A seismic and petrophysics-guided approach to subsurface characterization of the NW Limerick Syncline in the Irish Zn-Pb Orefield

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Summary

Several Zn-Pb massive sulphide bodies have been discovered in the Limerick Syncline as part of the Pallas Green and Stonepark prospects in the Irish Zn-Pb Orefield. The Limerick Syncline has many similarities to other Irish-type Zn-Pb deposits, the main difference being that the mineralization shows a close spatial and temporal association with igneous rocks. The structural framework and volcanic architecture of the Syncline are still poorly understood and difficult to interpret geophysically. To address these issues, we present an integrated study combining downhole petrophysics, laboratory petrophysical measurements of core samples and seismic reprocessing and interpretation for the subsurface characterization of the NW Limerick Syncline. The study has led to a much-improved recovery of important seismic reflectors, allowing for seismic facies analysis, tied to our understanding of deposition geometries. Major complexly segmented faults were identified across seismic lines. Recognition of coherent changes in downhole and on-core density and velocity data has allowed more confident mapping of formation boundaries and significant hydrothermal alteration zones in the reprocessed seismic reflection data.

Introduction

The Stonepark and Pallas Green zinc-lead prospects, located in the northwestern portion of the Limerick Syncline in southwest Ireland (Figure 1), are hosted in the Mississippian carbonate rocks which are intruded by and interbedded with a thick volcanic succession. Igneous activity in the Limerick area is believed to have contributed heat to drive fluid circulation thereby bringing ore-forming components to the system (Wilkinson and Hitzman, 2015), but did not act as a source of metals (Slezak *et al*., 2022). Also, unlike other Irish Zn-Pb deposits, those in the Limerick Syncline cannot yet be related to major normal faults.

To map these structures and the boundaries between lithological units in the Limerick Syncline, reflection seismic profiles are being used in this study. The seismic reflection method is known to provide subsurface images with greater penetration and sufficient resolution compared to other geophysical methods (Malehmir *et al*., 2012). However, the Syncline presents some challenges for seismic imaging, e.g. the presence of variably thick sequences of volcanic rocks (Knockroe Formation) overlying

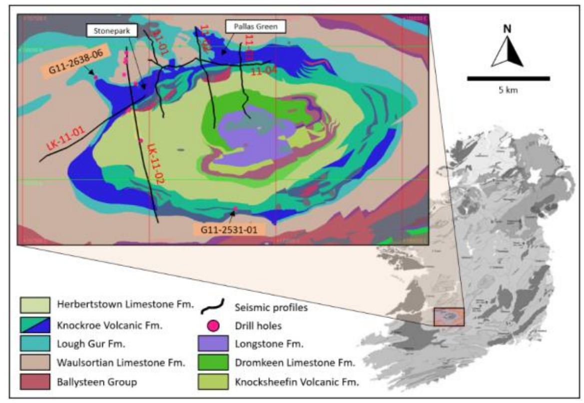

Figure 1. Bedrock geological map of Ireland (modified from Geological Survey of Ireland). The map shows the main formations in the Limerick Syncline, six 2D land seismic profiles, drill holes sampled for the petrophysics characterization and the Pallas Green and Stonepark prospects. Color legend follows the stratigraphic order from bottom left to top right.

Mississippian carbonate sequences. This may cause strong signal absorption and transmission loss (McBride *et al*., 2021). Moreover, complex fault zones and high lateral facies heterogeneity in some units such as the mud mounds of the Waulsortian Limestone Formation, demand appropriate seismic processing including more complex migrations (Singh and Malinowski, 2023).

To resolve this, we reprocessed six 2D seismic reflection profiles. What differentiates this reprocessing from previous workflows applied to the seismic reflection data, is the use of newly acquired petrophysical data to guide the semblance velocity picking process that generates a new stacking velocity model and the posterior use of this information as input for the seismic interpretation. Petrophysics characterization of the Stonepark Zn-Pb prospect was conducted based on both downhole and laboratory petrophysical data of the main lithological units. Detailed analysis of bulk density and P velocities drastically improved our understanding of the acoustic impedance distribution along the stratigraphy of the Limerick Syncline and the Stonepark area. This kind of integration is key to deeper exploration targets under thick cover, which requires greater reliance on geophysical methods (Dentith et al, 2020).

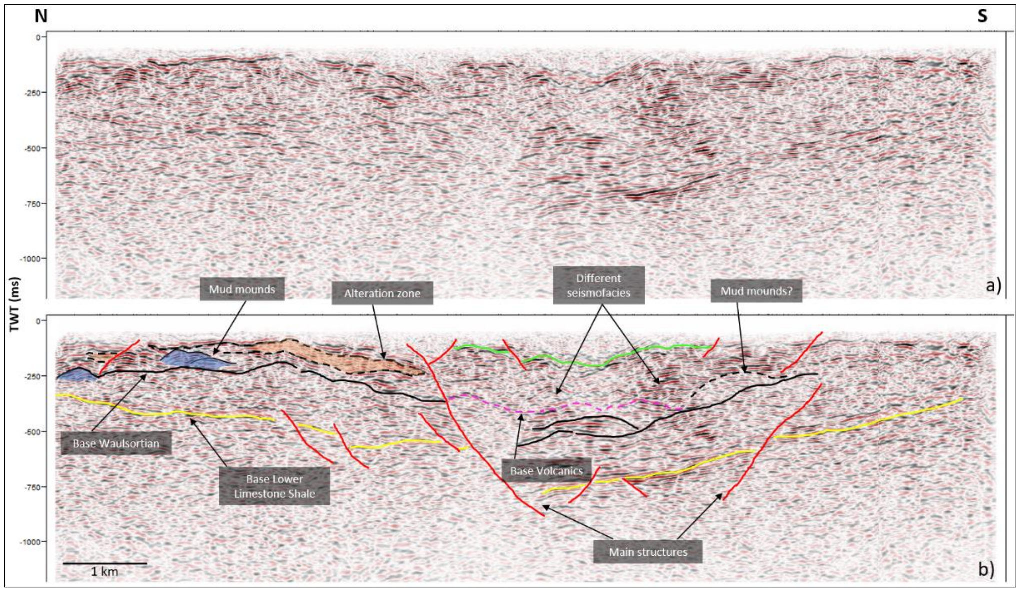

Figure 2. a) Profile LK-11-02 in TWT after application of new stacking velocity model and post-stack time migration. b) Interpretation of the LK-11-02 time section. The red lines represent the main faults in the profile. The yellow horizon represents the base of the Lower Limestone Shale Formation. The black horizon represents the base of the Waulsortian Limestone Formation. Mud mounds of the Waulsortian Limestone are identified with blue polygons and alteration zones in orange. The base of the Volcanics is identified with the purple dashed line.

Geological setting

The Lower Palaeozoic basement to the Devono-Mississippian units consists of deep marine greywackes, siltstones, shales, and volcanic rocks deposited in the Iapetus Ocean. Closure and collision of the Laurentian and Avalonian continents in the Late Silurian led to significant deformation and metamorphism associated with the Caledonian orogeny (Chew and Stillman, 2009; Wilkinson and Hitzman, 2015). By the end of the orogenic cycle, a series of grabens formed by sinistral strike-slip faults resulted in basins filled with continental red bed conglomerates, sandstones, and mudrocks of the Old Red Sandstone Formation.

After this tectonic phase, northward-directed marine transgression across Ireland during the early Mississippian (Sevastopulo and Jackson, 2009) deposited progressively deeper marine carbonates. The oldest Mississippian unit is the Lower Limestone Shales Group (LLS), comprising a series of interbedded shales, siliciclastics, and carbonates deposited in shallow marine typically inter to peritidal environments (Tyler, 1997; Blaney and Redmond, 2015). Succeeding sedimentation transitioned to a storm-influenced carbonate ramp environment of the Ballysteen Group, consisting of a sequence of argillaceous bioclastic limestones (ABL), often nodular bedded with variable contents of calcarenites and argillites. Laterally extensive micritic mud mounds of the Waulsortian Limestone Formation conformably overlie the Ballysteen Group (Sevastopulo and Jackson, 2009). The overlying Lough Gur Formation is a cherty, bioclastic, argillaceous limestone, which is succeeded by the Knockroe Volcanic Formation (Strogen, 1988), consisting of a series of basalts and volcanoclastic rocks. The overlying Herbertstown Limestone Formation, transitioning eastwards to the Knockseefin Volcanic Formation, is dominated by grainstones of shallow water origin (Sevastopulo and Jackson, 2009) and these from the youngest parts of the stratigraphic sequence of the study area. The Waulsortian-hosted deposits occur largely in the complexly faulted hanging walls of Mississippian normal faults within relay-ramp systems (Hitzman, 1999; Kyne *et al.*, 2019). However, despite the presence of significant mineralization, no large ore-controlling faults have been interpreted in the study area to date (Blaney and Redmond, 2015). Most Zn-Pb mineralization occurs near the base of the Waulsortian Limestone Formation, with brecciation and mineralization forming through alteration and precipitation-dissolution processes by hydrothermal fluids (Blaney and Redmond, 2015).

Petrophysics and seismic data

Downhole petrophysical data acquired from two drill holes, G11-2531-01 and G11-2638-06, and laboratory petrophysical data acquired from further 8 drill holes along the seismic profile LK-11-02 (Figure 1) that trends northsouth across the mineralization of the Stonepark area, provide information on chargeability, resistivity, conductivity, density, gamma-ray spectrometry, magnetic susceptibility, and seismic velocities of the main lithological units in the area. This data was combined with six seismic profiles (Figure 1) consisting of 2D split-spread surveys conducted in 2011.

Methodology: seismic reprocessing, drill hole and petrophysics data integration

We applied hard rock processing approaches to pre-stack time gathers to compensate for the common depth point dispersal and to maximize stacking events that are considered to be primary reflections. This was followed by ray-based post-stack time migration, which provides good results for targets that are well-illuminated in areas where geology is not overly complex, and where prominent impedance contrasts exist between lithologies (Singh and Malinowski, 2023), such as the top of the Lower Limestone Shales Group (Figure 2.b). The semblance velocity picking process to stack the time gathers was guided by the downhole and laboratory petrophysics data.

The petrophysical data was integrated at various stages in the workflow. Petrophysics was crucial to the velocity model building and quality control of migrations but most importantly, it was highly used for seismic interpretation. During the seismic interpretation (Figures 3.a and 3.b), the density and P-velocity data analysis was used to add value to the understanding of acoustic impedance contrast and how the seismic properties of the main lithologies vary across Stonepark.

Results and discussion

Figure 3 shows the interpretation of the petrophysical data for the drill hole TC-2638-074, which crosscuts a mineralized zone at the base of the Waulsortian Limestone Formation. Analysis of down-hole data in all 8 drill holes along seismic line LK-11-02 (Figure 1) reveals that clean carbonates show densities around 2.7 $g.cm^{-3}$ and velocities around 6200 m/s. Both density and compressional velocity data are affected by dolomitization, brecciation and mineralization. Mineralization shows densities higher than 3.2 $g.cm^{-3}$ and velocities lower than 6000 m/s. The decrease in velocity correlates with sulphide content. Hydrothermal alteration causes localised decreases in velocity (down to 5500 m/s). The overall effect is that of an increase in the variability of density and velocity.

These hydrothermal alteration and mineralization zones in the Waulsortian Limestone are expressed in the seismic profile as irregular low amplitude-chaotic seismic facies within otherwise continuous, mostly parallel, high amplitude reflectors (Figure 2.b). The contact between the Waulsortian Limestone and the Ballysteen Group is also expressed in both the petrophysics and seismic, where the petrophysics shows a decrease in P-velocity due to the increase in clay content, a common characteristic of the Ballysteen carbonates. This change in velocity is shown in the seismic profile as an easily identifiable reflector (Figure 2.b – base Waulsortian) which can be tracked all along the profile and is cut by the large south-dipping normal fault. This structure, combined with the thick volcanic sequence, imposes a severe signal loss, making it more difficult to interpret the same units on the South side of the seismic line. The interpretation was mainly based on seismic facies correlation and the use of the highly reflective Lower Limestone Shale Group (Figure 2.b) to have some control on the base of the Ballysteen Group.

Seismic interpretation of profile LK-11-02 (Figure 4.c) has led to several new elements to be identified in the Stonepark area. The LLS Group and Ballysteen Group show coherent thicknesses and geometries across the entire area, consistent

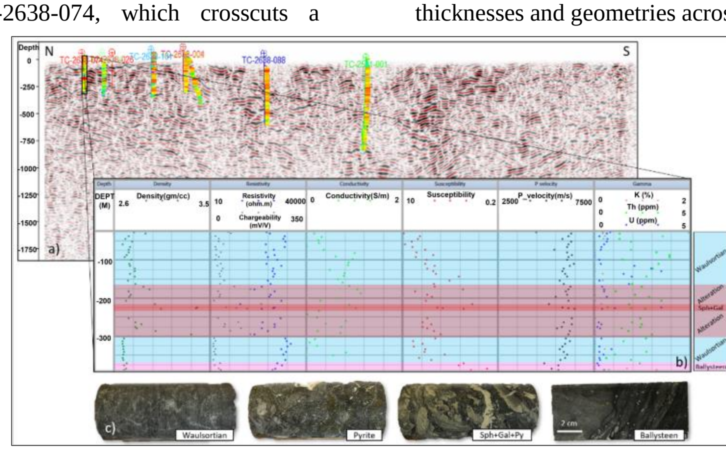

Figure 3. a) Seismic depth section with the P-velocity logs for drill holes used in the study. b) Interpreted strip log of drill hole TC-2638-074 showing physical properties measured by laboratory petrophysics. c) TC-2638-074 samples showing the main lithologies intersected.

with their expected deposition on a broad open ramp before rifting. This interpretation is comparable to previous work by Blaney and Redmond (2015) based on drilling in the Stonepark-Pallas Green prospects (Figures 4.a and 4.b). Detailed delineation of reflectivity in the Waulsortian limestones has allowed for the interpretation of likely mud mound geometries (as seen in outcrop locally), heavily assisted by continuous reflector delineation at the base of the Waulsortian. The improved velocity models assisted by on-seismic borehole constraints have allowed mapping out of significant (hydrothermal) alteration zones within the Waulsortian Limestone Formation. These typically occur as precursors or contemporaneous to mineralization.

A large south-dipping normal fault was identified, penetrating deeply into the Lower Palaeozoic basement, and potentially terminating upward in the Knockroe Formation. Several parallel smaller-scale faults are seen, consistently dipping basin-ward, forming downthrown terraces. These geometries represent relay-ramp structures along segmented fault systems recognised elsewhere in the Irish Midlands, crucial for localising fluid flow and mineralization (Hitzman, 1999; Kyne *et al.*, 2019). The deep penetration into the basement could mean this structure will have acted as an important conduit to the hydrothermal fluids bringing metals from the basement to the host rocks by thermal buoyancy (Wilkinson and Hitzman, 2015). Similar results are achieved for other profiles across the Pallas Green prospect (Figure 1). A picture is emerging of complexly interacting fault systems with large relay-ramp structures that have shaped the NW flank of the Limerick Syncline.

Conclusions

Petrophysical data adds much value to seismic interpretation by reducing uncertainties and integrating reliable physical properties information, e.g., the acoustic impedance analysis bringing new information about the density and compressional velocity contrasts between the main lithological units, mineralization, and alteration zones. Improved seismic processing also has a great impact on the final imaging and interpretation, recovering reflectors, improving continuity, and highlighting previously poorly imaged structures, like the large south-dipping fault and mud mounds and alteration zones inside the Waulsortian Limestone Formation, the main host for mineralization. The results from this reprocessing study are also key to bringing new knowledge and repurposing legacy data, giving new information in a non-expensive and more sustainable way.

Acknowledgements

We acknowledge Group Eleven Resources for providing the samples used in the petrophysical measurements. Glenn Morgan and ESP for providing pre-stack seismic data used for velocity updates and migrations. Eoin Dunlevy for the support with the database and geological discussions. Eoin McGrath and the Geological Survey of Ireland for hosting the petrophysics laboratory. Robertson Geo for the downhole petrophysics data acquisition. Juan Alcalde and David Marti for the support with seismic processing. Part of this research was supported by Science Foundation Ireland projects 13/RC/2092_P2 and 16/RP/3849.

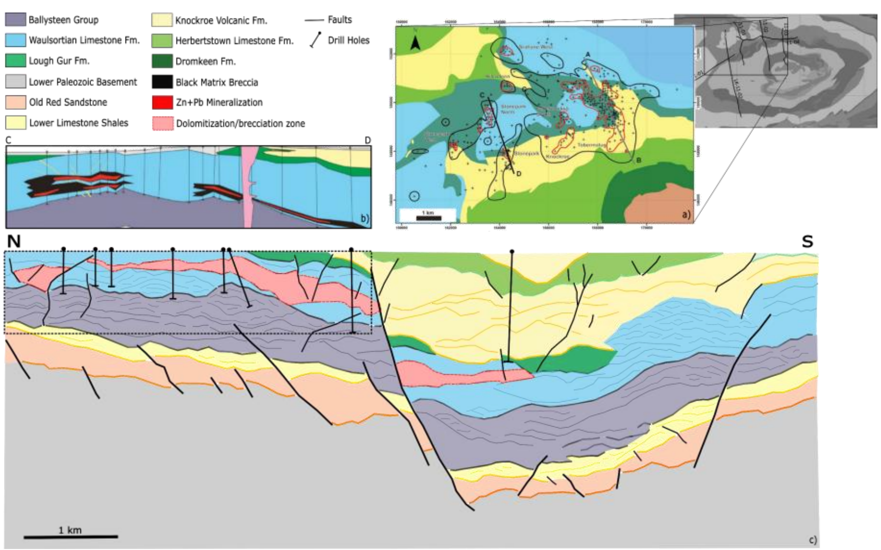

Figure 4. a) Geological map of the Stonepark-Pallas Green prospects with cross-sections. b) Cross-section C-D over Stonepark prospect (a and b modified from Blaney and Redmond, 2015). c) Interpreted cross-section along the seismic profile LK-11-02 highlighting cross-section C-D for comparison.