Preliminary LA-ICP-MS AFT & AHe Results, Offshore West of Ireland

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1. Introduction

Aim of study		Strategy
CHARACTERISING IAM UPLIFT & EROSION EVENTS		METHODS
1. EXTENT	*Where?* →	Sampling across **IAM**
2. TIMING	*When?*	**Vertical profile** sampling Apatite fission track (**AFT**) Apatite (U-Th)/He (**AHe**) *Supported by:* - re-interpreting **legacy** studies **- well** stratigraphy/lithology - **seismic** studies *Combined data QTQt modelling*
3. MAGNITUDE	*How much?*	
4. CAUSES	*Why?* →	**Integrating** results & regional geology

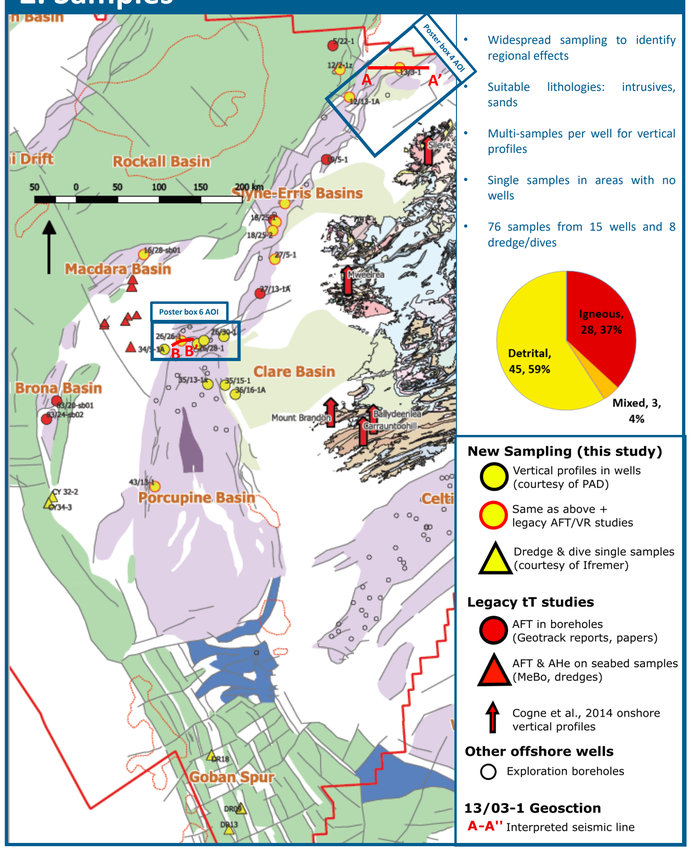
Main interests:

1) Provide input data for petroleum system elements risking (see **Doré *et al.*, 2002**).

2) Improving knowledge of passive margins subsidence/uplift behaviour and mantle plume interactions

3) Exploring the usability and limits of low-temperature thermochronology techniques

2. Samples



- Widespread sampling to identify regional effects
- Suitable lithologies: intrusives, sands
- Multi-samples per well for vertical profiles
- Single samples in areas with no wells
- 76 samples from 15 wells and 8 dredge/dives

New Sampling (this study)
- Vertical profiles in wells (courtesy of PAD)
- Same as above + legacy AFT/VR studies
- Dredge & dive single samples (courtesy of Ifremer)

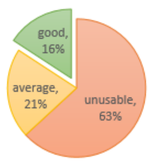
Legacy tT studies
- AFT in boreholes (Geotrack reports, papers)
- AFT & AHe on seabed samples (MeBo, dredges)
- Cogne et al., 2014 onshore vertical profiles

Other offshore wells
- Exploration boreholes

13/03-1 Geosction
A-A'' Interpreted seismic line

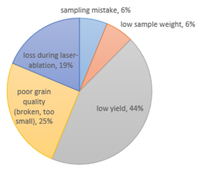
3. Offshore Sampling – Lessons Learnt

Sample Suitability for AFT Studies (19 samples)



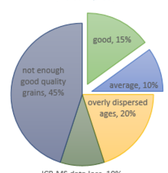
- Based on the analysis of the first 20 samples: overall very low amount of usable samples for AFT & AHe studies

Reasons for Unusable and Average Quality Samples (16 samples)



- Low yield seems to be preponderant for Eocene and Lower Albian sands
- Broken grains: probably due to jaw crusher & original drilling process
- Loss during LA: possibly over-polished samples

Sample Suitability for AHe Studies (20 samples)



- Only ~50% of samples yielded good quality apatites for AHe studies
- Of these, only ~50% yielded uniform AHe ages or dispersed ages that are correlatable to eU

Recommendations for processing of offshore cutting samples for AFT/AHe studies:

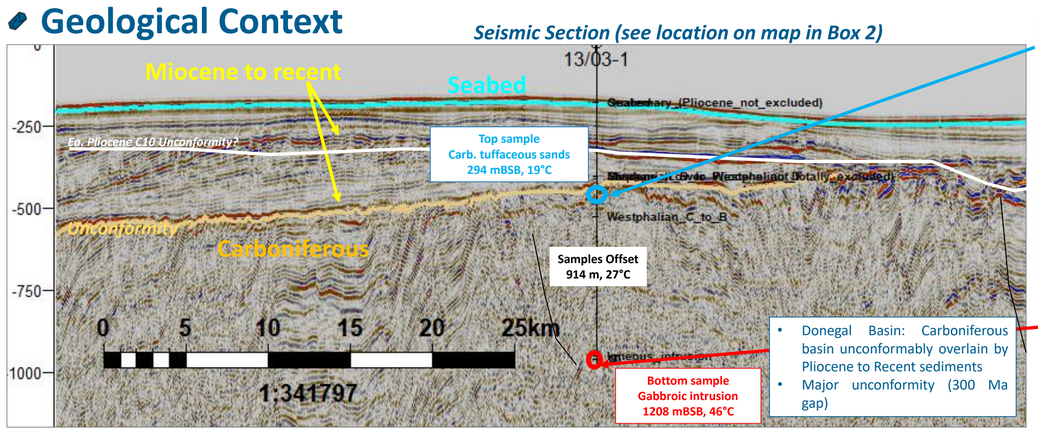
1. Sampling: Sample > 500 grams dry cuttings if possible; check both composite and mud/litho logs to define target depths
2. Mineral separation: Slow crushing with many iterations of sieving (to reduce breaking)
3. Picking: while picking for AHe, select many grains for AFT and align them on tape, particularly for sample with low yield
4. LA-ICP-MS: avoid over polishing in order to ensure that grains are not ejected during LA

Overall low percentage of usable samples when using offshore cuttings from legacy wells, unless coarse igneous rocks have been drilled

4. Prelimary Results – Well 13/3-1, Donegal Basin & the Irish Offsore Mainland Platform

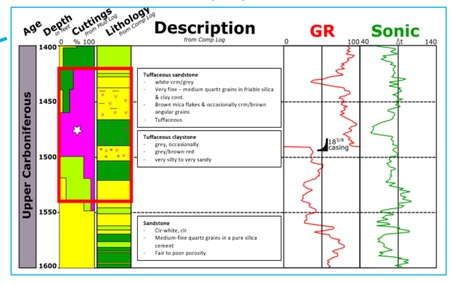
Geological Context

Seismic Section (see location on map in Box 2)



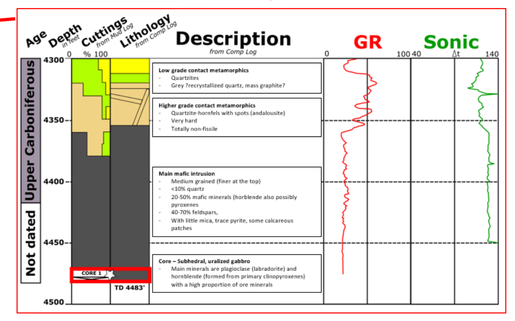
- Donegal Basin: Carboniferous basin unconformably overlain by Pliocene to Recent sediments
- Major unconformity (300 Ma gap)

Top Sample



Well Logs

Bottom Sample



AFT Results

(LAFT approach: U concentration measured by LA-ICP-MS in TCD (Dublin) following the approach of Chew & Donelick, 2012 and Chew et al., 2014 protocols)

13/03-1	Type	Stratigraphic age		Depth (m)	Temp.	Technique	Ns	$^{238}U/^{43}Ca$	Area (cm^2)	FT Age (Ma)	± 2σ (Ma)	# grains	$P(\chi^2)$	MTL (µm)	SE (µm)	# tracks	Dpar	^{35}Cl (ppm)	^{238}U (ppm)
Top sample	Tuff & sand	Up. Carboniferous	307.4 ± 4	320	19°C	LAFT (this study)	1978	1.12E-01	1.24E-03	172.1	8.2	25	<0.01	11.32	2.49	214	1.65	2663	31
Bottom sample	Gabbro	Up. Carboniferous	300 ± 100	1234	46°C	LAFT (this study)	141	7.71E-03	1.18E-03	164	14	23	<0.01	*12.76**	*0.73**	2*	1.71	436**	2.13
						EDM (McCulloch, 1993)	N/A			183.1	19.2	29	N/A			0	N/A	N/A	N/A

** Based on 2 track lengths only - not statistically meaningful*
*** Average value after changing all negative values to 0*

AHe Results

(U, Th, Sm & He for AHe ages measured by ICP-MS at UCL, London)

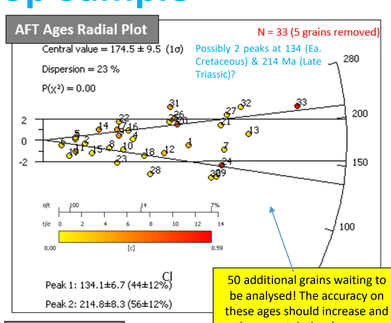
Well/Sample	Temp.	Grain	U (ppm)	Th (ppm)	Sm (ppm)	eU (ppm)	Th/U (weight)	He (nmol/g)	Age (Ma)	± 1σ (Ma)	Ft	Corrected Age (Ma)	± 1σ (Ma)
13/03-1 Top Sample	19°C	1	23.2	67.7	467.8	41.2	2.9	255440.4	**50.5**	8.3	0.8	66.5	8.3
		2	24.4	32.1	835.6	35.7	1.3	323069.1	**73.1**	20.1	0.7	97.6	20.1
		3	1.9	54.7	382.9	16.5	28.4	14335.0	**7.0**	0.0	0.7	9.5	0.0
		4	10.5	79.7	270.1	30.4	7.6	174730.8	**46.9**	4.9	0.7	67.9	4.9
		5	0.7	53.4	210.2	14.2	73.7	24874.3	**14.3**	0.1	0.7	19.5	0.1
		7	54.5	36.2	591.1	65.7	0.7	850683.1	**105.1**	44.9	0.7	160.8	44.9
		8	22.2	60.3	462.5	38.5	2.7	213222.9	**45.1**	6.7	0.6	70.6	6.7
		9	25.9	29.1	842.3	36.6	1.1	398174.2	**88.0**	29.8	0.7	132.9	29.8
13/03-1 Bottom Sample	46°C	1	2.3	10.9	1350.3	11.1	4.7	22715.5	**15.9**	0.4	0.7	23.3	0.4
		2	2.3	11.2	1399.3	11.4	4.9	12991.3	**8.9**	0.1	0.7	13.0	0.1
		3	2.1	11.2	1385.5	11.2	5.2	19555.0	**13.7**	0.3	0.7	20.9	0.3
		4	3.0	14.4	1681.4	14.2	4.8	27295.8	**15.0**	0.4	0.7	21.7	0.4

AFT/AHe Results Sample Analyses

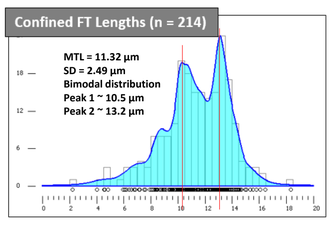
Top Sample

FTD 175 ± 10 Ma

AFT Ages Radial Plot — N = 33 (5 grains removed)

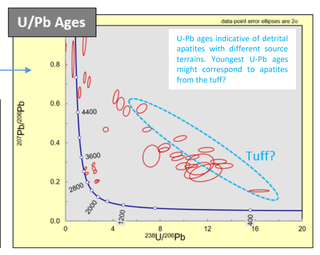


Confined FT Lengths (n = 214)

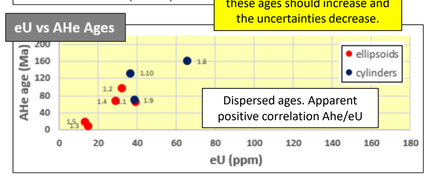


50 additional grains waiting to be analysed! The accuracy on these ages should increase and the uncertainties decrease.

U/Pb Ages



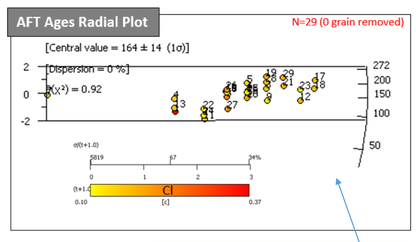
eU vs AHe Ages



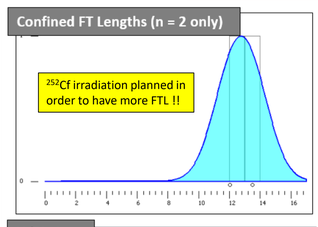
Bottom Sample

FTD 164 ± 14 Ma
U/Pb 311 ± 14 Ma

AFT Ages Radial Plot — N=29 (0 grain removed)

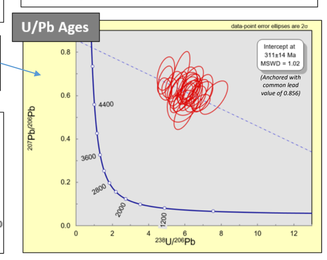


Confined FT Lengths (n = 2 only)

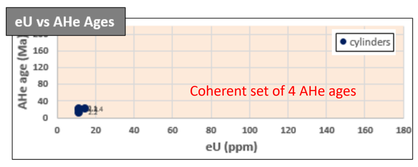


107 additional grains waiting to be analysed! The accuracy on these ages should increase and the uncertainties decrease.

U/Pb Ages



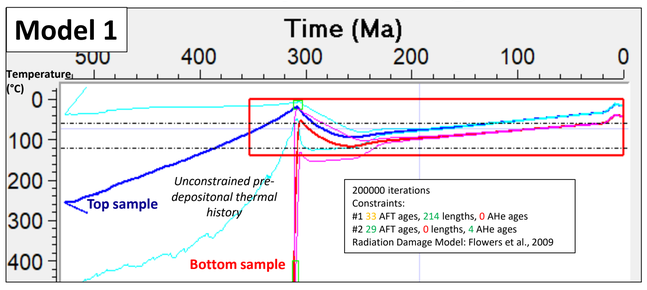
eU vs AHe Ages

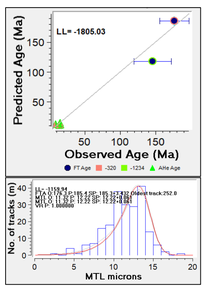


- U-Pb dating yield a 311 ± 14 Ma (Base Permian) age for this intrusion that was believed to be of Tertiary age according to the interpretation of the well report. This age is very close to the age of the tuff in sample 1 (307 ± 4 Ma). It may be possible that this gabbro and the tuff belongs to a same Permian volcanic event. More grains from these samples will be analysed soon and may improve the uncertainty associated with the dating of this intrusion.

Future work on this well:
- **More grains will be analysed** for these 2 samples (~80 more for sample 1 and ~100 more for sample 2).
- **U/Pb ages and/or trace elements geochemistry** of grains in sample 1 will be analysed in order to possibly discriminate 2 families of grains. These could be modelled as 2 different samples.
- Constraining the modelling by adding **1-2 temperature-time boxes** corresponding to some of the major exhumation events believed to have affected this area
- **Reduce** the time-temperature **search space** of the QTQt model
- Evaluate the value of the available **VR** data for this well. Test the effect of adding VR data in the QTQt modelling.

Thermal History Modelling with QTQt



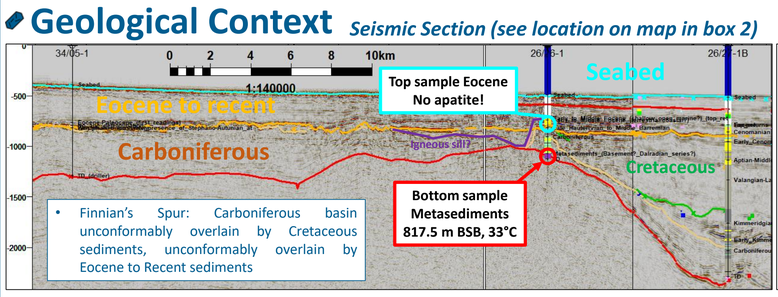


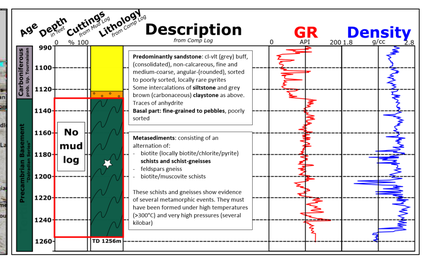
- Despite an apparent correlation between AHe ages and eU for sample 1, no model has been found yet that can reproduce these ages satisfactorily
- Model 1 on the left is constrained only by AFT ages and track lengths for sample 1 and AFT and AHe ages for sample 2. An unconstrained pre-depositional thermal history is permitted for sample 1. The results show a moderately good reproducibility of the AFT, AHe ages and MTL for both samples, however the bimodal distribution of the track lengths for sample 1 is not reproduced at all.
- The overall model shows a heating event during the Carboniferous-Permian followed by a long and slow cooling until the present-day.
- This thermal history is not in accordance with the regional stratigraphy and geological history of the area: basin-wide exhumation events are believed to be present at the base of the Cretaceous, at the base of the Eocene and a Neogene cooling event is also often reported; while the Upper Cretaceous is believed to be a period of sedimentation and burial over most of the area. The thermal anomaly associated with the rifting of the Rockall Basin is not taken in account as well.
- Analyses of more grains for each sample and exploration of new thermal models might improve our understanding of this location.

5. Prelimary Results – Well 26/26-1, Finnian's Spur

Geological Context

Seismic Section (see location on map in box 2)





AFT Results

(LAFT approach: [U] measured by LA-ICP-MS in TCD, method of Chew & Donelick, 2012 and Chew et al., 2014 protocols)

26/26-1	Type	Emplacement age		Depth (m)	Technique	Ns	$^{238}U/^{43}Ca$	Area (cm^2)
Bottom sample	Metasediments	Mid. Devonian	391 ± 15	818	LAFT (this study)	585	7.11E-02	5.66E-04

FT Age (Ma)	± 2σ (Ma)	# grains	$P(\chi^2)$	MTL (µm)	SE (µm)	# tracks	Dpar	^{35}Cl (ppm)	^{238}U (ppm)
142	7.6	19	0.05023	11.16	2.17	30	1.55	420**	19.8

** all negative values were changed to 0

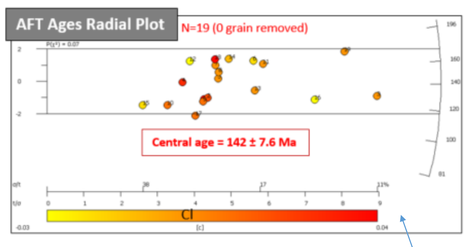
AHe Results

Well/Sample	Temp.	Grain	eU	Th/U (weight)	He (nmol/g)	Age (Ma)	± 1σ (Ma)	Ft	Req	Corrected age (ma)
Bottom sample	33°C	1	6.9	0.2	87981	93.2	35.8	0.85	93.2	109.5
		2	5.9	0.4	85341	103.1	41.2	0.84	87.4	123.0
		4	15.3	0.2	203385	100.6	42.7	0.81	72.3	124.9
		5	14.6	0.5	139752	74.8	23.2	0.77	59.8	97.8

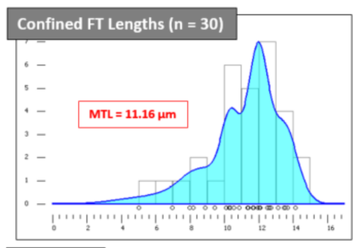
(U, Th, Sm & He for AHe ages measured by ICP-MS at UCL, London)

AFT/AHe Result Analyses

AFT Ages Radial Plot — N=19 (0 grain removed)

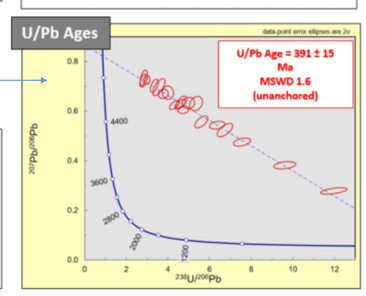


Confined FT Lengths (n = 30)

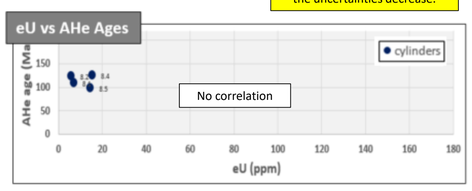


46 additional grains waiting to be analysed! The accuracy on these ages should increase and the uncertainties decrease.

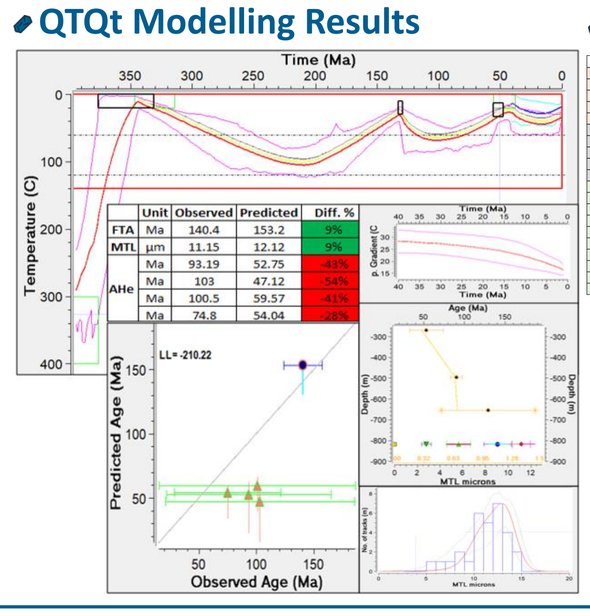
U/Pb Ages



eU vs AHe Ages



QTQt Modelling Results



QTQt Parameters

Inverse Model Prior Ranges	Mean	±
Time Mean	203	203
Temp. Mean	70	70
Max. dT/dt	1000	N/A
No reheating?	unticked	
Temp. gradient Mean	28.26	10
Temp. offset	15.5	5.5
Allow offset to vary with time?	ticked	
Present-doy temperature	10	10
Present-day gradient	28.26	0
Elevation difference	540	N/A
Input constraint 1 time	353.5	23
Input constraint 1 temp	10	10
Input constraint 2 time	131.15	1.8
Input constraint 2 temp	20	10
Input constraint 3 time	51.9	4.1
Input constraint 3 temp	23	10
Input constraint 4 time	Not used	
Input constraint 4 temp		
Input constraint 5 time		
Input constraint 5 temp		

MCMC chain		
	Burn-in	20000
	Post-burn-in	20000
	Thinning	1
Proposal Move	Time	40
	Temperature	40
	Offset	10
	FT Annealing	1
	He Diffusion	1
	VR	1
Proposal Outside prior	Resample proposed	no
	Reject proposed	yes
Reject complex models		yes
Acceptance rates	Time	0.4
	Temperature	0.15
	Offset	0.53
	FT Annealing	0.78
	He Diffusion	0
	VR	0
	Birth	0.04
	Death	0.04
	Outside priors	0.05

- Moderate prediction quality, particularly for AHe ages.
- Does not take in account the thermal anomaly expected during the rifting of the Porcupine Basin…
- Possible nearby sill spotted in the seismic section, impact on thermal history?
- More modelling work needed to extract useful geological information from the data

6. Conclusions

CONCLUSIONS

1) **Successful sampling** over a large area offshore West of Ireland

2) **Low percentage of usable results** (low yields in basalt, Eocene & Lower Cretaceous sands; restriction on sample weight; poor quality of grains (broken, too small); losses during laser-ablation)

3) **Mitigating actions**: more sievings while crushing, avoiding over-polishing the mounts, picking and aligning on tape as many apatites as possible while picking for AHe studies

4) **Basal gabbro in well 13/03-1** is provisionally dated at **311 ± 14 Ma**

5) **Well 13/03-1** has a set of **moderately good quality** AFT and AHe results. **Inverse modelling does not match all the results** but hints at a slow cooling and long residence time in the PAZ since deposition. This history is in opposition to the assumed burial & exhumation histories in the area.

5) The **additions of more analysed grains** for both sample, a possible discrimination between two apatite families in sample 1 (based on **U/Pb ages or trace element geochemistry**), adding **VR data** from the well, and a reduction of the Tt searching space in QTQt, might help to better constrain the thermal history of this well.

6) Basal metasediments in well 26/26-1 provisionally dated at 391 **± 15 Ma**

7) **Well 26/26-1** has a set of **moderately good quality** AFT and AHe results. **Inverse modelling matches the results moderately well** but AHe predictions still poor.

8) **Presently processing the Ifremer samples and second batch of PAD offshore cuttings.**

5. Acknowledgments

The authors would like to sincerely thank:
- Oonagh O'Loughlin, Michael Hanrahan and the core store crew (Petroleum Affairs Directorate - PAD) for facilitating the sampling at the PAD core store;
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- 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;
- Maria Judge from the Geological Society of Ireland for providing a seawater temperature dataset;
- Schlumberger for providing an academic license of Petrel.

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