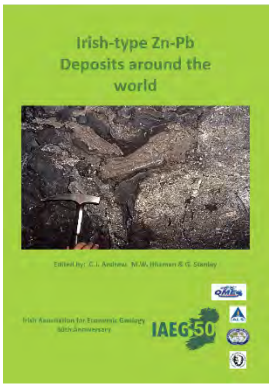

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The volcano-stratigraphic setting of the Pallas Green Zn-Pb deposit, County Limerick.

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The volcano-stratigraphic setting of the Pallas Green Zn-Pb deposit, County Limerick

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Abstract: The Pallas Green deposit located in County Limerick is being actively explored by Glencore Zinc Ireland Ltd. The deposit displays broad similarities with other Waulsortian Limestone hosted deposits in the Irish Orefield in terms of stratigraphical setting, ore-hosting breccia textures and sulphide mineralogy. However, there are a number of important differences, including a close association with igneous rocks, the scale of the ore-hosting breccia bodies, and the apparent absence of significant displacement normal faults controlling the mineralizing system.

The lack of obvious structural control, combined with spatial coincidence with volcanic rocks makes Pallas Green an "Irish-type" deposit with many unique characteristics and new insights into the origins of zinc-lead deposits in the Irish Orefield. This paper endeavours to outline the geological stting, influence of the volcanic activity, alteration and brecciation, and the nature and scale of the mineralizing system at Pallas Green and place the deposit in context and with respect to other "Irish-type" deposits,

Keywords: Pallas Green, volcanic rocks, Waulsortian, palaeo-seafloor topography, brecciation, dolomitization, Limerick Basin, Chadian stage.

Introduction

The Irish Zinc-Lead Orefield covers an area greater than 40,000km^2 and has been explored since the 1950's. To date five zinc-lead deposits have been developed into producing mines, namely, Tynagh, Silvermines, Navan, Galmoy and Lisheen and more than thirty significant, currently sub-economic mineral deposits have been discovered, including Ballinalack, Keel, Kilbricken, Kildare and Rapla (Figure 1). The deposits of the Irish Orefield are primarily hosted by the Lower Carboniferous-aged, carbonate rich, Waulsortian Limestone Formation and the carbonate / siliciclastic-dominated Navan Group. The regional scale of the Irish Orefield, the size and grade of the deposits and the intensity of the associated alteration and brecciation confirms the influence of very large-scale, hydrothermal, ore-forming mineralizing systems.

The Pallas Green Zinc-Lead deposit is located within the Limerick Basin (Philcox, 1984) in the southwestern quadrant of the Irish Orefield. The Limerick Basin is currently the focus of ongoing exploration, with Glencore Zinc Ireland Ltd., and a number of other mining exploration firms all currently performing exploration programmes. All of the zinc-lead deposits discovered to date in the Limerick Basin, are hosted by the Waulsortian Limestone Formation and are broadly similar to the other Waulsortian-hosted deposits in the Irish Orefield with respect to stratigraphic setting, structural control, hydrothermal breccia textures and sulphide mineralogy. There are however some significant differences between the deposits of the Limerick Basin and other Waulsortian-hosted deposits across the Orefield. In particular, the spatial and temporal coincidence of large-scale, volcanic activity with mineralization and the influence this has had on the geological setting, structural control, enhancement of ground preparation and the overall scale of the mineralizing system.

This paper will summarize the geological and structural setting of the Irish Orefield, placing the Limerick Basin and the Pallas Green deposit within a regional context; the exploration history, from discovery in 2002 until the present day, and will define the key events that have led to the definition and delineation of the Pallas Green deposit. The paper also includes a description of the geological, stratigraphic, and structural setting to demonstrate the overall complexity of the deposit and the influence of a suite of geological factors that have played varying roles in the development of this huge mineralizing system. New information will also be provided from the most recent drilling campaigns and the impact this has had on the delineation of the footprint of the deposit and on the development of our understanding of the fundamental geological controls on the mineralizing system.

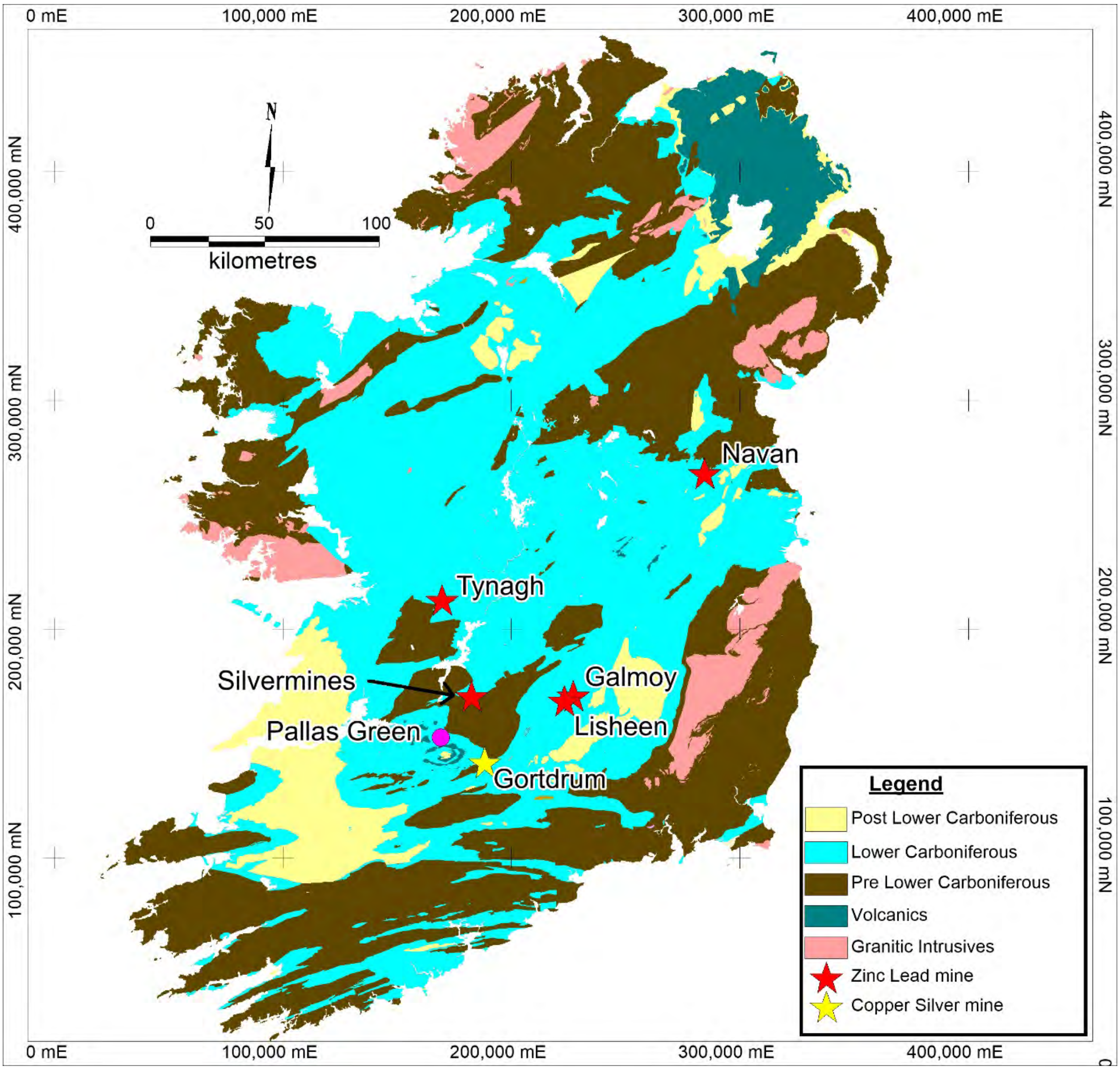

Figure 1: *Major Deposits and Mineral Occurrences of the Irish Orefield.*

The Irish Zinc-Lead Orefield

The Irish Orefield hosts five economic, and more than thirty sub-economic, zinc-lead deposits. The economic deposits are Navan, Lisheen, Silvermines, Galmoy and Tynagh; between them they contain more than 20 million tonnes (Mt) of combined zinc and lead metal. These deposits are hosted by a Lower Carboniferous-aged, transgressive marine sequence of carbonates, shales, and sandstones. The bulk of the Irish Orefield mineralization is hosted by either the Navan Group or the Waulsortian Limestone Formation. The Navan Group is sedimentologically diverse, carbonate rich, and consists of interdigitating, micrites, oolites, calcarenites, mudstones, shales and sandstones (Ashton, 1995; Hitzman, 1995). These sediments are interpreted to have been deposited in sabkha, beach, lagoonal, and sand bars, indicative of fluctuating sea level influencing near-shore environments (Philcox, 1984). The Waulsortian Limestone Formation consists of poorly bedded, pale grey micrites and fine-grained calcarenites with abundant primary cavities, stromatactii, infilled by radial fibrous, sparry calcite. The Waulsortian limestones were deposited with locally steep depositional dips (Lees, 1964) and became lithified soon after deposition. Waulsortian limestones were deposited as mudmounds, several tens to hundreds of metres in diameter, in a mostly aphotic marine environment with water depths of 150 – 300m (Lees & Miller, 1985). In the southern part of the Orefield, including the Limerick Basin, the mudmounds coalesced to form a 150 – 450m thick, poorly bedded unit.

The underlying basement played a key role in the history of the Irish Orefield, both as a source of metals and as the template for the complex structural architecture that exerted significant control on the development of the deposits. A deeply buried, crystalline basement, likely comprising Grenvillian gneiss and schist is inferred (Strogen, 1974). The crystalline basement is overlain by Lower Palaeozoic, volcano-sedimentary rocks that underwent low grade metamorphism during the Caledonian orogeny. The Lower Palaeozoic rocks are unconformably overlain by Devonian aged Old Red Sandstone (ORS): red bed, terrestrial conglomerates, sandstones, and mudstones. The faults controlling the emplacement of the Irish zinc and lead deposits penetrate to, and propagate from the basement (Johnston *et al.*, 1996; Murphy *et al.*, 2008). The Irish basement has been subdivided into seven distinct northeast–southwest striking terranes (Murphy *et al.*, 1990) that are characterised by their pre-Silurian history and contrasting lithotypes, stratigraphy, and isotopic characteristics. The basement terranes are bounded by regional-scale faults that show clear evidence of strike-slip displacements. The basement faults are a product of Lower Palaeozoic deformation resulting from subduction and closure of the Iapetus Ocean and subsequent collision of the northern Laurentian and southern Avalonian plates and subduction and closure of the Iapetus Ocean during the Caledonian Orogeny with the development of the Iapetus Suture. This collision zone is interpreted to involve oblique under-thrusting of the Avalonian plate beneath the Laurentian plate (Vaughan & Johnston, 1992). The exact position and nature of the Iapetus Suture is somewhat cryptic: resolution of the exact location of the Suture is unreliable due to paucity of outcrop, though the line may be traced with varying degrees of confidence through a series of faults that traverse the suture zone, which contains two or more tectonostratigraphic terranes (Todd *et al.*, 1991). The majority of the known zinc-lead mineralization in the Irish Orefield, and all of the large economic orebodies, occur within 50km on either side of the modelled trace of the Iapetus Suture.

Irish zinc-lead deposits exhibit strong structural control, and most of the deposits are hosted by the lowest, non-argillaceous carbonate horizons within the local stratigraphic succession (Hitzman & Beaty, 1996; Wilkinson & Hitzman, 2015). On a large scale, the deposits are controlled by segmented normal fault zones that developed during a Lower Carboniferous aged rifting event (Carboni *et al.*, 2003; Torremans *et al.*, 2018), which resulted in segmentation of the basin arising from north-south extension (Walsh *et al.*, 2015). The faults are laterally discontinuous, creating a horst and graben morphology within regional basins (Hitzman & Beaty, 1996). Faults controlling mineral deposits tend to be normal faults with oblique extension, facilitating the formation of arrays of *en echelon* fault segments, with associated complexity related to breaching and the development of ramps on a range of different scales (Torremans *et al.*, 2018). Structural and stratigraphical controls strongly influence the morphology and distribution of the mineralized zones. The Navan deposit which exhibits a complex structural and lithological control with a stacked lens morphology of several locally stratiform, but dominantly stratabound lenses trending in an east-northeast orientation with an approximate parallelism to the major fault controls (Ashton 1995). Lithological variation within the Navan Group exerted a strong control on the localization of mineralization, with a tendency for high grade stratabound layers to develop beneath sandy and/or shaley dolomite horizons (Ashton, 1995). The Waulsortian Limestone Formation-hosted deposits tend to consist of individual sulphide bodies preferentially developed along the hangingwall side of controlling (feeder) faults in a "string of pearls" morphology. Mineralization primarily occurs within the basal part of the Waulsortian limestone, although there are instances of discordant, crosscutting mineralized zones extending through the entire Waulsortian Limestone Formation, occasionally into the supra-Waulsortian rocks.

Irish zinc lead deposits are generally mineralogically quite simple, consisting mainly of sphalerite with associated subordinate galena and a varying amount of pyrite or marcasite. However, the more southerly deposits can also contain locally significant copper and nickel sulphides, often within the interpreted feeder faults or at lower stratigraphic horizons than the zinc lead mineralization. Significant quantities of barite is also found in a few deposits – most notably at Silvermines, (where approximately 5 million tonnes of barite was mined from the Magcobar Zone) and in the Garrycam deposit proximal to the Keel zinc lead deposit (Slowey, 1986). The Waulsortian hosted deposits are characterised by large breccia bodies. The breccia bodies are ubiquitous within these deposits and are intimately associated with mineralized areas, acting as ground preparation, hydrothermal fluid conduits and as a host for the sulphides. The different Waulsortian hosted deposits have a range of breccia styles and complexities dependent upon their respective geological and structural histories. The Kildare deposits are characterised by vertically extensive breccia bodies related to faulting, hydrothermal dissolution, and solution collapse (Holdstock, 1983; Emo, 1986). The Lisheen and Galmoy deposits are dominated by broadly stratabound, hydraulic and hydrothermal breccias imposed upon earlier sedimentary brecciation and facies variations (Doyle *et al.*, 1992; Fusciardi *et al.*, 2003). At Tynagh, synsedimentary and debris flow breccias associated with fault controlled, dilatant fracturing and brecciation controlled mineralization (Clifford *et al.*, 1986). The Silvermines deposit is very complex with numerous breccia styles, tectonic, debris flow, synsedimentary and hydrothermal (Andrew, 1986; Lee & Wilkinson, 2002). In the Limerick region there are extensive, multiphase and complex breccia bodies associated with the deposits that include hydrothermal, solutional collapse and intrusive related breccias (Blaney & Redmond, 2015).

Hydrothermal alteration is noted to have occurred at all the Irish zinc-lead deposits. It was often intimately associated with mineralization and in some locations formed laterally extensive haloes. Dolomitization occurred at varying intensity at all the deposits. Regional scale, early dolomitization at Lisheen and Galmoy where it was part of an extensive dolomitization event developed within the Waulsortian Limestone Formation that can be traced for almost 150km from the south. Immediately southwest of the Kildare deposits a similar regional dolomite event, although stratigraphically more extensive, is developed through the sub-Waulsortian Upper Argillaceous Bioclastic Limestone, Waulsortian Limestone, and the supra-Waulsortian Allenwood Beds. At Silvermines dolomite breccias are developed in the hangingwall and lateral to the B-Zone (Andrew, 1986) and at Lisheen and Galmoy the mineralized zones sit within a halo of hydrothermal breccias, developed at the base of the Waulsortian Limestone (Fusciardi *et al.*, 2003; Doyle *et al.*, 1992). Stratabound and stratiform iron formations consisting of silica, haematite and subordinate magnetite have been identified at some deposits. The most extensive and well developed is at Tynagh, where it is present to the north of the deposit at the base of the Waulsortian Limestone Formation and extends more than 600m from the margin sulphide mineralized zones (Clifford *et al.*, 1986). Less well-developed iron silica alteration has been noted at Silvermines, Lisheen and Navan. Silicification is noted at many of the Irish deposits but tends to be of limited scale and intensity.

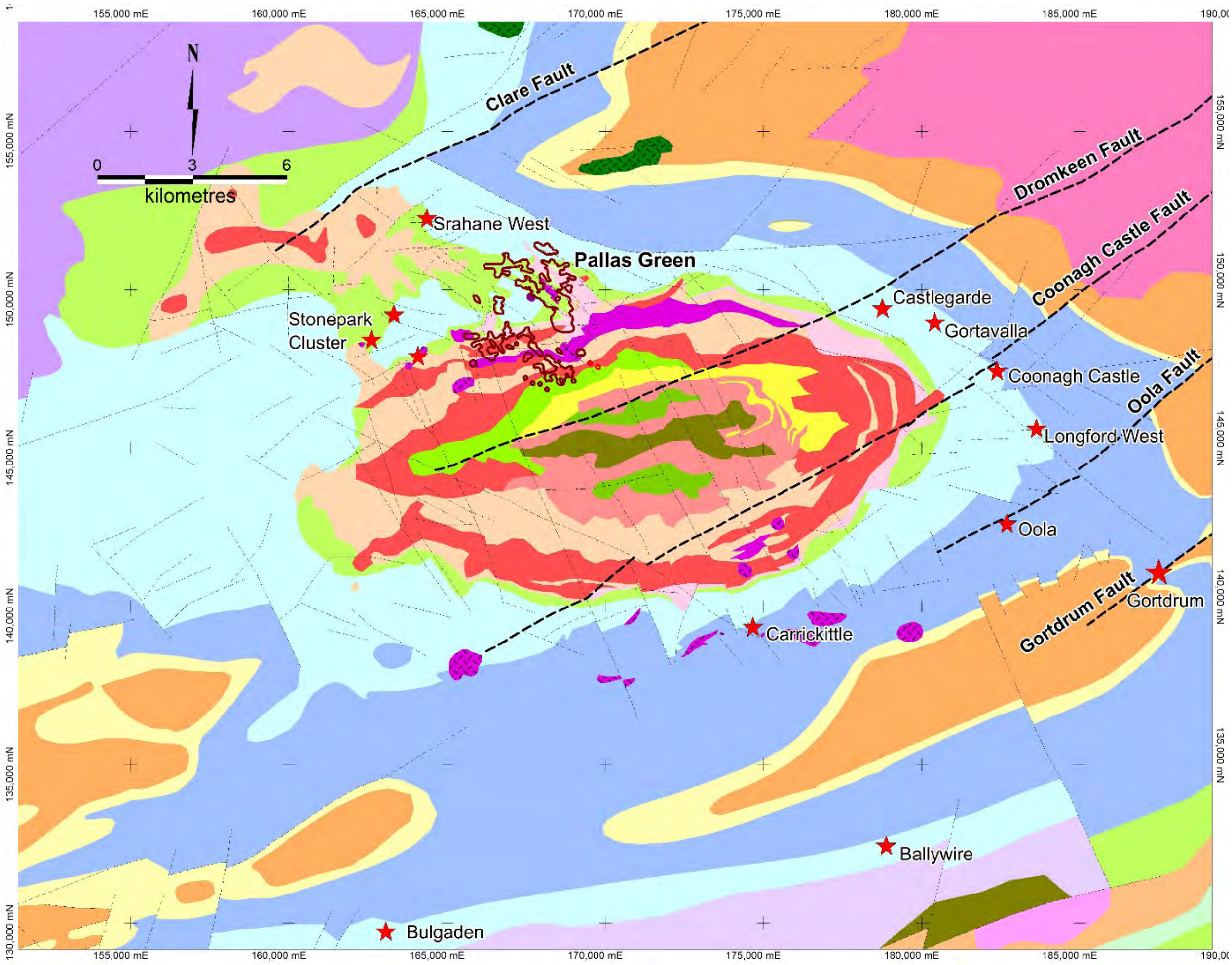

Figure 2: *Regional Geology and Mineral Occurrences of the Limerick Basin.*

The temperature of formation of the deposits of the Irish Orefield ranges from 70º to 280ºC (Hitzman, 1995), with the bulk of the deposits having temperatures of formation that are well in excess of the 90º to 120ºC range for Mississippi Valley Type (MVT) deposits (Leach & Rowan, 1993). Historically there was considerable debate regarding the potential source of the metals, with a number of concepts considered, including "Compaction Driven Expulsion" (Lydon 1986), "Basin Dewatering" (Williams & Brown, 1986), "Topographic Driven Flow" (Garven *et al.*, 1993) and "Deep Convection" (Russell, 1978, 1986). Lead isotope studies in the Irish Orefield have demonstrated that the principal source for metals is the weakly metamorphosed volcano-sedimentary rocks of the lower Palaeozoic basement (Caufield *et al.*, 1986; O'Keefe, 1986; Everett *et al.*, 2003). Sulphur in the deposits is dominantly isotopically light and was likely derived by bacterial reduction of contemporaneous seawater sulphate (Anderson *et al.*, 1998; Fallick *et al.*, 2001). Ore formation occurred when saline brine, derived from seawater, circulated downward and mixed with a metal-bearing fluid ascending along normal faults from the basement beneath the deposit (Wilkinson & Hitzman, 2015).

There is debate over the timing of the mineralization in the Irish Orefield. A range of independent studies have supported the proposal there was significant synsedimentary, exhalative component to the mineralization (Andrew 1986; Ashton *et al.*, 1986). Alternatively, there is evidence for a dominant epigenetic, replacement style component to the mineralization (Hitzman 1995). Clearly this is an important issue for exploration, but contradictory evidence can be found, often within a single deposit (See Ashton *et al*, this volume).

Pallas Green - Exploration History

The only recorded historic metal mining activity in the Pallas Green licence block was close to the village of Oola in County Tipperary, approximately 15km to the southeast of the Pallas Green deposit where nineteenth Century mining activity recovered lead, copper and barite from a series of hydrothermally altered dykes. (Strogen, 1995).

The modern phase of mineral exploration in the region began in the 1960s during the country wide exploration boom following the discoveries of Tynagh and Silvermines. This phase of exploration resulted in the discovery of the sub-economic zinc lead deposits at Courtbrown and Carrickittle, and the discovery and development of the Gortdrum copper, silver and mercury mine (Figure 2). The Gortdrum deposit was discovered in 1963 by the Lower Limestone Syndicate Company (Steed, 1986) and was mined between 1967 and 1975 producing 3.8Mt grading 1.2% Cu and 25g/t Ag with economic grades of mercury. Mineralized zones occurred in the Old Red Sandstone, Lower

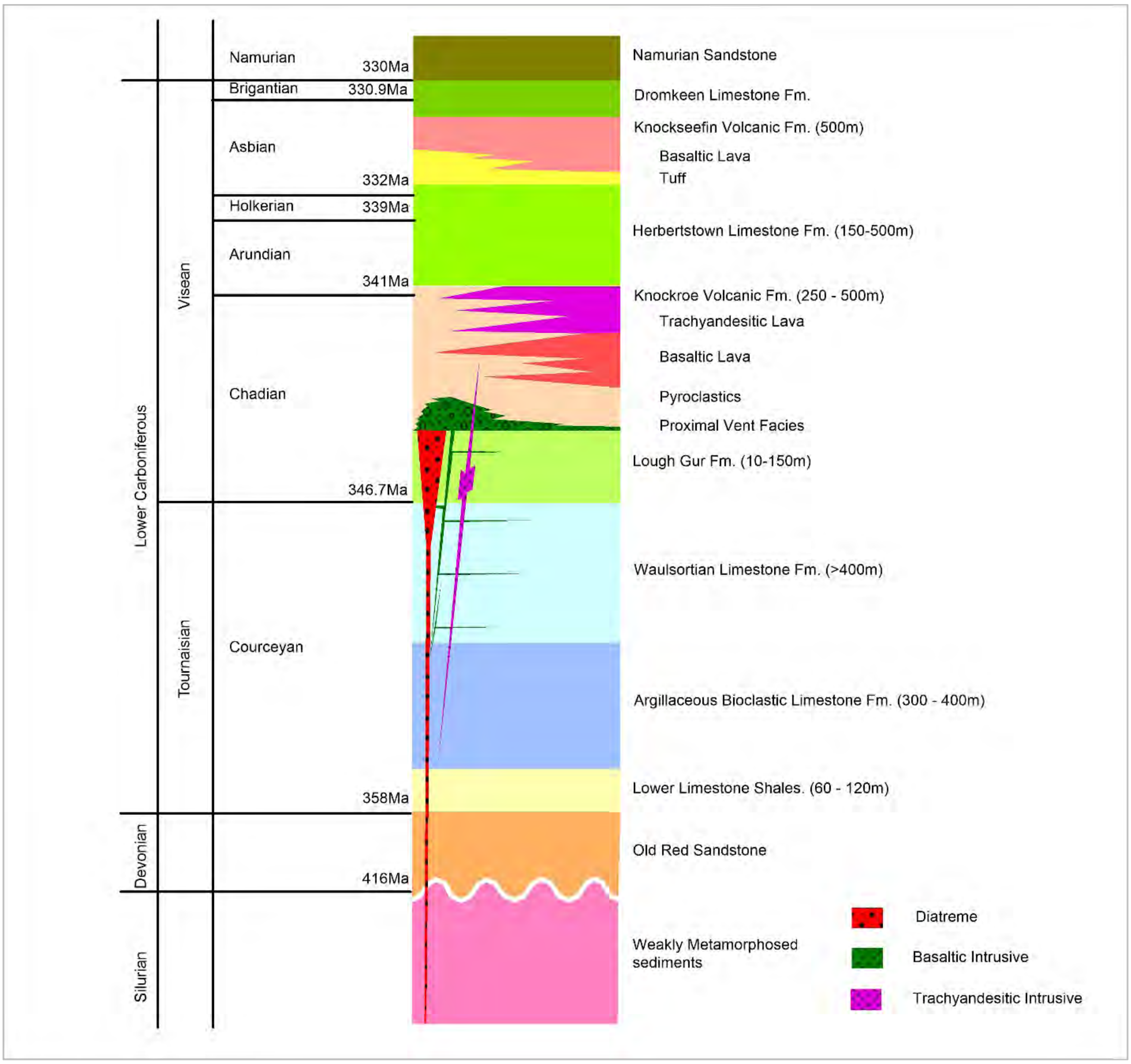

Figure 3: *Pallas Green Deposit Stratigraphical Column.*

Limestone Shales and altered Lower Carboniferous igneous intrusive rocks. The orebody was located within a complex structural wedge along the north-western side of the Gortdrum Fault. The dominant style of mineralization was in veins and as disseminations of chalcopyrite, mercurian tennantite and bornite with accessory cinnabar, realgar, cobaltite, arsenopyrite, native amalgam, stromeyerite, wittichenite and gortdrumite (a copper-mercury-sulphide mineral) (Steed, 1982).

In 1965 the basal Waulsortian Limestone Formation hosted, sub-economic, Carrickittle deposit was discovered by the Tara Exploration and Development Company Ltd. Three discreet lenses containing massive to semi-massive sulphide mineralization were discovered within a relatively small area. The mineralized zones contain massive, collomorph pyrite, sphalerite, and galena haloed by disseminated sulphides. The highest-grade zones of mineralized material occur in areas of dolomitization and breccia development and have grades of up to 35% Zn + Pb over thicknesses of up to 2m (Brown & Romer, 1986). Carrickittle is currently undergoing an active exploration programme by Group Eleven Mining and Exploration Ltd., and recent drilling returned an intersection of massive sulphide mineralization of 10.3m grading 14.6% Zn, 5.0% Pb and 43g/t Ag (Group Eleven, 2020).

In the 1970s a soil sampling programme carried out by Gortdrum Mines Ltd. discovered extensive zinc-lead anomalies in the Longford West, Carrickbeg, Gortavalla and Coonagh Castle regions close to the eastern closure of the Limerick Basin. A subsequent drilling programme discovered widespread, low-grade, disseminated sulphides, hosted by extensive hydrothermal breccias developed within the basal part of the Waulsortian Limestone Formation.

In the early 1990s Minco Ireland Ltd acquired the exploration licences that have become the core of the Pallas Green block, currently fully-owned and managed by Glencore Zinc Ireland Ltd. After an initial period of exploration, that included a joint

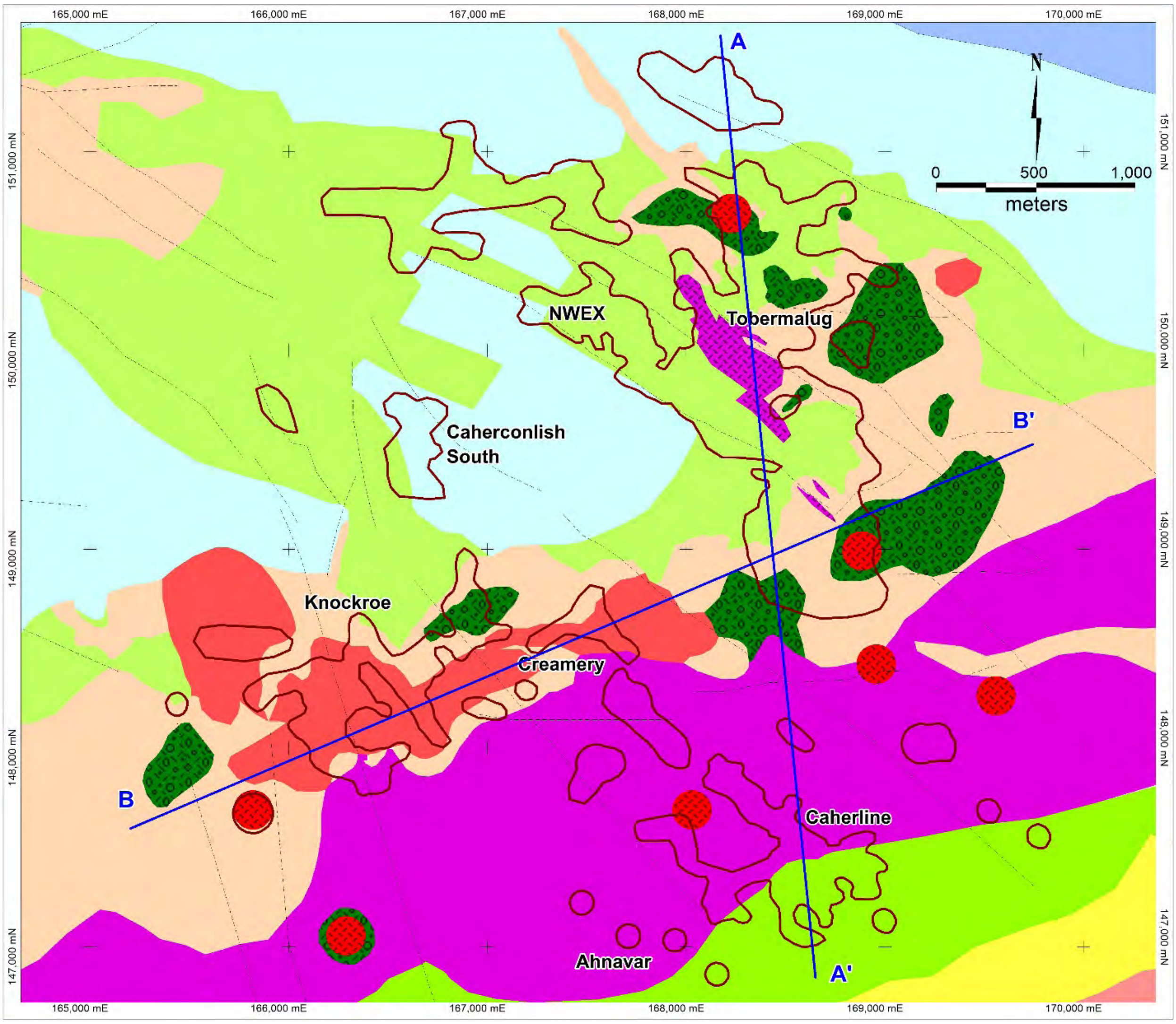

***Figure 4:** Geological Map of the Pallas Green Deposit*

venture with Billiton, Minco Ireland Ltd. signed a joint venture agreement in 1999 with Noranda Exploration Ireland Ltd. (now Glencore Zinc Ireland Ltd). The first phase of exploration was targeted to the east, along the relatively under explored region to the northwest of the historical, low-grade mineralized zones that had been discovered by Gortdrum Mines Ltd. Reinterpretation of the structural and geological models for the region suggested a significant northwest–southeast striking mineralized trend, referred to as the "Limerick Trend" (Blaney *et al.*, 2003). In 1999, when following up on anomalous lithogeochemical results, Noranda and Minco discovered a significant occurrence of high-grade mineralized material along the northeastern margin of the Limerick Basin at Castlegarde. The discovery drillhole, MN-3268-004, intersected an 8.0m thick lens of massive sulphide, consisting of 3.26m grading 21.2% Zn and 4.05% Pb. The Castlegarde occurrence comprises two lenses of basal Waulsortian limestone hosted massive sulphide. The style of mineralization varies from massive replacement to delicately banded colloform textures that are often overprinted with coarsely crystalline, euhedral galena (Blaney *et al.*, 2003). The mineralized zone is located within the basal 20m of the Waulsortian Limestone succession at depths of between 146m to 184m. The Castlegarde occurrence is now postulated to be a distal zone, related to a major mineralizing system and analogous to the K2 Zone at Galmoy (Lowther *et al.*, 2003) or the Cooleen Zone at Silvermines (Lee & Wilkinson, 2002).

From 2000 to 2002 the exploration programme, consisting of airborne and ground geophysics, lithogeochemistry and diamond drilling, was performed to the west of the licence block, into very poorly explored ground that was underlain by sub-outcropping Waulsortian limestone. In the summer of 2002 this work led to the discovery of the Pallas Green massive sulphide deposit with drillhole MN-636-008. The intersection consisted of >10m of low zinc grade, massive pyrite that was hosted by a vermicular breccia. The exploration team recognised that the style of massive sulphide and the nature of the host breccias was strongly analogous to the Silvermines B Zone, and the intersection was modelled as lying on the distal edge of a major mineralizing system. Due to a range of circumstances, it was not until 2007 that a significant exploration drilling resumed,

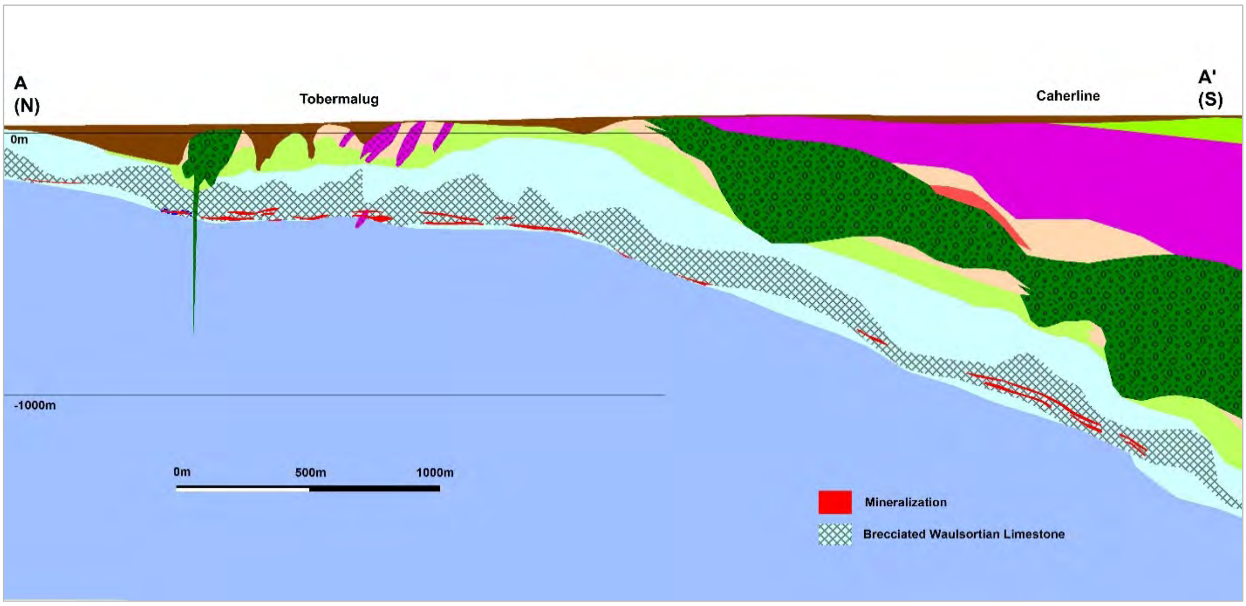

Figure 5: *North - South Cross Section through the Pallas Green Deposit.*

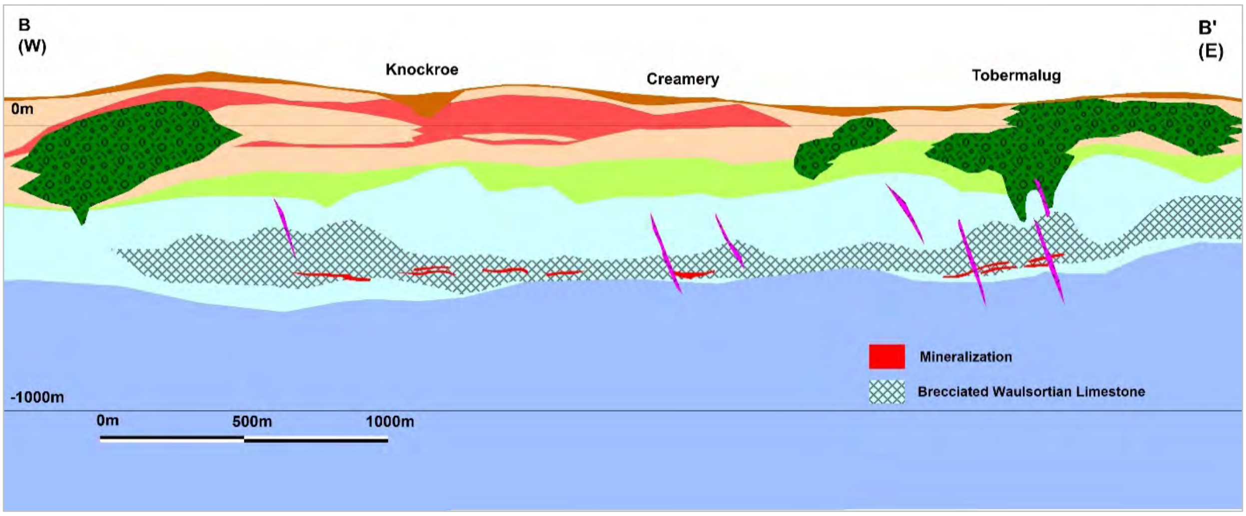

Figure 6: *East - West Cross Section through the Pallas Green Deposit*

and a series of intersections of thick, high zinc-lead grade, massive sulphide mineralized material confirmed the existence of a large deposit. A major drilling campaign was carried out between 2010 and 2014, utilising up to 24 diamond drilling rigs working simultaneously. By mid-2014 a total of 1013 diamond drillholes totalling 473,350m had been drilled by Glencore Zinc Ireland Ltd. on the Pallas Green block. This drilling has discovered significant massive sulphide mineralized zones hosted in seven discrete lenses namely: Tobermalug, NWEX, Srahane West, Caherconlish South, Knockroe, Creamery Zone, and Caherline; the latter had just been discovered when another hiatus in the drilling programme occurred.

In 2007, at a similar time as drilling recommenced at Pallas Green, Teck Ireland Ltd, and Connemara Mining Ltd. entered into a joint venture on licence blocks located immediately to the southwest of the Pallas Green block. Diamond drilling commenced in May 2007 and the fourth drillhole in the programme intersected a 4m zone of sulphide mineralized material containing 11.6% Zn and 3.5% Pb from 376m depth (Blaney & Redmond, 2015). This discovery became known as the Stonepark project and step-out drilling has defined a deposit with three discrete lenses of massive sulphides: Stonepark, Stonepark North and Stonepark West. The Stonepark project is currently operated by Group Eleven Mining and Exploration Ltd. who in April 2018 announced a NI43-101 compliant, Inferred Resource estimate for Stonepark of 5.1Mt grading 8.7% Zn and 2.6% Pb (Gordon *et al.*, 2018).

Drilling at the Pallas Green deposit resumed in 2018 was focused on the Caherline Zone where the drillhole with the highest metal endowment to date had been intersected (33.05m grading 11.44% Zn and 1.38% Pb). Drilling in 2019 continued to extend the footprint of the deposit. Towards the end of year two holes intersected high grade mineralization (3.55m grading 16.45% Zn and 2.56% Pb plus 3.65m grading 13.74% Zn and 2.31% Pb) interpreted as lying on the northern margin a potential new massive sulphide lens. This zone is known as Ahnavar, and it remains open.

The Pallas Green deposit currently has an Inferred Resource estimate (JORC) as at 31st December 2021) of 45.4Mt, grading 7% Zn / 1% Pb (Glencore reference – annual report 2022).

Volcano-stratigraphical setting of the Pallas Green Deposit

The Lower Carboniferous stratigraphy of the Pallas Green deposit is broadly similar to that seen in other parts of the Southern Midlands, as described by Philcox (1984) (Figure 3). The oldest exposed rocks in the region are the weakly metamorphosed, Lower Palaeozoic basement rocks, consisting of tightly folded, mudstones, siltstones, sandstones, and greywackes with minor volcanics, that are thought to underlie the deposit and outcrop approximately 15km to the north within the Slieve Phelim / Silvermines Inlier (Figures 4, 5 & 6) (Archer *et al.*, 1996; Sleeman & Pracht 1999). The Lower Palaeozoic rocks have not been intersected by any exploration drilling at the Pallas Green deposit.

The Lower Palaeozoic rocks in the Limerick Basin are unconformably overlain by Devonian aged Old Red Sandstone (ORS). The Old Red Sandstone of the Limerick / Tipperary region accumulated in equatorial latitudes on a slowly subsiding landmass, immediately north of the rapidly subsiding Munster Basin. The ORS succession of the Munster Basin is at least several kilometres thick, whereas the ORS of the northern Limerick Basin is only a few hundred metres thick. The margin of Munster Basin transects the Limerick Province with the thickest exposed ORS sequence located in the Galtee Mountains 20km south of the Pallas Green deposit (Archer *et al.*, 1996). The ORS outcrops to the north of the Pallas Green deposit on the southern flank of the Slieve Phelim-Silvermines Inlier. The ORS in this region is dominated by conglomerates, sandstones and mudstones that were deposited in a continental, fluviatile or lacustrine environment (Graham, 2009).

The onset of a northward migrating marine transgression at the beginning of the Lower Carboniferous resulted in the deposition of marine sediments in progressively deeper water environments. The oldest Lower Carboniferous unit in the Limerick area is the Lower Limestone Shale Group, comprising a series of interbedded shales, siliciclastics and carbonates (micrites, oolites and grainstones), which were deposited in a shallow marine, intra- to peri-tidal environment (Philcox, 1984; Tyler, 1997; Blaney *et al.*, 2003).

Rocks of the Lower Limestone Shale Group are conformably overlain by the Ballysteen Limestone Formation, a sequence of nodular bedded argillaceous calcarenites that are interpreted to have been deposited in a carbonate ramp setting (Sommerville & Strogen, 1992). A single exploration drillhole located near Cappaghmore, approximately 10km east of the Pallas Green deposit, has intersected the entire Ballysteen Limestone Formation succession. In the area of the Pallas Green deposit exploration drilling has only tested the upper 200m of this formation.

The Waulsortian Limestone Formation conformably overlies the Ballysteen Limestone Formation. There is a transitional contact with the underlying Ballysteen ranging in thickness from 1 to 25m and consisting of nodular-bedded bioclastic micrites with wispy laminated shale and bands or nodules of chert interpreted to be diagenetic. Within this transition there are locally developed, rapid lateral facies changes, from nodular micrites to encrinitic facies, which often contain >50% crinoidal ossicles. Massive, micritic Waulsortian Limestone, or its lateral equivalents, is the principal host lithology for the sulphides at many of the large zinc-lead deposits across the Irish Orefield, including Silvermines, Lisheen, Tynagh and Galmoy. The Limerick Basin was a major depocenter for the Waulsortian Limestone Formation with thicknesses of up to 1,200m estimated in the Shannon estuary (Shephard-Thorn, 1963). The thickness at the Pallas Green deposit only ranges between 140 – 450m, with an overall general thickening to the south and east. The Waulsortian Limestone Formation consists of accumulations or “mudbanks” of massive but subtly bedded, often steep sided micrite mud-mounds, which coalesce into a thick unit surrounded by varied but related “off bank” facies. The dominant lithofacies is a massively-bedded, very pale grey, weakly mottled micrite commonly containing stromatactis or sheet spars with large sparry masses, rich in crinoids and fenestrate bryazoa, which was deposited as a fine, multi-component carbonate mud. It is clear from studies that the rock underwent relatively early marine diagenesis and was at least partially cemented by calcite spar as the mud-mounds grew (Wilkinson, 2003; Lees & Wallace 2004). The very early cemented nature of the Waulsortian limestone, directly overlying soft, still relatively weak, shaly beds led to brittle fracturing, allowing cracks to open and develop filling with vertically layered micrites and calcite silts. Within the Waulsortian Limestone Formation an ‘equivalent’ facies, termed the Wavy Laminated Unit (or Wavy Laminated Facies), consists of micrite nodules in a banded, to bedded, argillaceous matrix. This facies tends to be crinoid rich and commonly contains stylolites and irregular patches of diagenetic dark chert. It was probably deposited on the flanks and in topographic lows between micritic mud mounds.

The Lough Gur Formation overlying the Waulsortian Limestone Formation, is a sequence of locally cherty, moderately bioclastic, nodular bedded, argillaceous limestones (Sommerville *et al.*, 1992). Its thickness varies from around 1m in areas where it directly underlies thick pyroclastic flows, to a maximum of 150m, focused within palaeo-topographic lows (sags) that developed along the upper Waulsortian Limestone Formation contact. The transitional contact between the Waulsortian Limestone and Lough Gur formations is dominated by medium to pale grey, wavy laminated style micrites, with minor blue-grey chert nodules, which grade up into nodular bedded micrites, with dark grey undolomitized micrite and increasing amounts of shale partings and cherty nodules.

The most significant difference between the Limerick Basin and the rest of the Irish Midlands is the volcanic activity that occurred during the Chadian to early Arundian Stages - the Knockroe Volcanic Formation - and in the Asbian Stage - the Knocksheefin Volcanic Formation (Sommerville *et al.*, 1992; Slezak *et al*, 2023). The Knockroe Volcanic Formation consists of a complex association of volcaniclastics, lavas and intrusions which range in composition from alkaline basalts to trachyandesites (Slezak *et al,* 2023). Strogen (1988) records that the thickness of the Knockroe Volcanic Formation in the Limerick Basin varies from <250m to 550m. In the areas with extensive drilling a more detailed study of the Knockroe Volcanic Formation has been performed. This has found that the volcanic sequence comprises variably oxidised, chlorite-epidote-sericite altered volcanic rocks of intermediate, transitional to intermediate or mafic composition. The volcanic rocks are lithic-scoria rich, pebbly to blocky breccia and crystal-lithic-vitric sandstones. They are generally gradationally bedded on the sub-metre to tens of metre scale. Visible limestone fragments are concentrated in the coarser-grained and lesser sorted breccia beds that are usually less than 10 metres thick. Variation in sorting, grain size and concentration of limestone fragments is likely a function of the energy state and mechanism of deposition of an individual volcaniclastic unit and the presence or absence of Waulsortian limestone at its source. Grading on various scales throughout the sequence indicates that it is right-way-up. Further to this the gradational contacts between many of the thicker-bedded units over sub-centimetre distances indicates steady accumulation without any significant hiatus. This is reinforced by the similar REE profiles displayed by the various rock series that make up the sequence (Figure 3). Comparatively very well-sorted and thin scoriaceous beds occur intermittently throughout the breccia and these generally have irregular but sharp contacts, indicating that they represent discrete depositional events within the volcano-sedimentary sequence. The lower portion of the volcanic sequence is generally coarser-grained, even blocky, and more thick-bedded. This largely volcaniclastic sequence is intermittently cut by thin mafic to intermediate subvolcanic intrusions and rare trachyte intrusions. The trachytes are largely confined to the Waulsortian Limestone Formation and sub-Waulsortian units, where they are hydraulically fractured, altered and sometimes mineralized. These intrusions are only rarely observed in the supra Waulsortian sediments and volcaniclastics. Mafic intrusions also occur in supra-Waulsortian and Waulsortian rocks and can also be hydraulically fractured, altered, and mineralized.

From chemo-stratigraphical and lithofacies associations observed in outcrop and drillcore, a plausible depositional model involves volatile-rich, sometimes phreatomagmatic, monogenetic eruptions of a small, reef-fringed, mostly subaerial, alkaline basalt shield volcano and its associated scoria cones, with its root in the shallow marine environment. The eruptive products were likely produced by a single, prolonged eruptive phase during which the magma evolved from alkaline basalt through to trachyte. Juvenile volcanic material entered the water column as primary pyroclastic falls or as gravity-driven debris flows moving into the water from the volcano's flanks. Upon reaching the seismically active, syn-volcanically faulted seafloor, debris flows traversed *in-situ* limestone, eroded it and entrained clasts of it. Limestone was also brecciated by explosive volcanism, thus becoming a component of the volcaniclastic succession. The debris flows' final spatial distribution was partly controlled by pre-existing seafloor topography, which was in turn, at least partly, controlled by syn-volcanic faulting. Detailed three-dimensional mapping of the Knockroe Volcanic Formation has been carried out in order to map the Chadian seafloor topography and locate faults active during the Chadian.

Monogenetic volcanoes tend to have a simple magma conduit system and it is likely that the various subvolcanic intrusions present in the sequence made use of the same fractures and syn-volcanic faults, with their spatial distribution again controlled by these syn-volcanic faults. Further to this, some of these faults were possibly part of a longer-lived system related to the extensional tectonic regime, as is the case with subvolcanic alkaline intrusions in the Munster Basin, where alkaline magmatism was induced by lithospheric thinning controlled by pre-existing zones of weakness in the Caledonide crust (Pracht & Kinnaird 1998). The linear, north-northwest, and east-northeast trends of the thicker Knockroe Volcanic Formation intrusions on surface might mirror the orientations of such pre-existing zones of weakness/syn-volcanic faulting. This is significant, given the strong spatial association that exists between dolomitization, mineralization and the hydrothermal alteration of the Waulsortian Limestones and the intrusions. This raises the possibility that these syn-volcanic faults were primary conduits for the mineralizing fluids (Tennent, 2009).

A significant intrusive event was the development of a swarm of fine grained, amygdular, alkali basalt sills and dykes hosted within the Waulsortian Limestone and lower Lough Gur formations across the Limerick Basin. The basaltic intrusive rocks are often brecciated, and clasts of altered basalts are commonly incorporated into breccia bodies (Polymictic Breccias – "PMB") where they can be preferentially mineralized (Blaney *et al.*, 2015). The basaltic intrusives are generally altered to a mixture of calcite, chlorite, albite, sericite, sphene and haematite (Strogen 1983). The margins of basaltic intrusions often contain amygdules formed either from magma degassing, or from steam generated through interaction of the magma with wall rock connate water. Vesiculation was greatest near the intrusive margins, decreasing in density and in size towards the centre of the intrusions (Kerr, 2013).

The early alkali basalt phase of igneous activity is also associated with the emplacement of multiple large diatremes at Tobermalug and Stonepark. The diatremes range in size from c.100 – 200m in diameter and some have been drilled to depths of over 800m. They often contain rounded to angular clasts of Waulsortian Limestone Formation, Lough Gur Formation and Sub-Waulsortian rocks. Deep crustal xenoliths have been found within diatremes at Stonepark (Redmond, 2010) which have been interpreted as indicating the magmas experienced a rapid, volatile-driven ascent from lower crustal levels (Elliott *et al.*, 2015).

The diatremes at Pallas Green have been only partially delineated by diamond drilling. However, given their subvertical geometry, relatively small footprint, and the fact that most drillholes have been vertical, it is likely that the number of mapped diatremes is an underestimation. The majority of drillholes only have partial diatreme intersections; however, a few drillholes have been drilled completely within the body of a diatreme, and the most complete diatreme section is from drillhole MN-2529-069 (Figure 7). This drillhole is 884.3m long and it is interpreted as collaring just below the maar crater and

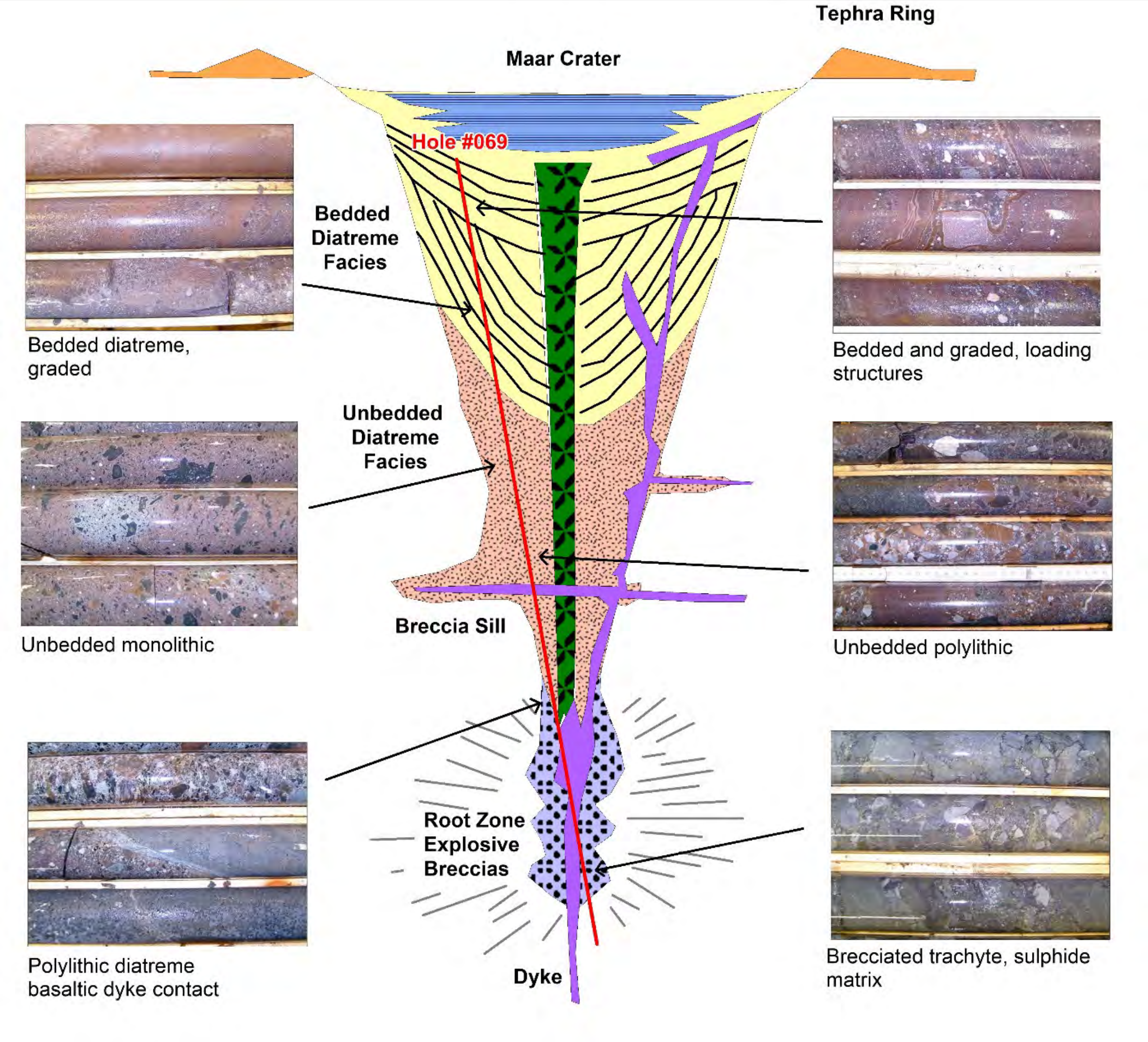

Figure 7: *Schematic Diatreme Section (Lorenz 1986), drillhole MN-2529-069 Facies Variation – Thumbnails.*

drilling through to the root zone. A trace of this drillhole, overlain on a typical diatreme schematic (Lorenz 1986), is presented as Figure 7, images of the various types of lithofacies intersected within the drillhole are included. The upper part of the drillhole intersected a stratified sequence of patchily to strongly and pervasively-altered mafic, lithic scoria rich, pebbly breccia and crystal-lithic sandstone generally gradationally bedded on the sub-metre to tens of metres in scale. Visible limestone fragments are concentrated in the coarser grained and less well-sorted breccia beds, and these are usually the thicker beds. The upper part of the drillhole is pervasively oxidised; this is likely a result of sub-aerial exposure. The unbedded sequence is chaotic and intermixed, and there is evidence of syn-sedimentary slumping and erosion and entraining of semi-lithified limestone into the volcaniclastic materials, possibly as fluidised debris flow of juvenile mafic debris. Mineralized and altered, glassy to aphyric trachyte intrusions occur within the root zone. These are sulphide veined in places with partial replacement of the matrix at the clast margins by pyrite and sphalerite. Below the aphyric trachyte, a notably altered phonolite intrusion occurs, indicating that alteration and mineralization seen within the root system of the diatreme postdates the Knockroe Volcanic Formation since this lithology is likely to be one of the final products of the evolving alkaline volcanic cycle.

The latest stage of intrusive activity associated with the Knockroe Volcanic Formation is the emplacement of a series of porphyritic, trachyandesitic, dykes, plugs and laccoliths. The dykes are particularly well-developed and intrude the entire sequence from the Ballysteen Limestone Formation to the volcaniclastic sediments of the Knockroe Volcanic Formation. The trachyandesitic dykes trend northwest-southeast and appear to have been intruded along pre-existing faults. The dykes have a strong magnetic susceptibility but are non-magnetic when intersected in the lower part of Waulsortian Limestone

Formation within the footprint of the Pallas Green deposit. This may be due to hydrothermal alteration destroying the magnetic susceptibility. The trachyandesitic dykes have been observed forming crackle breccias and hosting zones of intense vein and disseminated-style mineralization, with replacive pyrite, sphalerite and galena.

Indirect age dating of the Knockroe Volcanic Formation using limestone biostratigraphy (Sommerville *et al.*, 1992) indicates a predominantly Chadian age. This work has also determined that the age of the Knockroe Volcanics varies across the basin becoming younger to the east, suggesting that the volcanic centres migrated to the east through time. Recent research has carried out direct age dating of the earliest tuffaceous horizons related to the Knockroe volcanic event. These have been deposited at the base of the Lough Gur Formation and the bulk-rock and apatite trace element data, U-Pb zircon ages have confirmed an age of 348.2$\pm$2.4Ma (Koch, 2021). U-Pb dating of apatite in the Knockroe Volcanic Formation rocks establishes a primary crystallization age of c. 350Ma (Slezak *et al*, 2023).

The Knockroe Volcanic Formation is overlain by the Herbertstown Limestone Formation (Figure 3), which consists of thickly-bedded, clean, bioclastic calcarenites and interbedded oolitic units. It is postulated that the lithofacies and thickness variability of the Herbertstown Limestone Formation around the basin was caused by the burial of relic volcanic topography (Somerville *et al*., 1992). A thickness of up to 500m for the Herbertstown Limestone Formation is postulated within the Limerick Basin (Strogen, 1988; Somerville *et al.*, 1992).

The Asbian aged Knocksheefin Volcanic Formation outcrops in the eastern and central part of the Limerick Basin, stratigraphically above the Herbertstown Limestone. It is dominated by basaltic flows with associated lithic and vitric tuffs, however, in contrast to the Knockroe Volcanic Formation the volcanic facies have an ankaramitic petrography (Somerville *et al.*, 1992). The thickness of the Knocksheefin Volcanic Formation is estimated to vary from 0m to at least 500m thick (Strogen 1995).

The limestones of the Dromkeen Limestone Formation, which directly overlies the Knocksheefin Volcanic Formation in the core of the Limerick Basin, are massively bedded and relatively fine-grained.

The youngest rocks in this region are the Namurian sandstones and grits of the Longstone Formation which crop out as a small outlier located in the core of the Limerick Syncline. The Namurian rocks unconformably overlie both the Dromkeen Limestone and Knocksheefin Volcanic Formations.

Pallas Green Deposit – Structural Setting

The geology of the north Limerick region is dominated by a large west-southwest trending synform that has an ovoid subcrop with dimensions of approximately 12km by 22km. From a regional perspective the Limerick Basin is aligned along a major transition in fold style: to the northeast the complex perianticlinal folding of the Slieve Phelim, Silvermines and Devils Bit Mountains and to the southwest the fold orientation rotates to an east-northeast trend (Archer *et al.*, 1996; see also Figure 4). Drilling at the Pallas Green deposit has defined a marked increase in the regional dip broadly coincident with the subcrop of the Knockroe Volcanic Formation. The dip to the north the of the deposit is a uniformly gentle inclination of 5 – 10º to the south, however, south of the village of Caherconlish, the regional dip increases sharply to between 40–45º. The increased regional dip has meant the depth to target has increased significantly as exploration has progressed to the south (Figure 5).

From a regional perspective there are five northeast-striking, apparently reactivated Caledonian-aged fault zones, spaced approximately 4km to 6km apart, crosscutting the north Limerick area. These are the Gortdrum, Oola, Coonagh Castle, Dromkeen and Clare Faults (Figure 4). The Coonagh Castle, Dromkeen, and Clare Faults outcrop on the Slieve Phelim inlier to the northeast, both as topographic features and as offsets of the basal contact of the Old Red Sandstone (Tyler, 1997). The faults have an apparent normal sense of movement and dip at between 60º to 70º to the northwest. Locally there is evidence of some inversion on these faults, probably related to Variscan compression. The Coonagh Castle Fault has a pronounced reverse throw, estimated to be in the order of 400 to 600m (Blaney *et al*., 2003). The fault morphologies are analogous to the Gortdrum Fault Zone located 15km to the southeast of the Pallas Green deposit. Studies confirm that this fault developed within a reactivated, transtensional, dextral, structural regime during the Chadian to Arundian Stages that was overprinted by transpressional tectonism with the onset of the Variscan Orogeny (Johnston *et al*., 1996).

The major northeast striking fault zones are cross-cut and offset by a complex series of north-northwest to northwest-striking normal faults. These structures tend to be more extensively developed than the northeast striking faults. An example of this type of structure is the Caherconlish Fault Zone, which controls the NWEX Zone, consisting of a series of *en echelon*, subparallel normal faults that down throw to the northeast, with a maximum normal displacement of approximately 50m. The small throws and somewhat cryptic characteristics of these mineralizing structures would suggest that they are second or third order structures controlling the distribution of hydrothermal fluids on a local scale. Analogies with other Waulsortian-hosted deposits would suggest that a large, normal fault complex should be proximal to, and control the southern boundary of the mineralizing system. To date no large scale, domain boundary faults similar to the Killoran and Derryville faults at Lisheen (Fusciardi *et al.*, 2003) have been discovered.

The classic "Irish-Type" model would indicate that this fault complex should act as the main feeder fault for the mineralizing system, and it is where the thickest and highest-grade mineralization should be present (Andrew, 1986; Hitzman & Beatty 1996). Smaller-scale, subordinate faults, with throws in the metre to decimetre range will tap into the large regional structures and control the local distribution of mineralization. Evidence from detailed metal distribution plots and the development mineralization "hotspots" confirms that small scale faults with throws of 5 to 15m have a significant role in controlling the distribution of mineralization. These smaller faults have a number of orientations including northwest-southeast, northeast-southwest and north-northwest-south-southeast and

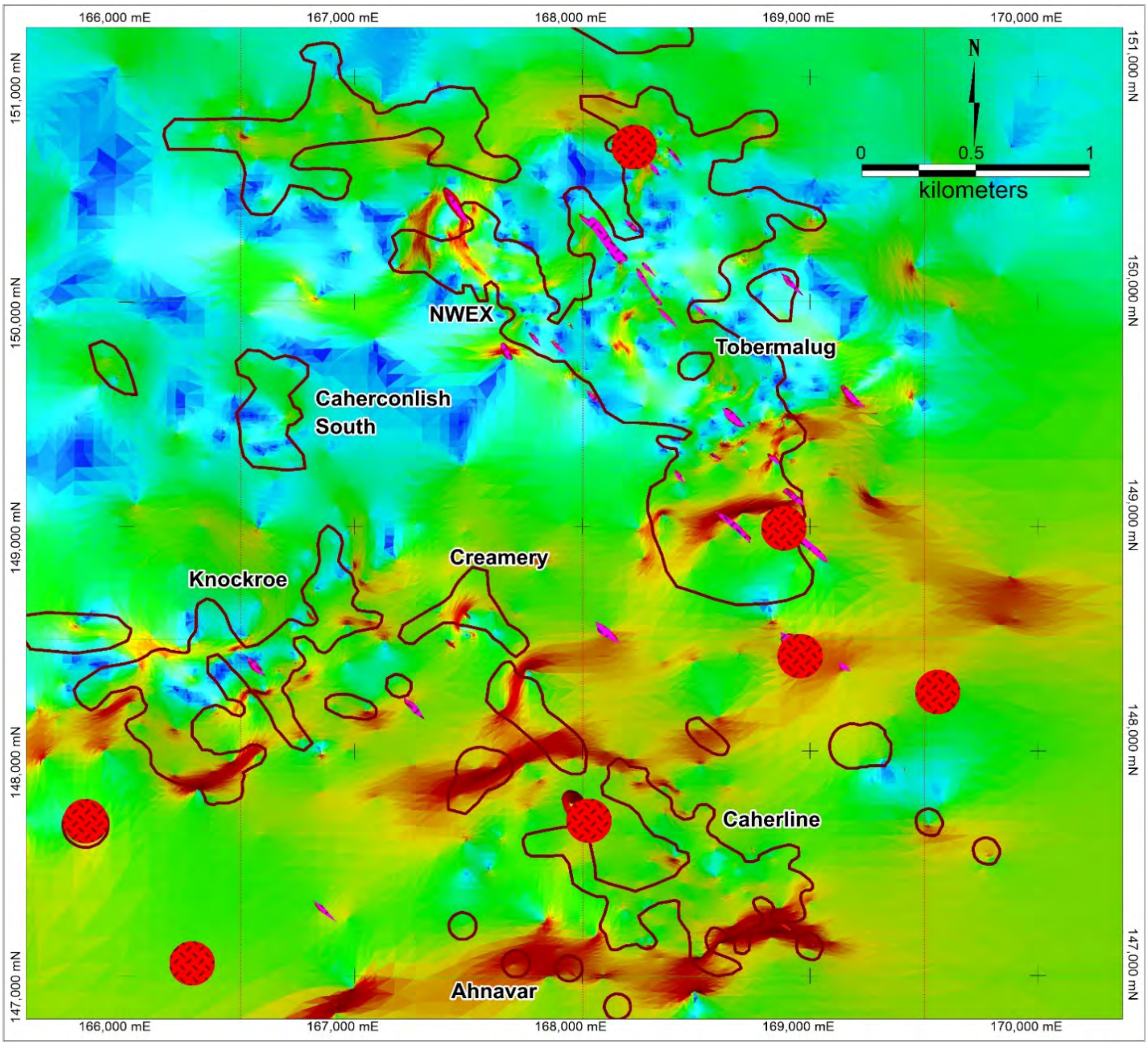

Figure 8: *Ballysteen Limestone Formation-Waulsortian Limestone Contact facedip Model, Diatreme Locations.*

they predominantly down throw to the north. Small scale faults are identified and modelled based upon offsets in the elevation of the base of the Waulsortian Limestone Formation, the only definitive timeline available in drilling database. Given that the basal contact of the Waulsortian Limestone Formation is gradational and tends to be undulating it is challenging to accurately infer and model faults with small throws.

The nominal drill spacing at Pallas Green is between 100 and 200m and at this drilling density it is not possible to model faults with a throw of <20m. In order to model structural setting of the deposit, the Ballysteen-Waulsortian contact, the best timeline for this region, was used to generate a facedip model (Figure 8) to assist with structural interpretation. The facedip Ballysteen Limestone Formation model presents a coloured map of the rate of change of dip of the Ballysteen -Waulsortian contact. The facedip Ballysteen model has been used as a proxy for faulting as it will define rapid changes in the dip of Ballysteen Limestone Formation. contact that may be related to structural offset. The patterns observed in the model show a marked change to the south of the deposit where the regional dip increases. In the southern area there is a very strong development of northeast-southwest striking, major steps down to the south. There are conjugate, northwest-southeast striking lineaments that are generating dextral offsets on the northeast-southwest lineaments. A very strongly-developed and pronounced northeast-southwest lineament with a dextral flexure is located to the south of the Caherline Zone extending across to the Ahnavar Zone. At the Knockroe Zone there is a series of discrete, northeast-southwest striking lineaments, interestingly, the strong northwest-southeast grain presented by the footprint of the massive sulphides is not repeated in the facedip Ballysteen Formation model, suggesting the northwest-southeast striking structures of this region, while constraining mineralization do not significantly offset the Ballysteen -Waulsortian contact (or have been reactivated with near nil resultant throw). To the south of Tobermalug a series of sub-parallel, northeast to southwest trending lineaments are mapped. These features have been confirmed by tight-spaced drilling and are small-scale, basal Waulsortian Limestone Formation faults with offsets of between 10 and 20m. Some of the highest-grade zinc-lead mineralization discovered to date within the Tobermalug Zone is controlled by these small structures. The NWEX zone shows some well-developed, low order, northwest-southeast lineaments that are the representation of the Caherconlish Fault, which has a maximum throw of 50m to the northeast.

The facedip Ballysteen Formation model has defined a large circular feature bounded by relatively strong curved offsets, located to the northwest of the Tobermalug Zone and northeast of the NWEX Zone. This feature is approximately 1km in diameter and is a region that is not mineralized and has very poorly developed brecciation. There is an interpreted diatreme located along the northeastern edge of this feature.

A northwest-trending fault controls the sub-cropping contact between the Waulsortian Limestone Formation and the Ballysteen Limestone Formation approximately 300m to the north of Tobermalug massive sulphide lens. This is the largest fault discovered to date at Tobermalug and has an apparent down throw in the order of 180m to the south.

Based upon the standard "Irish-Type" model, at least one, large-scale, normal fault, that has the potential to extend through the Lower Carboniferous succession into the basement, and act as a conduit for ascending, hot, acidic, metal-rich, hydrothermal fluids would be expected for a deposit of this size. To date no such fault has been recognized.

Brecciation, Mineralization and Alteration

The currently defined Pallas Green deposit consists of seven discrete lenses of massive sulphides, developed over a surface area of 15km^2. The main mineralized zones have been named Tobermalug, NWEX, Caherconlish South, Knockroe, Creamery, Caherline and Ahnavar (Figure 4).

Brecciation

The bulk of the zinc-lead mineralization at the Pallas Green deposit occurs within the lower half of the Waulsortian Limestone Formation as a series of flat lying, stratiform, generally 0.5 to 35m thick, semi-massive to massive, sulphide lenses, hosted within significantly thicker bodies of breccia (Figure 9). The breccia bodies generally have a vertical thickness of between 10m and 125m but locally up to 225m. The massive sulphides are usually hosted within the basal part of the breccia body, often within 20 to 30m of the base of Waulsortian Limestone Formation contact, although there are local variations dependent upon proximity to controlling structures or Waulsortian sub-facies distribution.

The thickness distribution of Waulsortian Limestone Formation hosted breccias in relation to the footprint of the massive sulphide bodies extrapolated to surface is presented as Figure 9. The coincidence of well-developed breccia bodies with the zones of massive sulphides is compelling. Regions with little or no brecciation are rarely mineralized, however, conversely there are regions where breccias are very well developed but have no significant mineralization, particularly to the southwest of the Knockroe Zone and to the east of the Tobermalug Zone. The breccia thickness isopach model shows a very clear northeast-southwest grain, with northwest-southeast trending offsets, a clear conjugate set that reflects the influence of the Caledonian structural architecture of the basement being reactivated and exerting control upon the Lower Carboniferous mineralizing system.

The breccias found at Pallas Green have been sub-divided into two broad categories (Figure 15). The first breccia category, which hosts the mineralization, are comprised of a spectrum that ranges from, brecciated intrusives to Polymictic Matrix ("PMB"), to monomictic Black Matrix Breccias ("BMB") to Vermicular Breccias. The massive sulphides of the Pallas Green deposit are dominantly hosted by BMB. The second breccia category is often associated with faulting or regional scale alteration that have a white calcite, and/or pink dolomite matrix, known as White Matrix Breccia ("WMB").

BMB-style breccias are volumetrically the most abundant breccia style. They are dominated by angular to sub-rounded, highly irregular shaped Waulsortian limestone clasts of variable size (2-100mm), typically the matrix is fine-grained, dark grey to black in colour, comprised of black dolomite and / or argillite, generally containing minor fine-grained disseminated pyrite with lesser amounts of sphalerite and galena. Textures range from clast to matrix supported, and the clast-matrix contacts range from diffuse or gradational to extremely sharp. This breccia style has been interpreted as an *in-situ* hydrothermal alteration associated with hydraulic fracturing; however recent models suggest there could be some relationship to epigenetic dissolution processes or slumping-related debris flows. Dolomitization, although common, is not essential in the definition of the BMB-type here.

Polymictic Breccias (PMB) comprise a spectrum of breccia types, consisting of variable percentages of intrusive and Waulsortian limestone clasts in an igneous (intrusive) and carbonate matrix. They range from typical BMB breccias containing a small percentage of intrusive clasts, to intrusive-hosted breccias with minor Waulsortian limestone and massive sulphide clasts. The typical PMB is a complex zone of interdigitating Waulsortian Limestone Formation and minor basaltic sills, which have undergone multiple phases of brecciation. This results in a rapid variation, often over only a few centimetres, between intrusive and Waulsortian limestone dominant clasts. Swelling clay minerals in some intrusive clasts results in the rapid deterioration of drill core. Some of the igneous clasts in PMB breccias display plastic deformation related to mechanical compaction indicating that the breccias were developing during the intrusive phase of the Knockroe Volcanics dated to the Chadian Stage. A similar style of plastic deformation of breccia clasts was described at Gortdrum (Steed, 1986).

Intrusive breccias are at the other end of the polymictic breccia spectrum, and consist of brecciated basaltic or, more rarely, trachyte intrusives. The host is typically the fine grained intrusive, with brecciation typically concentrated at the contact zones. Crackle breccia zones in porphyritic trachyte dykes typically host sulphide veinlets. Locally, intrusive breccias develop a complex polymictic style, incorporating country rock clasts, particularly when associated with zones of intense faulting. This breccia style is texturally similar to, and may actually be a precursor to, well developed, matrix-supported PMB and BMB described above.

A subclass of breccia is vermicular breccia, which is locally

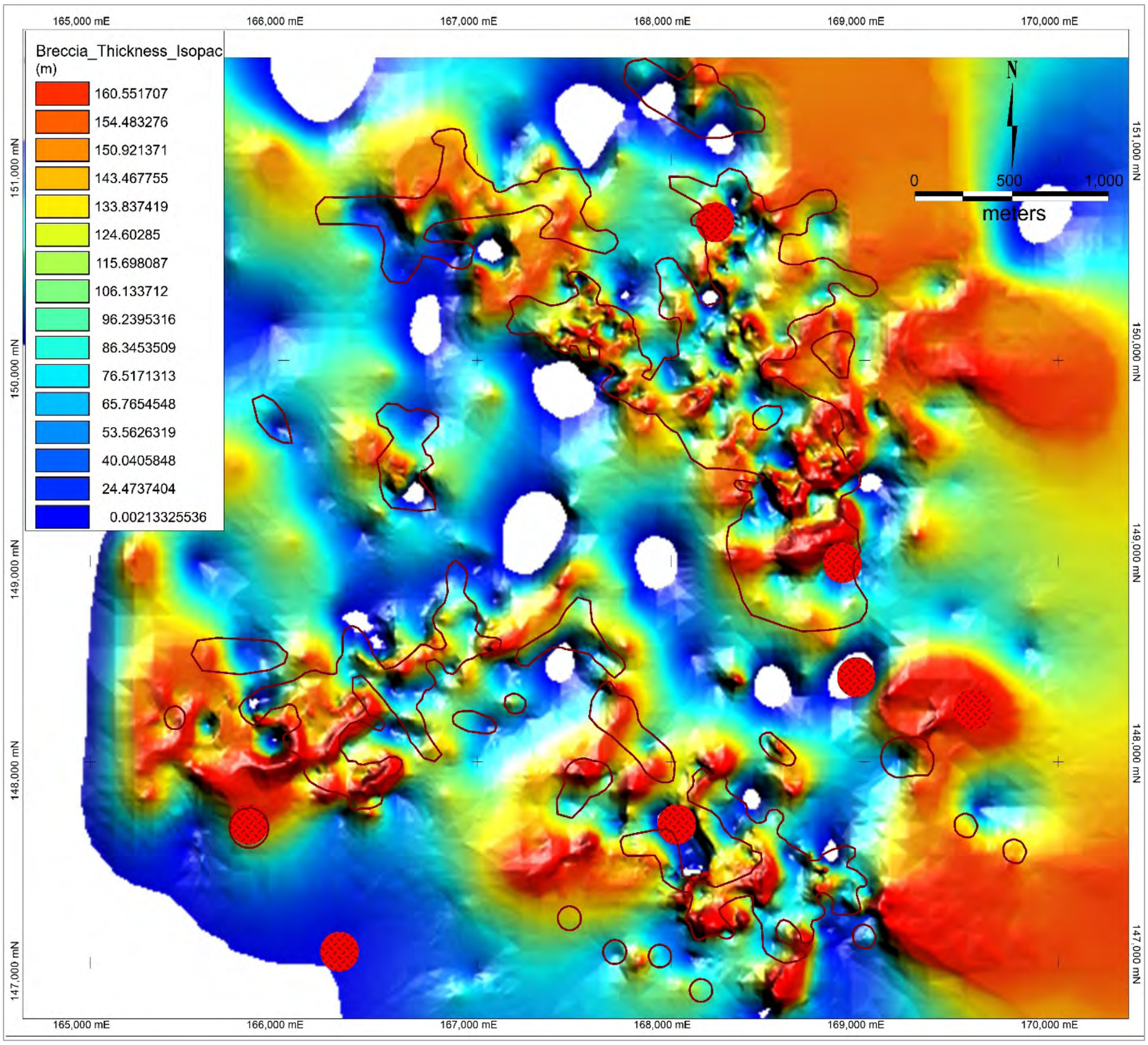

Figure 9: *Breccia Isopach Model.*

developed and often found in the more distal parts the deposit. It consists of small (5-15mm) elongated, tabular, often contorted, clasts of carbonate in a dark grey to black argillite matrix. Commonly the dolomite or calcite clasts are replaced by pyrite or sphalerite. The exact mode of formation of this style of breccia is not well understood, but it has an empirical relationship with massive sulphide mineralization. It has been described as a distal breccia particularly around the fringes of the B Zone at Silvermines (Andrew, 1986).

White Matrix Breccia (WMB) is dominated by angular Waulsortian limestone clasts in a white, calcite +/- dolomite matrix. Often these zones are recrystallised, with coarsely crystalline dolomite replacement of both clasts and matrix, and have variably developed oxidation, giving a buff-grey colour.

Sandstone matrix breccias consist of angular Waulsortian Limestone Formation clasts that varying size from cm to mega-clast (+2m), with very sharp contacts. They tend to develop within thick zones of disrupted/crackle brecciated Waulsortian limestone. The matrix is composed of poorly sorted, fine grained, lithic sandstones comprised of quartz (60%), feldspar (10%), clay minerals (10%), mica (0.5%), pyrite (0.5%), zircon (0.1%) and larger lithic fragments (15%), consisting of limestone, dolomite, siltstone, and tuff (Jones & Leacy, 2013). Feldspar grains are fresh, exhibiting very minor alteration to sericite, suggesting the sandstone did not travel far from source (Jones & Leacy, 2013 . At Stonepark some of the grains display authigenic quartz rims, many of which are truncated along grain edges, indicating that authigenic quartz growth occurred prior to incorporation of the quartz grains in the breccia (Kerr, 2013). This style of brecciation seems to be unique to the Limerick Province and has been encountered by drilling in a range of locations across the region, extending from Castlegarde to Stonepark.

The above descriptions of the breccias, combined with the spatial and thickness distribution, supports the conclusion that faults have played a critical role in the creation of the main host breccias of the Pallas Green mineralization.

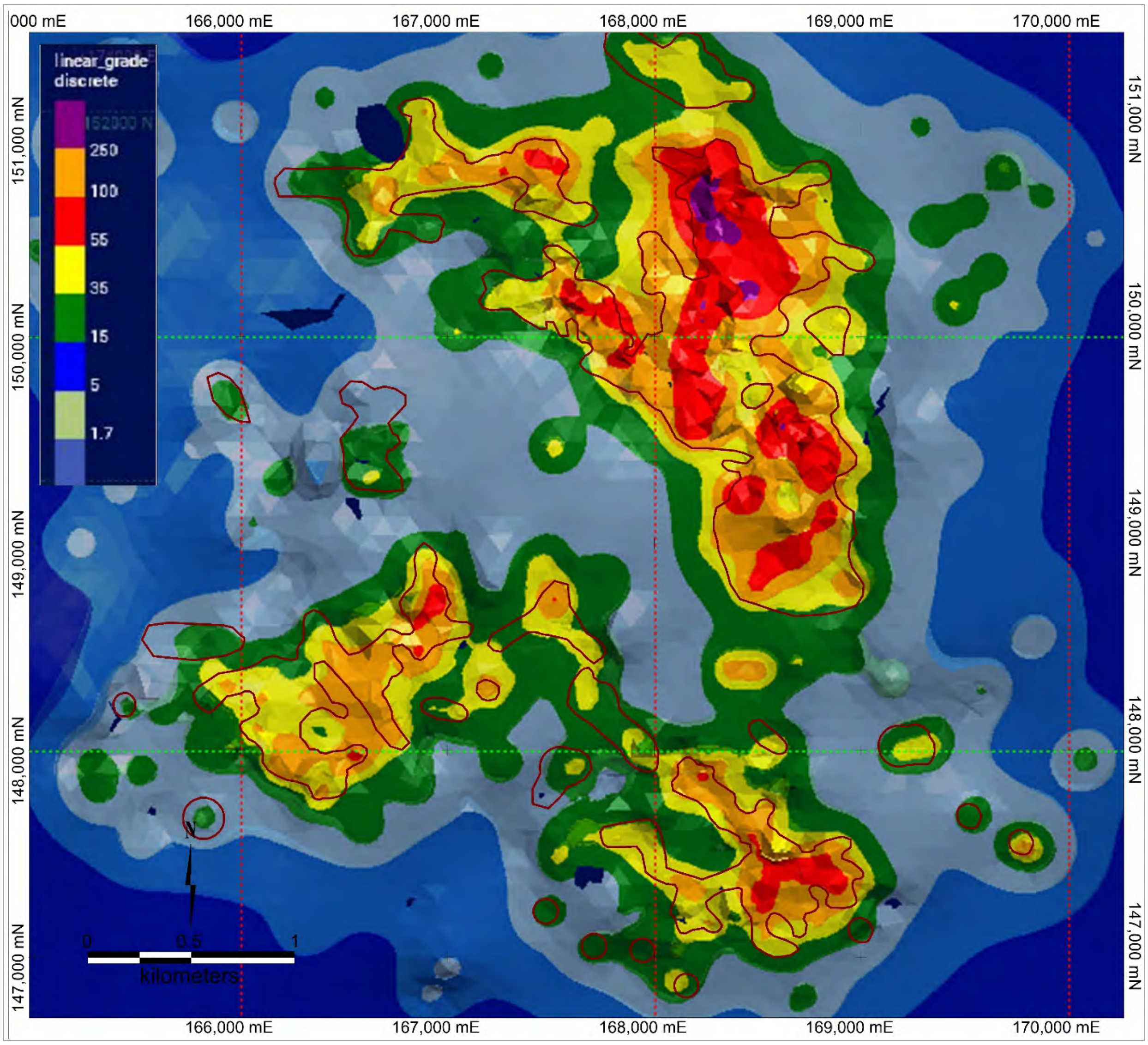

Figure 10: *Total Sulphide Model.*

Mineralization

The sulphide mineralogy at the Pallas Green deposit is relatively simple, primarily comprising pyrite, sphalerite, galena with minor marcasite. The style of the mineralization ranges from massive (>40% total sulphide) plumose, colloform and laminated sulphides to semi-massive (20–40% total sulphide), brecciated, disseminated (<20% total sulphide) and stringers or veins (Figure 16). Gangue phases include white calcite, white and pink dolomite. The host rocks for the mineralization is brecciated Waulsortian Limestone Formation with varying amounts of intrusive rocks. Smaller volumes of mineralization are hosted within porphyritic trachyandesitic dykes.

Low levels of pyrite is found as a halo around the deposit occurring as veins or stringers, disseminated blebs, or associated with stylolites within the Waulsortian Limestone Formation or intrusives. Fine-grained or blebby pyrite is commonly seen replacing the matrix of the breccias. Massive banded, plumose and colloform pyrite can form zones of massive pyrite and "pyrite caps" are locally developed above high-grade sphalerite and galena lenses. The vertical thickness of pyrite caps can vary from 0.5m to 30m, although significant variations are seen between the different zones. The sphalerite mineralization seen in the Pallas Green deposit is highly variable in colour and texture. The colour spectrum ranges from honey-yellow, pale grey, through cream to brown and dark brown-red or teak. The sphalerite ranges in texture from irregular anhedral masses to euhedral crystals, however, two textural styles appear to dominate; firstly, disseminated, fine grained, subhedral crystals or blebs of sphalerite within breccias or inter-grown with dolomite, and secondly, colour-banded, two-tone collomorph masses, particularly common in massive sulphides. Occasionally the sphalerite has a bladed-acicular texture, this is particularly well-developed in the NWEX Zone and the northern part of the Tobermalug Zone. It is thought to be related to sphalerite rimming and replacing dendritic galena. Galena is generally associated with sphalerite, as finely crystalline

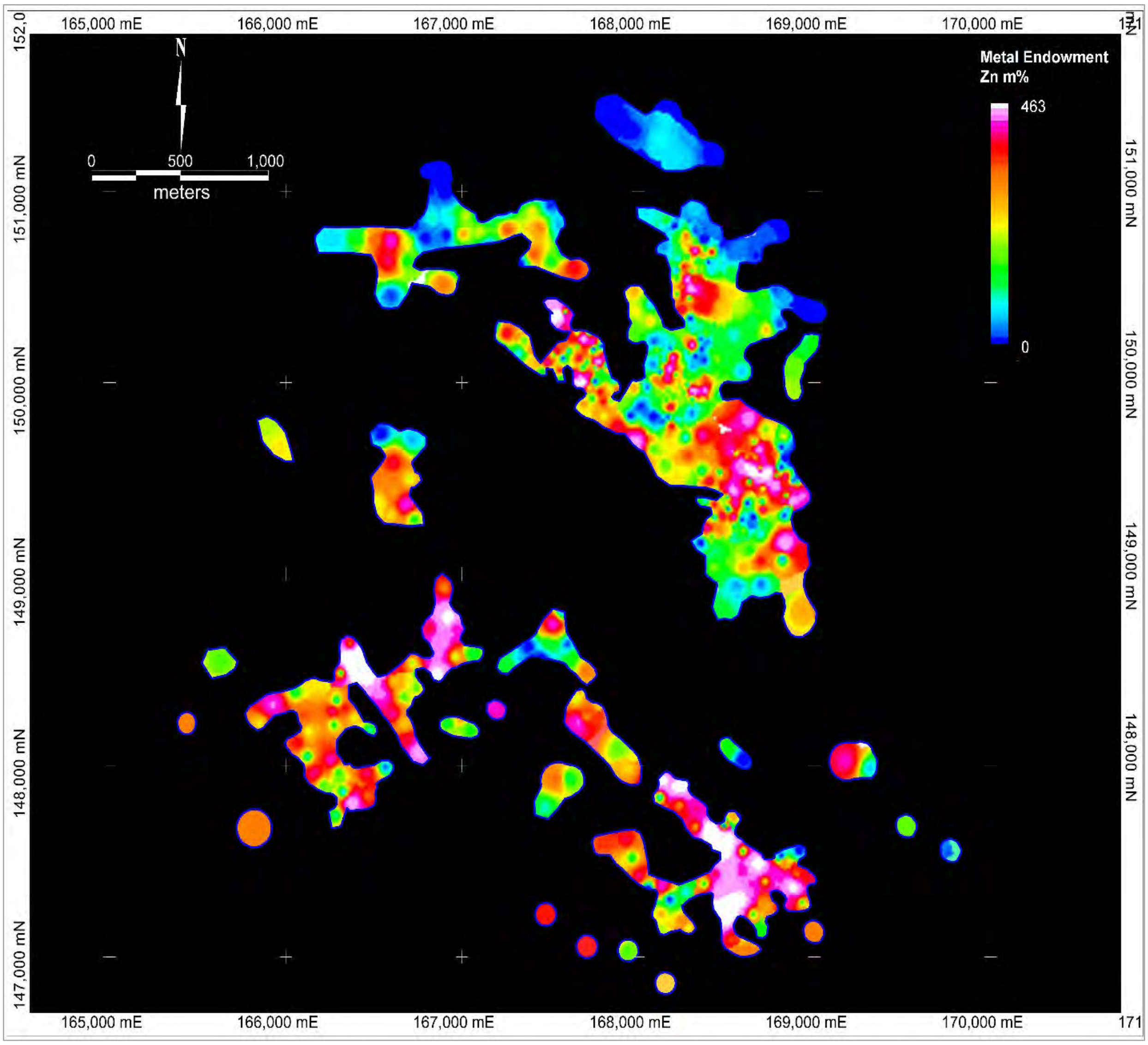

Figure 11: *Metal Distribution Zn (m%).*

disseminations and as disseminated, euhedral, crystalline blebs or with a coarsely crystalline aspect hosted by veins or stringers and within cavities. It tends to form anhedral masses in massive sulphide zones. The grain size of galena is often greater than the sphalerite it has inter-grown with. Occasionally a galena-rich zone, associated with massive pyrite, may be developed above the main body of sulphide mineralization.

The tenor and thickness of mineralization is extremely variable across the Pallas Green deposit. The thickness of the sulphide horizons can range from a few centimetres up to 70m and can contain up to three individual high-grade Zn-Pb sulphide lenses, which can often be correlated laterally for hundreds of meters. The upper and lower contacts between massive sulphides and host rocks are either sharp with sulphides terminating along a stylolite, a thin shale lamina, a basaltic sill or can be gradational with massive sulphides grading into disseminated or vein-controlled sulphides over several metres. Generally, the massive sulphides are found close to the small controlling feeder faults and grade outwards to vein and disseminated sulphides on the periphery of the lens.

A model of the grade thickness of the total sulphide at Pallas Green (Figure 10) has been used to model the incidence of basal Waulsortian-hosted mineralization across the region. The distribution of sulphides shows particularly thick zones within the main Caherline Zone which has some of thickest and highest-grade mineralization discovered to date. Caherline has a strong northwest–southeast grain and zinc endowment is best developed to the northeast and southeast of the zone. The Ahnavar Zone has recently been discovered and is the least well-explored zone. Widely spaced drilling has returned a series of individual, high grade, intersections on the northern edge of the zone.

The lead metal endowment plot (Figure 12) shows strong coincidence between zinc and lead enriched zones. However, there are some subtle differences between the zinc and lead

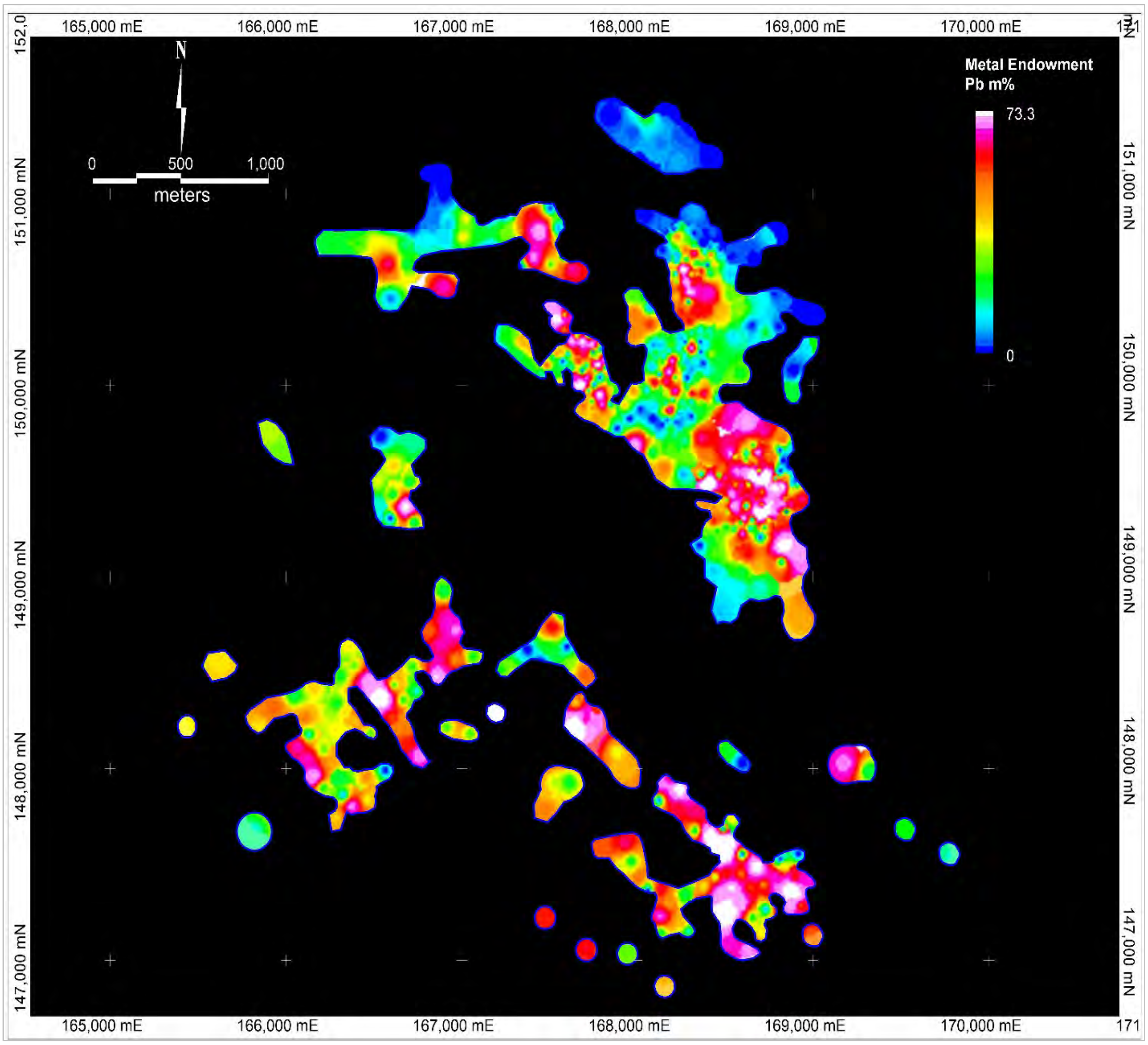

Figure 12: *Metal Distribution Pb (m%).*

plots. The lead enrichment at the Knockroe Zone is quite constrained and concentrated in the central part of the zone. At the Caherline Zone there is an anomalously lead-rich area developed to the north. At the NWEX Zone, the satellite area to the northwest shows an antithetic relationship between low zinc and elevated lead, in this area there is massive pyrite with associated high-grade galena but only minor sphalerite. In order to constrain potential feeder zones a lead:zinc ratio (Pb/(Zn+Pb)) map was generated (Figure 13). It was anticipated that, due to the lower mobility of lead within hydrothermal fluids, relatively higher concentrations of lead will occur proximal to feeder zones. The data shows that distributions across the various zones are complex and points to several epicentres of mineralization within most zones. The northern part of the Tobermalug Zone shows a number of discrete point anomalies that are coincident with some of the development of the thickest sulphide zones. The region to the south of Tobermalug has been confirmed as a major epicentre and feeder for mineralizing fluids. The NWEX Zone has a series of small point anomalies that seem to run at an oblique angle away from the main controlling fault, suggesting discrete, focused feeder zones along smaller subordinate faults. There is a very marked, high lead:zinc ratio in the satellite lens to the northwest of the NWEX Zone, this is related to a phase of relatively weak sphalerite mineralization associated with well-developed pyrite-galena mineralization. The plot for the Knockroe Zone indicates a single, very constrained anomaly in the centre of the zone, located along a northwest-southeast trending fault-controlled extension. A second feeder zone is defined at the extreme southwest of the zone, suggesting that the mineralizing fluids are controlled by northwest-southeast faults and have migrated away from the feeders to the northeast. The Caherline Zone has two very well-defined lead:zinc ratio anomalies to the southwest and the south along the margins of the massive sulphide mineralization. In the Ahnavar area there are generally low to mid order values suggesting the mineralization intersected to date is somewhat distal to the feeder zones.

A paragenetic sequence (Figure 14) is proposed for the Pallas Green deposit based upon cross-cutting relationships observed

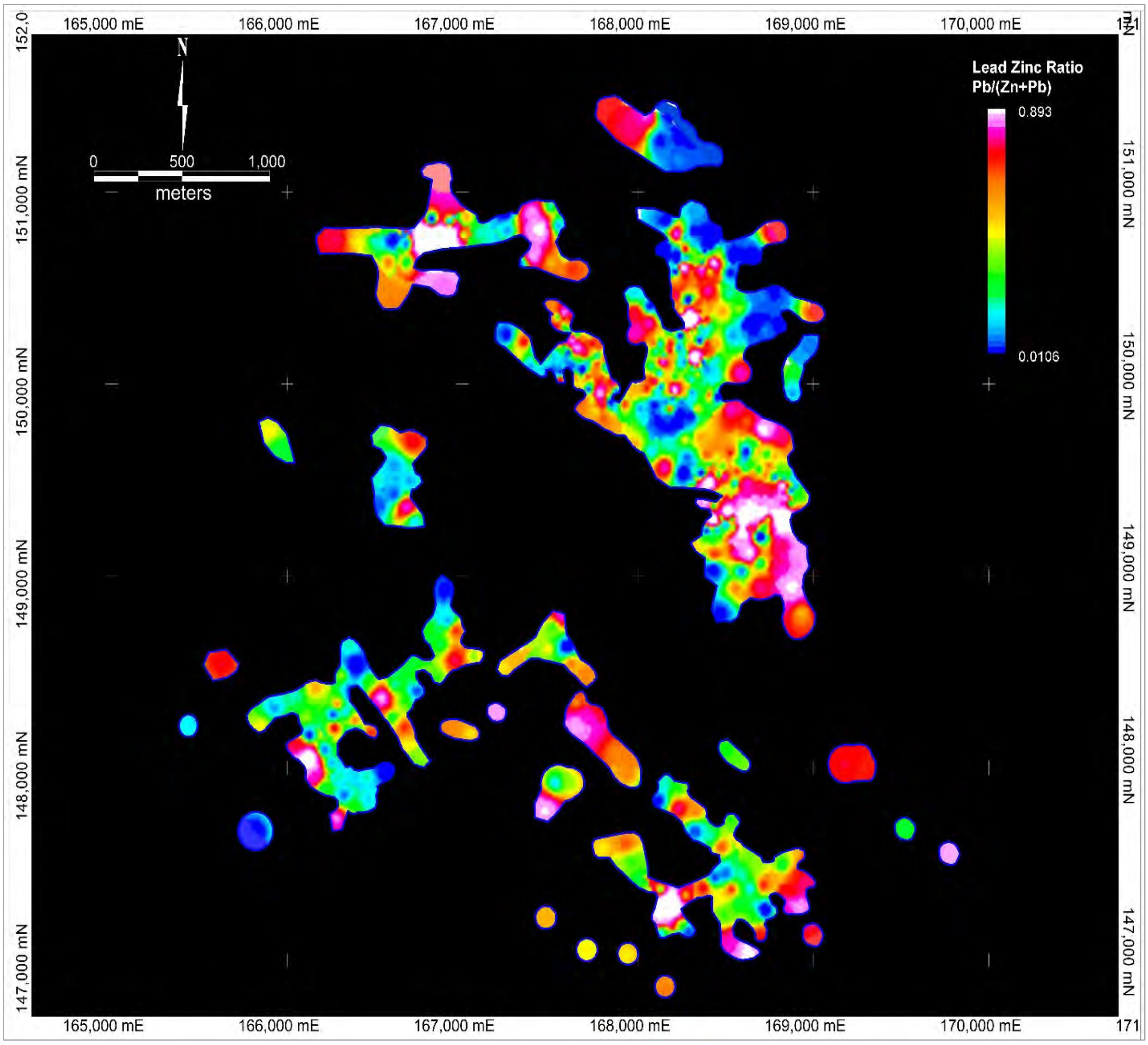

Figure 13: *Metal Ratio - Pb / (Pb+Zn).*

in hand specimens. It is broadly similar to the other Irish deposits and can be summarised as follows: 1). Pre-sulphide carbonate precipitation, 2). Iron sulphide deposition, 3). Sphalerite deposition, 4). Mixed sulphide deposition (sphalerite, galena and pyrite) and 5). Late carbonate precipitation. The timing of the mineralization is the subject of some debate. The diatremes and dykes cross cutting the Waulsortian Limestone Formation at Pallas Green are thought to be age-equivalent to the overlying Knockroe Volcanic Formation and of Chadian to early Arundian age. The dykes are incorporated into, crosscut, and cap ore-hosting breccias, this suggests that dyke and diatreme emplacement spanned breccia and ore formation. It is worth noting that at Pallas Green no xenoliths of sulphide mineralization occur within the diatremes, however, brecciated, aphanitic, trachytes located in the root system of the diatremes can be brecciated, with partial replacement of the matrix and clasts by sulphides. The trachyandesitic porphyritic dykes, intersected within the footprint of the mineralizing system have all lost their magnetic signature, and are often brecciated, and crosscut by stringers and replacement style, fine-grained, pale grey, sphalerite, pyrite and minor galena.

Alteration

Hydrothermal alteration at Pallas Green is similar in style to other Irish-type zinc-lead deposits and primarily consists of dolomitization of the Waulsortian Limestone Formation. Dolomitization in the Pallas Green area is divided into an early event that formed non-ferroan dolomite, termed “regional dolomite”. The regional dolomite has preferentially replaced the fine-grained, micritic portion of the Waulsortian Limestone, which generally displays relic sedimentary textures. The regional dolomite forms tabular horizons, generally developing at the middle and top of the Waulsortian Limestone. The regional dolomite can also form small discontinuous lenses of partial dolomitization throughout the upper half of the Waulsortian Limestone Formation. Regional dolomite commonly displays a fine vuggy texture, suggesting that regional dolomitization resulted in an increase in the porosity and permeability relative to undolomitized Waulsortian Limestone Formation. Hydrothermal dolomite and dolomite matrix breccias at the Pallas Green deposit are similar to the hydrothermal dolomite breccias described at other Irish-type Zn-Pb deposits.

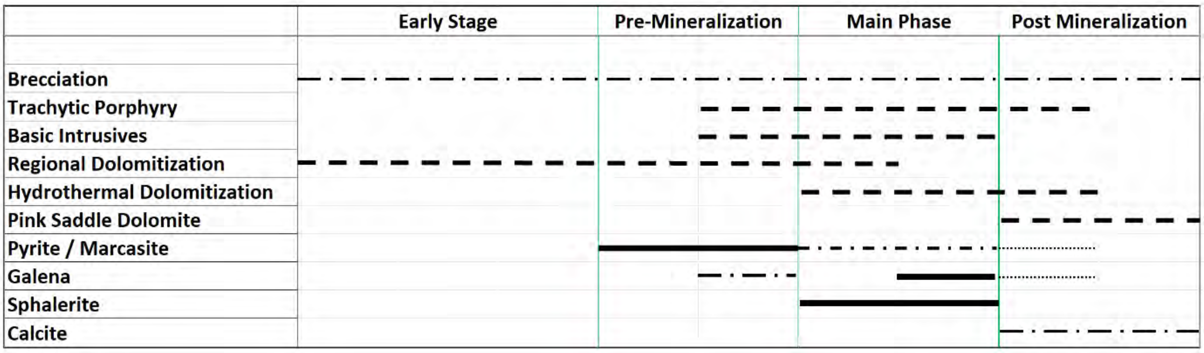

Figure 14: *Paragenesis of the Pallas Green Deposit*

Late stage, crosscutting, coarse-grained pink ferroan dolomite forms steeply dipping veins and breccia zones that cut earlier dolomite phases. The pink dolomite has a saddle habit and can form individual crystals up to 5mm in diameter. Pink dolomite breccias often contain vugs up to 10cm in diameter lined with the saddle dolomite crystals, often with small, isolated crystals pyrite or rare chalcopyrite. Such pink dolomites are observed at many locations across the Irish Orefield and are always late stage.

Hydrothermal silicification is a minor phase of alteration and it tends to be developed in the hangingwall, adjacent to normal faults close to the base of the Waulsortian Limestone Formation, and in some Waulsortian Limestone Formation equivalent facies. It occurs as a very fine-grained, partial to total replacement of the host rock with good preservation of primary sedimentary textures.

Conclusions

This paper has described the volcano-stratigraphy, structural framework, alteration, mineralogy, and paragenesis of the Pallas Green zinc-lead deposit. The Pallas Green Deposit is a variation on the theme of "Irish Type". The deposit displays broad similarities with other Waulsortian Limestone Formation hosted deposits in the Irish Orefield, in terms of stratigraphical setting, ore-hosting breccia textures and sulphide mineralogy. However, there are a number of important differences, including a close association with igneous rocks, the huge scale of the ore-hosting breccia bodies, and the absence of large-scale domain boundary faults controlling the mineralizing system.

The distribution of the thickness, grade and metal endowment of mineralization displays a very well developed, conjugate, northeast-southwest and northwest-southeast grain. This pattern is analogous to Caledonian structural orientations and is considered to be evidence supporting the association of the Pallas Green mineralization with reactivated Caledonian faults. The structural interpretation, based on drilling offsets and indirect evidence such as facedip modelling, confirms that no large-scale faults controlling the mineralizing have been discovered to date. The controlling faults delineated to date are thought to be 2nd or 3rd order structures, with displacements of less than 50m. It is considered unlikely that faults of this scale would have the ability to extend into the basement to tap into a hydrothermal convection cell and act as a main conduit for mineralizing fluids.

Diatremes are a significant component of the geological setting of the Pallas Green deposit. The overall impact they have had on the development of the mineralizing system is the cause of some debate. It has been postulated that the diatremes at the Stonepark deposit may have acted as the main feeder systems for metal rich mineralizing fluids (Elliott *et al* 2018). Alteration within the diatreme, BMB distribution, sulphur isotope data and grade distribution are cited as evidence that the diatremes are the fundamental control for the hydrothermal fluids. If the diatremes are acting as the main conduits for the mineralizing fluids, then it would be expected that "bullseye patterns in the thickness and distribution of breccias and metal endowment would develop around and be centred on the diatremes". As can be seen from the evidence presented in this paper, both the breccia thickness and metal endowment display linear and elongate patterns, that parallel the main structural grain. The diatremes studied at Stonepark (Elliott *et al* 2015, 2018, & Kerr 2013) exhibit dolomitization, oxidation and alteration of the lower part of the structure. The basal part of the diatremes at Pallas Green do not exhibit a similar alteration pattern, in fact oxidation is often present in the upper zones and interpretated as being related to sub-aerial exposure. However, there is crosscutting brecciation and mineralization of trachytic intrusions in the basal root zones of the diatremes suggesting they had been intruded just before the mineralization. It is considered probable that faulting is the fundamental fluid control for the Pallas Green region for both hydrothermal and magmatic fluids and given the close temporal and special association they are likely to be overprinting each other. The diatremes, violently intruding into the rock mass will access zones of low pressure or weakness along the active, dilatant, extensional faults and as such diatremes can be used as an indication of fault zones that were active during the Chadian to Arundian.

The breccias hosting the mineralization at the Pallas Green deposit have strong similarities to breccia systems developed at other deposits, in particular Lisheen and Galmoy (Fusciardi *et al*., 2003; Doyle, 1992), and Silvermines (Andrew, 1986). The scale of the breccia systems at Pallas Green are very large, with maximum thicknesses of up to 225m and developed over a surface area of at least 18km^2. It is highly likely that influence of magmatism has significantly contributed to the development of such extensive brecciation, by adding energy to the hydrothermal system, contributing chemicals such as acid forming volatiles, and various mechanisms associated with intrusive

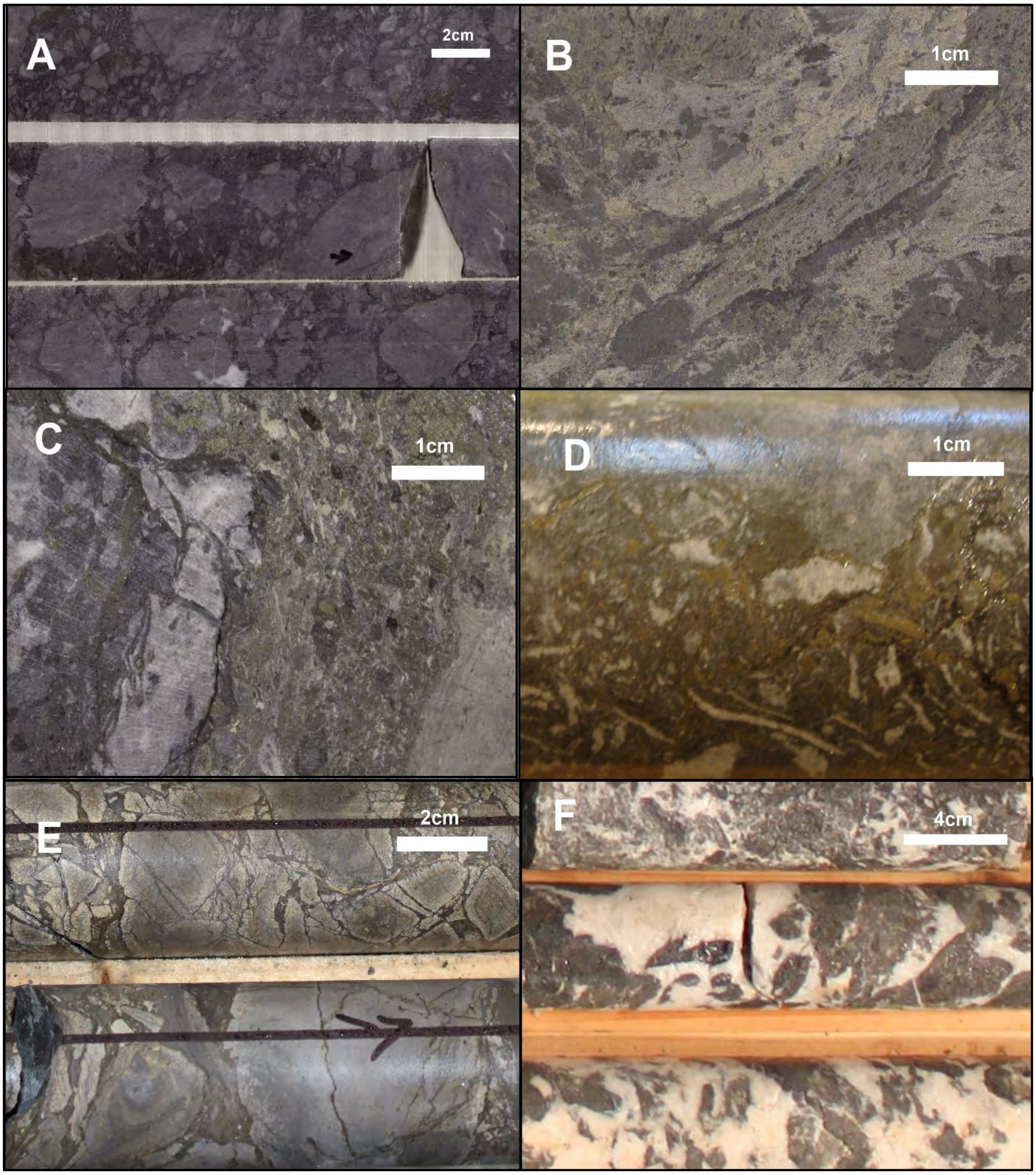

Figure 15: *Breccia Photograph collage;* ***A.*** *BMB variably matrix and clast supported, poorly sorted, carbonate clasts in a dark grey / black dolomite matrix,* ***B****. PMB irregular vesicular clasts of altered basalt, with plastic deformation, small rounded clasts of micrite in an intrusive matrix,* ***C****. PMB discrete clasts of BMB, sub-angular clasts of fine grained altered basalt, in agranular pyritic matrix,* ***D.*** *Vermicular breccia, elongate contorted clasts of dolomite -partially replaced by pyrite in a dark grey dolomite / argillite matrix,* ***E****. Brecciated / altered trachyte angular clasts with bleached margins partially replaced by pale, fine grained sphalerite in a dolomite pyrite matrix,* ***F****. WMB angular clasts of Waulsortian micrite in a white/cream coarsely crystalline dolomite matrix.*

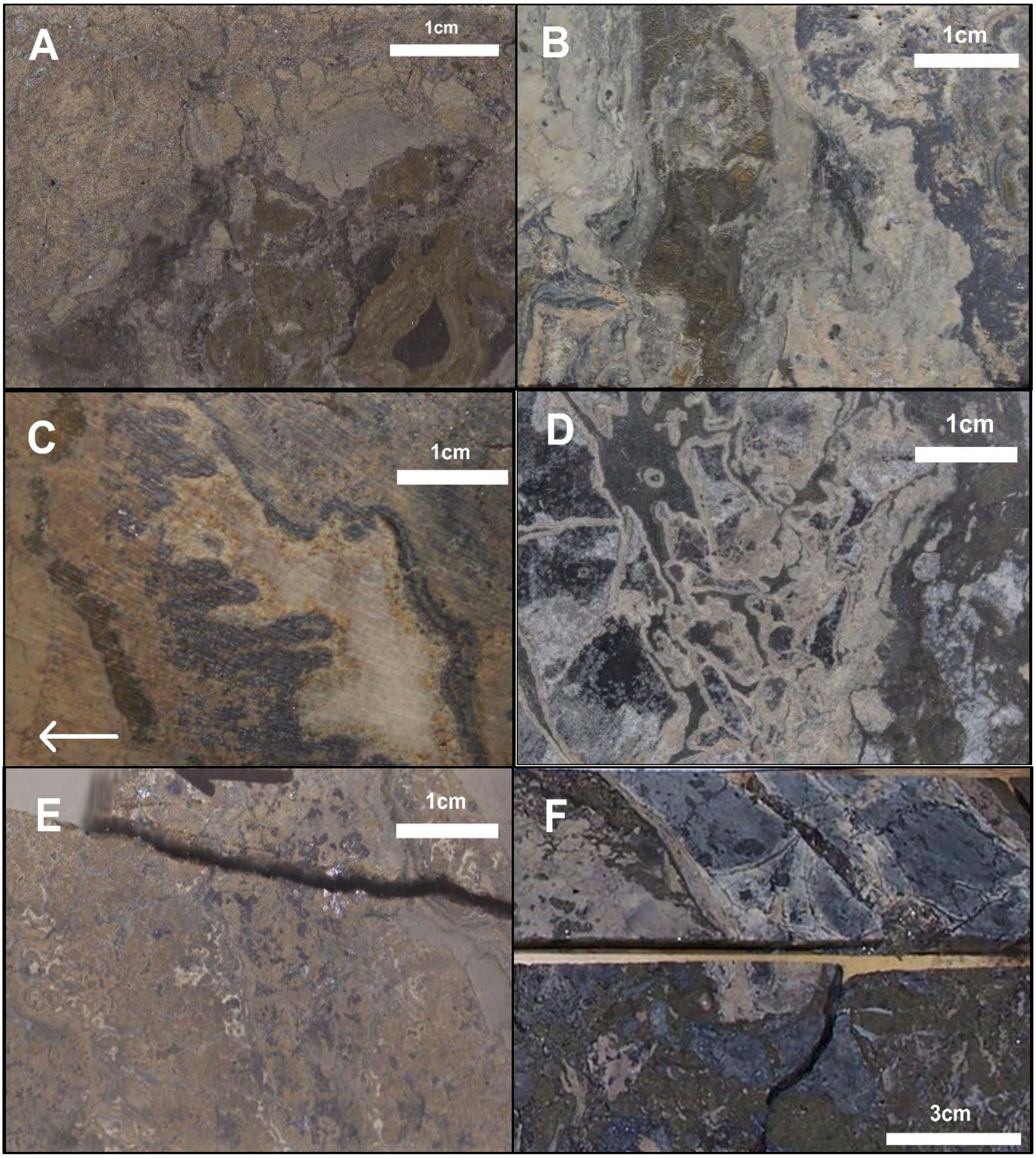

Figure 16 : *Mineralization Photograph collage;* ***A.*** *crackle brecciated light orange brown / tan coloured, fine grained sphalerite, relic laminated, collomorph pyrite in bottom left,* ***B****. Very fine grained pale sphalerite with relic clasts of multiphase pyrite, left side of image is collomorph banded galena,* ***C.*** *Massive, fine grained pale grey brown sphalerite, Dolomite filled cavity with stalactitic galena developed on roof of cavity (arrow showing way up),* ***D****. Clasts of carbonate with millimetric scale pale brown, fine sphalerite rims and partial replacement of the matrix by pyrite,* ***E.*** *Finely collomorph brown, fine-grained sphalerite, with euhedral galena and late-stage creamy dolomite,* ***F.*** *Clasts of porphyritic trachyte, partially replaced and rimmed by pale brown / grey fifine-grained sphalerite, in a matrix of fine grained pale brown sphalerite and partially replacing pyrite.*

activity, such as steam fronts. Breccias are an essential precursor to and control of the mineralization, there are significant zones of unmineralized breccias, however, there are no instances of mineralization of unbrecciated host rocks. The breccias are the essential and fundamental ground preparation phase, and they act as both fluid conduits and as the sites of sulphide deposition. They have acted as highly permeable zones facilitated the migration of both mineralizing fluids and magmas. The breccia systems are complex, primarily focused with the Waulsortian Limestone Formation and extensively developed across the entire region.

During the Chadian to Arundian-aged Knockroe volcanic event, the Pallas Green region would have been subject to high heat flow and an elevated geothermal gradient. Magmatic heat may have been an important component of ore-related hydrothermal fluid flow in the region. Excess heat and energy in the system may explain the scale of the system, contributing to a relatively long-lived event and the multiple overprinting of multiple phases of brecciation and mineralization seem within different parts of the deposit, and particularly well-developed to the north of the Tobermalug Zone and the Knockroe Zone. The igneous activity, rather than being the cause of breccia development and mineralization, instead served to enhance its development.

influence of Chadian palaeo-seafloor topography on facies type and thickness distribution of the Knockroe Volcanic Formation is of particular relevance for the exploration programme. The primary pyroclastic falls and gravity-driven debris flows moving into the water from the volcano's steep-sided flanks were controlled by the seismically active, syn-volcanically faulted seafloor. The final spatial distribution of volcanic facies was partly controlled by pre-existing seafloor topography, which was in turn, at least partly, controlled by syn-volcanic faulting. Detailed three-dimensional mapping of the Knockroe Volcanic Formation is facilitating mapping of the Chadian seafloor topography and locating faulting likely to have been active during the Chadian.

The impact of the magmatism does not appear to have influenced the mineralogy of the deposit. It is strikingly similar to many of the Irish Orefield deposits, being relatively simple, and comprising mainly pyrite, sphalerite, galena, and minor marcasite. In fact, geochemical results to date show no relative enrichment of metals that would be expected to be associated with a hotter hydrothermal system, such as silver, copper, or nickel. This may be due to the nature of the metal endowment of the underlying basement source rocks, or an indication that the Pallas Green deposit is in fact distal to its fundamental structural control, where higher tenor, thicker mineralization with significant copper, silver and nickel may occur. An alternative hypothesis suggests that the Pallas Green region could be subject to vertical zonation, and a copper-silver deposit, analogous to Gortdrum, is located in the Lower Limestone Shales Group or ORS stratigraphically below the zinc-lead mineralization.

The Pallas Green deposit is an exciting addition of the Irish Orefield stable of deposits. The unusual spatial and temporal coincidence of a large hydrothermal system with a volcanic centre has produced an atypical deposit with many unique characteristics. Work on furthering our understanding of this deposit is ongoing and further research, particularly; fluid inclusion, sulphur isotope, breccia morphology and lithogeochemistry and petrophysics is in progress.

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