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

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

Research Programme
- Short Call 2020, Final Report -

Lead Applicant Name	Dr. Margaret Jackson
Host Organisation name	Trinity College Dublin
Project Title	Abrupt Climate Change in Ireland: Redefining our climate future through a lens of high resolution glacial construction
Contract Number	2020-sc-026

This report covers the period 1st December 2020 to project end date 30th June 2022)

2. (a) Project information:

Final project report (*max 2500 words, excluding figures and headings*):

Executive summary (lay abstract, approx. 250 words):

Glaciers are highly sensitive to changes in climate. As glaciers wax and wane they leave evidence of their past fluctuations on the Earth surface. Through mapping the extent and elevation of these glacial sediments we can determine not only where glaciers were in the past, but the climate conditions associated with these past glacial extents. In addition, through dating these same glacial deposits we can determine *when* glacier extent - and thus climate - changed. Ireland is host to a rich array of glacial sediments; the Glen of Imaal in the southwestern Wicklow mountains holds a particularly well-preserved, and as yet undated, surface record of past glaciation. We used detailed surficial mapping and advanced geochemical techniques to determine the timing and rate of past glacial fluctuations in the Glen of Imaal. Our preliminary results indicate that valley glaciers in the Glen of Imaal reached their maximum extent roughly 22 thousand years ago. This former glacial extent represents a cooling of roughly 9 degrees Celsius relative to modern conditions. After this time glaciers in the Glen of Imaal began to retreat from their maximum. As mountain glaciers may only exist in the absence of an overlying ice sheet we note that these results place minimum limiting constraint on the timing of former Irish Ice Sheet recession past this site, and so provide novel target data for ice sheet modellers. Moreover, our results provide absolutely dated benchmarks for palaeoclimate modellers from a region where such terrestrial data are sparse. Additional results pending will yield further information on the rate of valley glacier recession in the Glen of Imaal as the world warmed rapidly following the last ice age.

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

Prior to fieldwork, we conducted preliminary remote mapping of the Glen of Imaal using high-resolution satellite imagery available through the Government of Ireland Geohive Portal (https://www.geohive.ie/)(Figure 1). Once in the field, we ground-truthed these initial remote interpretations and added additional detail to our map. The final glacial-geomorphic map (Figure 2) highlights the Glen's rich glacial geomorphology (See Deliverable 2).

While mapping the Glen we used two distinct methods to estimate the equilibrium line altitude (ELA) of the former glaciers based on moraine elevation and extent (Table 1). The ELA is sometimes termed the 'snowline', and is considered a useful approximation of former atmospheric freezing level (See Deliverable 4).

Moraine	MELM ELA	THAR ELA	Δ Temp (C°)	
NP Corrie	660 m	668 m	7.4	
NP Intermediate	386 m	507 m	8.4-9.1	
Rocky Ridge Outer	320 m	N/A	9.5	

***Table 1**: ELA reconstructions and associated temperature depression (relative to modern) for Glen of Imaal glaciers. ELA results are reported as determined using two methods: maximum elevation of lateral moraines (MELM) and toe-headwall-altitude ratio (THAR). THAR results are as calculated using a ratio value of 0.36. Temperature depression estimates are based on a lapse rate of 6°C/km and a modern freezing level height of 1900 m above sea level. Moraines are as labelled in Figure 1.*

In the course of mapping we observed that certain glacial sediments within the Glen of Imaal have been affected by (now extinct) meltwater outlets and streams, which washed over and dissected many moraines. We identified four primary glacial moraine ridges unaffected by post-glacial meltwater alteration and focused our sampling efforts on these features. These include the North Prison valley corrie moraine (NPC), the North Prison valley intermediate moraine (NPI), the Rocky Ridge outer moraine (RRO) and the Rocky Ridge inner moraine (RRI).

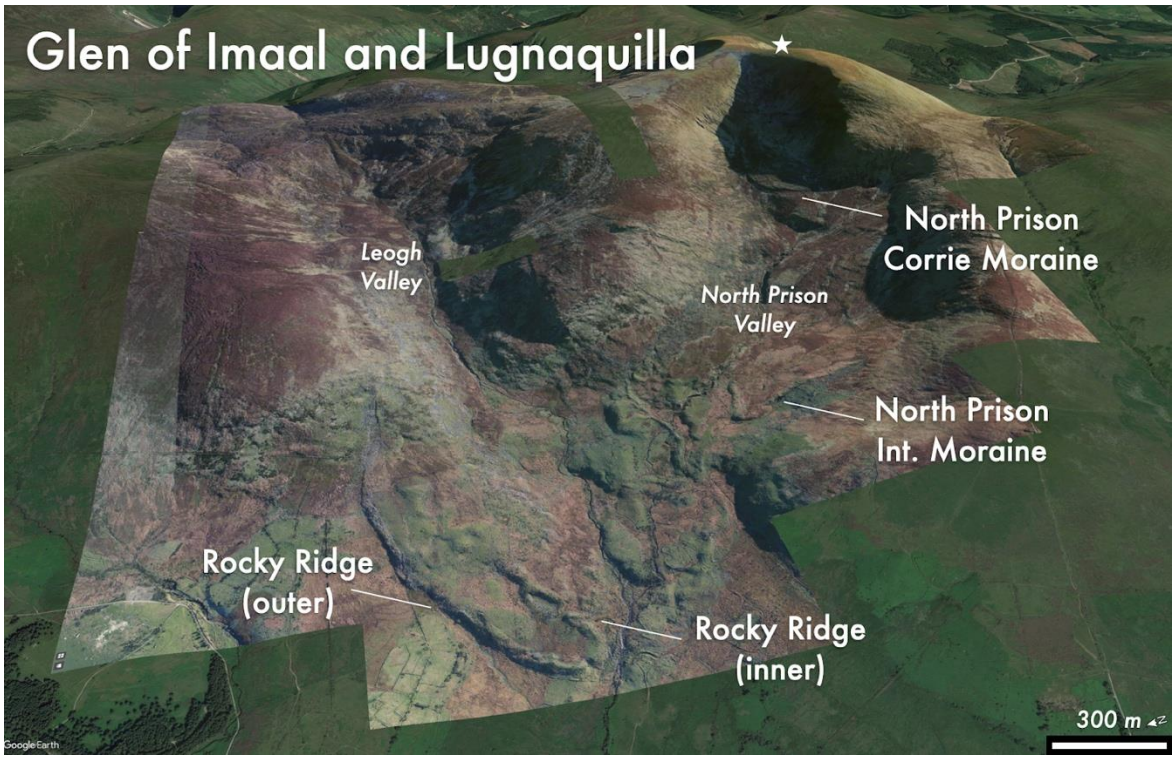

***Figure 1.** The Glen of Imaal and Lugnaquilla. High-resolution DigitalGlobe satellite imagery overlain atop 30-m DEM in GoogleEarth. Locations mentioned within the text are labelled. The peak of Lugnaquilla is marked by a white star. Note that north is toward the left side of the image.*

Fieldwork focused primarily on collecting samples for beryllium-10 surface-exposure dating (Figure 3). We collected 19 samples in all from five distinct landforms/areas, including each of the four moraines mentioned above. We also collected samples from the ridgeline above the Glen of

Imaal, along the slope to the summit of Lugnaquilla. Details of these samples are listed in Appendix 1. Our preliminary beryllium-10 surface-exposure dating results (Figure 2) (Deliverable 7) reveal exciting new insight into the glacial history of the Glen of Imaal and of the wider Irish Ice Sheet.

The RRO moraine represents the most extensive former ice position in the valley during the last glacial cycle, a time when glaciers from the North Prison and Leogh valleys coalesced to form a single ice lobe that extended onto the Glen of Imaal plain. Samples from this ridge yield an arithmetic surface-exposure age of 22.2 ± 0.8 ka (Figure 2). This is the first direct determination of the timing of valley glaciation in the western Wicklow Mountains. These results also constrain the position of the former Irish Ice Sheet margin at this time. Notably, these results stand in contrast to recent Irish Ice Sheet reconstructions (e.g., Hughes et al., 2016; Clark et al. 2018) and indicate the ice sheet was less extensive at 22 ka than is widely presumed.

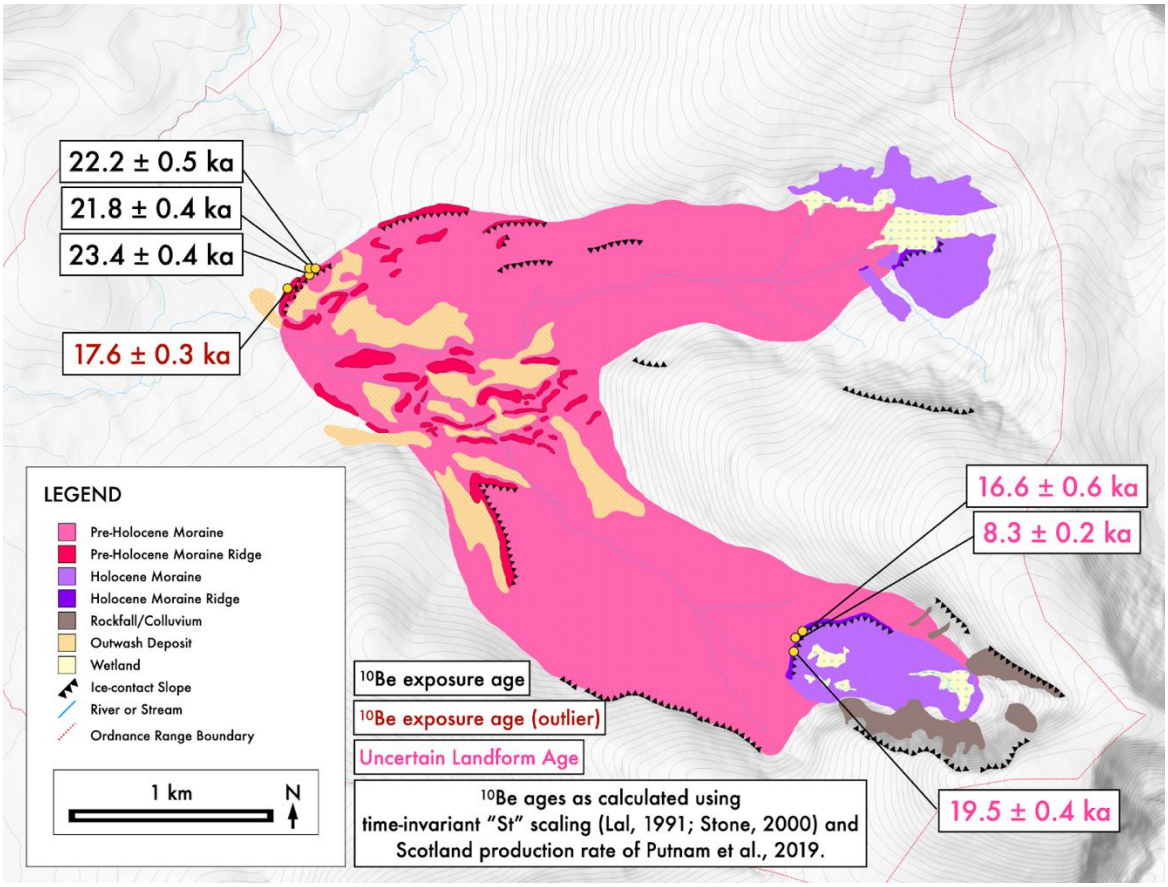

Figure 2. *Glacial-geomorphic map of the Glen of Imaal. Preliminary surface-exposure ages of boulders on moraine ridges are shown in white boxes. Sample locations are marked by yellow circles. A larger version of this map is available on the Irish Ice Age Trail website.*

Three surface-exposure samples from the NPC moraine yield ages of 19.5, 16.6, and 8.3 ka, respectively. These scattered, apparently 'old' ages suggest the presence of so-called 'inherited' beryllium. In this case glacial erosion during the last ice age was insufficient to remove the surface of the samples and so to 'reset' the exposure age, leaving 'old' beryllium remaining in the surface as new beryllium accumulated. This may indicate that the NP corrie held thin, non-erosive ice, or perhaps thicker ice frozen to its bed, that was incapable of eroding the boulder surfaces. It is also possible that these boulders were 'recycled' from earlier periods of glaciation. Additional beryllium-10 ages from this landform are pending and will help clarify the history of this moraine ridge.

Remaining samples will be included in the scheduled July and September 2022 mass accelerator runs at Lawrence Livermore National Laboratory (LLNL) for beryllium measurement.

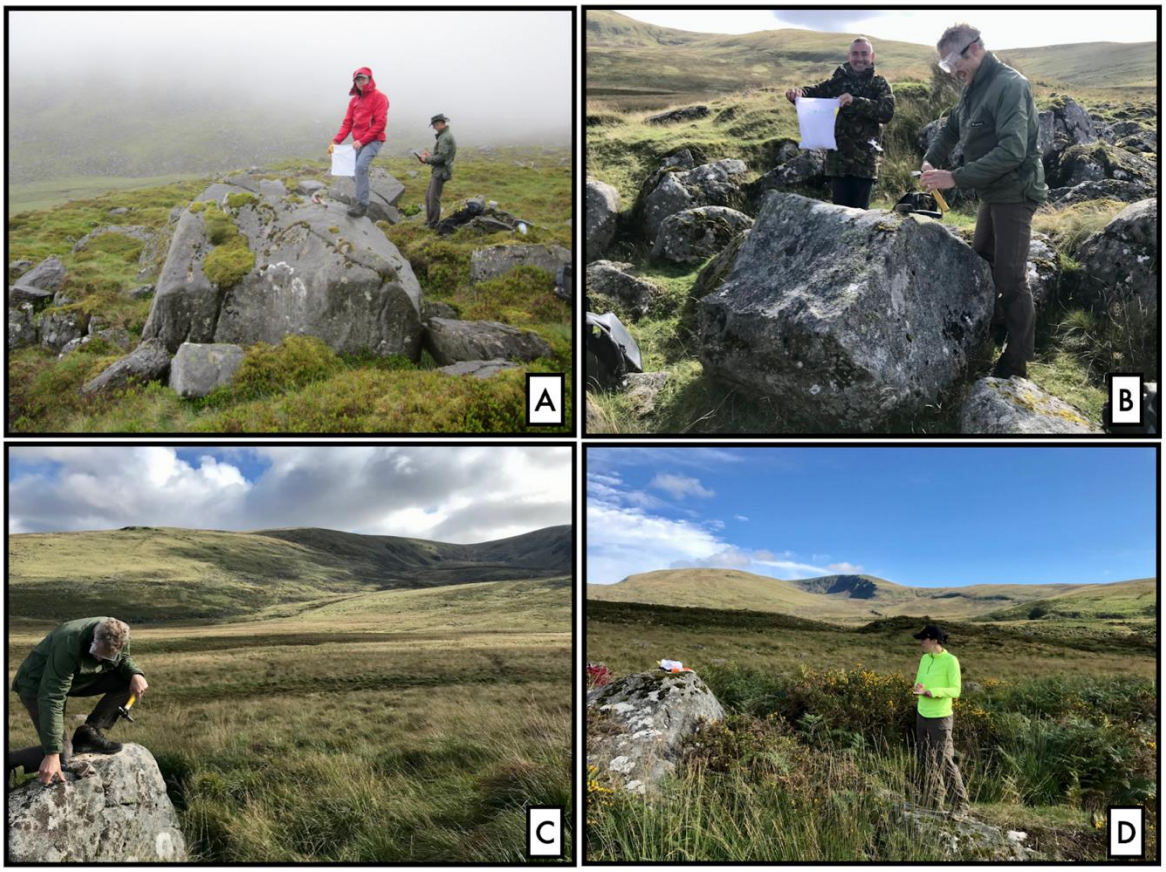

Figure 3. *Fieldwork in the Glen of Imaal. (A) The North Prison (NP) corrie moraine is marked by large, sub-rounded boulders characteristic of clasts affected by glacial erosion and transport and has 2-3 m relief above the valley floor. The NP intermediate moraine (B and C) is a lower-relief feature, with roughly 2 m relief above the valley floor. The NP corrie moraine ridge can be seen in the background of panel C. The Rocky Ridge moraine (D) features 3-5 m relief above the valley floor and is composed of many large (2-2.5 m diameter) boulder clasts.*

(ii) Implementation (milestones, deliverables, project management)

Below we detail the work completed and associated deliverables, as well as any still ongoing work associated with the project. Where deliverables are pending or incomplete we detail when and where these items will be available.

Deliverable 1: Details of collected samples from the Glen of Imaal.
This deliverable is complete. Details of all samples, including geographic coordinates, elevation, and associated landform, are provided in Appendix 1 (Section 4). Once all beryllium ratio measurements are complete these data will be uploaded to the open-access ICE-D alpine glacier database (alpine.ice-d.org) for public archival.

Deliverable 2: Detailed glacial geomorphic map of the study area.

This deliverable is complete. The final map (Figure 2) highlights the rich glacial geomorphology found in the Glen of Imaal. The map is now available on the *Irish Ice Age Trail* website and will be updated to include the full glacial chronology once all sample measurements are in hand.

Deliverable 3: Sedimentary radiocarbon data.
We are unfortunately unable to complete this project task and associated deliverable. After discussions with Defence Forces staff at the Glen of Imaal it was determined that collecting subsurface sediments within the field area posed too great a risk of encountering unexploded ordnance.

Deliverable 4: Snowline reconstruction of former Glen of Imaal glaciers.
This deliverable is complete. Snowline (ELA) reconstructions enable surficial glacial geomorphology to be associated with discrete climate conditions. Table 1 provides the results of these calculations and the estimated temperature depression associated with each former glacial position. These data will be included in the ultimate project publication.

Deliverable 5: Preliminary sample preparation for cosmogenic surface-exposure dating.
This step is now complete. All samples collected from the Glen of Imaal for cosmogenic surface-exposure dating have been carefully measured and pulverised to the ideal size fraction and subsequently leached in hydrofluoric and nitric acids to isolate and etch quartz grains. This prepared quartz was then sent to the University of Maine for processing.

Deliverable 6: Sample processing for cosmogenic surface-exposure dating.
All remaining samples are now at the University of Maine cosmogenic nuclide laboratory in the final stages of preparation for cosmogenic beryllium analysis at the Center for Accelerator Mass Spectrometry (CAMS) at LLNL. We anticipate the samples will be included in the scheduled July and September 2022 LLNL mass accelerator runs. As part of this project, Co-Investigator Bromley visited Maine in the autumn of 2021 to assist in sample processing and to learn more about cosmogenic isotope laboratory function as part of his ongoing work to establish such a facility at NUIG.

Deliverable 7: Measurement of beryllium ratios at LLNL.
This task will be complete by the end of summer 2022, as the remaining Glen of Imaal samples are anticipated to be included in the scheduled July and September mass accelerator runs at LLNL.

Deliverable 8: Irish Ice Age Trail outreach materials
This deliverable is available on the Irish Ice Age Trail website: https://sites.google.com/view/irishiceagetrail. Materials thus far include a 360º virtual tour of the Glen of Imaal and associated educational materials for second and third-level instructors, as well as the detailed glacial-geomorphic map of the field area. These materials will be updated with additional information on the timing and rate of glacial (and climate) change once the completed glacial chronology is in hand.

Deliverable 9: Presentation of results at international conferences.
PI Jackson presented the preliminary results of this work at the recent European Geosciences Union General Assembly (May, 2022). Jackson earlier presented the project aims and scope at the IQUA Spring Symposium (2021) and will present final project results at the IQUA Conference Meeting in the Autumn of 2022 and at the American Geophysical Union (AGU) General Assembly in December, 2022.

Deliverable 10: Submission of manuscript to a high-impact, peer-reviewed journal.
This deliverable is pending. We anticipate manuscript submission in the late autumn or early winter of 2022 once all sample measurements are in hand. The publication will include the detailed

glacial-geomorphic map, interpretations of landforms and landscape process history, the cosmogenic nuclide chronology, and an assessment of the climatic and topographic factors that influenced glacial fluctuations in the Glen since the last ice age. We will also address the implications of our Imaal glacial reconstruction for wider Irish Ice Sheet dynamics. Target journals currently include *Geology* and *The Cryosphere*.

Deliverable 11: Final project report.

(iii) Outputs to date

PI Jackson presented the goals of the project at the Irish Quaternary Association (IQUA) Spring Symposium in 2021, and presented preliminary results of the project at the recent European Geosciences Union (EGU) General Assembly held in May, 2022 (see Deliverable 9.) The abstract for this presentation is available online: (https://meetingorganizer.copernicus.org/EGU22/EGU22-12198.html).

PI Jackson produced a virtual tour of the Glen of Imaal (Deliverable 8). The virtual tour is hosted on the PI's *Irish Ice Age Trail* website (https://sites.google.com/view/irishiceagetrail), along with curricular materials for second and third-level students to explore glacial geomorphology.

The glacial-geomorphic map of the field area is also available on the *Irish Ice Age Trail* website.

A list of all samples collected is provided in Appendix 1 (Section 4). Once all beryllium measurements are complete, these data will be archived in the open ICE-D alpine glacier database (alpine.ice-d.org).

(iv) Impact

- Relevance/application to GSI programmes, where applicable

The output of this project supports the GSI Research Roadmap objectives of (i) risk mitigation for geologic hazards and (ii) public perception of geosciences.

The final project results will elucidate the timing and magnitude of glacial fluctuations at the Glen of Imaal over the last 22 ka. These data will provide a novel, directly dated record of past climate variations in Ireland over this period and so will provide a means to assess the terrestrial expression of past abrupt climate change following the last ice age, which will aid in future climate adaptation and planning. In addition, the virtual tour of the Glen of Imaal provides a unique venue to share project results and to introduce concepts in palaeoclimate and geomorphology to the wider public.

- Other impacts

Although complete results are still pending, the preliminary results of this project indicate that the final dataset will provide firm benchmarks for ice sheet modellers. In particular, through demonstrating the presence of alpine glaciers at the site at 22 ka, and thus the absence of any overlying ice sheet, the implications of this work are of vital importance to our understanding of long-term ice sheet response to climate change and large-scale warming. In particular, these results suggest that prevailing Irish ice sheet reconstructions, based primarily on offshore or near-shore data, likely place too much ice (for too long) over this sector if Ireland.

The virtual tour of the Glen of Imaal (Deliverable 8) provides the general public the opportunity to explore a region usually off limits to visitors. Jackson will utilise the virtual tour and wider project

Publications:

Jackson, M.S., Bromley, G.R.M., and Hall, B.L, 2022. Glacial fluctuations in the southwestern Wicklow Mountains, Ireland. *European Geosciences Union General Assembly*, Vienna, Austria. [https://meetingorganizer.copernicus.org/EGU22/EGU22-12198.html]

3. *Supplemental information/datasets*

Appendix 1: Samples collected in the Glen of Imaal

Sample ID	Latitude	Longitude	Elevation (m)	Landform
GIM-21-01	52.973627	-6.484204	570	NP Corrie Moraine
GIM-21-02	52.97337	-6.48446	573	NP Corrie Moraine
GIM-21-03	52.97313	-6.484705	569	NP Corrie Moraine
GIM-21-04	52.972898	-6.484879	568	NP Corrie Moraine
GIM-21-05	52.972917	-6.484998	568	NP Corrie Moraine
GIM-21-06	52.976221	-6.505665	386	NP Intermediate Moraine
GIM-21-07	52.977238	-6.50588	380	NP Intermediate Moraine
GIM-21-08	52.976902	-6.505766	383	NP Intermediate Moraine
GIM-21-09	52.978551	-6.50652	361	NP Intermediate Moraine
GIM-21-10	52.978717	-6.506631	358	NP Intermediate Moraine
GIM-21-11	52.988288	-6.51933	242	RR Inner Moraine
GIM-21-12	52.988288	-6.51933	242	RR Inner Moraine
GIM-21-13	52.987972	-6.520344	239	RR Inner Moraine
GIM-21-14	52.987962	-6.52053	282	RR Inner Moraine
GIM-21-15	52.989258	-6.521414	234	RR Outer Moraine
GIM-21-16	52.989406	-6.521104	234	RR Outer Moraine
GIM-21-17	52.98948	-6.521089	231	RR Outer Moraine
GIM-21-18	52.989502	-6.52099	234	RR Outer Moraine
GIM-21-19	52.989473	-6.521163	232	RR Outer Moraine
GIM-22-01	52.967398	-6.490111	654	Lugnaquilla Ridge
GIM-22-02	52.967982	-6.49428	631	Lugnaquilla Ridge
GIM-22-03	52.970293	-6.503447	520	Lugnaquilla Ridge
GIM-22-04	52.969995	-6.504591	532	Lugnaquilla Ridge
GIM-22-05	52.970237	-6.505389	532	Lugnaquilla Ridge
GIM-22-06	52.9700065	-6.505592	521	Lugnaquilla Ridge

[Appx. 1] Table 1 - Samples collected from the Glen of Imaal for cosmogenic surface-exposure dating. Sample landforms are as marked in Figure 1 .