Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

Research Programme
- Short Call 2022 –
- Final Report -

Lead Applicant Name	Aline Melo
Host Organisation name	University College Dublin
Project Title	Petrophysical characterization of the Zn – Pb mineralisation of the Lisheen deposit in Ireland
Contract Number	2022-sc-009

This report covers the period 1st November 2022 to project end date (31/12/23)

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Research Programme
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2. (a) Project information:

Final project report:

Executive summary:

Lisheen is a lead-zinc-silver deposit located in the Rathdowney Trend in Ireland that was mined until 2015. In this study, we collected 130 rock samples of different mineralisation types and analysed the relationship between variations in the content of three main sulphides (pyrite, sphalerite, and galena) and physical properties such as conductivity, resistivity, magnetic susceptibility, P-wave velocity, and density. The high-grade ore, which is rich in sphalerite and galena, have high density, low conductivity, low susceptibility and low velocity. This is an important result as it shows that the strong positive anomalies are associated with the early hydrothermal alteration stages that formed pyrite and might be spatially close the high-grade mineralization; or in some cases, might not have evolved to the advanced hydrothermal stage that formed the high-grade ore. The experimental results contribute to understand the relationship between the geological units and geophysical methods, providing valuable prior information for future geophysical studies of Irish-type deposit, which can be used in mineral exploration.

(i) Results, scientific/engineering targets reached beyond the state of the art and conclusions

The main research objective was to characterize the petrophysical response of the different mineralization types in Lisheen deposit aiming to quantify their physical properties. A total of 130 core samples (BQ diameter and approximately 10 cm length) distributed in 30 drillholes (yellow squares in Figure 1) from Lisheen main ore body were sampled for this study. The classification in different groups was based on chemical data estimated from a portable XRF handheld device (Vanta) measured on the samples (average from 6 measurements points per sample). A total of 8 groups were identified based on the percentage of the three most abundant sulphides in Lisheen, which are pyrite, sphalerite, and galena (Table 1). In the next few subsections, the petrophysical characteristics for each physical property (inductive electrical conductivity, magnetic susceptibility, density, P-wave velocity, and galvanic electrical resistivity) that were measured in this study will be discussed.

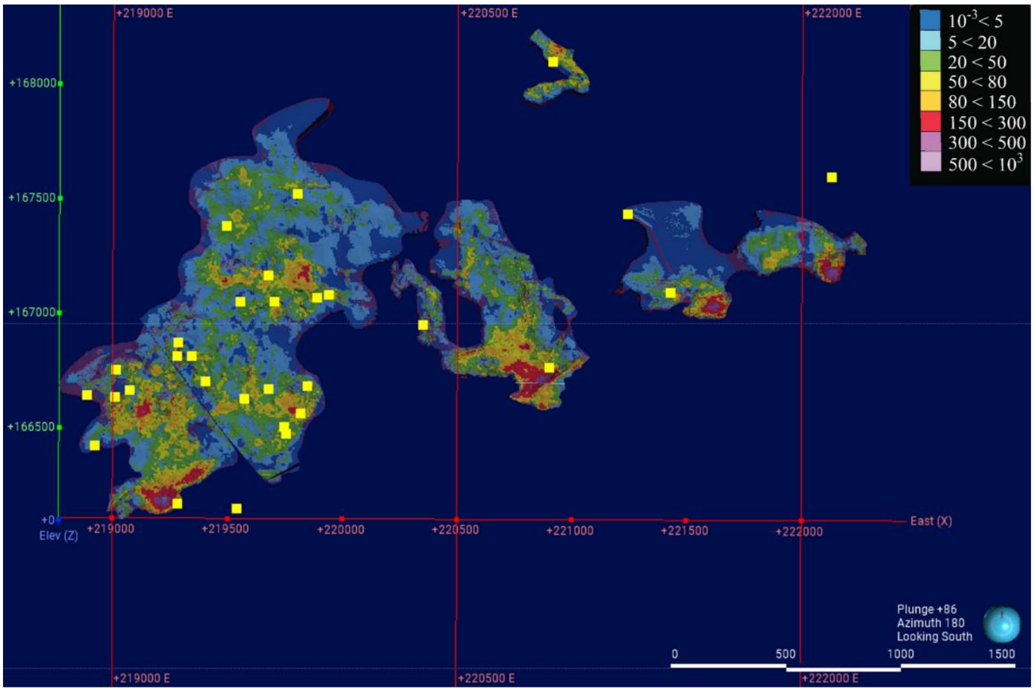

Figure 1 - Map with metal tonnage distribution of Zn showing the 30 boreholes (yellow

squares) that the 130 samples were extracted from for this project (adapted from Torremans et al. (2018)).

Table 1 – Classification of the samples of the Lisheen ore body based on their content of pyrite, galena, and sphalerite.

Group	Sphalerite	Galena	Pyrite	Number of samples	Total amount of sulphides	Criteria
1a	**High** 23-78%	**Low** 0-4%	**Low** 1-19%	14	26-80%	Percentage of sphalerite: >=20% high, <20% low Percentage of pyrite: >=20% high, <20% low Percentage of galena: >=3% high, <3% low
1b	**Low** 1-19%	**Low** 0-2%	**High** 20-81%	23	20-80%	
1c	**Low** 0-16%	**Low** 0-1%	**Low** 0-19%	33	5-27%	
1d	**High** 20-58%	**Low** 0-3%	**High** 21-57%	23	55-84%	
1e	**High** 40-73%	**High** 4-18%	**Low** 1-19%	8	50-84%	
1f	**Low** 5%	**High** 3%	**High** 38%	1	47%	
1g	**Low** 8-13%	**High** 4-8%	**Low** 5-187%	2	22-33%	
1h	**Very low** 0-2%	**Very low** 0%	**Very low** 0-4%	26	<5%	Black matrix breccia (BMB) Percentage of total sulphides: <5%

Lisheen deposit is the primary source of Irish-type lead-zinc ore. The ore body is predominantly composed of sphalerite, galena, and pyrite, accompanied by multiple stages of calcite and dolomite precipitation. Before mineralization, early-stage pyrite typically covered by the pre-existing pyrite, with both stages often replaced by the main ore-stage sphalerite. The main mineralization phase is primarily responsible for the formation of sphalerite and galena through mineralizing fluids (Doran et al. 2022).

(i.i) Inductive electrical conductivity

The results (Figure 2) show that the samples of Group 1f (high galena and pyrite with inductive conductivity median around 6.3 S/m), Group 1d (high sphalerite and pyrite, median around 2.51 S/m) and Group 1b (high pyrite, median around 1.26 S/m) have higher conductivity than the samples of groups without pyrite. The content of pyrite is strongly positively correlated with conductivity. High content of galena (Group 1g) also shows high conductivity, with median around 1.58 S/m.

However, a high content of sphalerite with low pyrite leads to a decrease in conductivity. In comparison to Group 1h (BMB, without sulphides, 0.63 S/m) and Group 1c (low content of all three types of sulphides, 0.4 S/m), the groups containing high sphalerite (1a and 1e) exhibit lower conductivity values, ranging between 0.18 S/m and 0.25 S/m.

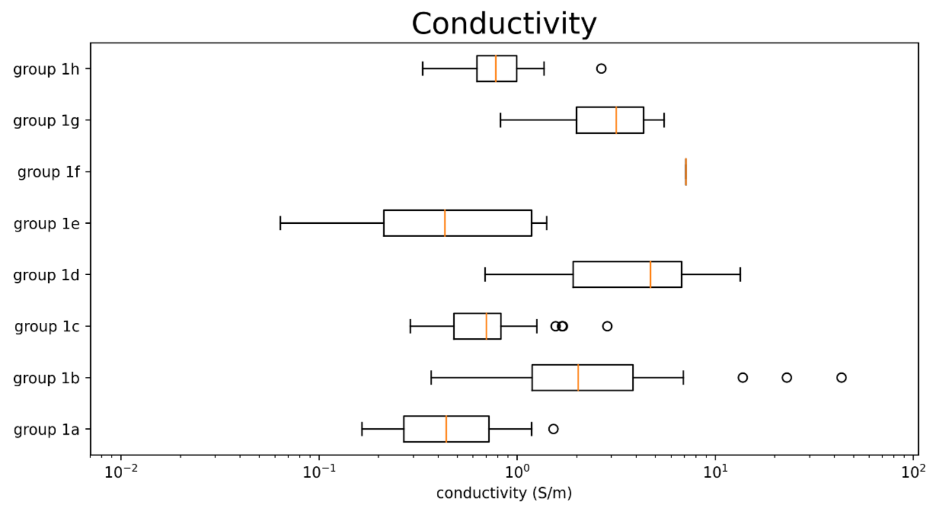

Figure 2. Box plots showing Conductivity for the samples collected from each lithological class.

Outliers' analysis

Group 1a

In this group, the content of sphalerite is high (more than 20%), while galena and pyrite are low (less than 20%). There is only one outlier with higher conductivity than the others, which is A0115 (Figure 3). According to the pXRF data, sample A0115 contains roughly 75% massive sphalerite, 0.4% galena in veins and 8% disseminated pyrite. The specific information is shown in the table 3 below.

Figure 3. Sample A0115 that contains 75% massive sphalerite, 0.4% galena in veins and 8% disseminated pyrite and corresponding to an outlier of high conductivity.

Group 1b

In this group, the content of pyrite is high (more than 20%), while galena (less than 3%) and sphalerite are low (less than 20%). There are three high conductive outliers, which are A0230, A0060 and A0058, conductivities are 13.7 S/m, 22.9 S/m and 43.35 S/m, respectively. According to the pXRF data, sample A0230 (Figure 4a) contains roughly 2.7% sphalerite in fracture, 0.2% disseminated galena and 73% massive pyrite. Sample A0060 (Figure 4b) contains roughly 8% sphalerite in veinlets, 0.9% disseminated galena and 72% massive pyrite. Sample A0058 (Figure 4c) contains roughly 7.8% patchy sphalerite, 2.4% disseminated galena and 73% massive pyrite.

In order to compare to the samples with high conductivity, three samples with low conductivity in this group are selected to show, which are A0128 (conductivity of 0.37 S/m), A0247 (conductivity of 0.76 S/m) and A0163 (conductivity of 0.99 S/m). According to the pXRF data, sample A0128 (Figure 4d) contains roughly 0.8% massive sphalerite, less than 0.1% galena and 20.45% pyrite in breccia clasts. Sample A0247 (Figure 4e) contains roughly 11% patchy sphalerite, 1% galena in veinlets and 20.5% pyrite in breccia clasts. Sample A0163 (Figure 4f) contains roughly 7.7% patchy sphalerite, 0.25% disseminated galena and 23.7% pyrite in breccia matrix.

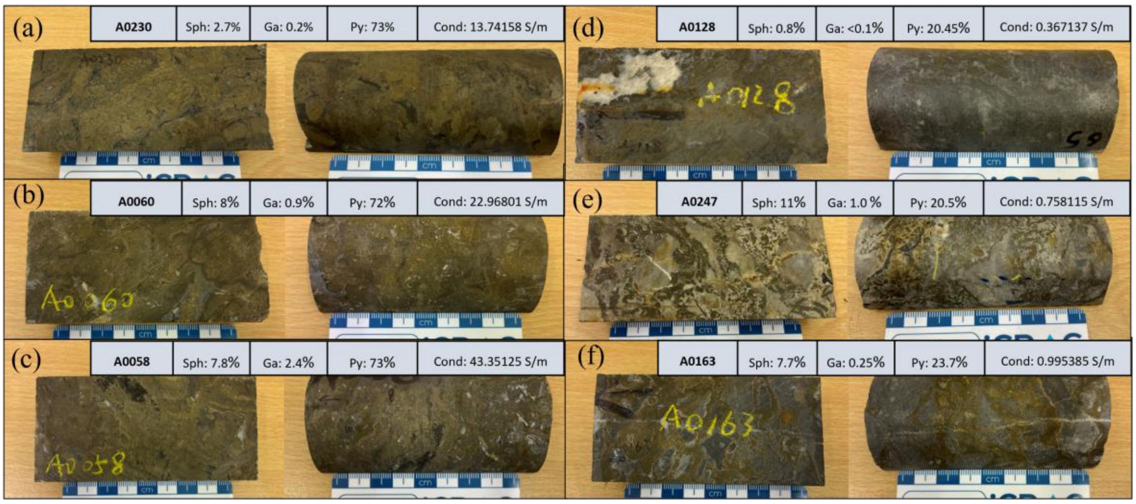

Figure 4. Group 1b (a) sample A0230, (b) sample A0060, (c) sample A0058, (d) sample A0128, (e) sample A0247, (f) sample A0163.

Group 1c

In this group, all of the content of three types of sulphides are low (less than 20%). The median conductivity value in this group shows relatively low, about 0.18 S/m. However, there are three high conductive outliers, A0166 (1.7 S/m), A0250 (1.68 S/m) and A0161 (2.8 S/m). According to the pXRF data, sample A0166 (Figure 5a) contains roughly 1.2% sphalerite in fracture, less than 0.1% disseminated galena and 19% pyrite in veins. Sample A0161 (Figure 5b) contains roughly 7.3% sphalerite in breecia matrix, 1% galena in veinlets and 19.2% pyrite in veins. Sample A0250 (Figure 5c) contains roughly 3.5% patchy sphalerite, 0.14% disseminated galena and 1.4% pyrite in breccia clasts.

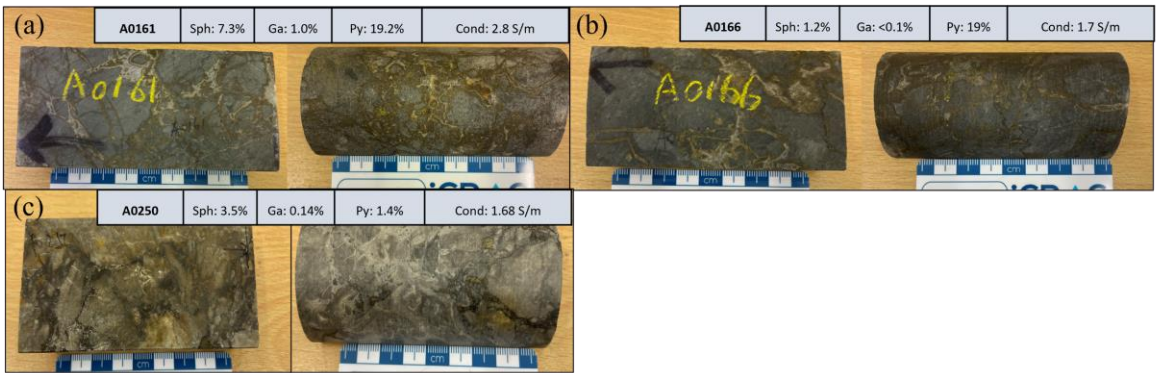

Figure 5. Group 1c (a) sample A0161, (b) sample A0166, (c) sample A0250.

Group 1h

This group is composed of samples of black matrix breccia (BMB) with less than 5% of sulphides and has median conductivity of 0.63 S/m. There is one high conductive outlier, A0093 with 2.65 S/m conductivity. According to the pXRF data, sample A0093 (Figure 6) contains roughly 0.3% sphalerite in veins, less than 0.1% galena and 1.4% patchy pyrite.

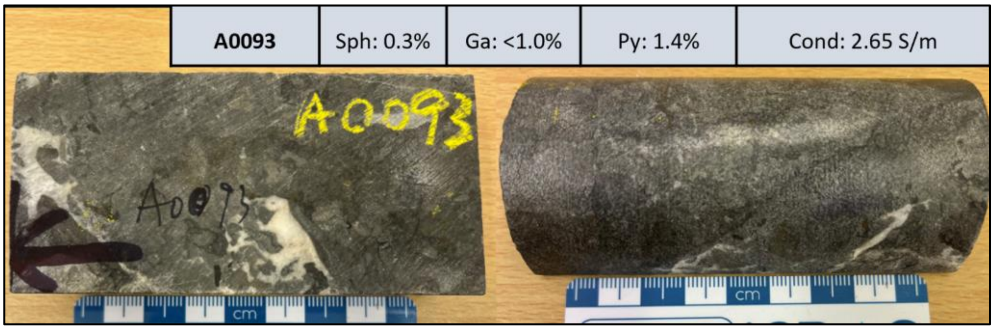

Figure 6. Group 1h sample A0093.

Table 3. The content and texture of three sulphides of the outliers mentioned above. MSB: massive sulphides, FRC: fracture coatings, VTS: veinlets. PAT: patchy, BXM: breccia clast, VEN: vein, BXC: breccia matrix, DSM: disseminated.

	Sphalerite%	**Sphalerite**	**Galena%**	**Galena**	**Pyrite%**	**Pyrite**	**Conductivity (S/m)**
A0115	75.0	MSB	0.4	DSM	8.0	VEN	1.5
A0230	2.7	FRC	0.2	DSM	73.0	MSB	13.7
A0060	8	VTS	0.9	DSM	72.0	MSB	22.9
A0058	7.8	PAT	2.4	DSM	73.0	MSB	43.4
A0128	0.8	MSB	<0.1		20.5	BXC	0.4
A0247	11.0	PAT	1.0	VTS	20.5	BXC	0.8
A0163	7.7	PAT	0.3	DSM	23.7	BXM	0.9
A0161	7.3	BXM	1.0	VTS	19.2	VEN	2.8
A0166	1.2	FRC	<0.1		19.0	VEN	1.7
A0250	3.5	PAT	0.1	DSM	1.4	BXC	1.7
A0093	0.3	VEN	<0.1		1.4	PAT	2.7

(i.ii) Magnetic susceptibility

Group 1h (BMB with less than 5% sulphides) and Group 1c (low sulphides) exhibit significantly higher magnetic susceptibility (approximately 0.63×10^{-3} SI) compared to the high-sulphide groups (Figure 7). In contrast, Group 1f (high galena and pyrite) and Group 1e (high sphalerite and galena), which both contain high content of two types of sulphides, show markedly lower median value of magnetic susceptibility, ranging from 0.012×10^{-3} SI to 0.015×10^{-3} SI.

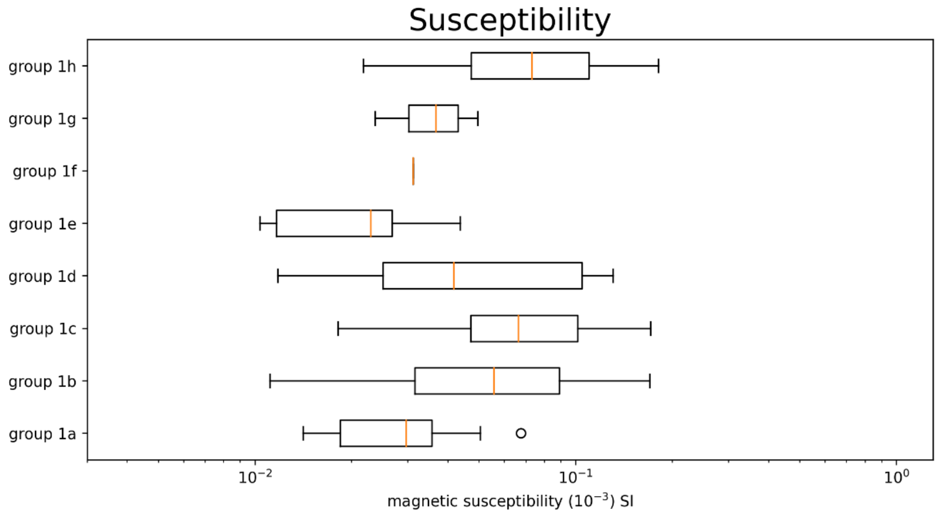

Figure 7. Box plots showing magnetic susceptibility for the samples collected from each lithological class.

(i.iii) Density

According to the density ranking plot from the Canadian Rock Physical Property Database (Enkin et al., 2020), in an ideal scenario, the densities of pyrite, sphalerite and galena are relatively presented as follows: 5.01 g/cm^3, 4.08 g/cm^3 and 7.60 g/cm^3.

It can be intuitively observed that Group 1h (BMB with less than 5% sulphides) and 1c (with low content of sphalerite, galena, and pyrite) have significantly lower density values, ranging from 2.65 g/cm^3 to 2.9 g/cm^3, and from 2.85 g/cm^3 to 3.5 g/cm^3 respectively. Samples without or with a minimal quantity of sulphides exhibit lower densities compared to those with a substantial quantity of sulphides (Figure 8).

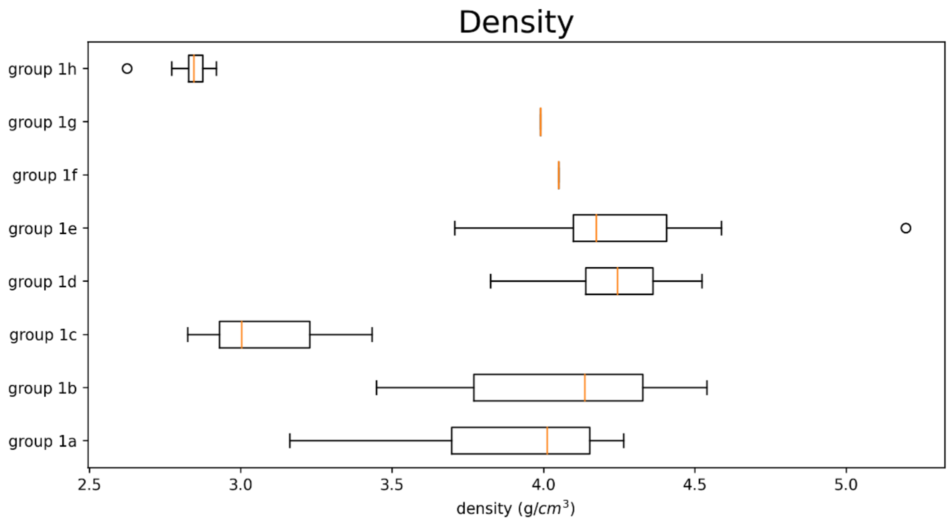

Figure 8. Box plots showing Density for the samples collected from each lithological class.

The samples from the Lisheen orebodies are composed of a mixture of minerals, including host rocks and sulphides, in varying proportions. The lowest-density sample

A0109 (3.16 g/cm^3) in Group 1a contains 26% sulphides (Figure 9), with 23.6% sphalerite, less than 0.1% galena and 2.7% pyrite.

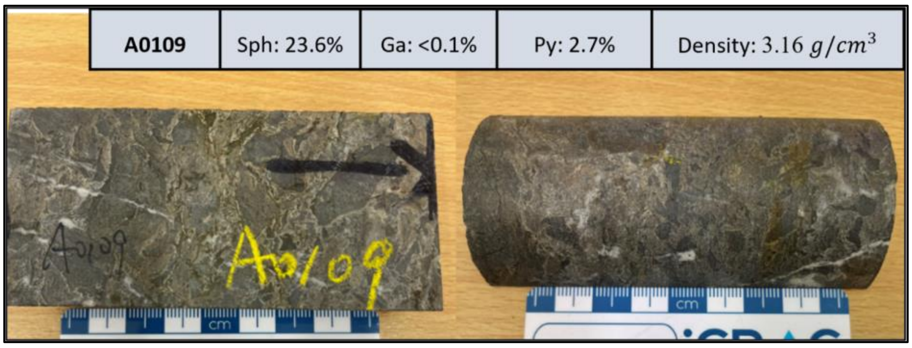

Figure 9. The lowest-density sample (A0109) in Group 1a.

The lowest-density sample A0128 (3.4 g/cm^3) in Group 1b contains 21% sulphides, with 0.8% sphalerite and 20.5% pyrite (Figure 10a). Sample A0060 has the maximum density of the group and is composed of 81% of sulphides, with sphalerite constituting 7% and pyrite constituting 73% of the total (Figure 10b). In Group 1e (high sphalerite and galena), there is a high outlier that contains 84% sulphides, including 73% sphalerite, 4% galena, and 6.6% pyrite (Figure 11).

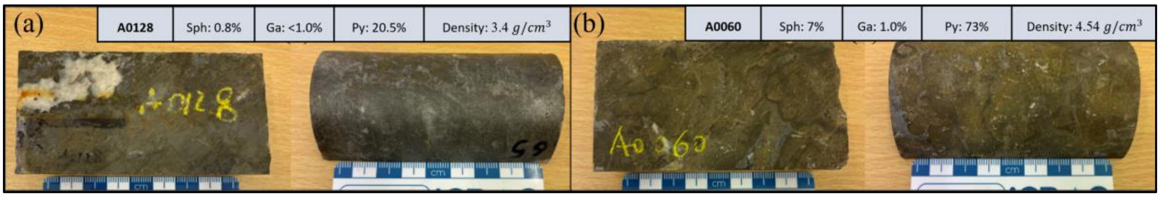

Figure 10. The lowest-density samples in Group 1b (a) A0128, (b) A0060.

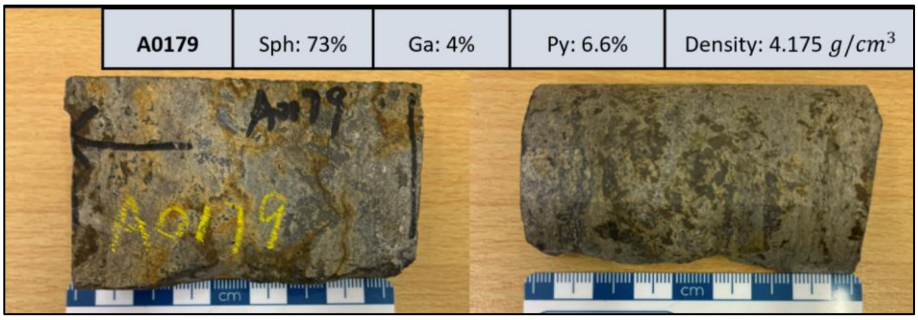

Figure 11. The highest-density sample in Group 1e (A0179).

<u>(i.iv) P-wave velocity</u>

Group 1b (high pyrite), Group 1d (high sphalerite and pyrite), and Group 1f (high galena and pyrite) exhibit overall higher P-wave velocities (Figure 12) than the groups with high sphalerite or galena content, such as Group 1g (high galena), Group 1a (high sphalerite), Group 1e (high sphalerite and galena).

The group with high pyrite content has a median P-wave velocity ranging between 6100 m/s and 6300 m/s. Among these groups, Group 1b (high pyrite) has the highest velocity. In contrast, the groups with high galena (Group 1a) and high sphalerite (Group 1g)

content exhibit P-wave velocities of 5500 m/s and 5300 m/s, respectively.
This result is consistent with what is mentioned in Salisbury et al (2000), concluding that, groups containing high pyrite have a higher velocity (~8000 m/s) than groups containing high sphalerite (~5500 m/s).

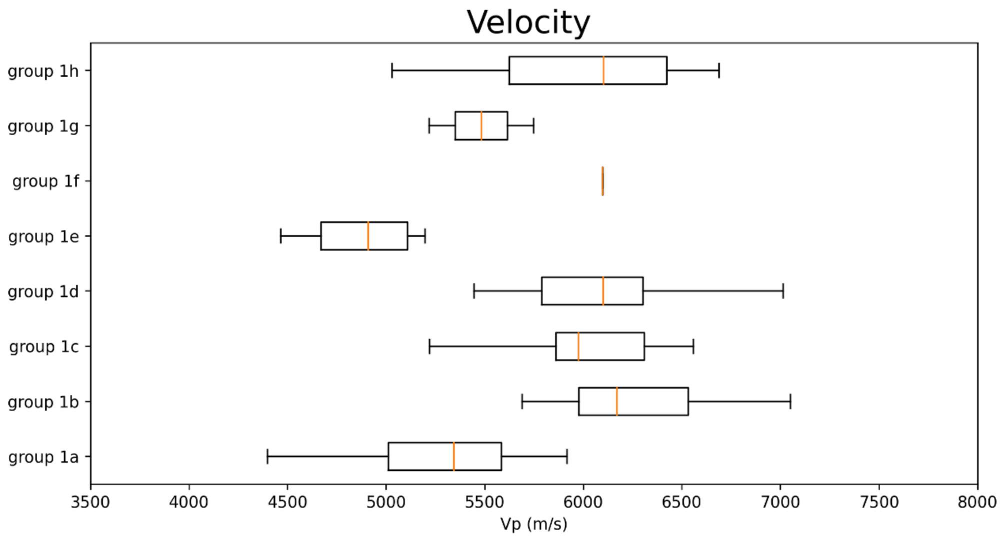

Figure 12. Box plots showing P-wave velocity for the samples collected from each lithological class.

After identifying a strong positive correlation between pyrite content and velocity, we proceeded to describe the texture of pyrite in Group 1b (high pyrite) and categorized it into the following types: vein breccia (VBX), disseminated (DSM), massive (MSB), breccia matrix (BXM), and breccia clast (BXC). Applying the same texture classification method to Group 1d (high sphalerite and high pyrite), a difference is that we introduced two new categories named veinlet (VTS) and vein (VEN) to account for specific characteristics in this group.

In Group 1b (Figure 13), when pyrite appears in the style of breccia matrix, massive sulphides, and vein breccia, it exhibits high velocities ranging between 6200 m/s and 7200 m/s. When pyrite is present in a disseminated and a breccia clast style, the velocities range between 5500 m/s and 6300 m/s. The maximum velocity of the samples in Group 1d (Figure 14) is 6500m/s, which is lower than for Group 1b. The massive pyrite texture shows the highest velocity (median value of 6400 m/s), while the velocity of pyrite in veins, disseminated, and in breccia matrix are ranging from 5800 to 5900 m/s, in contrast the group of pyrite in breccia clast shows the lowest velocity, which is around 5400 m/s.

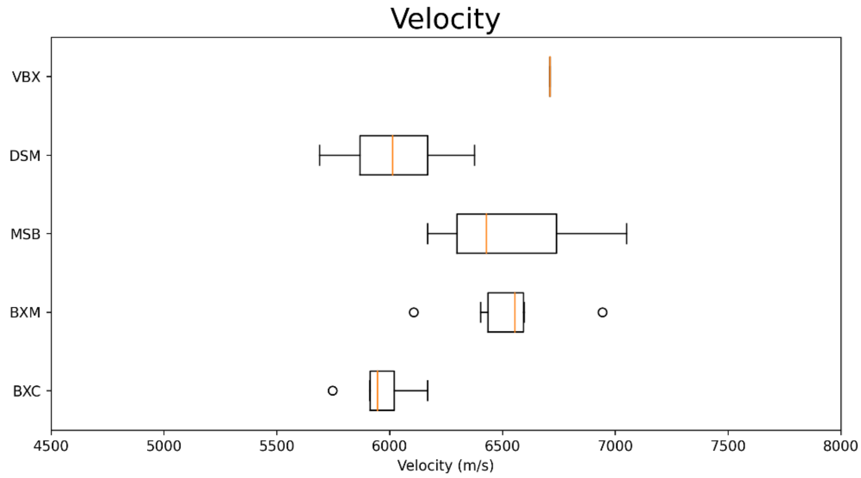

Figure 13. Box plots showing P-wave velocity for different textures of Group 1b (high pyrite, low galena and sphalerite).

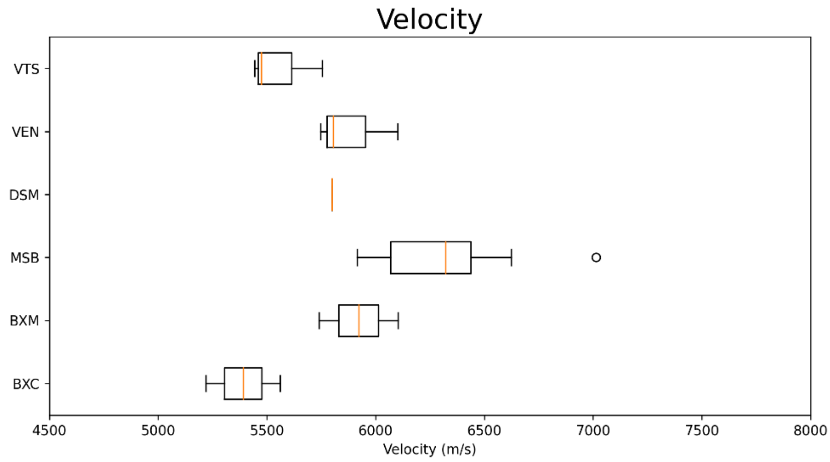

Figure 14. Box plots showing P-wave velocity for different textures of Group 1d (high pyrite and sphalerite).

(i.v) Galvanic electrical resistivity

Due to limitations in the precision of the instrument, our equipment is unable to accurately measure the resistivity of samples below 100 ohm.m. In such cases, the instrument will display "less than 100 ohm.m" without specifying an exact reading. Consequently, we substitute the recorded value with 99 ohm.m to be able to plot the results.

The resistivity exhibits a trend opposite to that of conductivity since the concepts of resistivity and conductivity are inverse properties. But in the laboratory, inductive conductivity and galvanic resistivity are measured separately, which leads to results that are not totally reciprocal to each other. In the Figure 15, groups 1b (high pyrite), 1d (high sphalerite and pyrite), 1f (high galena and pyrite) and Group 1g (high galena) exhibit low resistivity (groups 1d, 1f, and 1g are less than 99 ohm.m, and Group 1g around 158 ohm.m). The results are aligned with the conductivity section that we conclude the samples with high pyrite and galena are more conductive than those samples with high sphalerite.

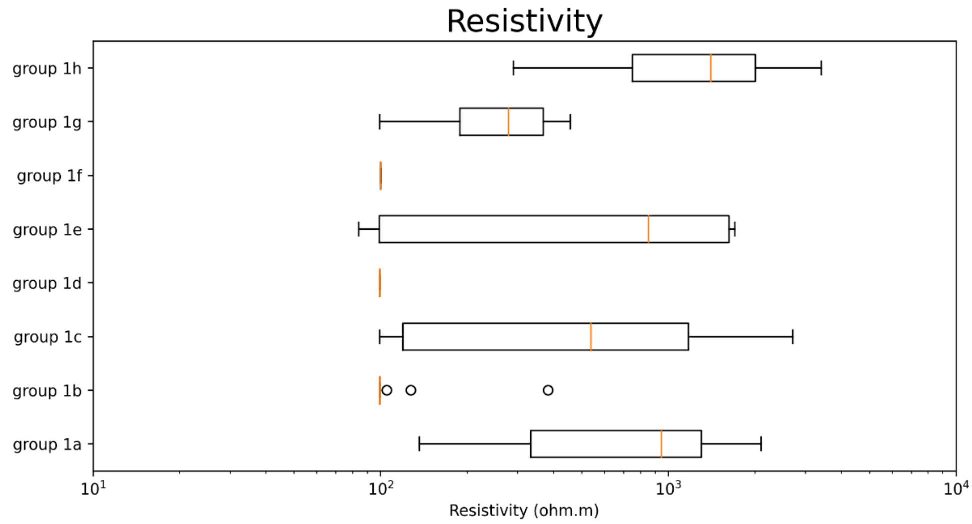

Figure 15. Box plots showing resistivity for the samples collected from each lithological class.

<u>(i.vi) Comparison with Santa Maria Zn-Pb deposit in Brazil</u>

The ore deposit of Santa Maria, Brazil (Araujo et al., 2021) is described as a Zn–Pb (Cu–Ag) epigenetic distal magmatic-hydrothermal system, whereas the Lisheen ore deposit is a Zn-Pb-Ag Irish-type system. Even though they are different types of deposits, we decided to carry on the comparison because no other petrophysical studies of Zn-Pb deposits were found. The Zn-Pb-Cu mineralisation at Santa Maria is hosted in a succession of siliciclastic rocks consisting of sandstones, conglomerates and siltstones, whereas the Zn-Pb mineralisation at Lisheen is hosted in Lower Carboniferous Waulsortian carbonate rocks. Araujo et al. (2021) describe 4 lithotypes: sandstone, rhythmite, conglomerate and andesite. Sandstone, rhythmite and conglomerate are detailed as ore-bearing host rocks and contain similar ore textures to some of the textures found at Lisheen, i.e. disseminated and stringer.

Despite these differences in geological systems and in host rock lithologies, there are some similarities between Santa Maria and Lisheen mineralization that make these two deposits comparable. Firstly, both deposits exhibit similar ore-forming mineralisation processes, as they are both epithermal (i.e, a relatively shallow deposit) and both types of mineralisation are controlled by normal faulting, which act as conduits for hydrothermal fluids. Secondly, both deposits host similar ore mineralogy, with the ore mineralogy of Santa Maria consisting of pyrite, galena and sphalerite with rare chalcopyrite, bornite and chalcocite, stephanite, native silver and covellite and the ore mineralogy of Lisheen being pyrite/marcasite, sphalerite and galena with minor tennantite, chalcopyrite and niccolite. Araujo et al. (2021) describe that the maximum concentration of pyrite is 0.17% which is relatively low compared to samples at Lisheen, of which some are massive pyrite (>40%). The maximum concentration value of sphalerite is 25.74%, which is similar to some concentrations of sphalerite found in samples at Lisheen. The maximum concentration value of galena is 9.49%, which is similar to the maximum concentration of galena found at the samples in Lisheen. There are similar average concentrations of galena in samples at Santa Maria and Lisheen, ranging from <0% to 9%. Thirdly, the Santa Maria and Lisheen deposits both contain a zone of hydrothermal alteration which envelopes the mineralisation. At the Santa Maria Zn–Pb system, this hydrothermal alteration zone is formed by illitization and chloritization processes with secondary quartz-sericitization, carbonatization, and hematitization. At the Lisheen Zn–Pb system, the hydrothermal alteration is formed by replacement processes, with dolomitic hydrothermal alteration forming a dark-grey, hydrothermal black matrix breccia (BMB) via microcrystalline dolomite precipitation from solution (Guven et al., 2023).

The Santa Maria deposit in Brazil and the Lisheen deposit in Ireland are therefore comparable for petrophysical data, based on their geological similarities. Clear differences are shown in the deposit types (magmatic-hydrothermal vs. Irish-type system) and in the host rock lithology (siliciclastic vs. carbonate). On the other hand, they are both fault-controlled, have similar ore-forming mineralisation processes and ore mineralogy.
In terms of electrical conductivity, Araújo et al. (2021) describe that samples with more sulphides and clay minerals (galena, sphalerite, chalcopyrite and bornite in addition to illite, chlorite and minor pyrite) have a higher inductive resistivity and lower inductive conductivity in comparison to samples with no or low sulphides and clay minerals. This could be associated with the absence of pyrite.

In terms of magnetic susceptibility, our results are generally consistent with what is mentioned in Araújo et al. (2021). Thet conducted a quantitative assessment of minerals using scanning electron microscopy (QEMSCAN). The findings reveal that minerals such as galena, sphalerite, pyrrhotite, and ilmenite exert a strong negative influence on the rock magnetic susceptibility. As the percentage of sulphide minerals increases, there is a corresponding decrease in the value of magnetic susceptibility.

(i.vii) Conclusions

Our study developed a new classification scheme of the different mineralization types in Lisheen using pXRF data and with that it was able to identify important characteristics of their physical properties. The presence of pyrite has a significant impact on the conductivity and velocity of the samples. The combination of pyrite and galena increases even more the conductivity, but the texture is also important, if the pirate is disseminated it will not have the same impact. The high-grade ore, which is rich in sphalerite and galena, have high density, low conductivity, low susceptibility and low velocity. This is an important result as it shows that the strong positive anomalies are associated with the early hydrothermal alteration stages that formed pyrite and might be spatially close the high-grade mineralization; or in some cases, might not have evolved to the advanced hydrothermal stage that formed the high-grade ore.

(i.viii) References

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"Petrophysics applied in mineralizations, hydrothermal alterations and lithology mapping: A case study from the Zn–Pb (Cu–Ag) epithermal deposit of Santa Maria, Brazil." Geophysical Prospecting 70, no. 4 (2022): 765-789.

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(ii) Project Implementation

The project was implemented as originally planned but the deliverables were delayed by 2 months because of the incident in the petrophysics laboratory and a 2-months extension was requested and granted by the GSI team.

The deliverables were completed on month 11 for the database of petrophysical data, month 12 for the interpretation of the petrophysical data, month 13 for the comparison with other Zn-Pb deposits, and month 14 for the final report and integrated database.

(iii) Outputs to date

Zenodo is an open repository for all scholarship, enabling researchers from all disciplines to share and preserve their research outputs, regardless of size or format. Free to upload and free to access, Zenodo makes scientific outputs of all kinds citable, shareable and discoverable for the long term. The main output is the database of petrophysical data, which will be published in the Zenodo platform (https://zenodo.org/) when the main research paper from this work is published. The plan is to submit the paper in 2024.

(iv) Impact

- Relevance/application to GSI programmes, where applicable

The main impact project of this project is to provide quantitative benchmark values of the physical properties of the Zn-Pb ore and hydrothermal alteration to be used as guides for vectoring new mineral deposits.

- Other impacts

The petrophysics data measured in this project can be used for future integration with geochemical data for subsurface resource assessment. The outcome of this project gives more confidence for geophysical targeting in mineral exploration and produce data that can be used for future subsurface characterization.

<u>Publications:</u>

Tormey, Tommie; Melo, Aline; Wei, Nanyu; Torremans, Koen; Guven, John. Geological characterization of the Zn – Pb mineralisation of the Lisheen deposit in Ireland. Poster presented at the PDAC-SEG Student Minerals Colloquium 2024, Toronto, Canada.

3. Supplemental information/datasets *(please clearly mark any sensitive or confidential information that should not be published and include a justification for the request)*