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The University of Dublin



Laidlaw Scholars Research and Leadership Program

2025 Cohort

**Cones have a point: Using the cone sheets of the  
Carlingford Igneous Complex to understand deeper  
crustal architecture and mineralisation in the system.**

Meabh Ní hÉalaithe

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A Reflective Report on the research undertaken as part of Summer 1 of the Laidlaw  
Program.

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## **Abstract**

Cone sheets are radial injections from deeper reservoirs below the magma chamber which offer us a glimpse into the deeper processes in Earth's crust. These cone sheets carry clinopyroxene (Cpx) crystals up from said reservoirs to the areas surrounding the magma chamber. Clinopyroxene is a magmatic mineral which records the pressure at which it crystallised in its chemistry. Using these minerals, magma storage depths can be constrained to give better picture of subsurface processes involved in Platinum Group Element (PGE) mineralisation. In this project clinopyroxene crystals of different kinds including in situ in the groundmass of the cone sheets, as inclusions in plagioclase crystals, and as inherited phenocrysts in a 'mush' in the groundmass were analysed. These crystals were from 16 separate samples collected from different cone sheets and vent agglomerate in locations around the Paleogene Carlingford Igneous Complex in Co. Louth, Ireland. Multiple analyses were conducted on these samples to gather data on the crystals, this data was then run through a machine learning model (Ágreda-Lopez et al. 2024) to give crystallization depths for each crystal.

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## 1.0 Introduction

The EU Critical Raw Materials (CRM) Act (2024) mandates member states to develop their CRM potential to address geopolitical concerns surrounding supply security. PGEs are important CRMs, due to their essential role in green technologies (e.g. catalytic converters and in advanced fuel cells); with an increasing demand for electric vehicles, PGE demand is expected to increase sharply over the coming decades and securing European supply is vital for achieving sustainable development goals.

The Palaeogene-aged (65-55 million years old) igneous intrusions in Ireland and Scotland have been identified as some of the most prospective European PGM exploration targets (Anderson, 2004). These ancient magma chambers include the Slieve Gullion and Carlingford complexes in the north of Ireland. Carlingford (Co. Louth) is of particular interest as it was subject to extensive exploration for PGEs until the ~1990s and recent research in Trinity has identified deposits containing PGEs. Despite the occurrence of PGEs in Carlingford, the mineralising processes remain poorly understood.

The focus of this project is on the cone sheets of the Carlingford Igneous Complex. These cone sheets have previously been classically studied by Le Bas (1960,1965,1970) and more recently by Meade et al. (2014) and Russell et al. (2021) though these studies did not specifically focus on the deeper magma chambers supplying the melt needed for the cone sheets. These cone sheets carry minerals up from the deeper crust to the present-day surface. Analysis of these minerals, specifically clinopyroxene crystals can give insight into the depths at which magma is stored underneath the system. Understanding the deeper crustal architecture is imperative for the investigation of PGE emplacement. Magma storage depths recorded in crystal chemistry indicates the presence of magma reservoirs, which may have an important role in PGE enrichment.

## 2.0 Materials and Methods

Materials, equipment and reagents for sample preparations, XRF and bulk rock analysis were supplied by the ESRL. Optical Microscopy was conducted using the Nikon ECLIPSE LV100ND, Scanning Electron Microscopy was conducted using the Tescan TIGER MIRA3 FEG-SEM – both of which are located in the Centre for Microscopy and Analysis in Trinity College Dublin. Electron Probe Microanalysis was conducted using the Jeol JXA-8200 WD/ED Combined Microanalyzer in the Archaeology Laboratory of the University of Oxford. Sample preparation protocols can be found in Appendix 1.

### 2.1 Field Work

My supervisor Dr. Stock, Chief Geologist of Northern Ireland Dr. Mark Cooper, PhD student Jack Beckwith and I conducted a full day in the field. We travelled to multiple locations shown to have cone sheets recorded on existing geological maps. Samples were collected from six separate locations, totalling nine samples collected on the first day, two of which contained mineralised PGEs. A second day of field work was then undertaken by Jack and I. A further 8 locations were sampled, collecting



**Figure 1.** Map of Carlingford and surrounding area showing sample locations (black and white spots) and location of Carlingford in Ireland (Google Earth 2025).

8 samples in total. Extensive field notes were taken at each sample location to include sketches, GPS coordinates, strike and dip of the cone sheets, descriptions of the cone sheets and the texture of the sample taken. All samples were placed in plastic bags labelled with the sample number. The samples were then transported to the geology department in Trinity College.

### 2.2 Sample Preparation

All field notes were digitised and relevant software downloaded such as qGIS. qGIS was used to mark the sample locations on a map (Figure 1). Samples were cut to an

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appropriate size for thin sectioning and crushing. Any samples that were deemed unsuitable were then marked as such on the sample bag, only one sample was unsuitable out of 17, notes were taken on each sample recording texture, minerals visible and suitability for further testing. A total of 20 thin sections were created from suitable samples. After ultrasonic cleaning and drying, samples were then chosen to be crushed and powdered, this was done by using a tungsten jaw crusher and an agate mill. Once powdered, pressed pellets and fused beads were made from each chosen sample for a total of 16 pressed pellets and 16 fused beads for bulk rock wavelength dispersive X-ray Fluorescence Analysis. Fused beads were used for measuring major elements, and pellets for measuring trace elements.

### **2.3 Sample Analysis**

Unfortunately, the Earth Surface Research Laboratory was unable to provide accurate data due to a calibration issue at the time of analysis. Optical microscope images were taken of thin sectioned samples with potential clinopyroxene crystals. Scanning Electron Microscope images were also taken of these sections to be used as maps for further probe work. 9 samples were then chosen for further probe work and coated with 12 $\mu$ m carbon coating. These 9 samples were transported to the Archaeology laboratory in the University of Oxford. An Electron Probe Microanalyzer was then used to analyse the chemistry of selected crystals the samples. The probe was programmed to take data from specified points on the sample, including the cores, middles and rims of clinopyroxene, plagioclase, and suspected olivine crystals. Images were also taken of point of interest on the samples (Figure 2.). The data collected from the probe was then converted using machine learning thermobarometry (Ágreda-Lopez et al. 2024) which gave the pressure at which the crystals formed in kilobars. Plots were made using RStudio to show the density distribution of the depth of emplacement of specific crystals. These depths then allowed us to elucidate magma storage depths and the placement of magma reservoirs in the deeper crust beneath the complex. The following equation was used to convert the depth in kilobars to kilometres depth:

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**Equation used to calculate kbar to km depth conversion:**

$$h = P(\rho g)$$

h = depth in m

g = acceleration due to gravity

$\rho$  = avg density of crust ( $\text{kg}/\text{m}^3$ )

P = pressure in pascals

1kbar = 100,000,000Pa

Avg. density of crust below Ireland =  $2,830\text{kg}/\text{m}^3$

Acceleration due to gravity =  $9.8\text{m}/\text{s}^2$

So:

$$h = 10\text{kbar} \times \frac{100,000,000\text{Pa}}{2,830 \times 9.8}$$

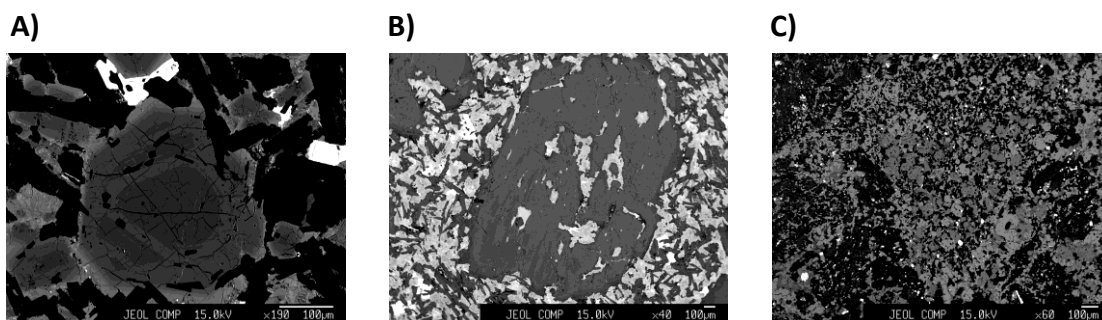
$$h = \frac{1,000,000,000}{27,734}$$

$$h = 36,056.83\text{m}$$

$$h = \frac{36,056.83\text{m}}{1,000}$$

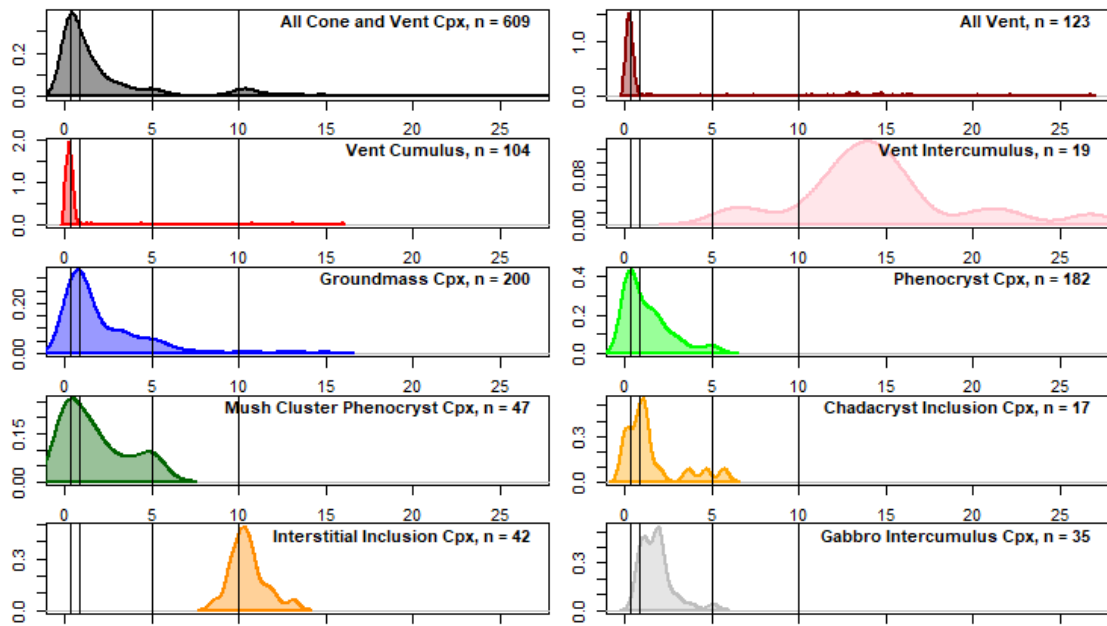
$$h = 36.056\text{km depth at } 10\text{kbar}$$

This was repeated for 5kbar, 1.5kbar, 0.9kbar, 0.3kbar.

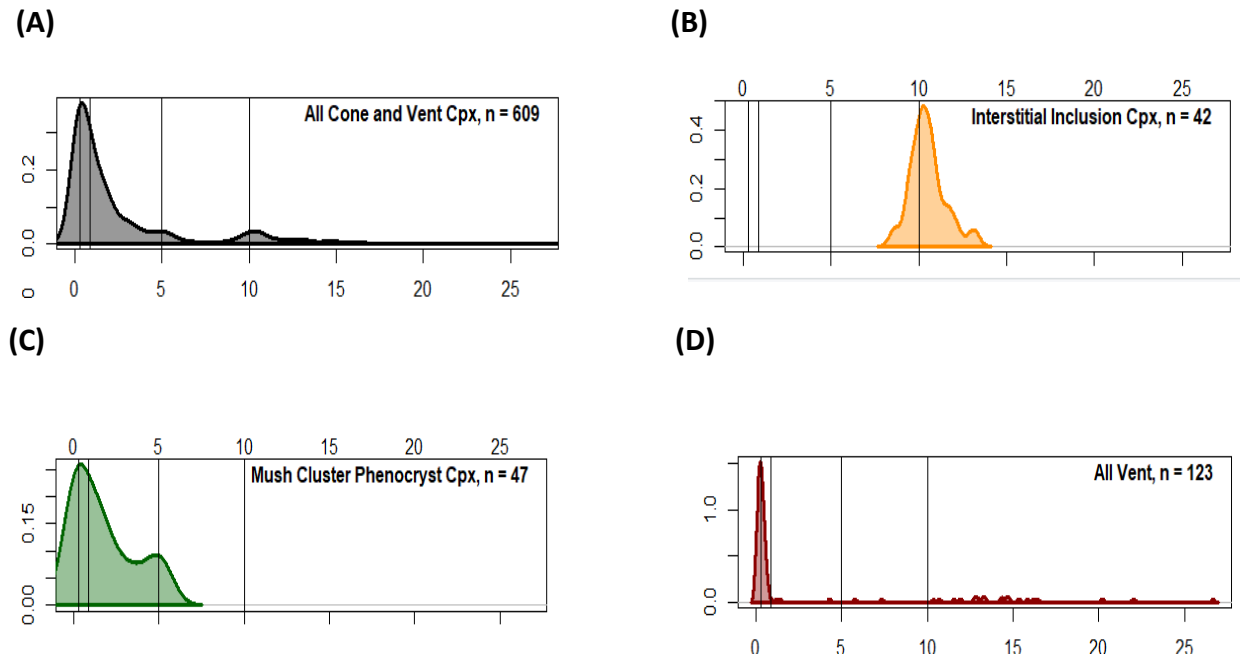


**Figure 2.** Images taken using the electron probe microanalyzer. **A)** Shows a zoning in a Cpx crystal caused by alteration as the magma it was in ascended. **B)** Shows a Plagioclase Crystal (dark grey) with Cpx inclusions (light grey inside, which would have been carried upwards within the Plagioclase. **C)** Shows Cpx 'mush' in one of the vent agglomerate samples, this 'mush' is formed from many very small Cpx crystals.

### 3.0 Results



**Figure 3.** Density plots showing the distribution of crystallization depths of different types of crystals analysed in the samples. X-axis shows the pressure at crystallization in kbar. Y-axis shows the density of crystals.



**Figure 4.** (A) Density plot showing the three main magma storage depths found in cone sheet and vent agglomerate cpx, shown as peaks at 0.3, 5 and 10kbar. (B) Interstitial inclusion cpx found in plagioclase crystals in four separate samples show magma storage depths of up to 10kbar. (C) Mush clusters recorded some storage depths of up to 5kbar. (D) Vent agglomerate samples show crystallization depths closest to the surface.

Clinopyroxene crystals showed crystallization depths of 0.3kbar, 0.9kbar, 1.5kbar, 5kbar, and 10kbar these were converted to km depth using the above equation to give: ~1.08km, ~3.25km, ~5.41km, ~18.03km, and ~36.1km depths respectively. The vent agglomerate contained the shallowest crystallization depths. Groundmass Cpx was slightly deeper, although still too shallow to have crystallized in one of the magma storage chambers. The Cpx mush clusters in some of the samples came from a depth thought to be the first magma reservoir. Four samples contained Cpx crystals that crystallized at a pressure of 10kbar.

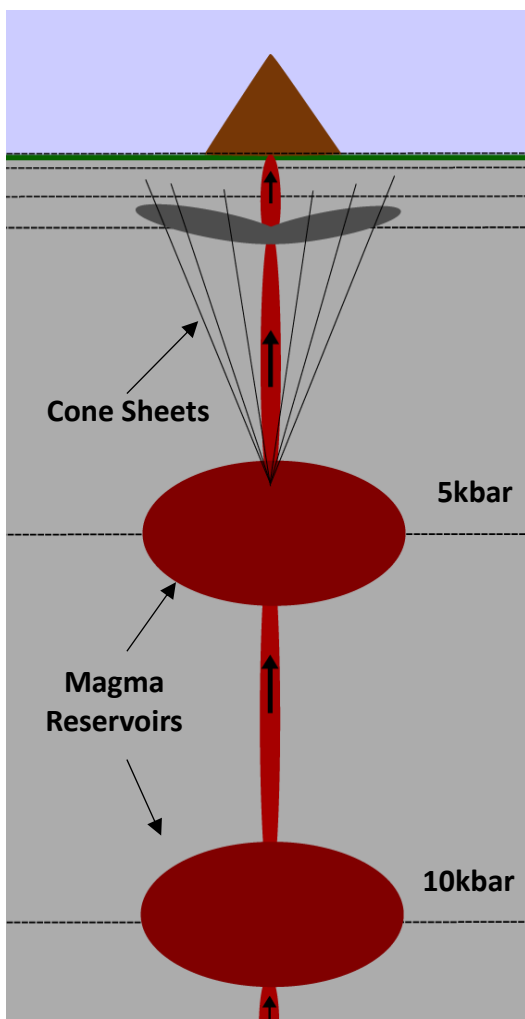


Figure 5. Simplified model of the Carlingford Igneous Complex.

#### 4.0 Discussion

The results of this project show what was originally planned, but in a more accurate and comprehensive way. The results from the vent agglomerate samples that we did have showed incredibly shallow crystallization depths, which was unexpected. This meant that the cone sheet data that was collected is much more useful for the objectives of this project. Proof of the presence of a deeper magma reservoir at ~36.01km was not expected, but it fits with the original objective of understanding the deeper crustal processes beneath the complex. This indicates that there was a much deeper magma chamber beneath the one previously mentioned by Cook and Murphy (1952) and Mitchell (2004) which sits at ~18.03km according to the data

obtained from the cone sheets in this project. As the magma moved up from the lower crust above the mantle plume, it would have accumulated in this reservoir, allowing for the magma to cool and for clinopyroxene and plagioclase crystals to form. The mafic

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nature of the magma means it was highly liquid, this made the system highly dynamic and the movement of crystals much easier than if it were a more evolved melt. The crystals would have been transported through the crust upwards to the second magma reservoir at 15km depth as mentioned in previous literature. Cone sheets were then emplaced as magma radiated and pushed through the crust and the magma chamber of the volcano at an average angle of 47°. A simplified model of the system was created using the results from sample analysis to show the general position of the magma reservoirs. Results of major element analysis can be seen in Appendix 2. The discovery of sulphide (PGE rich) cone sheets implies that mineralisation processes are occurring at depth. More analysis will be carried out on the two samples shown to have PGE mineralisation in the future. Constraining the depths of these reservoirs provides us with a greater understanding of the subvolcanic architecture, and where mineralisation may occur in the system. Further research in this area needs to be conducted to prove there is indeed a few deeper chambers feeding the system and the depth at which they reside, it makes sense as nature is rarely model perfect, it is unlikely there is a perfect line of ascent from the mantle to the large reservoir and then the large reservoir to the magma chamber, it is likely that there is more in the surrounding crust. Further research through geophysics, more cone sheet data, and geochemical/thermobarometric analysis on the rocks present in the complex. Further research will hopefully yield more results on the deeper mineralisation processes of PGEs in the Carlingford Igneous Complex, which will lend itself incredibly useful to future exploration in similar complexes.

#### **4.1 Limitations Encountered**

##### **4.1.1 Land Access**

The original plan for this project was to investigate the Cpx in the rocks of the vent agglomerate in Slievenaglogh, Co. Louth as opposed to the cone sheets in the greater Carlingford area. This was made impossible on the first day of field work due to the land containing the outcrop being inaccessible.

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#### 4.1.2 Inaccurate Mapping

Geological maps from the GSNI, GSI, and a BHP map were used to locate cone sheets to sample in the area. Some of these maps had mislabelled cone sheets as dykes, or some of the cone sheets recorded were no longer visible

#### 4.1.3 Equipment Malfunction

As stated previously the ESRL had calibration issues with some of the equipment and therefore the bulk rock analysis has not yielded a confident result.

### **5.0 Reflection**

Having undertaken my own research for the first time I feel I have grown immensely not only as a researcher but as a leader. This project did not originally go to plan and had to be changed within the first day of field work. This initial setback actually led to a more interesting and relevant project, it also taught me that the course of research never does run smoothly.

I was very lucky to work with experts in the field of igneous petrology, who offered their insights into my research and without whom I would not have been able to complete it. My supervisor ensured that I was part of his research team as a whole which allowed me to broaden my perspectives on my research and garner new opinions, and to make new friends. The person I worked with most was my supervisor's PhD student Jack Beckwith, we spent two days in the field together, he trained me on all of the instruments for sample preparation and analysis, and he helped me with the interpretation of my results. This project has shown me that research is impossible without teamwork.

In my PDP one of the main things I wanted to work on was my assertiveness and confidence. This project has massively improved both of these, being put in a leadership role where I was responsible for my own project meant I had to quickly develop these skills to ensure the project ran smoothly. This summer has made me realise that I am much more capable than I had originally thought, something which I am incredibly grateful for as it was something which has weighed me down before. This newfound

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confidence in my work allowed me to get a lot of feedback on my work, critique is useful and it pays not to take it personally!

In all the entire project has been one of the most rewarding things I have ever done, I have always wanted to conduct research and this has led me in the direction to continue on this path in the future. Being able to get extra hours in the field, reading, and in labs I have only dreamt of being in has inspired me for the rest of my journey through Laidlaw and the remaining years I have in college - of which I hope there are many more!

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## Appendices/Supplemental Material

### Appendix 1.



Ultrasonic Cleaning  
of Samples.pdf



Using the Jaw  
Crusher.pdf



Using the Agate  
Mill.pdf



Making Pressed  
Pellets.pdf



Fused Bead Mass  
Calculations - Jack Beckwith

Fused Bead mass calculations were calculated by Jack Beckwith.

### Appendix 2.



XRF Majors Fused  
Bead Cone Sheet.csv