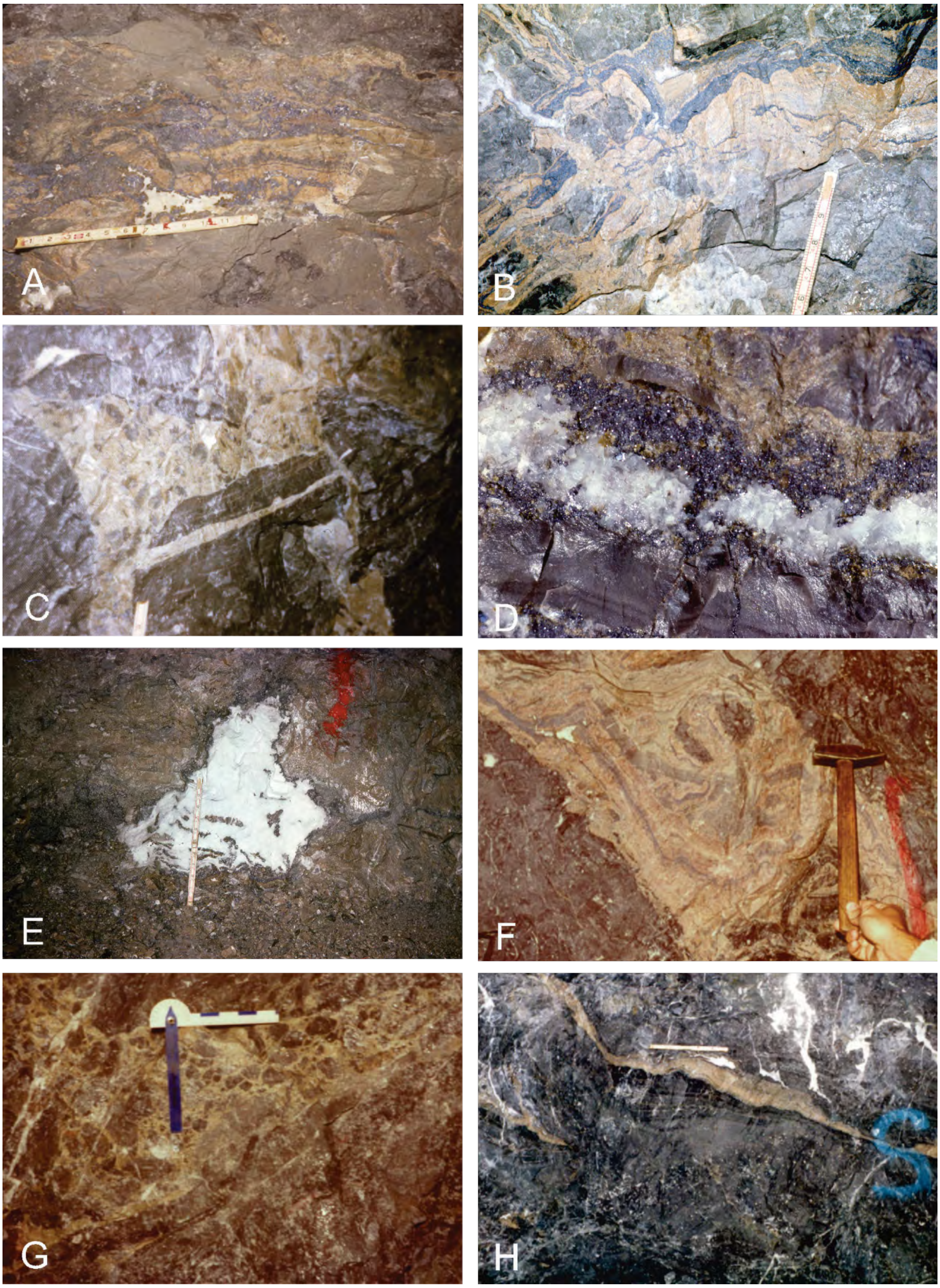

Plate 4. Mineralization from Tynagh

A. Rhythmic banding of sphalerite and galena, Zone II "L2c Reef Core".
B. Deformed sphalerite and galena bands.
C. Pale sphalerite infilling spaces between Reef clasts Zone III "L2b Reef Breccia".
D. Close up of barite cavity fill with galena and sphalerite, Zone III.
E. Large cavity fill of white barite with a fringe of tennantite within L2b Reef Breccia, Zone III.
F. Cavity fill of disrupted colour banded sphalerite within L2c Reef Core, Zone II.
G. Hydraulic fracture breccia infilled and cemented by sphalerite cutting L2c Reef Core, Zone III.
H. Band of laminated sphalerite lying on large clast of Reef within Reef Flank Breccia (L2b), Zone III.

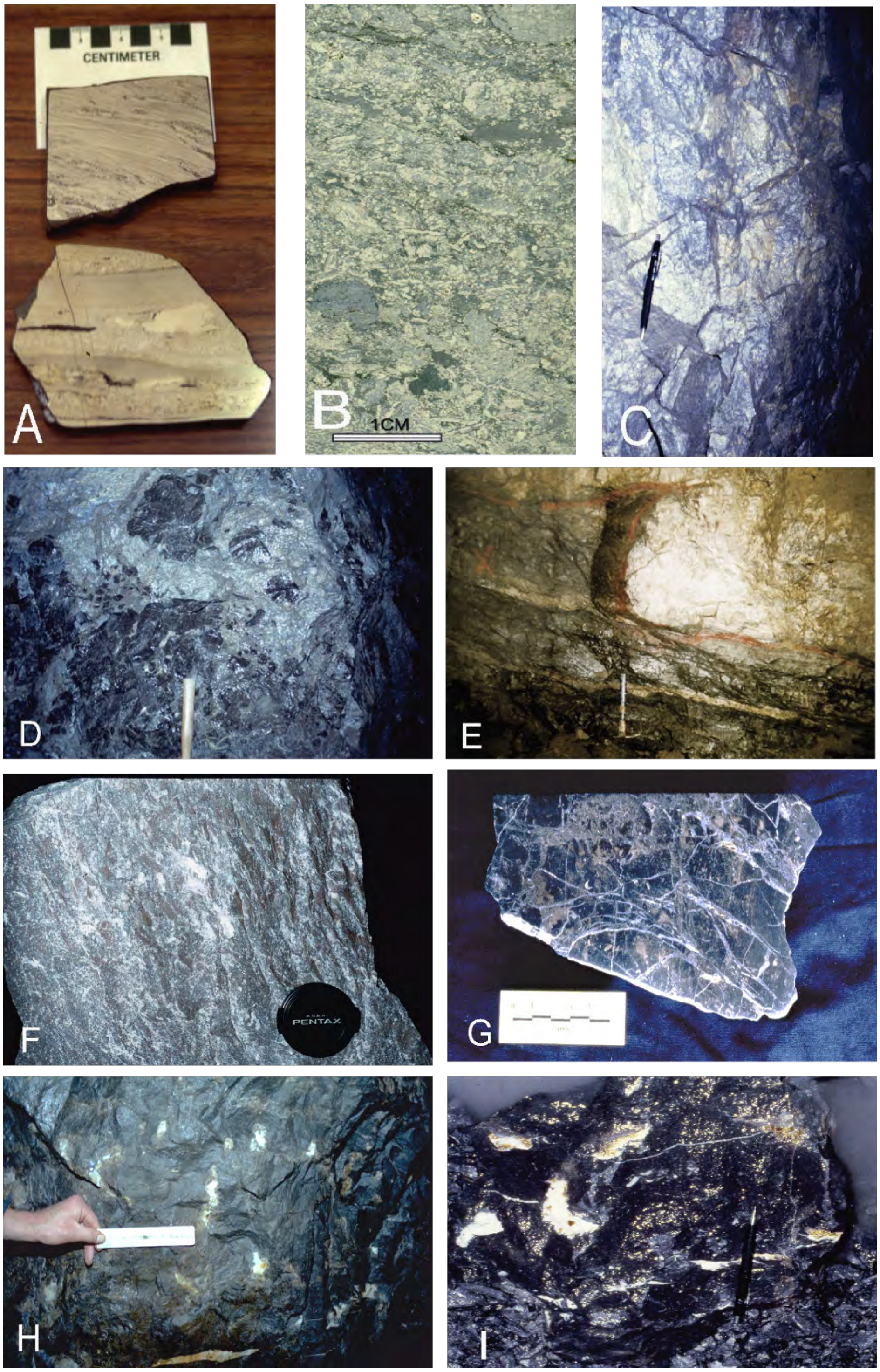

Plate 5. Mineralization from Silvermines

A. Pyrite sulphidite sediment 309 stope Upper G Zone.
B. Pyrite Breccia Cooleen Zone – note various styles of pyrite and galena clasts.
C. Pyrite 4609 Room B Zone, rich galena and sphalerite cutting earlier massive pyrite.
D. Fine grained galena and sphalerite in matrix of Waulsortian limestone breccia 4400 Area B Zone.
E. Slumped contact between sphalerite- rich siderite and irregularly layered silica-sphalerite at footwall of B Zone 4603 Room.
F. Hand sample of massive barite, upper B Zone (near Magcobar pit).
G. Lower G Zone 1-E-1 South Stope pyritised Lower Dolomite cut by galena veins.
H. Mineralized vuggy mineralization in Lower Dolomite, K Zone. 5100 Area.
I. Close up of H.

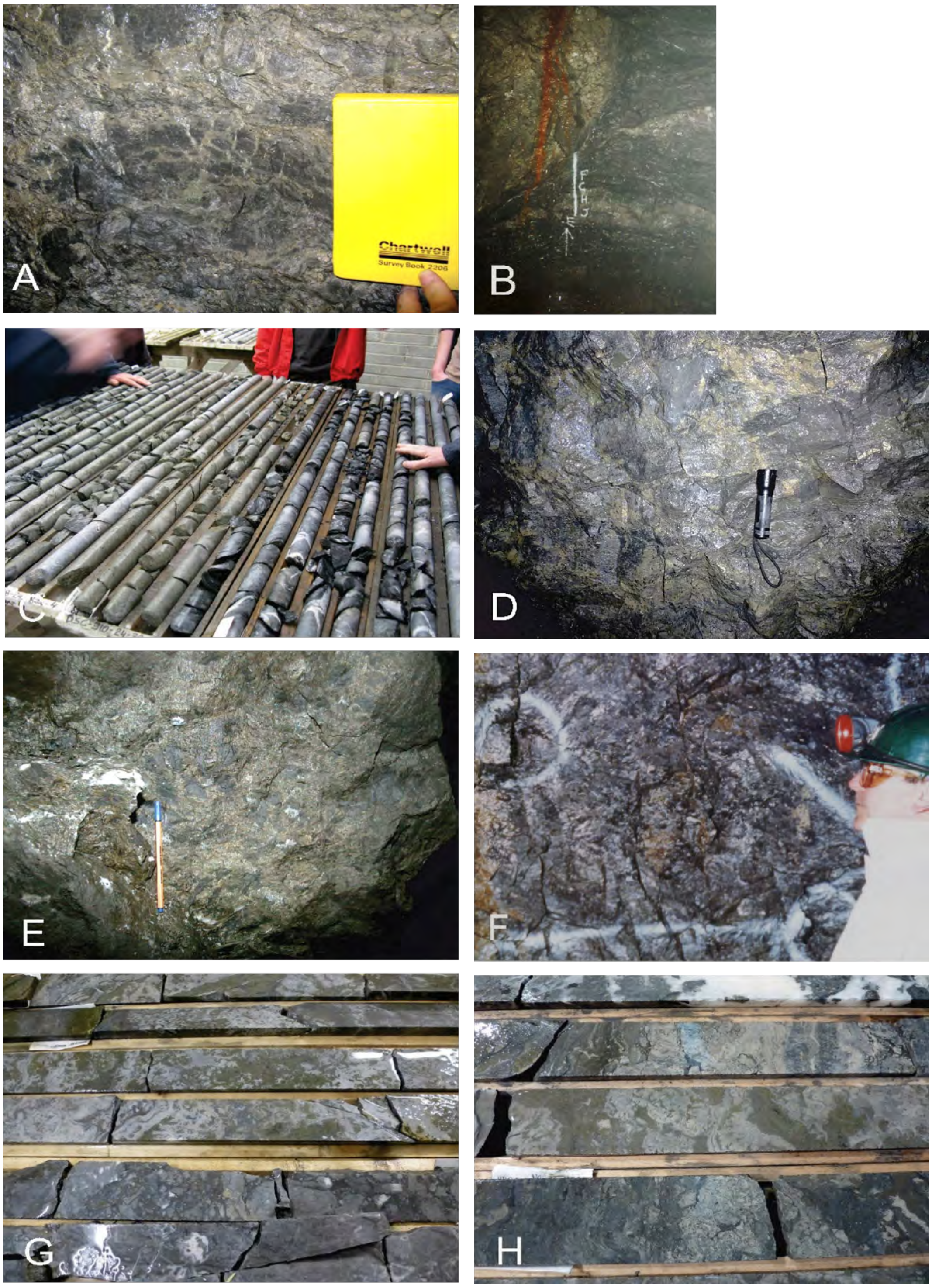

Plate 6. Mineralization from Galmoy and Lisheen

A. Massive coarse-grained pyrite, K Zone, Galmoy.
B. Massive pale fine-grained sphalerite, CW Zone, Galmoy.
C. Massive sulphide in core overlying footwall ABL, Lisheen.
D. Fine grained sphalerite replacing dolomite, Lisheen.
E. Fine replacive sphalerite near footwall of Bog Zone, Lisheen.
F. Massive pyritic ore zone cut by thrust at Derryville, Lisheen.
G. High grade sphalerite and pyrite with dolomite breccias in core, Pallas Green.
H. High grade sphalerite and pyrite in core, Pallas Green.

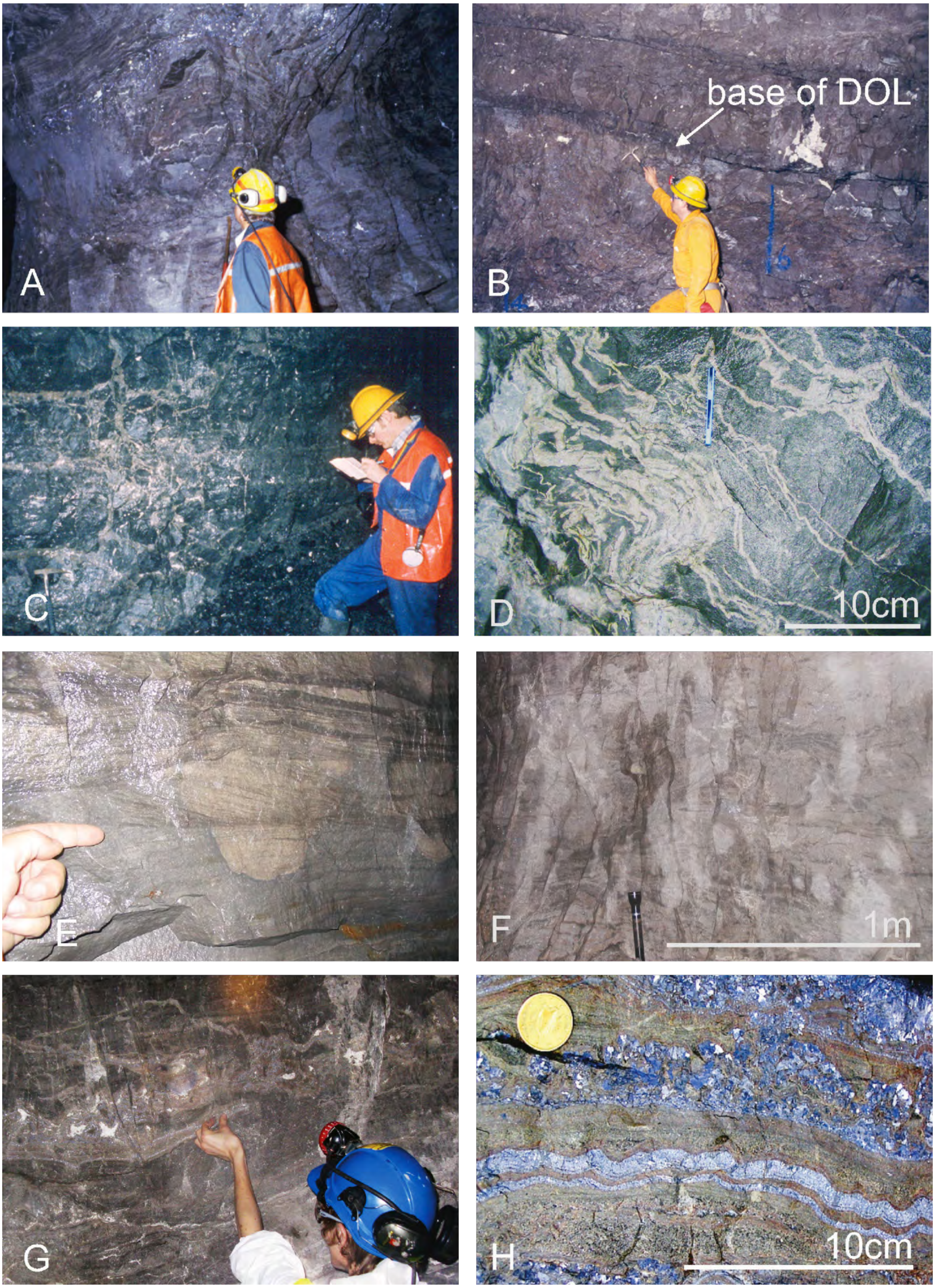

Plate 7. Mineralization from Navan (Pale Beds)

(Captions overleaf)

Plate 7. Mineralization from Navan (Pale Beds)

A. High grade Zn+Pb mineralization in 3 Lens (Main orebody, south). Calcarenites have been delicately replaced with fine pale sphalerite over the entire face. In the upper part of the photograph more aggressive replacement has resulted in growth of much coarser galena mineralization.
B. Dolomite in the 5 Lens (Main orebody NW). Sphalerite-galena mineralization is localized below a prominent horizon of massive dolomitized sandy-oolites.
C. Sub vertical mineralized breccia 5 Lens (Main orebody central). A northeast trending breccia zone has been cemented by sphalerite-galena mineralization, which also extends laterally into the host rocks as thin bedding-parallel bands.
D. Contorted sulphide veins 5 Lens (south central SWEX). E. Disseminated ZnS in U lens.
E. Selective replacement of sedimentary features in calcareous sandstones (central SWEX).
F. Massive fine grained disseminated ZnS causing almost total replacement of U Lens calcarenites (central SWEX).
G. Thin mineralized layer in the 1 Lens (north-central SWEX). Sphalerite-galena mineralization in bedding-parallel horizon shows geopetal fabrics and former voids infilled by barite. Host-rock above and below the mineralized layer are irregularly veined with sulphides.
H. Massive 1 Lens mineralization (south central SWEX). Alternating layers of sphalerite and coarser galena in a high-grade band.

Plate 8. Mineralization from Navan (Boulder Conglomerate)

A. Massive layered fine-grained pyrite with paler sphalerite and galena layers comprising Conglomerate Group Ore (south central SWEX).
B. Waulsortian limestone clast in Boulder Conglomerate showing deformation of mudstone layer containing laminated framboidal pyrite (Main Orebody south).
C. Clasts of sphalerite-galena mineralization in Boulder Conglomerate (Main Orebody south).
D. Clast of layered sphalerite galena mineralization in Boulder Conglomerate (south central SWEX).
E. Boulder conglomerate close to the M Fault (south central SWEX) containing mineralized clasts with layered pyrite in top right. (MF= M Fault plane)
F. Enlargement of clast from E) showing veins of ZnS in clast of 3-U Lens material truncated at clast margins.
G. Pale stratiform band of sphalerite-galena mineralization in the Thin Bedded Unit (basal UDL; Main Orebody south, Zone 3).
H. Enlargement of stratiform sphalerite-galena layer from G.

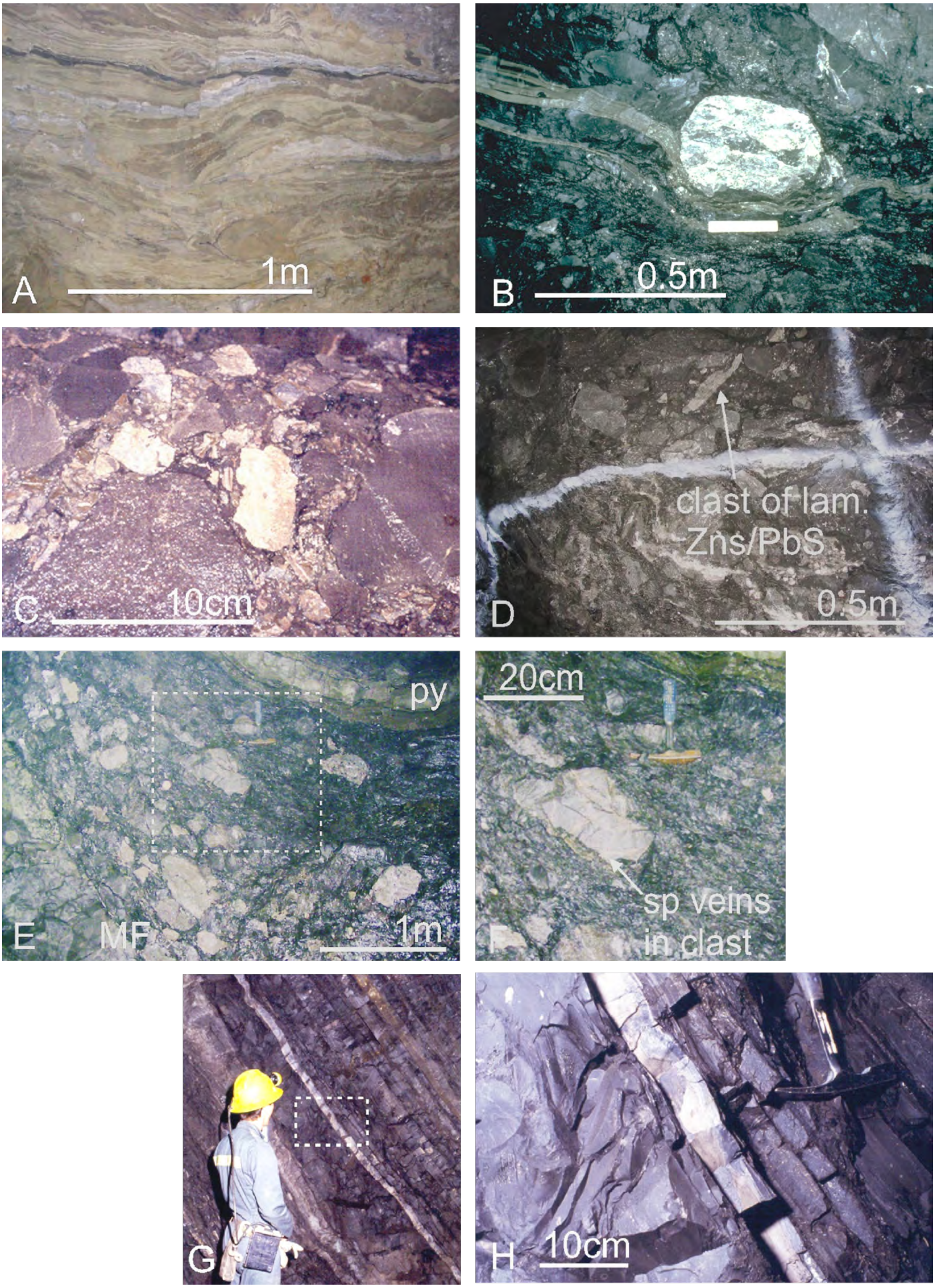

Plate 8. Mineralization from Navan (Conglomerate Group)

(Captions overleaf)

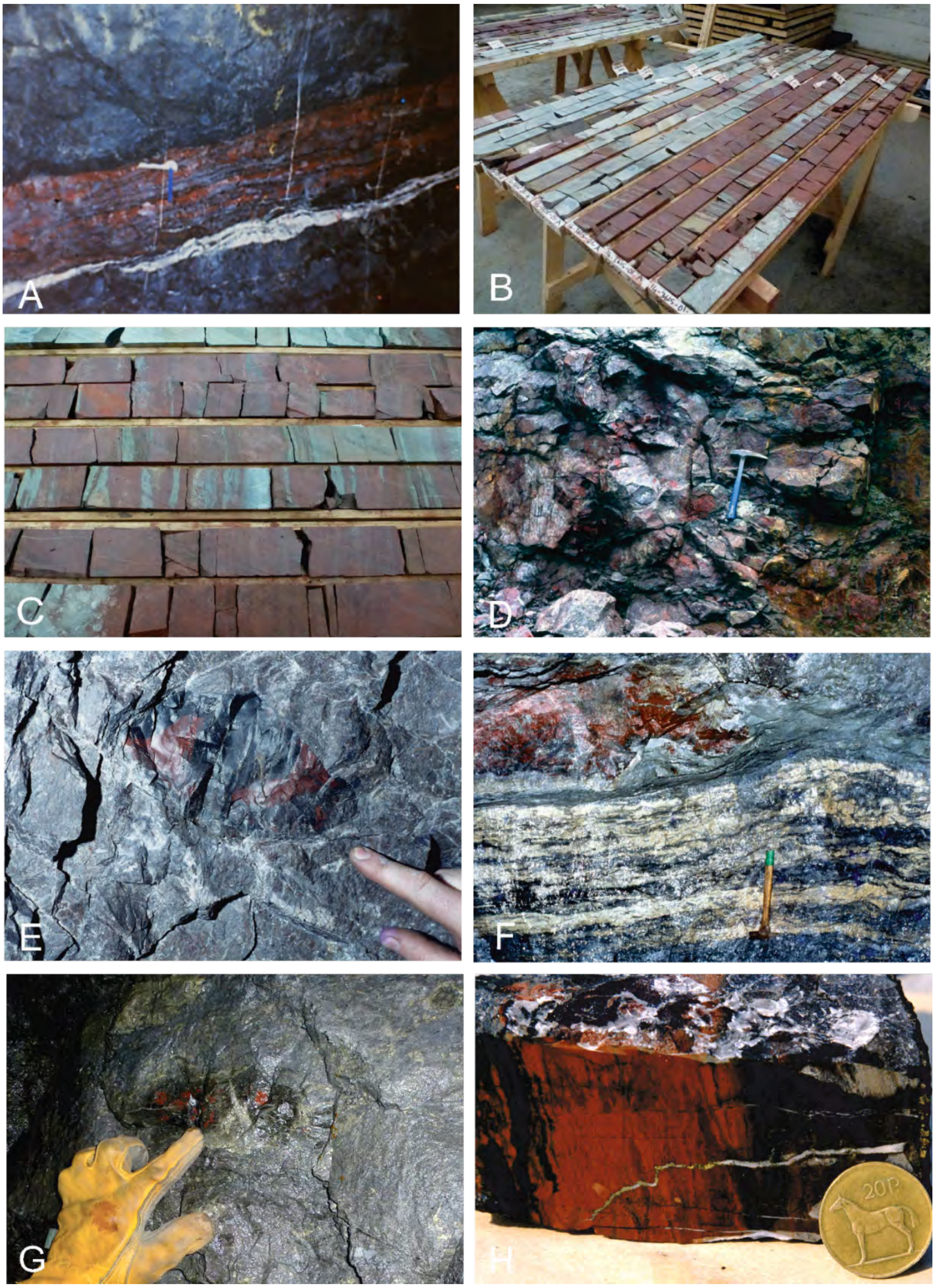

Plate 9. Iron Formation

- A. *Underground photograph of haematite layer at Tynagh.*
- B. *Drill intersection of Tynagh Iron Formation.*
- C. *Close-up of drill core from B.*
- D. *Haematitic barite in wall of Magcobar barite open-pit at Silvermines.*
- E. *Clast of silica -haematite in mineralized barite, 4932 Room Upper B Zone, Silvermines.*
- F. *Haematitic barite overlying fine grained sphalerite, 345 Stope Upper G Zone foot-wall. Green shale at contact.*
- G. *Haematite-silica nodule enclosed by pyritic ore, Lisheen.*
- H. *Silicified haematite in dark argillite near the Boulder Conglomerate – Upper Dark Limestone contact (Main orebody south, Zone 3 southwest).*