The multi-scale control of crustal structures on the exhumation of the British-Irish Isles, revealed by 40 years of AFT studies

Rémi Rateau[1] and David Chew[1]

[1]Trinity College Dublin

November 21, 2022

Abstract

A compilation of legacy and new low-temperature thermochronological data from the British-Irish Isles and their surrounding offshore shelves yielded c. 700 AFT ages and c. 180 AHe ages from 29 peer-reviewed papers, 27 Geotrack industry reports and several new unpublished studies from offshore Ireland. The compilation shows for the first time a regional age pattern, with older AFT ages in Scotland and Northern Ireland than in the rest of Ireland. This pattern is tentatively attributed to the influence of the Anton-Dohrn Transfer Zone (ADTZ) during an Early Cretaceous phase of plate-wide uplift that resulted in more exhumation to the SW of the transfer zone than to the NE. Caledonian faults might also create differential exhumation of the tectonic blocks between them, as is observed in the compilation of AFT data from northern Scotland and this could explain the dispersion in the timing of exhumation seen on the North Porcupine High, offshore Ireland. Finally, the Paleogene exhumation visible in the Central Irish Sea, and attributed in recent years to igneous underplating, has not been detected in the Malin Sea-Outer Hebrides, despite the area being underlain by a high-velocity body also interpreted as igneous underplating. In conclusion, a detailed analysis of a large dataset of low-temperature thermochronological has revealed the possible influence of major crustal structure on the Mesozoic exhumation of this part of the NE Atlantic Margin, with large-scale decoupling occurring at a transfer zone and medium-scale decoupling occurring along regional-scale faults. The dataset also shed some doubts on the generic nature of exhumation caused by igneous underplating which has been much discussed in recent years.

Thermo2020 Santa Fe, NM

The multi-scale control of crustal structures on the exhumation of the British-Irish Isles, revealed by 40 years of AFT studies

Rémi Rateau[1*], David Chew[1]

[1] Department of Geology, Trinity College Dublin

* rrateau@tcd.ie

Trinity College Dublin, The University of Dublin

iCRAG Irish Centre for Research in Applied Geosciences

Irish-British Isles Database of Apatite Thermochronology (IBIDAT) – 1977-2021

New insights from a synthesis of old and new apatite fission track and (U-Th-Sm)/He (AtT) data

IBIDAT so far:

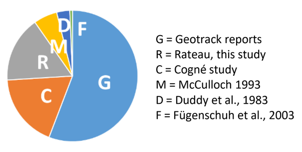
- All onshore/offshore, surface and borehole AtT data for Ireland
- Only onshore surface data for Northern England, Wales and Scotland

Onshore

- 478 AFT ages
- 120 AHe ages

Offshore

- 62 locations
- 264 attempted samples
- 229 AFT ages
- 154 ages suitable for modelling
- Source of suitable samples:



- 26 AHe ages

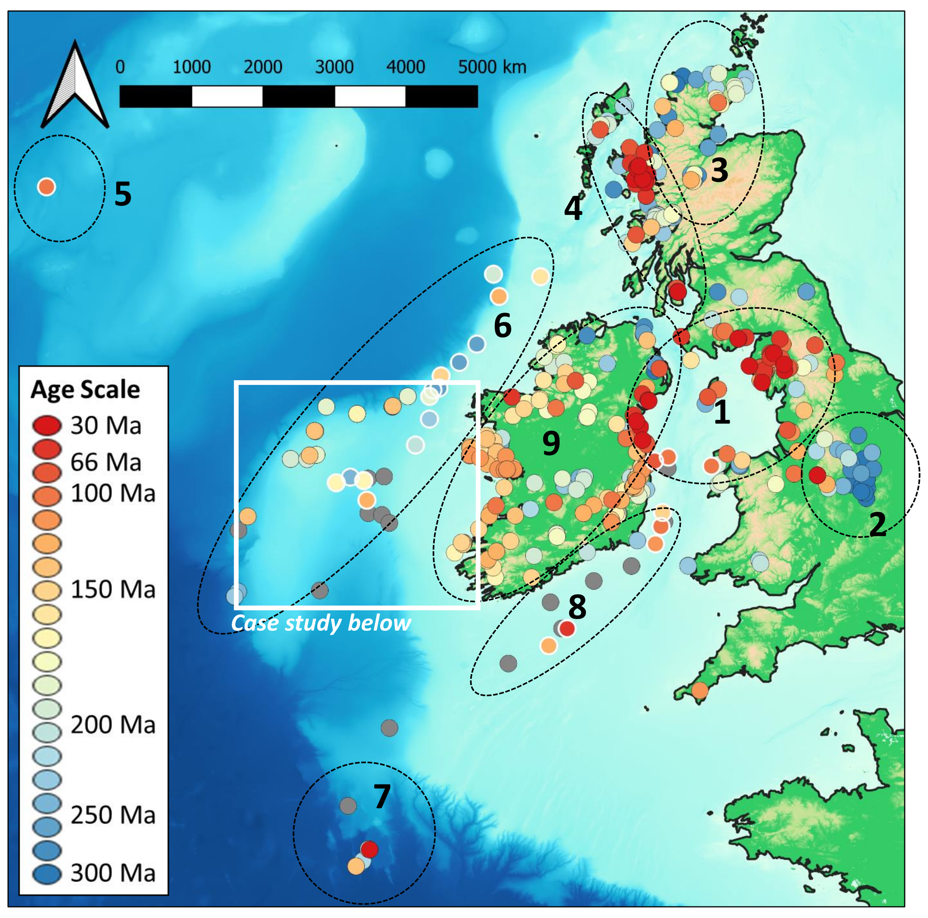
AFT age range (surface only):

- 28 Ma to 546 Ma

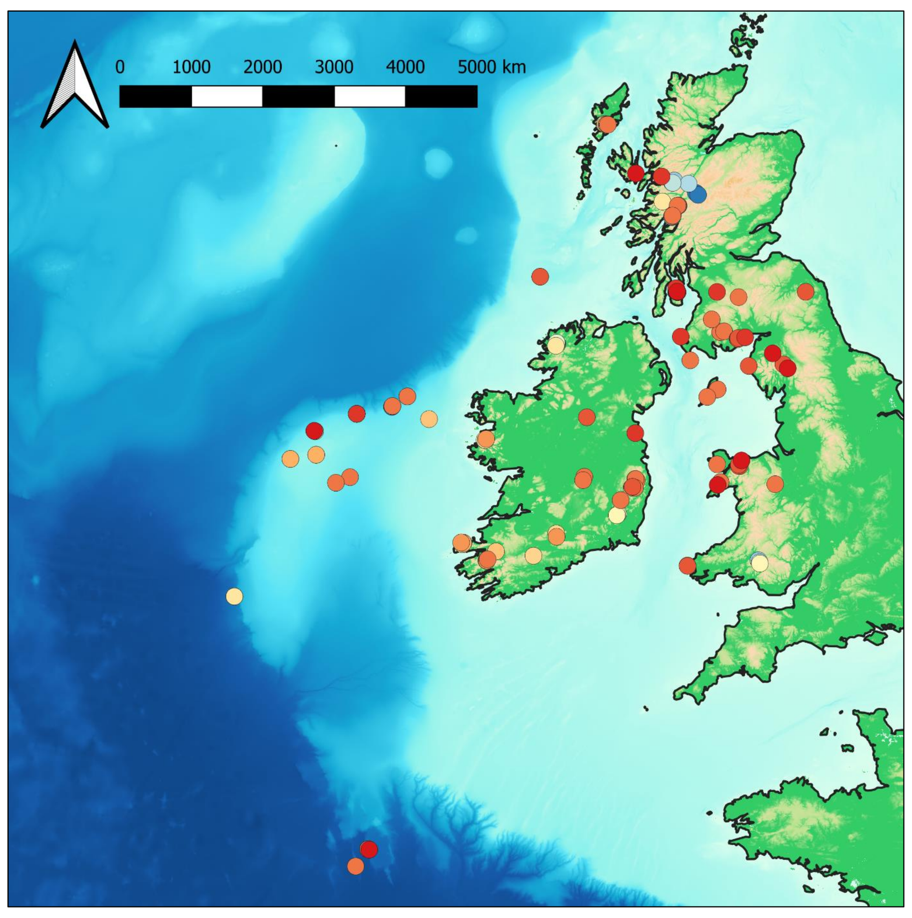
Ahe age range (surface only):

- 14.6 Ma to 459 Ma

AFT Ages (surface)



AHe Ages (surface)



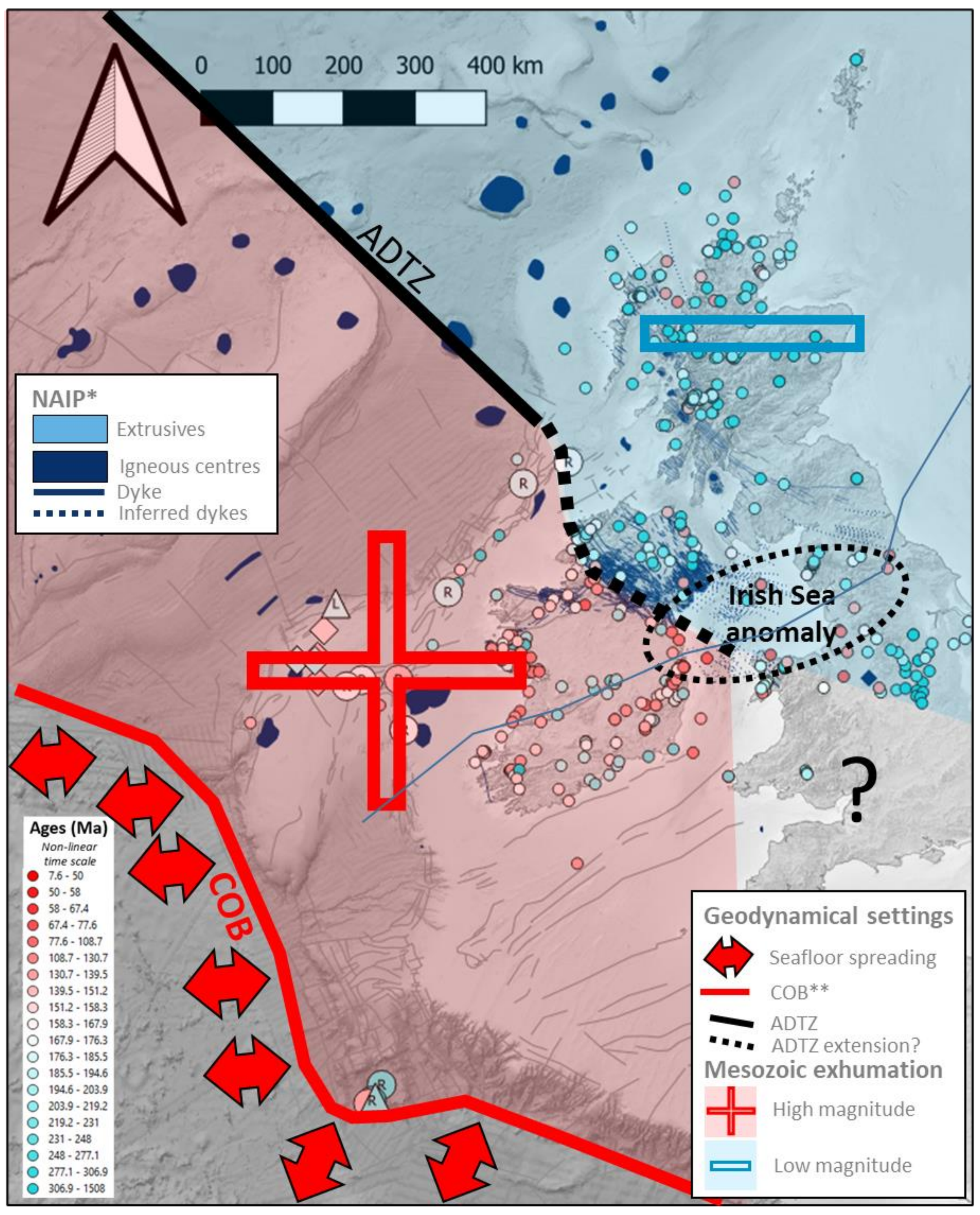
1 **Irish Sea and bordering highs** (Lake District and eastern Ireland): Long-debated and still mysterious Irish Sea thermal anomaly. Small-scale variability showing that the cause of the thermal anomaly had complex short-wavelength thermal effects
2 **English Midlands**: stable craton with old AFT ages (young age is from an intrusion from the Lower Tertiary dyke swarm)
3 **Scottish Highlands:** First AFT ages published in the Irish British Isles (Hurford, 1977). Mixed ages showing a complex pattern of denudation. Old helium ages demonstrating limited amount of burial of summits and highs.
4 **Hebrides Tertiary Igneous Province**: all young AFT and AHe ages are related to the emplacement of the igneous centres rather than burial. Some old FT ages spread around the igneous centres (so the Irish Sea anomalous area does not extend to the Hebrides region)
5 **Hatton Basin**: Oldest AFT study offshore West of Ireland (1983 DSDP borehole). Upper Cretaceous ages from some Eocene sands.
6 **Porcupine High, Basin and offshore NW Ireland**: Main focus of this project. Mixed age signal showing a yet poorly constrained denudation history.
7 **Goban Spur**: AFT and AHe data from dredge and dive samples showing Mesozoic exhumation. Presence of an anomalous basement sample with Eocene AFT and AHe ages (probably ice-rafted from the Hebrides?)
8 **Celtic Sea**: AFT showing important Paleocene erosion linked to compressional structures
9 **Onshore Ireland:** Dominated by Mesozoic ages, complex denudational fingerprint. Older ages in Antrim.

Reference	Location	Methods		Samples	Etching protocol	Age eq.		Lengths		Kin.	Modelling
		AFT	AHe			Grains	Type	MTL	Proj.		FMorIM
Hurford, 1997a	Scotland - Highlands	POP EDM SAME	-	24	5M 10-30s@20°C	Aliquot	Abs.	-	-	-	-
Hurford 1977b	Scotland - Lowlands	POP	-	5	5M 20s@room T.	Aliquot	Abs.	-	-	-	-
Duddy et al 1983	Ireland - Rockall Plateau	EDM	-	5	5M 20s@20°C	Single	Abs.+Zeta	Yes	-	-	-
Green 1986	England - North	EDM	-	23	5M 20s@room T.	Single	Zeta	Yes	-	-	-
Green 1989	England - East Midlands	EDM	-	62	?	?	Zeta	Yes	-	-	-
Carter 1990	Wales - North	EDM	-	5	5M 15s@20°C	?	Zeta	-	-	-	-
Hurford 1990	England - Northwest	EDM	-	2	?	?	Zeta	-	-	-	-
Lewis et al 1992a	Scotland - Islands	EDM	-	39	?	?	Zeta	Yes	-	-	AFTAMOD
Lewis et al 1992b	England - Northwest	EDM	-	45	?	?	Zeta	Yes	-	-	AFTAMOD
Keeley et al 1993	Ireland - Southeast	EDM	-	10	?	Single	Zeta	Yes	-	-	AFTAMOD
McCulloch 1993	Ireland - All onshore & offshore W Ireland	EDM	-	64	5M 20s@room T.	Single	Zeta	Yes	-	-	Yes
McCulloch 1994	Ireland - Northeast	EDM	-	16	5M 20s@room T.	Single	Zeta	Yes	-	-	?
Carter et al 1995	Scotland - Highlands	EDM	-	2	?	Single	Zeta	Yes	-	-	-
Chen et al 1996	England - Southwest	EDM	-	4	?	Single	Zeta	Yes	-	-	Yes
Thomson et al 1999	Scotland - Highlands	EDM	-	31	?	Single	Zeta	Yes	-	Cl(?)	Yes
Green et al 2000	Ireland - All onshore	EDM	-	32	?	Single	Zeta	Yes	-	?	?
Allen et al 2002	Ireland - All onshore	EDM	-	71	5M HNO3 20s@20±1°C	Single	Zeta	Yes	-	-	Yes
Green 2002	England - Northwest	EDM	-	6	?	Single	Zeta	Yes	-	?	?
Fugenshuh et al 2003	Ireland - Goban Spur	EDM	-	1 (6)	6.5% HNO3 40s@20°C	Single	Zeta	Yes	-	-	-
Jolivet 2007	Scotland - Highlands	EDM	-	17	6.5% HNO3 45s@20°C	Single	Zeta	Yes	-	Dpar	AFTSolve
Persano et al 2007	Scotland - Islands & Highlands	EDM	AHe	7/12	n/a	Aliquot	Zeta	Yes	-	Dpar	AFTSolve
Holford et al 2010	Scotland - Islands & Highlands	EDM	-	78	?	Single	Zeta	Yes	-	-	*in-house*
Cogné et al 2014	Ireland - West	LAFT	AHe	23	5.5M 20s@21°C	Single	L-Zeta	Yes	Yes	Dpar/Cl	QTQt
Cogné et al 2016	Ireland & UK - Peri-Irish Sea	LAFT	AHe	42	5.5M 20s@21°C	Single	L-Zeta	Yes	Yes	Dpar/Cl	QTQt
Doepke 2017	Ireland & Scotland	LAFT	AHe	18	5.5M 20s@21°C	Single	L-Zeta	Yes	Yes	Dpar/Cl	QTQt
Łuszczak et al 2017	Northwest England & Scottish Lowlands	EDM	-	22	5.5M 20s@20°C	Single	Zeta	Yes	Yes	Dpar	QTQt
Fame et al 2018	Scotland - Islands & Highlands	-	AHe	15	n/a	Single	N/A	n/a	n/a	n/a	QTQt
Łuszcak et al 2018	Northwest England & Scottish Lowlands	-	AHe	20	n/a	Single	N/A	n/a	n/a	n/a	QTQt
This study	**Ireland - Offshore W Ireland**	**LAFT**	**AHe**		**5.5M 20s@21°C**	Single	**L-Zeta**	Yes	Yes	**Dpar/Cl**	**QTQt**
Geotrack, 1991	27/13-1	EDM	-	3	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 1992	27/13-1	EDM	-	6	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 1993a	42/12-1, 48/19-1, 49/9-1, 50/3-1, 57/9-1	EDM	-	9	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 1993b	12/13-1	EDM	-	6	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 1994	56/14-1	EDM	-	7	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 1995a	42/12-1, 42/17-1	EDM	-	6	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 1995b	33/17-1, 33/21-1, 33/22-1,	EDM	-	14	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 1996	27/05-1	EDM	-	7	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 1997a	18/20-1	EDM	-	10	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 1997b	19/05-1	EDM	-	6	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 1997c	18/20-1, 27/05-1, 27/13-1	EDM	-	26	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 1999	42/16-1, 42/21-1	EDM	-	8	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 2001a	16/28-sb01, 83/20-sb01, 24-sb01, 02	EDM	-	12	5M HNO3 20s@20°C	Single	Zeta	Yes	-	Cl	*in-house*
Geotrack, 2001b	05/22-1	EDM	-	7	5M HNO3 20s@20°C	Single	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Geotrack, 2002	26/28-1, 35/08-2	EDM	-	6	5M HNO3 20s@20°C	Single	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Geotrack, 2003	12/02-1	EDM	-	6	5M HNO3 20s@20°C	Single	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Geotrack, 2004a	43/13-1	EDM	-	5	5M HNO3 20s@20°C	Single	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Geotrack, 2004b	19/11-1A	EDM	-	4	5M HNO3 20s@20°C	Single	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Geotrack, 2004c	18/20-1, 18/25-1, 18/25-2, 19/05-1, 11-1A	EDM	-	40	5M HNO3 20s@20°C	Single	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Geotrack, 2005a	48/30-1, 49/26-1A	EDM	-	11	5M HNO3 20s@20°C	Single	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Geotrack, 2005b	42/21-1	EDM	-	9	5M HNO3 20s@20°C	Single	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Geotrack, 2008	19/08-1	EDM	-	7	5M HNO3 20s@20°C	Single	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Greater Irish Sea
Scotland
England & Wales
Ireland (onshore)
Ireland (offshore, west)
Ireland (offshore, east)

1) Decoupling at a transfer zone

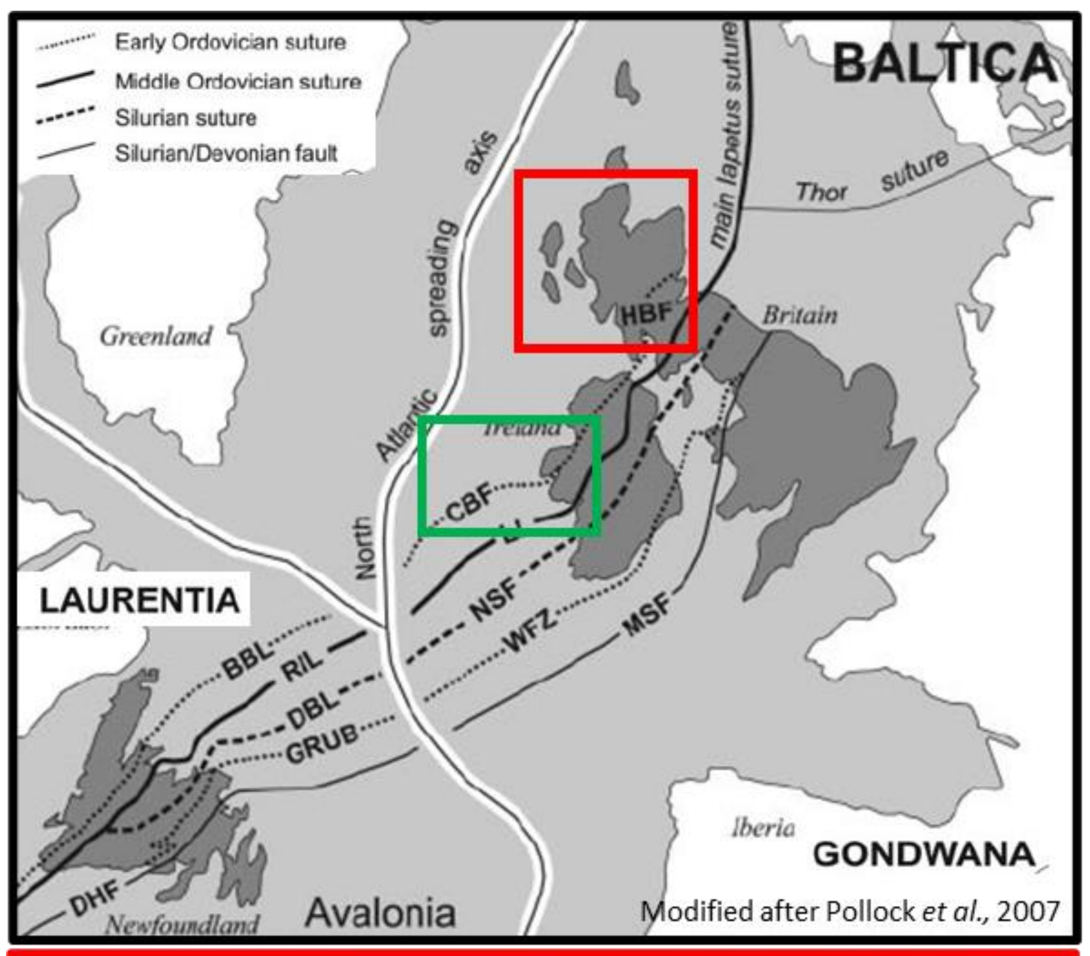
Large-scale – 1,000s km

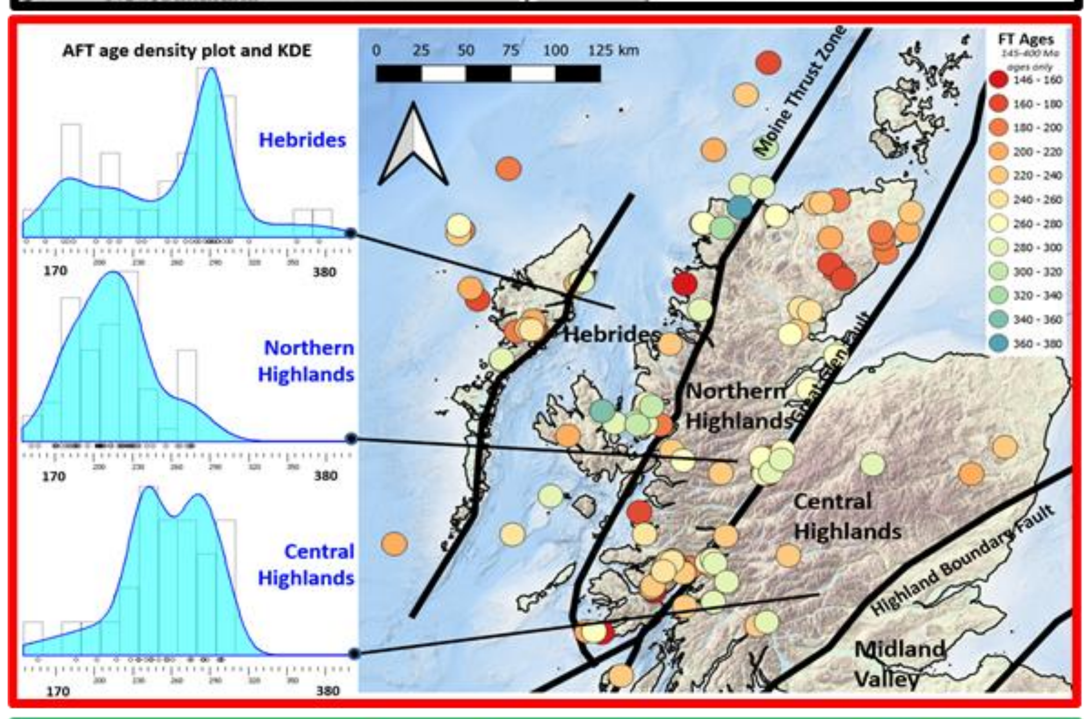


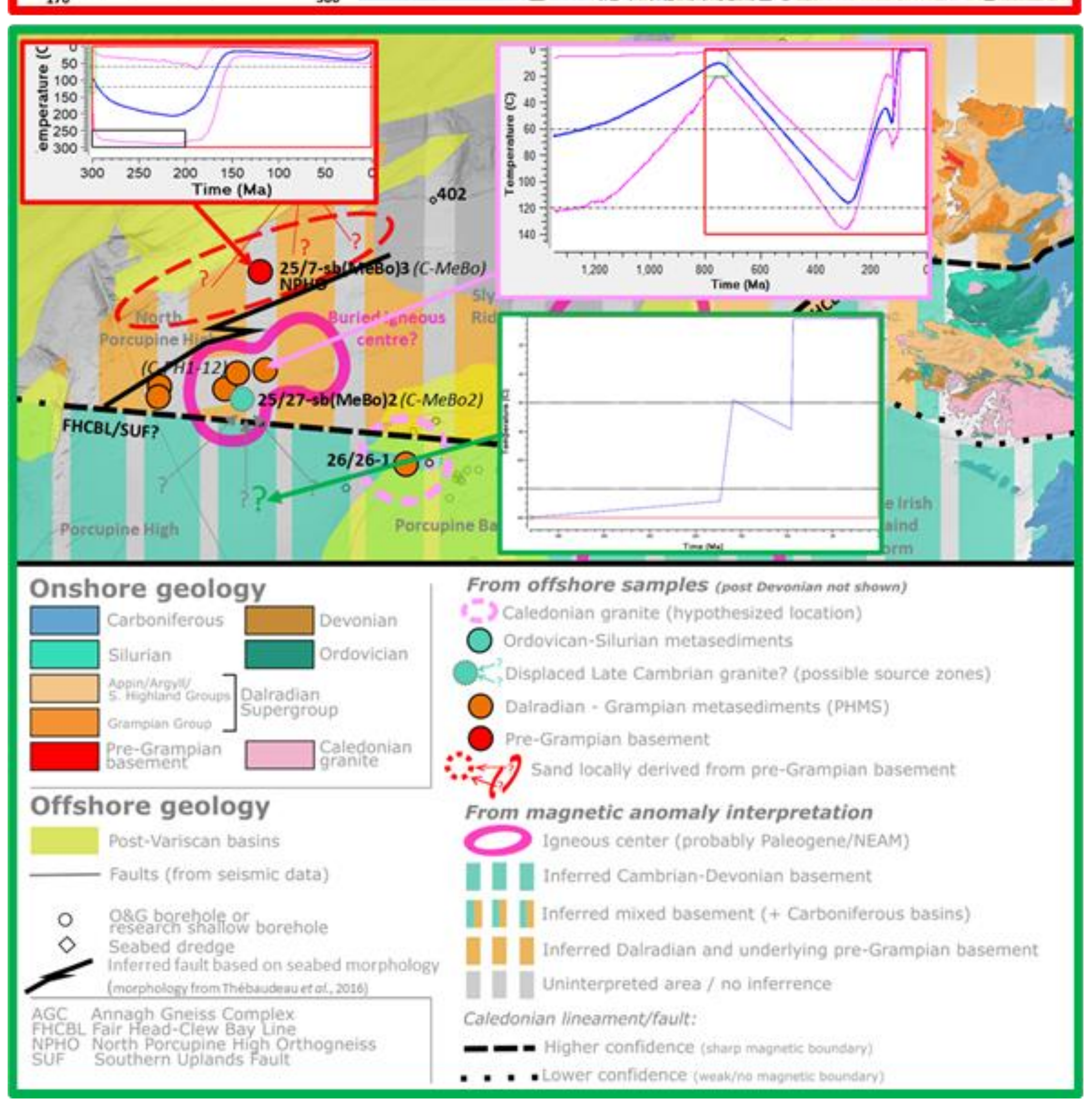
- After data filtering: **older** AFT ages in **Scotland and Northern Ireland** in comparison to **Ireland**.
- **Discrete** rather than gradual boundary. Spatial correlation with 1) a possible extension of the offshore **Anton Dohrn Transfer Zone (ADTZ)** to the NW; 2) the southern edge of the locus of the **Paleogene igneous dyke swarm**.
- *Hypothesis*: **The Anton Dohrn transfer zone extends onshore to the SE and acted as a zone of weakness during Mesozoic rifting = greater amount of exhumation to the SW than to the NE.**

2) Decoupling at orogenic lineaments

Medium-scale – 100s km



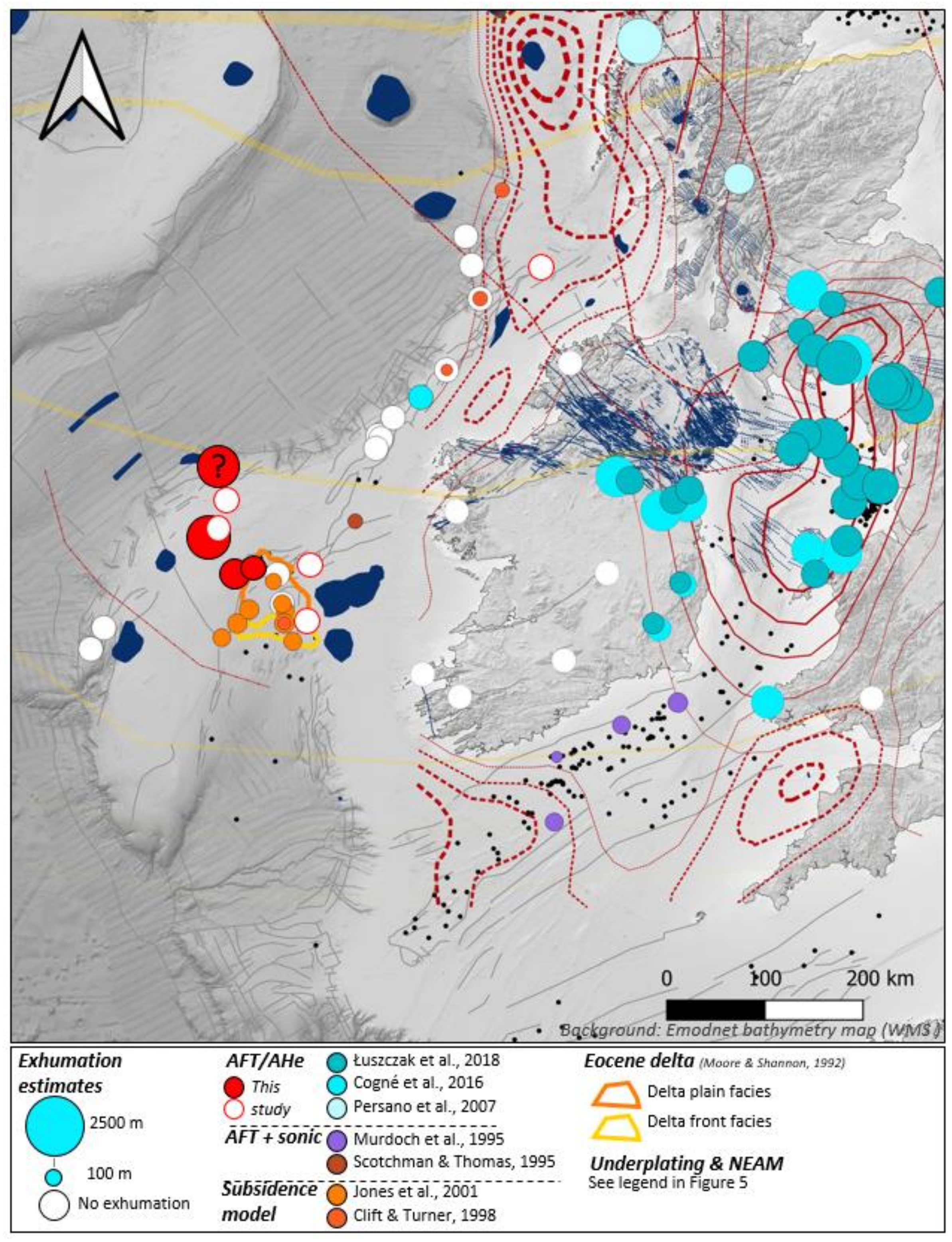




- **Caledonian faults** = orogenic regional-scale faults, correlated to faults in NE Canada.
- Caledonian faults delinate **tectonic blocks** and **basement terranes**.
- **Younger** AFT ages in the **Northern Highlands** terrane *vs* **older** ages in the surrounding **Central Highlands and Hebrides** terranes.
- *Hypothesis:* **Difference in ages = Differential response to Mesozoic exhumation controlled by Caledonian faults**
- Offshore Ireland, on the **North Porcupine High**, dredge and cored basement samples revealed thermal histories with significantly different timings of the main Mesozoic exhumation event.
- **Major Caledonian faults** in the area based on magnetic anomaly and basement samples
- *Hypothesis*: **Discrepancies in age of main phase of exhumation due to differential exhumation across inferred Caledonian faults** (similar to Northern Scotland example).

3) Igneous underplating

Medium-scale – 100s kmv



- **Greater Irish Sea Anomaly**, GISA = Anomalously young (Paleogene) AFT ages in and around the central Irish Sea. Main focus of thermochronological studies in the British-Irish Isles over the last few decades.
- Recent studies: correlated exhumation to the presence of a high velocity body at the base of the crust, interpreted as **igneous underplating** (emplaced during the Paleogene and derived from the Icelandic plume).
- Igneous underplating can lead to significant localized exhumation due to isostatic compensation and subsequent erosion-led isostatic compensation.
- **New studies** offshore Ireland: **No Paleogene exhumation** despite the presence of a thick high-velocity body at the base of the crust such as in the **Donegal Basin** and further north in the **Outer Hebrides**.
- The absence of significant exhumation despite the presence of these bodies reveal the **non-systematic exhumation response to igneous underplating** and therefore the large uncertainty present when using them as a prediction tool for exhumation.

Conclusions

- Compilation of a large AFT/Ahe database for the British-Irish Isles and offshore shelves + new offshore AFT/AHe ages.
- The database reveal for the first time the control of certain crustal structures (transfer zone and orogenic faults) on the Mesozoic exhumation of the area.
- The Anton Dohrn Transfer Zone might extends onshore to the SE and might have acted as a zone of decoupling during Mesozoic exhumation, with the zone to the SW being more uplifted than the zone to t he NE.
- Caledonian faults delineate tectonic blocks that seem to have responded differently to Mesozoic exhumation.
- The previously discovered mechanism of igneous underplating is shown to be ambiguous as it does explain the Greater Irish Sea Anomaly but is in contradiction with the old AFT ages found in the Donegal Basin and Outer Hebrides.
- Th

This publication has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) under Grant Number 13/RC/2092 and co-funded under the European Regional Development Fund and by PIPCO RSG and its member companies.

Ireland's European Structural and Investment Funds Programmes 2014-2020. Co-funded by the Irish Government and the European Union

European Union European Regional Development Fund

Science Foundation Ireland For what's next

ACKNOWLEDGMENTS

- Ewan Pelleter and Thierry Dalle Mulle from Ifremer for facilitating the sampling at their core store in Brest
- Andy Carter and Pieter Vermeesch from UCL for their help on the (U-Th)/He analyses
- Oonagh O'Loughlin, Michael Hanrahan and the core store crew (Petroleum Affairs Directorate - PAD) for facilitating the sampling at the PAD core store
- Alice Mitchinson and Martin Davies from the Irish Petroleum Infrastructure Programme (PIP) for providing industry reports (including thermal history studies)
- PAD for the use of the seismic and well data

PIP Petroleum Infrastructure Programme