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	Sam Kelley
Host Organisation name	University College Dublin
Project Title	TOPDOWN: Examining the vertical expression of the last glaciation of Ireland
Contract Number	2022-SC-020

This report covers the period 1st December 2020 to project end date (31/08/2024)

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2. (a) Project information:

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

Executive summary (extended abstract, e.g. for use by policy/other stakeholders):

1. Introduction

The Irish highlands present a perplexing problem; weathered bedrock found at high elevations suggests a landscape much older than glacially abraded landscapes found in the lowlands. These contrasting geomorphological regimes led to speculation that the highlands were exposed as nunataks (fig. 1A) during the last glaciation[ex.1]. This idea was supported studies using single cosmogenic isotopes that yielded exposure ages older than the present interglacial (fig. 2)[2]. These ages were considered to be affected by inheritance, a store of cosmogenic nuclides from previous periods of exposure, supporting the hypothesis that some summits must have been exposed as nunataks throughout the last glaciation.

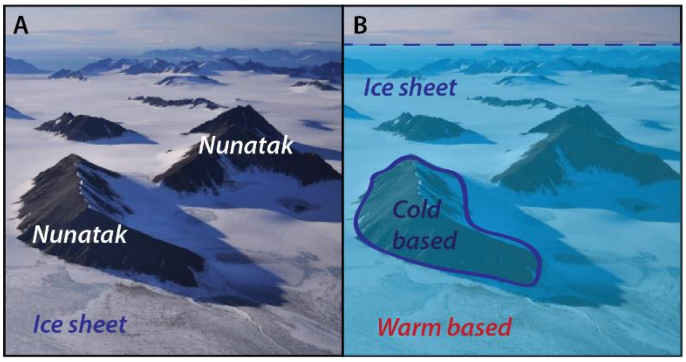

Figure 1. Illustration showing the two hypotheses proposed to explain the high concentration of cosmogenic nuclides found at high elevations in Ireland. (A) Photo of nunataks. Nunataks are mountains that stick up through an ice sheet. (B) Di gram illustrating variations in the basal thermal regime of an ice sheet: cold-based ice = little to no erosion, warm-based = erosion.

More recent work has found that weathered upland areas can contain high concentrations of nuclides due to differential erosion caused by variations in the basal thermal regime of the ice, not continuous exposure[3]. Thus, a second hypothesis formed; the Irish highlands were buried under cold-based, non-erosive ice during the last glaciation[4] (fig. 1B).

Currently, neither hypothesis can be rejected based on existing data, however the answer is crucial to our understanding of ice sheet evolution and landscape modification in Ireland, as well as constraining regional isostatic constraints on relative sea level rise. Our research aims to answer the question: Were Irish mountains exposed as nunataks during the last glaciation? To do so, we collected samples from four Irish mountain summits for paired ^{10}Be and ^{14}C cosmogenic exposure dating to test if Irish mountain summits were paleonunataks during the Last Glacial Maximum (LGM, ~25 ka), which should allow us to better constrain the thickness of the last British-Irish Ice Sheet (BIIS) in Ireland.

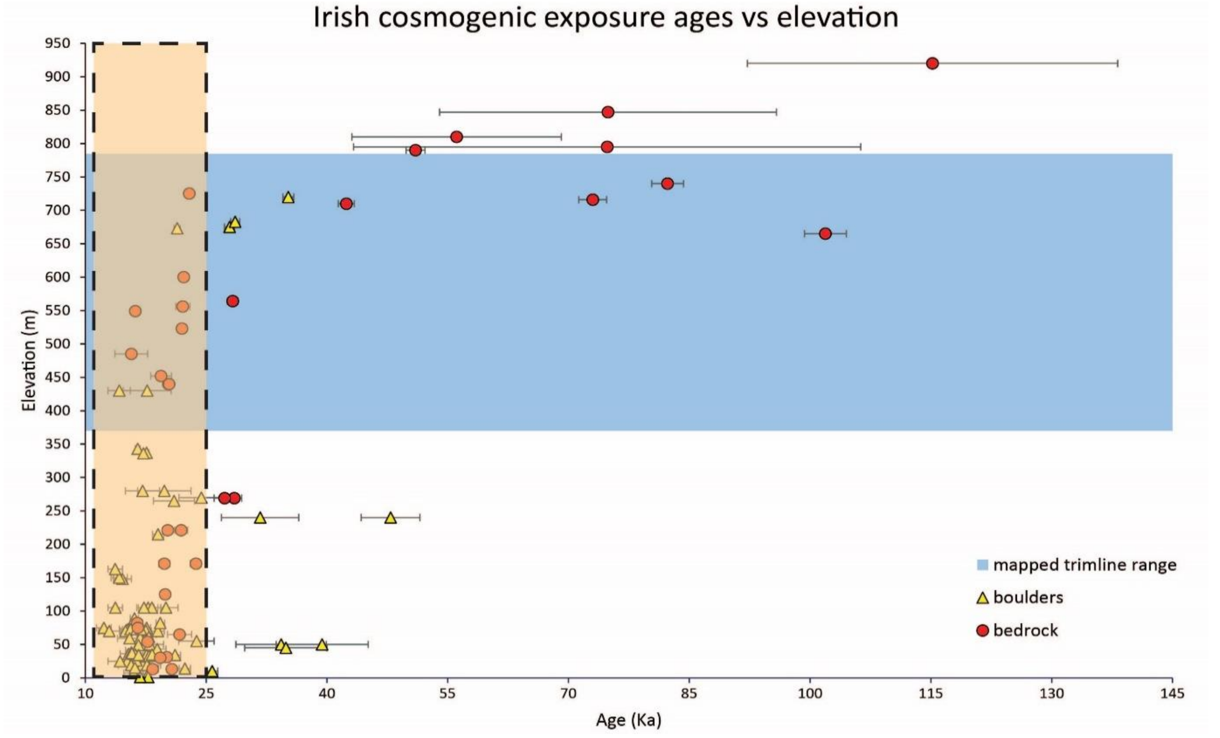

Figure 2. The plot above compares all of the published cosmogenic exposure ages constraining glaciation in Ireland (from 10 to 145 ka) vs. the elevation of the sample site. Note, all Be ages are recalculated using the global production rate and LSDn scaling, Cl ages are left as originally published. At low elevations, ages cluster at <25 ka; this broadly agrees with the timing of regional deglaciation of the British-Irish Ice Sheet. Many samples from >500m elevation yield ages considered to be affected by inheritance. The blue shaded region represents the elevation of mapped trimlines in Ireland.

2. Methods

Samples for cosmogenic exposure dating were collected from four study sites: the Mourne Mountains, The Wicklow Mountains, Mount Brandon on the Dingle Peninsula, and the Dublin Mountains (fig. 3). Sample collection was guided by previously mapped trimlines, tors, and blockfields, and previous studies using cosmogenic exposure dating. All samples were collected from above mapped trimlines and from bedrock surfaces exhibiting features of long-term subaerial weathering (e.g. weathering pits, elevated grains/clasts, rounded joints).

Figure 3. Map of sample locations for this study.

2.1 Cosmogenic nuclide exposure dating

Cosmogenic nuclides are produced in the Earth's surface via bombardment from cosmic rays and can be used to gain quantitative information about surface processes such as duration of exposure or burial. The long half-life of cosmogenic ^{10}Be ($t_{1/2}$ = 1.36 Ma) makes it susceptible to inheritance if insufficient erosion has occurred to 'reset the clock'. Due to the short half-life of ^{14}C ($t_{1/2}$ = 5,730 yrs), inheritance from previous exposure cannot be preserved as concentrations will decay to background levels in the span of one glaciation. Thus, using ^{14}C in conjunction with ^{10}Be allows us to resolve the problem of inheritance versus exposure, and determine if landscapes at high elevations were continuously exposed throughout the last glaciation or if they were preserved under cold-based ice (fig. 4).

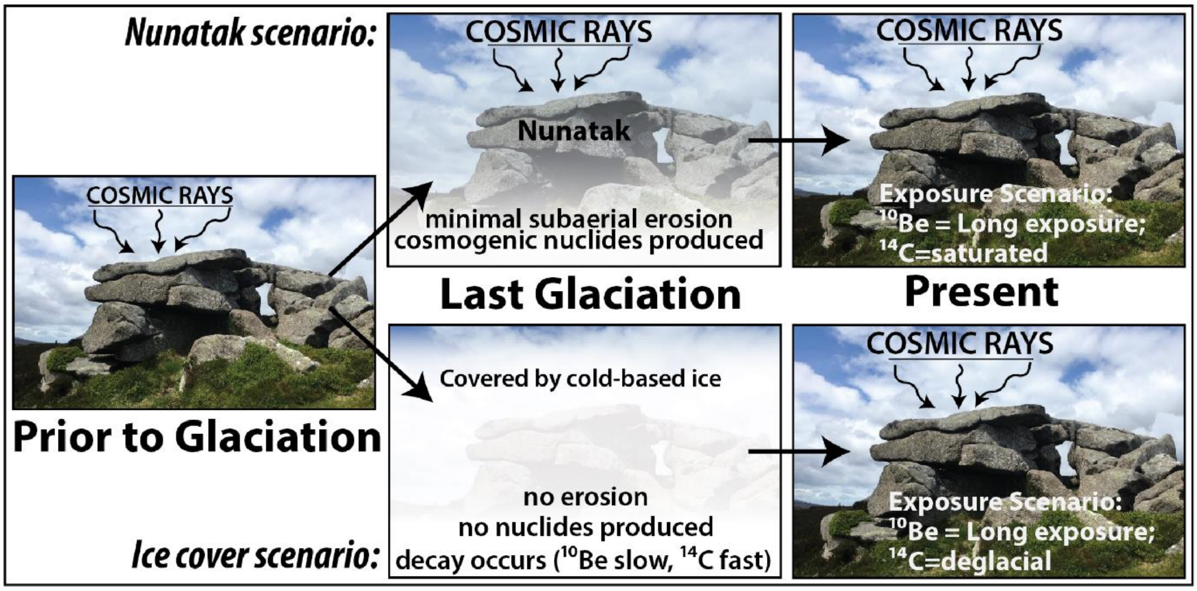

Figure 4. Possible end-member scenarios that will be used to classify sample sites as paleonunataks or areas of cold-based ice based on cosmogenic exposure ages.

2.2 Laboratory techniques

Quartz was extracted from whole rock for ^{10}Be and ^{14}C extraction at UCD Cosmogenic Isotope Facility (UCIF). Samples for ^{10}Be measurement are prepared at UCIF and sent to the Lawrence Livermore National Laboratory for measurement, while quartz separates underwent ^{14}C extraction and measurement at Purdue Rare Isotope Measurement Laboratory (PRIME) [5]. Exposure ages were calculated using version 3 of the University of Washington online calculator (https://hess.ess.washington.edu/), using the global production rate[6] and LSDn scaling[7]. We use the global production rate to be able to compare our ^{10}Be ages and ^{14}C ages, as it is currently the only production rate calibrated for both nuclides.

3. Results

We measured cosmogenic isotope concentrations in a total of 14 samples from bedrock: three from Slieve Binnian, three from Mullaghcleevaun, five from Mount Brandon, and three from Three Rock. We report individual ages with 1σ uncertainty in thousands of years (ka). The calculated ^{10}Be ages produced a wide range, from 10.2 ka to 123.6 ka. The samples from Slieve Binnian returned the oldest ^{10}Be ages, ranging from 98.1 ka to 123.6 ka. Two Slieve Binnian samples, SB-23-05 and SB-23-06, returned satistically identical ages (98.1 ± 1.6 ka and 98.8 ± 1.6 ka). These samples were taken from the same group of tors and similar elevations (749 m and 752 m). Interestingly, the oldest age (123.6 ± 2.0 ka) came from a lower elevation (677 m).

Table 1. 10Be and 14C cosmogenic exposure ages of samples with 1σ uncertainty.

Sample ID	Elevation (m a.s.l.)	^{10}Be age (ka)	^{10}Be age uncertainty (ka)	^{14}C age (ka)	^{14}C age uncertainty (ka)
Slieve Binnian					
SB-23-03	677	**123.6**	2.0		
SB-23-05	749	**98.1**	1.6		
SB-23-06	752	**98.8**	1.6		
Mullaghcleevaun					
MC-23-01	842	**39.8**	0.8		
MC-23-02	842	**44.7**	0.8		
MC-23-03	843	**36.2**	0.7		
Mount Brandon					
MB-23-01	855	**16.2**	0.3		
MB-23-02	810	**40.2**	0.8		
MB-23-03	793	**38.4**	1.0		
MB-23-04	950	**10.2**	0.3		
MB-23-05	875	**15.2**	0.4		
Three Rock					
TR-23-01	461	**20.5**	0.4		
TR-23-02	452	**22.0**	0.4		
TR-23-03	447	**23.1**	0.5		

Results pending

The Mullaghcleevaun samples also ages older than the most recent deglaciation. Samples MC-23-01 (39.8 ± 0.8 ka) and MC-23-02 (44.7 ± 0.8 ka) were taken from two tor stubs ~2 m apart on the northwestern side of Mullaghcleevaun (842 m). MC-23-03 was taken from a tor on the southwest side of Mullaghcleevaun, ~15 m from the other two, at an elevation of 843 m, and yielded an age of 36.2 ± 0.7 ka. Previous work reported ages of

The Mount Brandon samples produced the widest range of ages at an individual site (10.2 ka to 40.2 ka). MB-23-04 was our highest elevation sample, at 950 m, but it yielded our youngest age (10.2 ± 0.3 ka). MB-23-02 and MB-23-03, provided older ages of 40.2 ± 0.8 ka and 38.4 ± 1.0 ka. Both samples came from similar elevations (~800 m) and both were taken from the southern ridge of Mount Brando. MB-23-01 was also taken on the southern ridge at a slightly higher elevation (815 m) and produced an age of 16.2 ± 0.3 ka. Our last Mount Brandon sample, MB-23-05, was taken from the northern ridge of the mountain, at an elevation of 875 m and produced an age of 15.2 ± 0.4 ka.

The three samples from Three Rock produced the most well-clustered group of ages (20.5 to 23.1 ka). These samples were taken from three different tors at a similar elevation, and were the lowest elevation samples collected in our dataset.

4. Discussion

More than half of our samples yielded ^{10}Be exposure ages older than the timing of local deglaciation. Two of our sample sites, Slieve Binnian and Mullaghcleevaun, have potential to be paleonunataks as their ^{10}Be ages were significantly older than the last glacial maximum. If these sites were paleonunataks, then we would expect the ^{14}C concentrations to be saturated.

The Mount Brandon samples produced an interesting range of ^{10}Be ages (10.2 ka to 40.2 ka). Two samples from this location were older than the LGM (40.2 ka and 38.4 ka) and two potentially align with regional deglaciation (16.2 ka and 15.2 ka). Our highest elevation age from Mount Brandon was our youngest age overall (10.2 ± 0.3 ka). This was very surprising, as the summit bedrock appeared quite weathered. The range of ^{10}Be ages at Mount Brandon could mean several things: (1) The older ages represent continuous exposure as a nunatak, in which case the ^{14}C ages for those two samples would be saturated. (2) The young ages represent deglaciation and the ^{14}C ages will match deglacial timing (~10-15 ka). (3) All of the ages are 'correct' and record an ice cap thinning, in which case we would

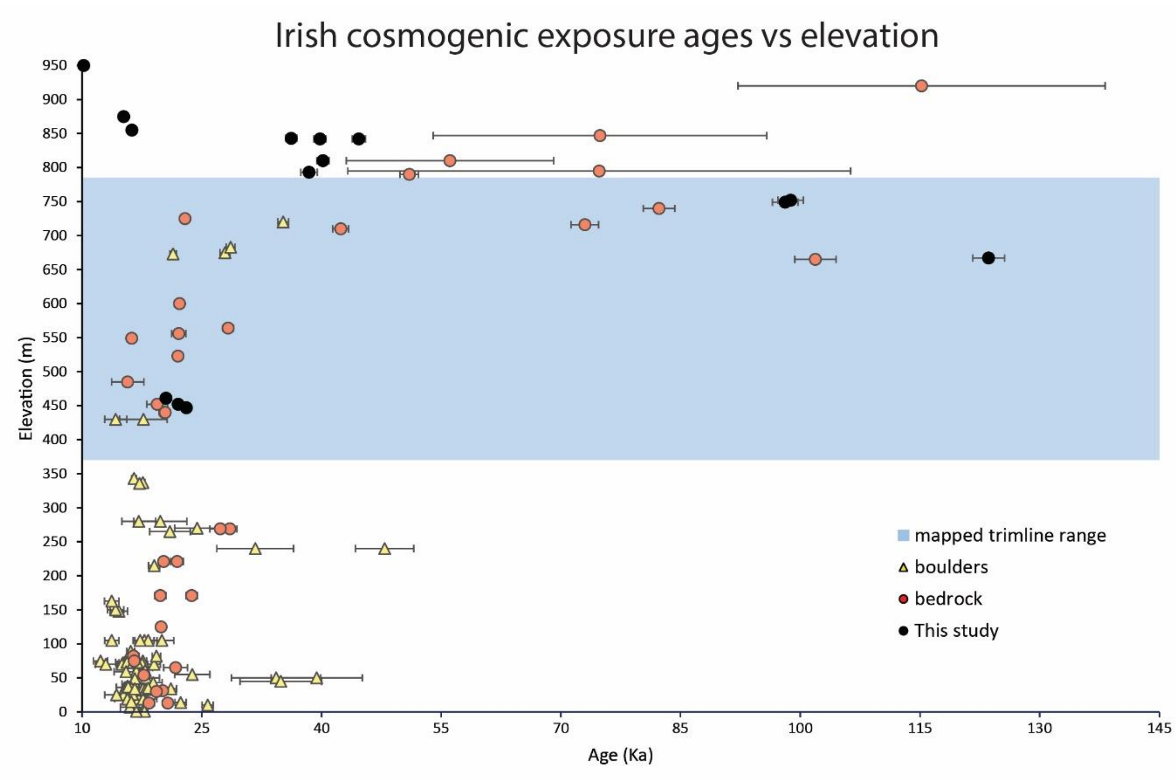

Figure 5. Plot of our ^{10}Be exposure ages (black circles) vs. the elevation of the sample site with the mapped trimline range shaded in blue. ^{10}Be bedrock ages plotted in black. The semi-transparent yellow triangles (boulders) and red (bedrock) circles represent cosmogenic ages from previously published studies.

expect the ^{14}C ages to show a range of ages similar to the ^{10}Be ages. We find it unlikely that the youngest age (10.2 ka) represents deglaciation as this is several thousands of years younger than local deglacial constraints (~16-22 ka). It is more likely that this sample represents the removal of overlying material, either by post glacial rockfall or human activity, which led to an anomalously young age.

The Three Rock ^{10}Be ages appear to fall close to the timing of local deglaciation, however this is inconsistent with the geomorphological evidence (tors and weathering pits) found on site. Features like tors and weathering pits are signs of long-term subaerial exposure, which associated with high concentrations of cosmogenic nuclides. If the ^{10}Be ages do represent deglaciation, case we would expect the ^{14}C ages to agree with the ^{10}Be ages, however this would require the erosion and removal of ~ 2 m of material to 'reset' the cosmogenic clock. We find this scenario unlikely as that would have removed the weathering features. More likely, the site contains some inherited 10Be atoms form a previous glacial, and will yield ^{14}C ages younger than 20 ka, indicating the true timing of deglaciation.

4.1 Implications

Using ^{14}C in conjunction with ^{10}Be should allow us to resolve the problem of inheritance versus exposure and provide better constraints on the thickness of the former BIIS. Numerical models of relative sea-level (RSL) are important tools for predicting coastal geohazards and developing mitigation strategies. The thickness of former ice sheets remains one of the largest uncertainties in RSL models and future sea-level rise predictions. This work has implications for refining local ice sheet reconstructions across northeast Europe, as well as, for assessing and refining the ability of numerical ice sheet models to reconstruct past ice sheet thickness of past and modern ice sheets.

5. Conclusions

The first paired ^{10}Be and ^{14}C samples collected in Ireland have thus far yielded interesting results. ^{10}Be results support two locations as being potential paleonunataks (Slieve Binnian and Mullaghcleevaun). We are awaiting ^{14}C ages to place our Be results in context. Constraining the thickness of the last BIIS in Ireland has implications for assessing and improving numerical ice sheet models and RSL rise models, which are important tools for stakeholders and policy makers.

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(i) Project Implementation

The details for research are given below. For materials currently pending, anticipated dates for completion are provided.

- Sampling occurred in January (Mournes), April (Dingle), May (Wicklow), Dublin Mountains (June) of 2023.
- Quartz isolation occurred in batches which concluded in May, 2023, and then in April 2024.
- Samples were sent to Purdue for ^{14}C extraction and measurement in July, 2023. Extraction of carbon in complete, but samples are still awaiting measurement (anticipated Oct. 2024).
- Beryllium was extracted from quartz samples at UCD in two batches, the first was completed in Sept. 2023, the second in April, 2024.
- Measurement of beryllium was performed in Sept. 2023 and in June 2024.

(ii) Outputs to date

- Database of cosmogenic ages around Ireland and associated map
- New paired ^{10}Be and ^{14}C cosmogenic exposure ages
- Training for two early career researchers in lab procedures and field work
- UCD College of Science Scholarship (Dakota Youngeagle) for work associated with this project on trimlines in Ireland.
- Application to SFI frontiers for the future funding call based on the outcomes of this pilot study (in prep., anticipated submission autumn 2024)

Poster presentations:

Crowell, C.E., Youngeagle, D.D., Kelley, S.E., Lifton, N. (2023). Constraining the thickness of the last Irish ice sheet using in situ cosmogenic ^{10}Be and ^{14}C measurements. CHESS field school. Lyngen Alps, Norway.

Crowell, C.E., Youngeagle, D.D., Kelley, S.E., Lifton, N. (2023). TOPDOWN: Examining the vertical expression of the last glaciation in Ireland. GSI fall meeting. Dublin, Ireland.

Crowell, C.E., Youngeagle, D.D., Kelley, S.E., Lifton, N. (2024). TOPDOWN: Examining the vertical expression of the last glaciation in Ireland. Irish Geological Research Meeting. Galway, Ireland. **Won award for best student poster and received grant from Irish Quaternary association to attend conference (500€).*

Crowell, C.E., Youngeagle, D.D., Kelley, S.E., Lifton, N. (2024). TOPDOWN: Examining the vertical expression of the last glaciation in Ireland. COSMO 2024. Cologne, Germany. **Received grant from QRA to attend conference (750€).*

Oral presentations:

Crowell, C.E., Youngeagle, D.D., Kelley, S.E., Lifton, N. (2024). TOPDOWN: Examining the vertical expression of the last glaciation in Ireland. UCD Interdepartmental seminar. Dublin, Ireland.

Kelley, S.E., Doughty, A., Butler, M., Moucheron, M., Warren., (2023) Looking Up: A multidisciplinary project on glacial geology and early prehistoric heritage in the Cairngorm Mountains. IQUA Spring Meeting. University College Cork (March 25th, 2023)

Community and public engagement:

- August 9th, 2023: A public field trip was co-led by myself and Sam Roberson (GSNI) for the Mourne-Gullion-Strangford Aspiring UNESCO Geopark on the local glacial geology of the Mourne Mountains and my ongoing research project (GSI funding was acknowledged). Additionally, a brochure was made with copies given to the aspiring geopark for distribution a further events (flyer in supplemental figures). A total of ~15 people attended.

- A class field trip was taken to the Dublin Mountains with the UCD GEOL40490 class in February, 2024 to examine the glacial geology of the area. The process of collecting a sample was discussed, as were the initial findings and implications of this work.

- May 6th 2024: A public field trip was led as part of the Dublin Mountain festival entitled Monuments, Geology & Ecology Guided Hike. The trip explained the glacial geology of the Three Rock area (as well as local archaeology and ecology), with specific focus on the tors at Three Rock and initial findings of this work (GSI funding was acknowledged). A total of ~ 30 people attended.
  Links about the event:
  https://www.dublinmountains.ie/news/latest_news/

(iii) Impact

This work provides a proof-of-concept study for paired ^{14}C-^{10}Be analysis of palaeo-nunataks, allowing for future research to close a key knowledge gap about former ice sheet loading and its role in regional relative sea level rise. This pilot data is being employed as part of a larger research proposal to investigate the BIIS on the whole to improve forecasts for relative sea level change in northwest Europe, as well as provide improved datasets for training ice sheet models used in forecasting future change. Additionally, this project directly aligns with the recently published DECC Research and Innovation Strategy by training student researchers and expanding the pool of personnel with research and innovation expertise.

<u>Publications:</u>

Crowell, C.E., Youngeagle, D.D., Kelley, S.E., Lifton, N. (2023). Constraining the thickness of the last Irish ice sheet using in situ cosmogenic ^{10}Be and ^{14}C measurements. CHESS field school. Lyngen Alps, Norway.

Crowell, C.E., Youngeagle, D.D., Kelley, S.E., Lifton, N. (2023). TOPDOWN: Examining the vertical expression of the last glaciation in Ireland. GSI fall meeting. Dublin, Ireland.

Crowell, C.E., Youngeagle, D.D., Kelley, S.E., Lifton, N. (2024). TOPDOWN: Examining the vertical expression of the last glaciation in Ireland. Irish Geological Research Meeting. Galway, Ireland.

Crowell, C.E., Youngeagle, D.D., Kelley, S.E., Lifton, N. (2024). TOPDOWN: Examining the vertical expression of the last glaciation in Ireland. COSMO 2024. Cologne, Germany.

Crowell, C.E., Youngeagle, D.D., Kelley, S.E., Lifton, N. (2024). TOPDOWN: Examining the vertical expression of the last glaciation in Ireland. UCD Interdepartmental seminar. Dublin, Ireland.

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Figure 7. Photographs of weathered bedrock from different sampling sites with cosmogenic ages. ^{10}Be ages are reported in black and ^{14}C ages in green. (A-C) Granite, Slieve Binnian, Mourne Mountains (Co. Down). (D-H) Sandstone, Mount Brandon, Dingle (Co. Kerry).

Figure 8. Photographs of weathered bedrock from sampling sites with cosmogenic ages. ^{10}Be ages are reported in black and ^{14}C ages in green. (A-C) Granite, Mullaghcleevaun, Wicklow Mountains (Co. Wicklow). (D-F) Granite, Three Rock, Dublin Mountains (Co. Dublin). (G) Weathering pits in sandstone found on bedrock near MB-23-05. (H) Positive weathering feature in sandstone found on bedrock near MB-23-02.

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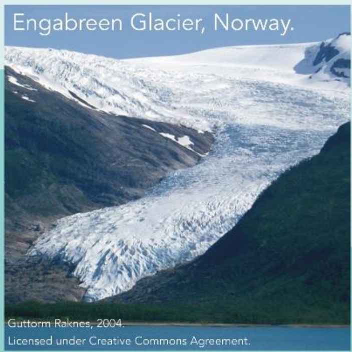
What is a glacier?

A glacier is a **massive body of ice**, made mostly from compressed snow.

A glacier is created over a few hundred years by the build up of many layers of snow. The weight of all the snow layers crushes the snow crystals at the bottom, creating ice.

Glaciers are made up of thousands of tonnes of ice, and are so big that they flow downhill by themselves.

Glaciers move across the landscape like a river, carving out valleys and transporting rocks.



Engabreen glacier (above) is flowing downhill under its own weight.

The snow and ice that made the glacier fell on a mountain range next to the sea in Arctic Norway.

Where is it?

Carrick Little Car Park, Old Town Road, Annalong, BT34 4RW

Is it for me?

We will be walking about 5 miles on footpaths and rough, rocky ground.

We will walk for about 2 hours in total, keeping together as a group. No one will be left behind!

What should I bring?

Make sure you have suitable shoes or boots.

Take enough food and drinks to keep you going.

Bring a *waterproof coat* in case it rains; a *hat* and *suncream* for sunny weather.

Glaciers of the Mourne Mountains

The Annalong Valley

Walking Field Trip

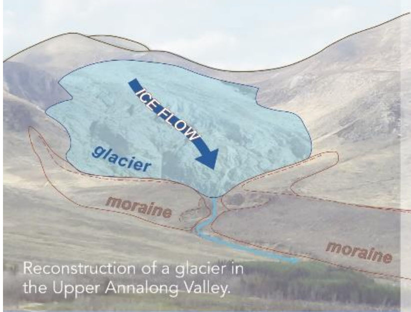
During the Ice Age, the Mourne Mountains were home to glaciers for many thousands of years.

Join us on a walking tour of the Annalong Valley, Co. Down. Discover where the glaciers were and what evidence they left behind for us to find.

Ice Sheets

There is lots of evidence that huge glaciers, known as **ice sheets**, covered the whole of Ireland as far south as the Celtic Sea! The ice sheet was so thick that it might have completely covered the Mourne Mountains.

The tops of the highest mountains, like Slieve Donard and Slieve Binnian, may have poked up through the ice sheet. Mountain tops surrounded by ice are known as **nunataks**.



Reconstruction of a glacier in the Upper Annalong Valley.

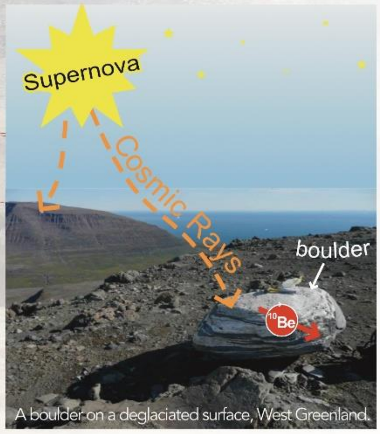
Nunataks in Svalbard – mountain summits poking up through an ice sheet.

Moraines

Glaciers grind up rocks as they move, acting as conveyor belts for the rock fragments that they create. The rock fragments build up at end of the glacier, forming large mounds called **moraines**.

Moraines help us understand the previous position and movement of small mountain glaciers, like our reconstruction in the Upper Annalong Valley.

Cosmogenic Nuclides



A boulder on a deglaciated surface, West Greenland.

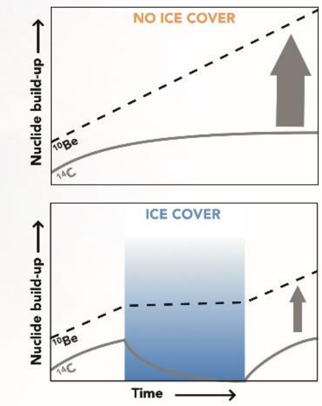
Cosmic rays from space cause elements in rocks at the Earth's surface to form **cosmogenic nuclides** like Beryllium-10 or Carbon-14.

Cosmogenic nuclides build-up and break down at known rates. Understanding this means we can calculate how long rocks have been sitting at the Earth's surface for. This technique is called **exposure dating**.

Exposure Dating

Rocks covered by ice sheets are sheltered from cosmic rays, preventing the build-up of cosmogenic nuclides and allowing break down to take place.

Once the ice sheet is gone, cosmogenic nuclides build up again.



^{10}Be builds-up and breaks down much more slowly than ^{14}C.

This knowledge helps us to tell if mountain tops such as Slieve Binnian were covered by ice.

Figure 9. Flyer created for public field trip held in the Mourne Mountains in conjunction with GSNI for the Mourne, Gullion, Strangford aspiring geopark. Copies of the flyer were left with the geopark for further distribution. The digital file was shared as well.