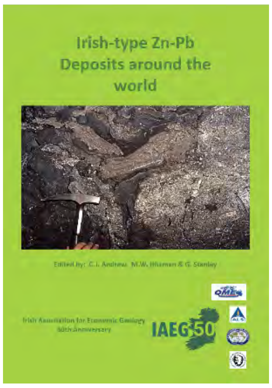

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A mineral system approach to the East Clare Syncline – integration of seismic profiles and potential field processing with drilling data at Kilbricken deposit and beyond

Finbarr C. Murphy[1], Lars Dahlenborg[2], Michael Hudson[2] & Glenn Morgan[3]

[1] *Fractore Pty Ltd, 91 Fenwick St, Carlton North, Melbourne, Victoria, 3054, Australia.*

[2] *Hannan Metals Ltd, 1305 1090 West Georgia Street, Vancouver V6E 3V7 BC Canada.*

[3] *Morgan Seismic Services Pty Ltd, Brisbane, Queensland, Australia*

Corresponding Author: Barry Murphy fcm@fractore.com

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Abstract: This paper considers some broad scale aspects of the mineral system and its application to exploration in the East Clare Syncline. With existing mineral resources defined at Kilbricken, the exploration for further ore bodies has extended to other fertile areas through application of high-resolution seismic reflection profiles and detailed ground gravity. The seismic data has been calibrated against drilling constraints. Processing of the gravity using edge detection routines (worms) has allowed a refined integration with the seismic profiles. Examples are shown where the dips of seismic defined faults correlate with the inferred dip direction of gravity gradients. The inference is such gradients may be applied as indicators of fault dip, in the absence of seismic or drilling constraint. Beyond Kilbricken, the southern limb of the East Clare Syncline is shown to be controlled by a major north dipping fault, the Kilmurry Fault. This shows evidence for extensional faulting, alteration and mineralization in an analogous position to Silvermines, Pallas Green/Stonepark, Galmoy and Lisheen. Further drilling is planned to test a high amplitude seismic reflection signal, possible massive sulphides, in the hanging wall of the fault.

Keywords: East Clare Syncline, Kilbricken, high-resolution seismic profiles, growth faults.

Introduction

The Irish Carboniferous contains more zinc per km^2 than any other province, globally (Penney *et al*. 2004). Why it is so well endowed is a matter of ongoing scientific endeavor (Wilkinson & Hitzman 2015). Where the next orebody might be found holds the attention of explorers. As a mature region, a key metric is how many orebodies remain at explorable depths. Over decades, there has been extensive exploration, with drilling to increasingly greater depths of investigation, and with more reliance on potential field and seismic data. Few hard rock areas in the world have such a richness of geological and geophysical data sets.

The East Clare Syncline has several permissive elements for hosting major zinc deposits being in a similar setting to known deposits in the region (Silvermines, Pallas Green – Stonepark and Tynagh) and has preserved Waulsortian host rocks and basement reactivated fault structures. The Kilbricken discovery (Figure 1) is evidence of the mineralizing process operating in the area. Beyond the Kilbricken deposit, Hannan Metals have undertaken an ambitious, regional scale programme of geophysics and drilling, exploring new areas to depth, the results of which are described below. This work has led to a refined structural architecture and identified new target areas. We adopt a mineral system analysis (Wyborn *et al*. 1994) in the first instance, taking a broad scale approach to the multiscale factors that combine to result in the formation of an ore deposit, a methodology further refined by the Predictive Mineral Discovery*CRC (www.pmdcrc.com.au).

Five key questions are considered briefly below with respect to the Irish zinc province, as a backdrop to exploration in the East Clare Syncline.

What is the regional setting?

The Irish zinc Orefield is, broadly, a carbonate-dominated platform that passes southwards into the clastic-dominated South Munster Basin (Phillips & Sevastopulo 1986). This was a Devonian to Carboniferous basin in a foreland position with respect to the evolving Hercynian (Variscan) orogen in continental Europe (Sanderson 1984). This platform overlies a Caledonian (pre-400Ma) basement that had a complex evolution involving closure of the Iapetus oceanic basin, with Ordovician forearc and back-arc environments that transitioned to a

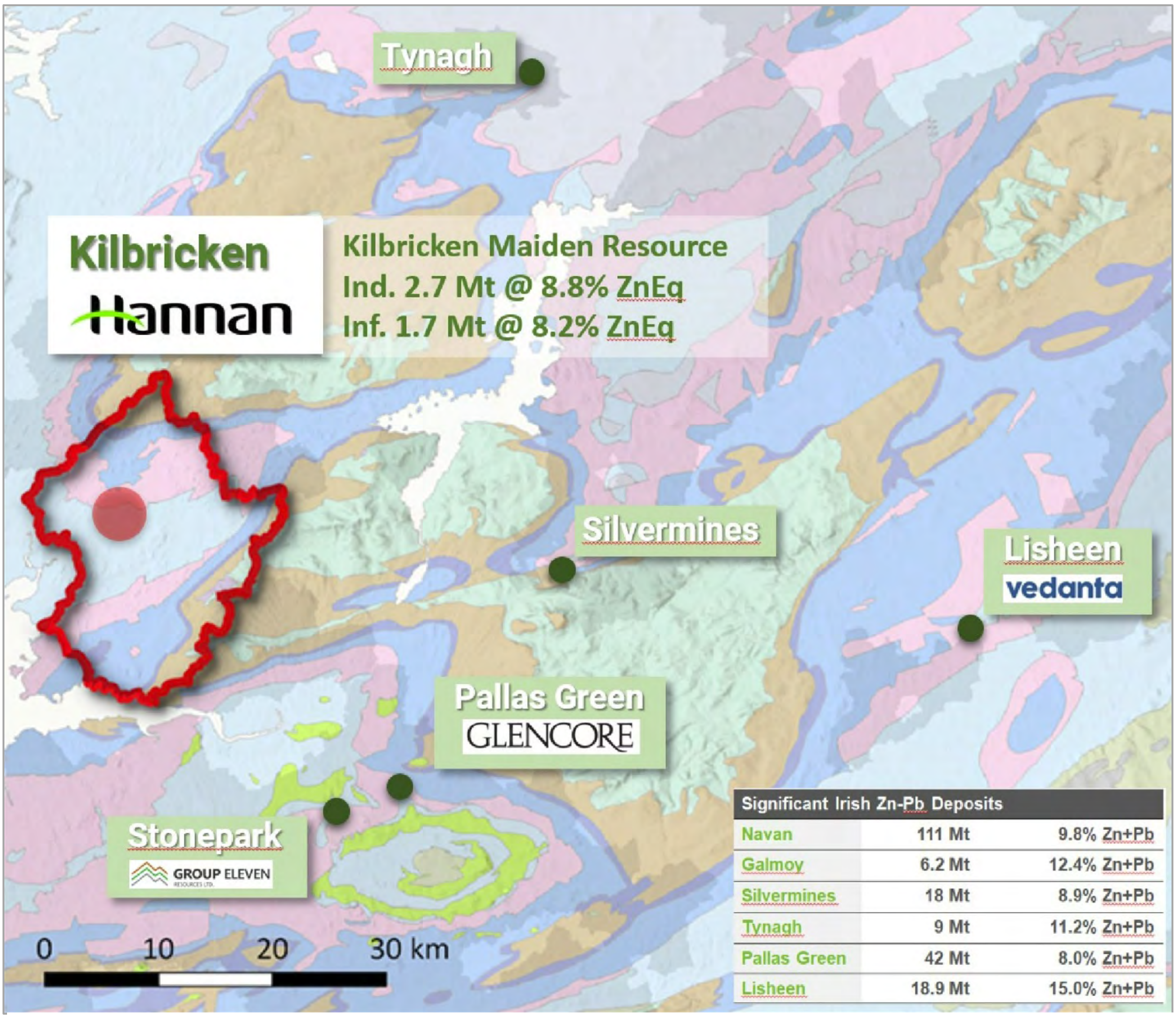

Figure 1: *Regional geology Irish midlands and location of Hannan Metals Clare project.*

Silurian successor basin (Hutton & Murphy 1987) culminating in early Devonian orogeny. The suture zone comprises fault bounded blocks in an anastomosing system, with the Navan-Silvermines Fault (Phillips *et al.* 1976) as a dominant element, in a family of terrane-bounding structures (Todd *et al.* 1991). The zone has an arcuate trace through Ireland and seismic reflection profiling (Brewer *et al.* 1983) shows a north-dipping detachment zone. In addition, late-to-post tectonic granitic intrusions were emplaced, being locally of batholithic extent. The variety of possibly metal bearing, fertile rocks in the suture zone, its deep-seated faults and tectonothermal evolution are considered key factors, as metal source rocks, contributing to the richness of the overlying Orefield.

What is the local setting?

The stratigraphy comprises basal red bed sedimentary rocks that pass upwards and northwards to shales (Lower Limestone Shales), followed by Argillaceous Bioclastic Limestones and the Waulsortian limestone mudbanks (Phillips and Sevastopulo, 1986). In the northern part of the platform, the Navan Group is equivalent to the Lower Limestone Shales and are preserved separately from the rocks to the south (Figure 2). The carbonates are, in turn, eventually overlain by Namurian deltaic sediments. The zinc-bearing intervals are often located in hangingwall positions (Johnson *et al.* 1996) towards the base of the Waulsortian and towards the base of the Navan Group (Figure 2).

Historically, basement penetrating faults have been highlighted as conduits for mineralization (Russell 1978; Johnson *et al.* 1996). Such faults underwent reactivation, as growth faults in the early Carboniferous, and locally as compressional structures during the Hercynian (Hitzman *et al.* 1998). Waulsortian-hosted deposits occur in the hanging walls of normal faults that were active during sedimentation, with segmentation across relay ramp zones (e.g., Lisheen, Figure 3; Torremans *et al.* 2018). North-dipping faults appear more mineralized than south dipping faults (Hitzman 1999; Murphy *et al.*2008); the nature of this association remains obscure, either by post-mineral differential preservation (north dipping faults underwent less inversion), or by a more genetic relationship of fault orientation and polarity of fluid flow during mineralization.

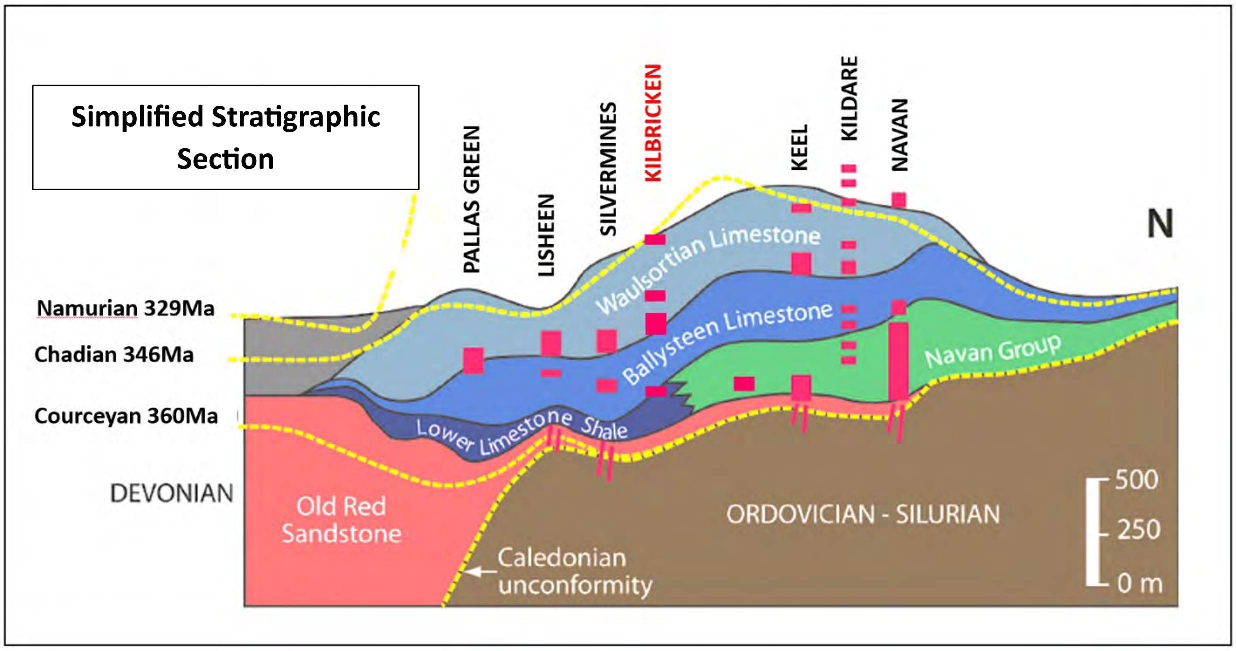

***Figure 2:** Diagrammatic stratigraphic section of the Midlands Platform and South Munster Basin. Red bars indicate stratigraphic positions of mineralization (after Andrew, 1986).*

What are the fluids and their sources?

Isotopic data from selected deposits indicate local basement sources of lead (e.g., O'Keefe 1986). Fluid mixing at the deposit scale has been demonstrated through fluid inclusion studies (Wilkinson 2010). This involved bittern brines that permeated through the basement and subsequently mixed with fluids from shallow levels in the stratigraphy or from surficial fluids drawn down on faults.

What are the fluid flow drivers and pathways?

Lower Carboniferous transtension and rifting is the most accepted driver model, through normal faults undergoingdeformation (re-activation of basement faults). This is supported by the occurrence of primary massive sulphide clasts in conglomerates at Navan, and by dating of some deposits (e.g., Schneider *et al.* 2007).

Late Carboniferous inversion is considered less significant as a driving mechanism (Hitzman *et al.* 1998). Murphy *et al.* (2008) modelled this scenario, where the Lower Limestone Shale acted as a regional seal between two fluid reservoirs and fault breaching of the shale became a locus for fluid flow and mixing to occur. This can occur during extension and/or mild compression. Areas of maximum fault displacement and relay ramps appear important with respect to the location of mineralization (Figure 3; Torremans *et al.* 2018).

What are the metal transport and deposition processes?

Ground preparation is a key aspect of the depositional process, through space filling and replacement (Hitzman *et al.* 1998). This is represented by extensive regional and local scale dolomitization events and by hydrothermal dissolution breccias in the near-ore environment (Hitzman *et al.* 2002). The stratigraphic positions of mineralization (Figure 2) reflect fluid access to the first accessible reactive host sequence above the basement interface allowing fluid mixing.

East Clare Syncline Project

Hannan Metals is exploring for Waulsortian-hosted deposits in the Clare Basin (Figure 4). The target stratigraphy is preserved on either limb of a regional NE-SW trending syncline. On the northern limb, the Kilbricken deposit (Figure 5) has a NI 43-101 indicated resource of 2.7 Mt at 8.8% Zn+Pb and an additional inferred resource 1.7 Mt at 8.2% Zn+Pb. The deposit comprises two main zones of mineralization, 'Chimney' and 'Fort'. Outside of this, there are several historic and emerging prospects (Figure 4) and of these, Kilmurry, on the southern limb of the regional syncline, is considered to have the greatest potential for the discovery of an economically significant zinc deposit.

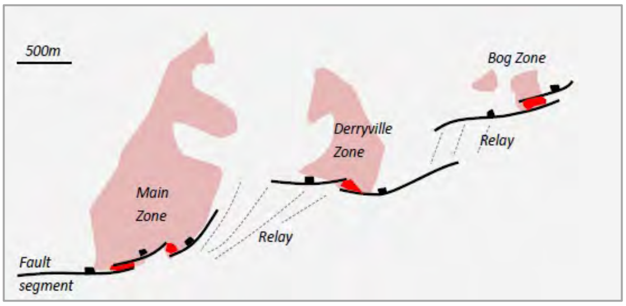

***Figure 3**: Schematic map of Lisheen deposit showing segmentation of ore zones and faults*

(modified from Torremans et al. 2018).

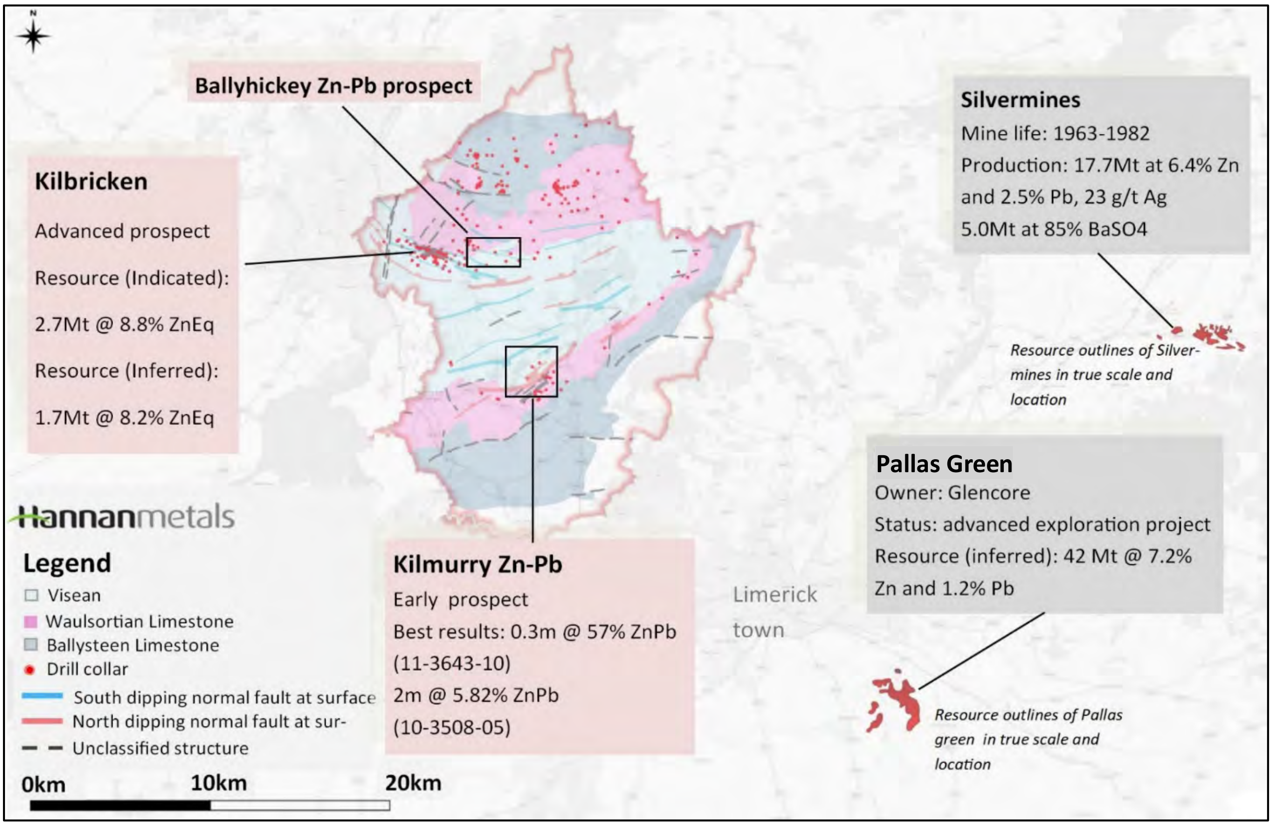

Figure 4: *Geology of the Clare project and surrounding areas with zinc deposits.*

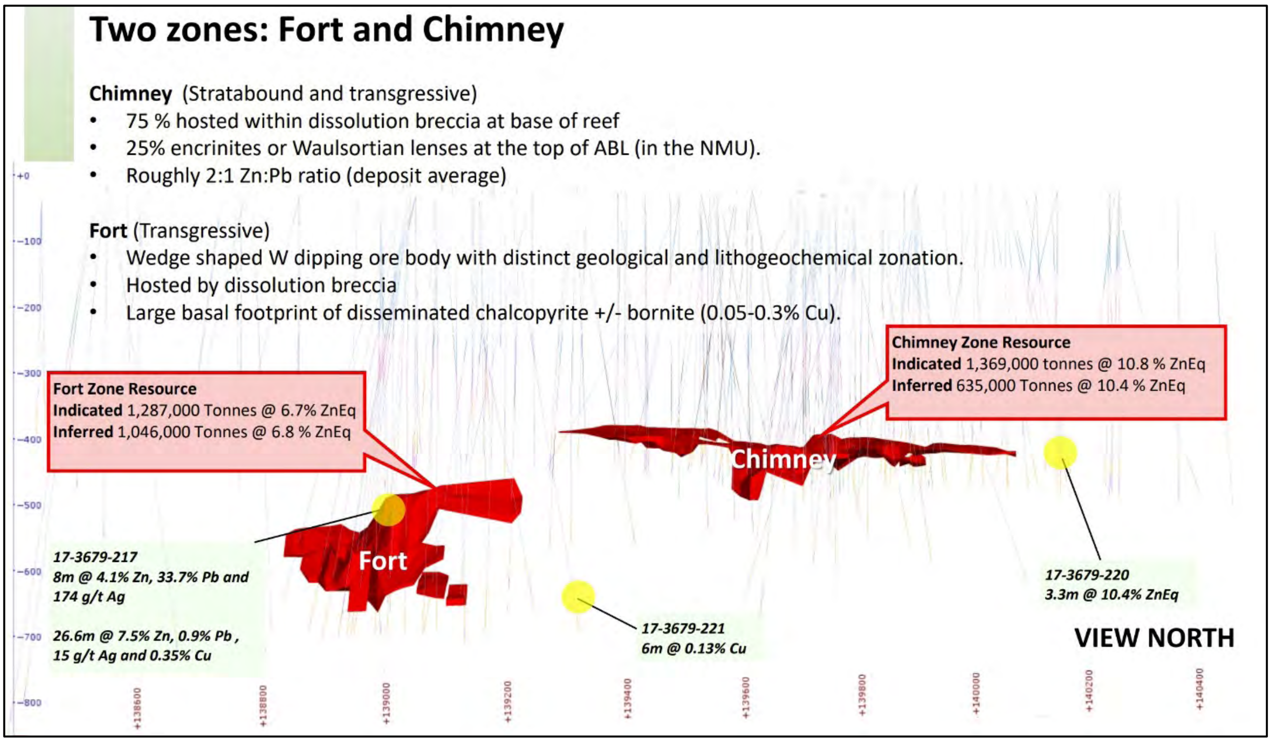

Figure 5: *Long section of the Kilbricken deposit, showing Chimney and Fort zones.*

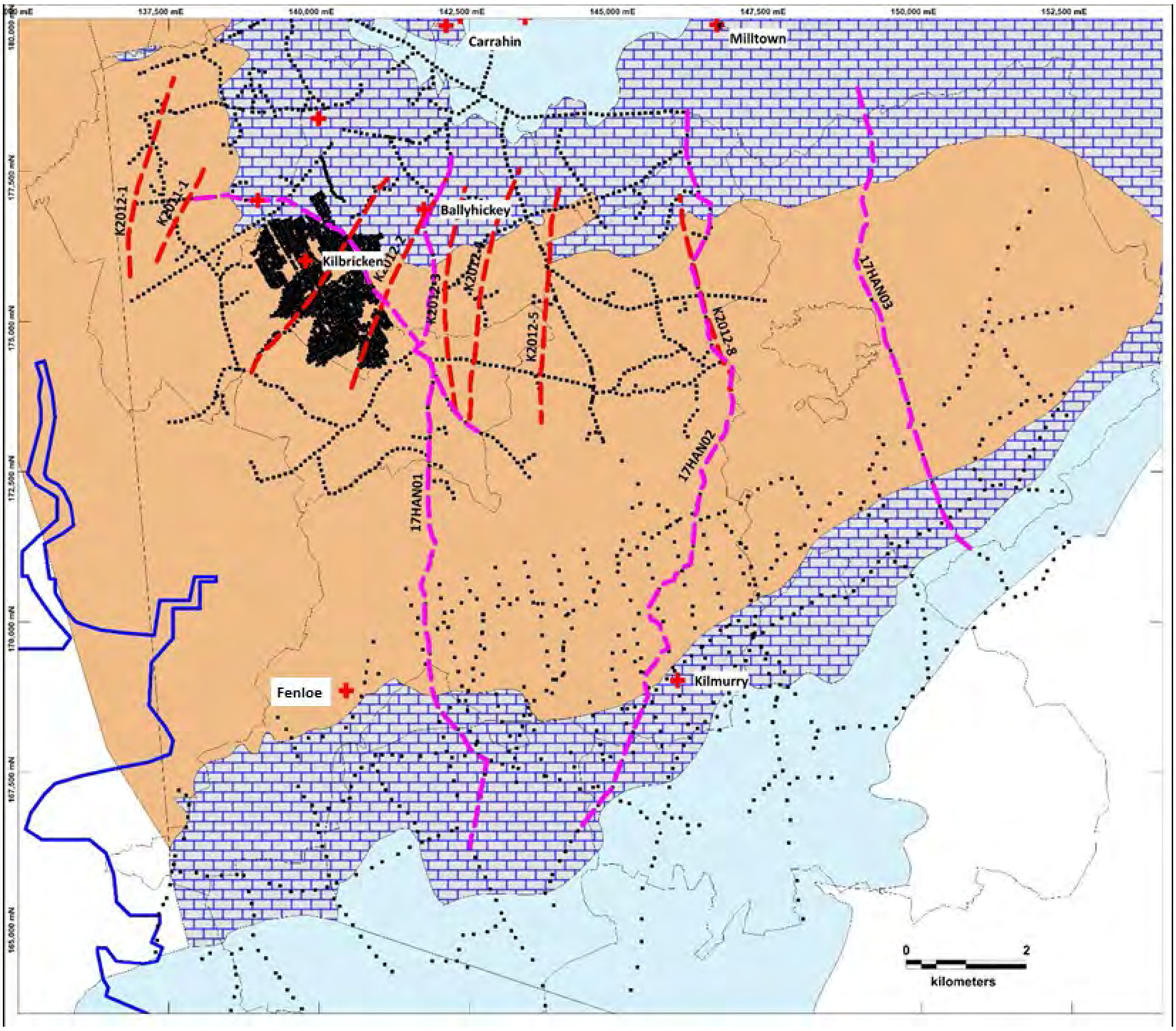

Figure 6: Map of Carboniferous units with gravity stations (black dots) and seismic lines (Red- Lundin, Magenta – Hannan Metals). Blue line – coast, Grey lines – PL boundaries.

Exploration History

Regional exploration has involved mapping, soil geochemistry, drilling, and geophysics. The 19th century 6" sheets by Geological Survey Ireland (GSI) have been especially useful for recording outcrops that are no longer preserved. Historic exploration during the 1960-1980s found shallow prospects along the northern limb, and along the southern limb at Kilmurry. During the 1990's the Milltown prospect was discovered (Figure 6) and airborne magnetic and EM surveys were completed. From 2000-2007, Belmore Resources undertook soil and drilling programmes which led to the Kilbricken discovery hole with massive sulphides. From 2010-2012, Lundin Mining drilled Kilbricken, which established two mineralized zones, and further drilling at Kilmurry yielded encouraging results. Seismic (3D and 2D) and ground gravity surveys were conducted. Hannan Metals purchased the project from Lundin in 2016 and commenced a systematic programme to constrain the geological framework using seismics and gravity as inputs. Hannan commenced drilling at Kilbricken in May 2017 and subsequently completed 16 holes for a total of 7,189.3 metres in the East Clare Syncline. Hannan's drilling initially focused around Kilbricken with many holes intersecting significant mineralization and extending both the Fort and Chimney Zones.

Gravity Surveys

Regional ground gravity DIAS data has been effective in delineating the basement fault architecture in the Irish ore province (e.g., O'Reilly *et al.* 1997). Local surveys, by Lundin and Hannan Metals, augment the DIAS data, for a total of 3500 stations. Gravity station coverage is shown in Figure 6; note a paucity of data in the central and NE part of the East Clare Syncline. The Bouguer data shows a gravity low through the synclinal region, with highs on the northern and southern flanks (Figure 7).

Processing of the gravity employed an automated edge detection routine, called "worms" (Hornby *et al*, 1999; Archibald *et al*. 1999). This helps to reduce ambiguity in determining the

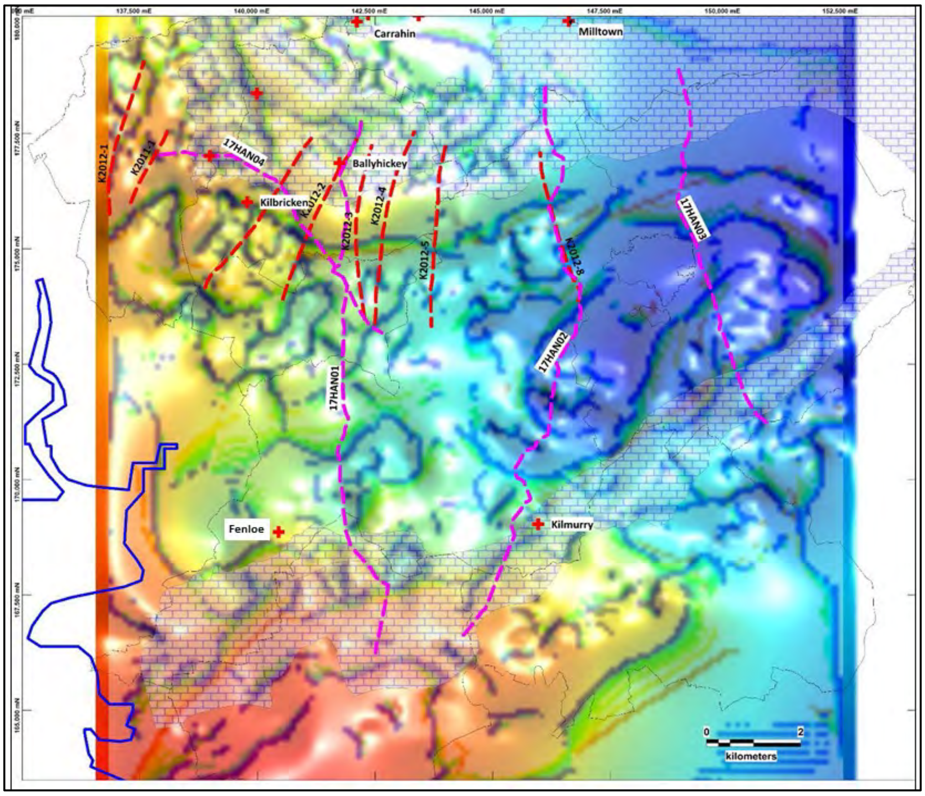

Figure 7: *Bouguer gravity image with superimposed worm traces (blue- near surface, orange – high level). Seismic lines – magenta.*

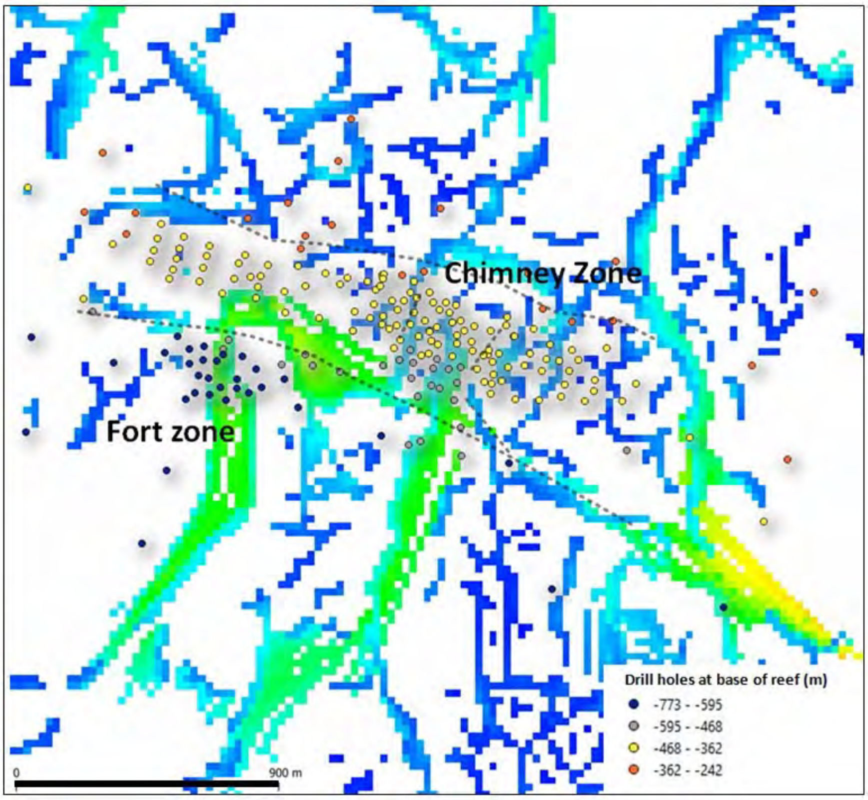

Figure 8: *Detail map of Kilbricken (Chimney and Fort Zones), with drill collars (coloured by depth to base of reef) and with superimposed gravity worm sheets coloured by amplitude. This shows alignment of gradients with southward dipping fault zones.*

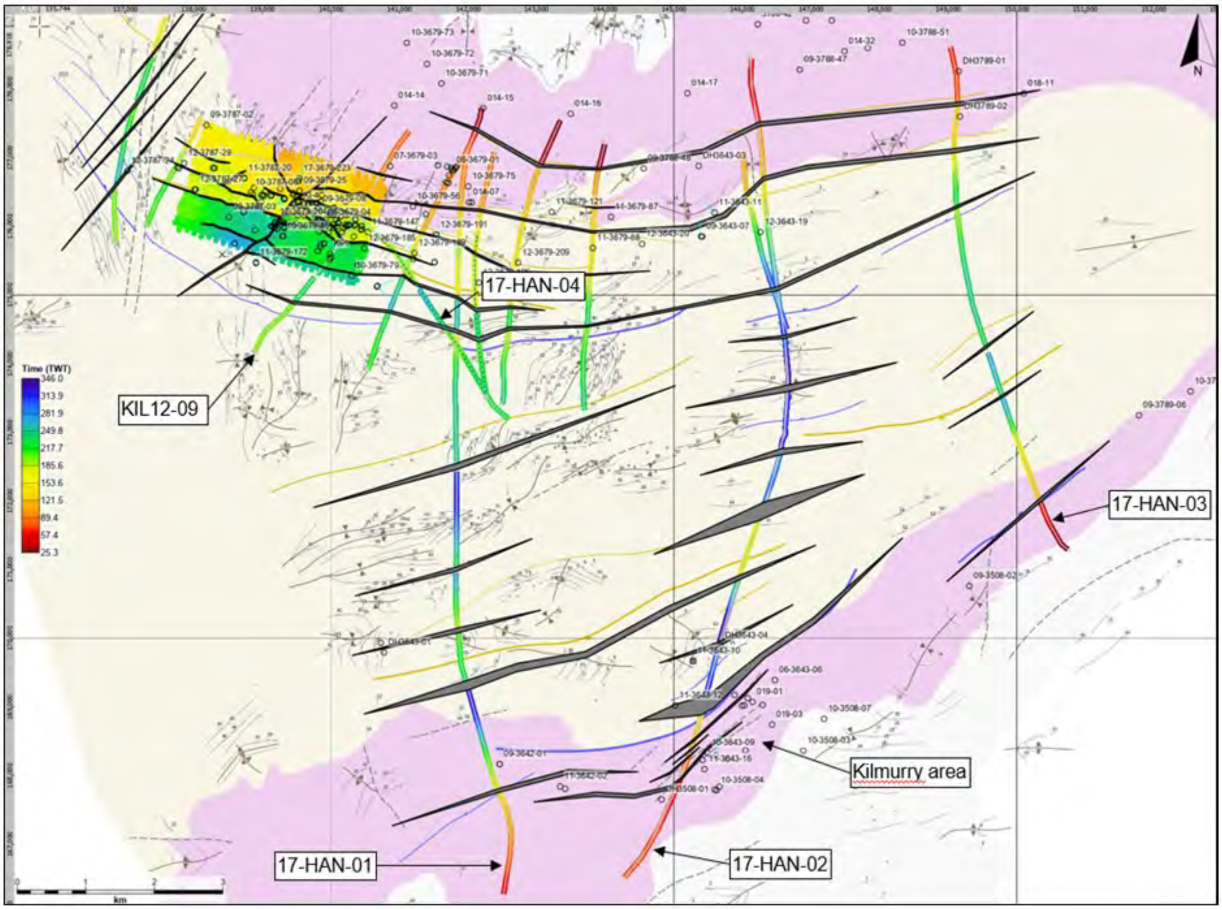

***Figure 9:** Map of seismic lines coloured by TWT "depth" of Nodular Micrite Unit (NMU) and positions of faults detected along the lines. Superimposed bedrock geology and structures.*

positions of gradients and breaks in gradients. The technique generates a 3D point cloud of maximum horizontal gradient across successive upward continued heights above ground. It is important to note that the above ground 3D shapes of worm sheets can mirror image below ground geological features (Hornby *et al*. 1999; Holden *et al.* 2000) and can inform the interpreter of the apparent dip directions of significant faults in 3D. In the East Clare data, several linear gradients are interpreted as related to fault structures and other contacts in the basement and cover rocks.

The worm data (Figure 7) has picked a number of mostly NE-SW trending gradients that characterize the change in gravity signature on either limb and strongly supports a fault control along either margin. At the Kilbricken deposit, detailed gravity allows the variation in gravity worm amplitude (a measure of strength of contrast across a gradient) which closely follows the main faults controlling the deposits (Figure 8). This observation is important as hard data from dense resource drilling provides strong geological control to the interpretation.

Seismic

Seismic surveys have been used in the exploration for metalliferous deposits in Ireland for many years.The most notable example of this was at the Boliden Tara Mine, where seismic surveys played a key role in the discovery of the Tara Deep orebody in 2012 (Ashton *et. al.*, 2018). In 2017, Hannan Metalsacquired 41-line km of 2D seismic data across the Clare project (Figure 6). This seismic survey comprised four lines (17-HAN-01, 17-HAN-02, 17-HAN-03 and 17-HAN-04) and added to the existing 27 line-km of 2D and 5 km^2 of 3D seismic data previously acquired by Lundin over the Kilbricken area. The seismic surveys provide a regional subsurface dataset that has enabled the structural architecture of the area to be better understood, and the fault positions and dips to be better defined. This is shown in map view (Figure 9) and seismic profile section (Figure 10).

Overall, the data quality of the 2017 seismic data was fair, but coherent seismic reflector packages are present across most of the seismic lines to guide horizon interpretation, and reflector discontinuities were present throughout the sections to guide the fault interpretation. Figure 10 shows seismic line 17-HAN-02 with the horizon and fault interpretation. The Nodular Micrite Unit (NMU) at the base of the Waulsortian Limestone and Transition Unit (TU) into shelf sediments above the Waulsortian, are the main marker horizons that could be mapped. The significant number of drill- holes in the area provided calibration points for seismic interpretation. The 2D seismic data enabled the location and dip of the faults to be determined in section view (Figure 10). To determine the strike and likely lateral extents of the seismic faults, the seismic interpretation was integrated with the bedrock mapping data (Figure 9)

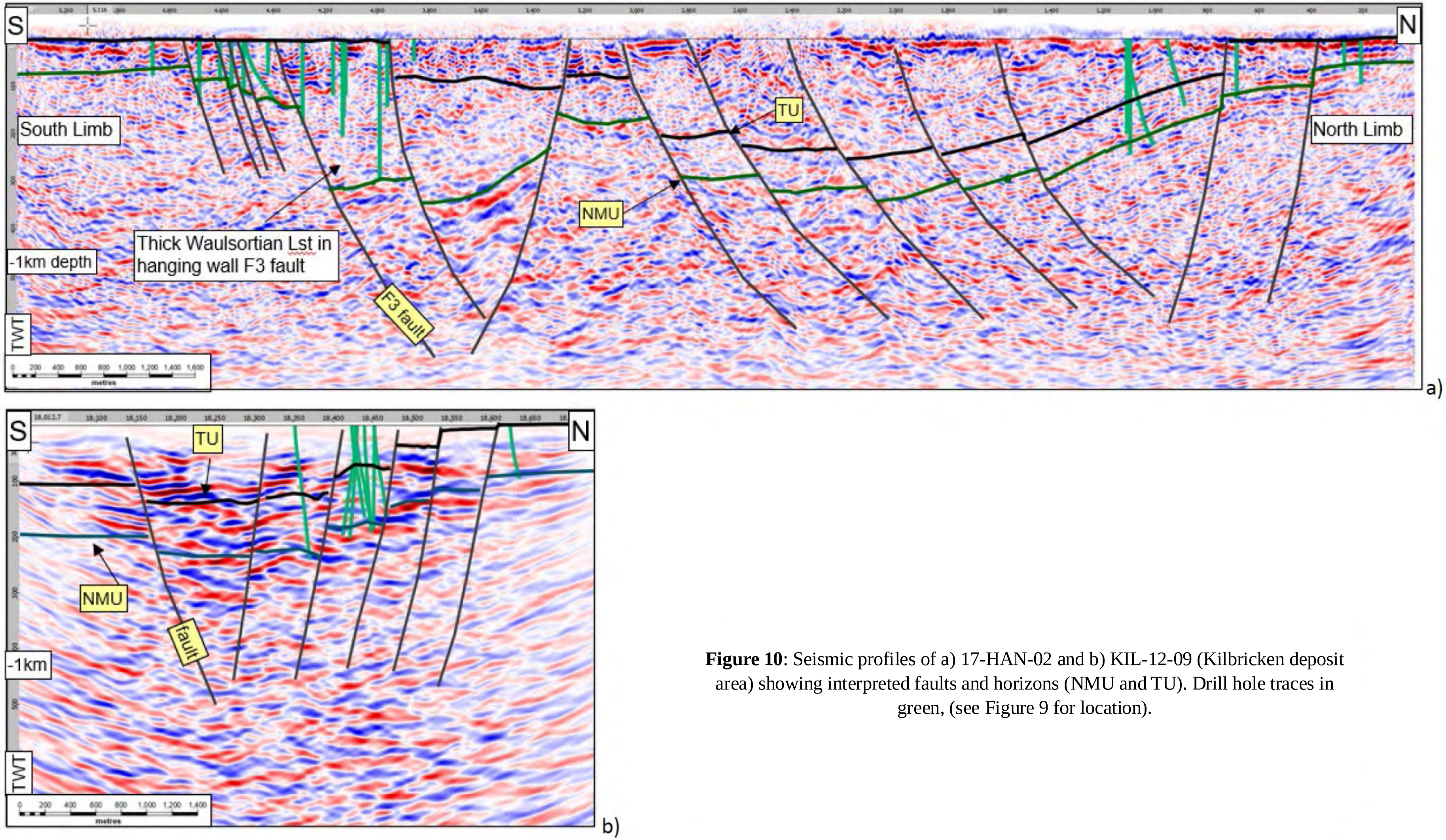

Figure 10: Seismic profiles of a) 17-HAN-02 and b) KIL-12-09 (Kilbricken deposit area) showing interpreted faults and horizons (NMU and TU). Drill hole traces in green, (see Figure 9 for location).

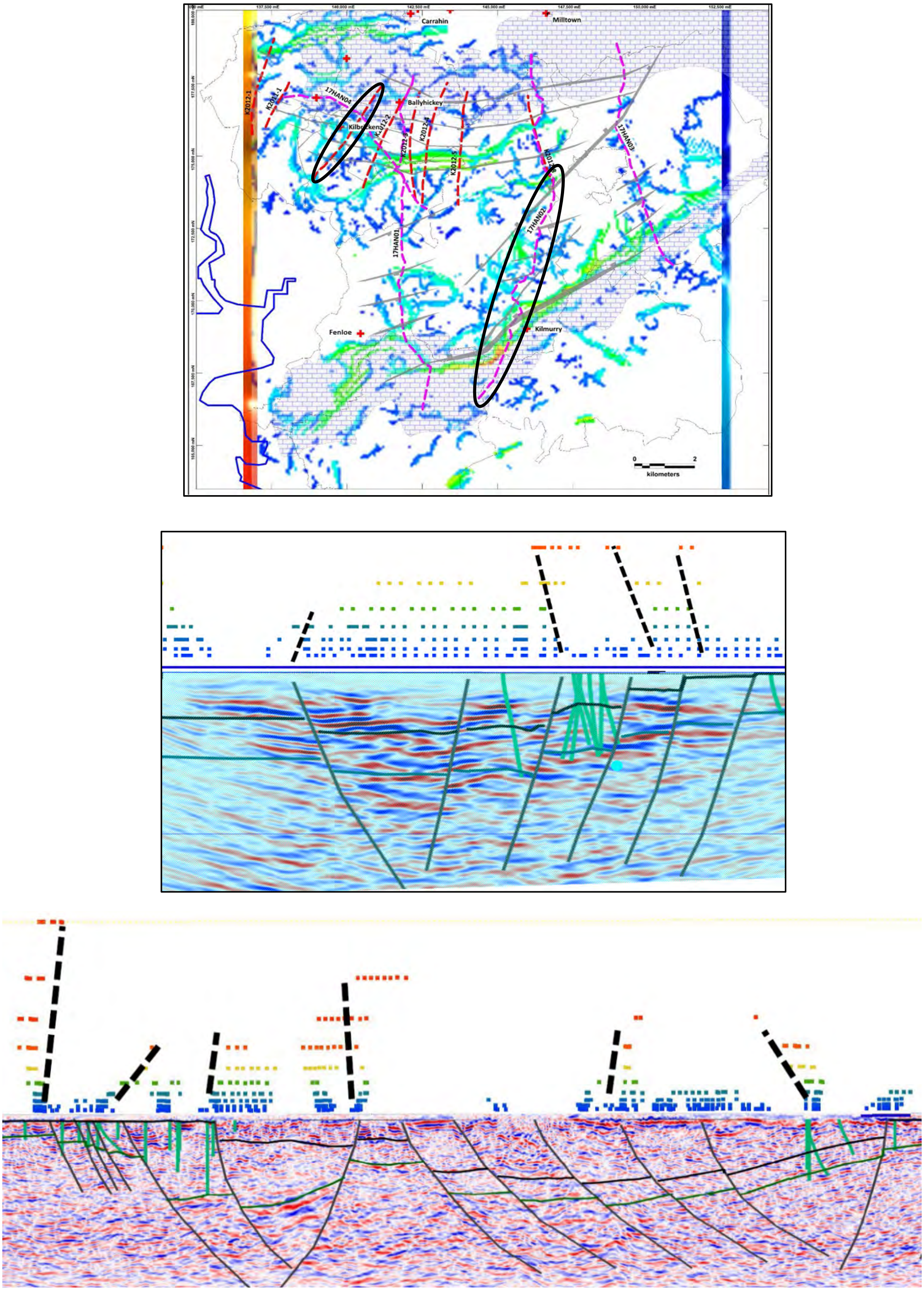

Figure 11: *Combined seismic and gravity worm images, a) map of seismic lines (see Figure 9) superimposed on gravity worms, coloured by amplitude, and seismic profiles with upward continued gravity worms for* ***11 b)*** *Kilbricken KIL-12-09 and* ***11c)*** *Kilmurry 17-AN-02. Black dashed lines show indicative dip directions of gravity worm sheets relative to seismic interpreted faults.*

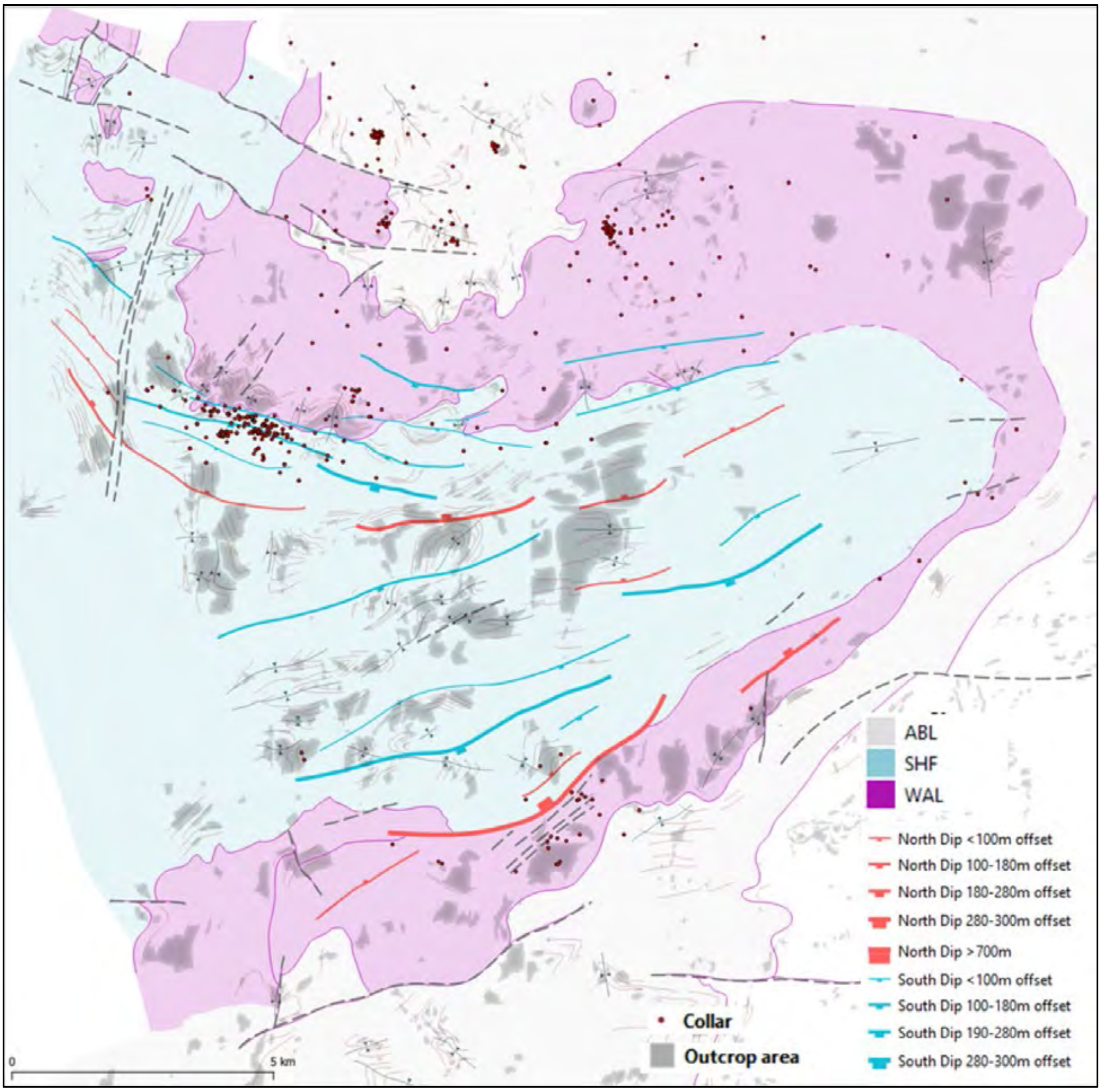

***Figure 12:** Structural map and drill collars. Faults coded by dip direction and magnitude of offset.*

The gravity was found to be consistent with the positions of the large-offset faults interpreted from the seismic data. This is particularly the case in the Kilmurry area where the major north dipping faults, and their deflection across an interpreted relay ramp, interpreted from the seismic and drill- hole data (Figure 11) show a good match to the high amplitude gravity worms. This consistency between the datasets enabled the faults interpreted on seismic data to be extrapolated away from the seismic lines with some confidence.

Drilling data

Drilling has mainly focused on the northern part of the licence block at shallower targets and around the Kilbricken deposits. Figure 12 shows surface geology and drill collars positions. In 2018 Hannan updated the surface geological interpretation using the 19th century "6 Inch" scale sheets from the Geological Survey Ireland (GSI).

Outside of Kilbricken, a priority target region was identified at the Kilmurry Fault zone along the southern limb of the syncline. This is supported by drilling, seismic and gravity data sets. Previous drill intercepts yielded encouraging results. Also, the north dip of the fault structure indicates it to be a prospective hanging wall location for zinc mineralization. Geological sections were made in Kilmurry to couple the surface geology with drill results (Figure 13) The cross sections highlight the significant extensional offset of the Nodular Micrite Unit (NMU) horizon across the Kilmurry structure.

The fault architecture has been refined and modeled as a relay ramp,(Figure 14a) constrained by detailed seismic reflectors and drilling intercepts (figure 14b). Drill holes into the hanging wall of the fault zone returned positive results, in particular

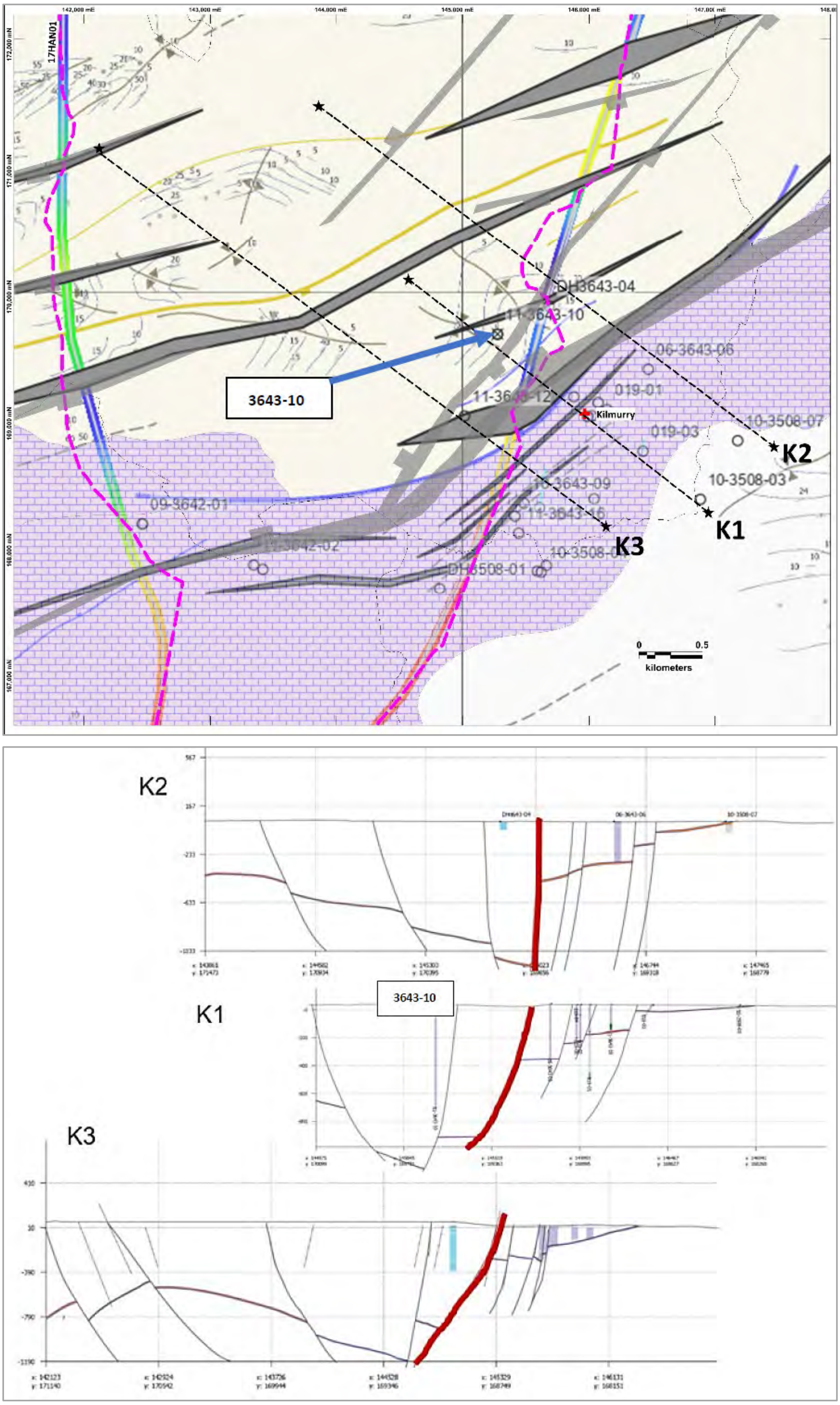

Figure 13: *Kilmurry Fault bend/relay structure **a)** map, **b)** interpreted cross sections. Red line- Kilmurry Fault, with drill traces and NMU offset positions. Location of Hole 11-3643-10 indicated.*

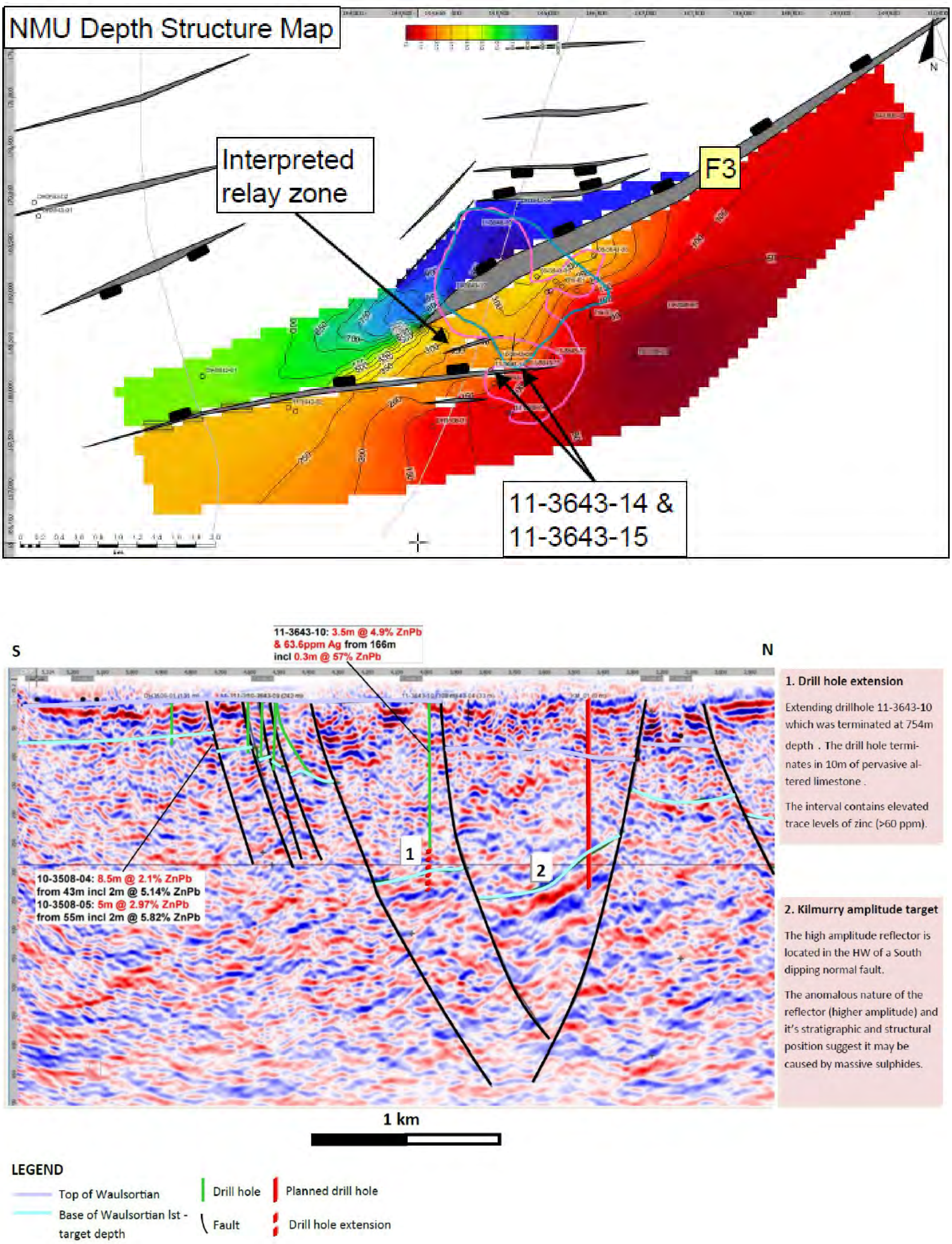

Figure 14: *Kilmurry Fault zone,* ***a)*** *Model of depth to NMU and interpreted faults,* ***b)*** *seismic profile 17-AN-02 with interpreted positions of reflectors, base of Waulsortian (blue), existing drill traces (green).#1 = drill hole extension, #2 = planned drill hole into amplitude target (?massive sulphides).*

Hole 11-3643-10 which Hannan extended in 2019. The target was a seismic and de tailed gravity defined structural and stratigraphic target mapped by Hannan over greater than 15km strike and 1-2km width. Historic drilling identified significant alteration and mineralization immediately south in the footwall of the Kilmurry target (Figure 14a). The original upper parts of the hole intersected dissolution textures, alteration and mineralization in the upper sequence of the hanging wall, including 0.3m @ 56% zinc and lead at 166m depth. Extensive fault scarp debris was within the sediments encountered in the drill hole suggesting the Kilmurry Fault was active during sedimentation. The drill hole ended (before this extension) in three to four times background levels of zinc (>60 ppm) in highly altered limestones Hannan's extension of hole 11-3643-10 encountered intense hydrothermal haematite for 4m at the base of the potential mineralized horizon and calcite/dolomite breccia over more than 60m with sporadic gossanous patches after pyrite and calcite textures suggesting replacement of barite. The hydrothermal haematite alteration is highly significant as it lies proximal to mineralization at Irish-style deposits such as Lisheen, Tynagh and Silvermines and can be considered a potential "near-miss" indicator. Further drilling is required (#1 in Figure 14b).

The seismic data shows a high amplitude reflector in the immediate hanging wall of the Kilmurry Fault. This may be a massive sulphide response. Drilling of this priority target is currently planned.

Summary

Re-activated basement faults play an important role in ore genesis in this setting (e.g., Johnston *et al.* 1996) with large dimension faults creating the optimum fluid mixing locales leading to ore deposition. Typically, such faults are expressed as high upward continued gradients in gravity (and magnetic) data, and by offset reflectors in seismic reflection profiles. A minimum requirement for high mineral potential faults is that they breach a base stratigraphic seal, allowing migration of metal bearing fluids from the underlying basement. The East Clare project meets several conditions of the mineral system framework, as evidenced by the Kilbricken deposit. Nearby, at Kilmurry, is one of the few remaining high priority targets in the Irish Carboniferous, comprising a major north dipping, syn-sedimentary fault with widespread zinc anomalism and extensive hydrothermal alteration and brecciation.

The East Clare project offers some unique visualizations through the integration of seismic and gravity gradient data, to better inform and prioritize targets for further drilling programmes.

Acknowledgements

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