

**Constraining small magnitude exhumation and basin inversion events in the Irish offshore, Dr David Chew and Dr Nathan Cogné, TCD**

**20 January 2015. Final Report**

**Project:**

IS12/02: Constraining small magnitude exhumation and basin inversion events in the Irish offshore

**Research Student:**

None

**Investigators:**

Dr David Chew

Dr Nathan Cogné

**Introduction**

This project aimed to characterize the thermal evolution of the Western Irish offshore. We undertook low temperature thermochronology analyses on four studied wells using the apatite fission track (AFT) and apatite (U-Th)/He (AHe) methods. The data are then modelled using thermal history analysis software which can employ a vertical modeling approach, with the goal of producing highly constrained models of the thermal evolution of the studied wells and to detect potential small magnitude exhumation events.

**Sampling Strategy**

Samples have been collected with the agreement of Statoil for wells 26/28-1 (4 samples), 26/28-2 (3 samples), 26/28-4 (3 samples) and Shell for well 27/5-1 (3 samples). In total we have 13 samples (Table 1) that cover the North Porcupine Basin and the South Slyne Basin. Three main points have been taken into account during the sampling: (1) To maximise the chance to recover apatites from the samples we selected the sandstone intervals in the sampled wells. (2) The goal was to detect post-Jurassic inversion events in the basins so we sampled rock of Devonian to Oxfordian age for well 26/28-1, from Bathonian to Albian age for well 26/28-2, from the Westphalian to the Bathonian in well 26/28-4 and from the Lower Triassic to the Bathonian for well 27/5-1. (3) Because we wanted to undertake modelling of

the data using a vertical profile approach, we also sampled a relatively large range of depth for each wells (i.e. 500 m to 1 km of vertical offset between the top sample and the bottom sample).

Well	Core	Top of Core (m)	Bottom of Core (m)	Lithology	Age
26/28-1	1	2249.7	2259.15	Sandstone/Mudstone	Upper Jurassic (Oxfordian-Kimmeridgian)
26/28-1	2	2259.15	2277.76	Sandstone/Mudstone	Upper Jurassic (Oxfordian-Kimmeridgian)
26/28-1	3	2419.1	2437.5	Mudstone/Sandstone/Limestone	Middle Jurassic (Bajocian-Bathonian)
26/28-1	4	2765	2770.6	Siltstone	Carboniferous (Stephanian)
26/28-1	5	3299.1	3202.1	Conglomerate	Devonian?
26/28-2	1	1189	1199	Sandstone	Lower Cretaceous (Albian)
26/28-2	2	2091.8	2097.25	Sandstone/Mudstone	Middle Jurassic (Bathonian)
26/28-2	10	2182.1	2189.4	Sandstone	Middle Jurassic (Bathonian)
26/28-4Az	1	2056	2061	Mudstone/Sandstone	Middle-Upper Jurassic (Bathonian-Oxfordian)
26/28-4Az	2	2316	2325	Sandstone/Mudstone	Middle Jurassic (Bajocian-Bathonian)
26/28-4Az	3	2401	2407	Mudstone/Sandstone	Carboniferous (Westphalian)
27/5-1	1	497	506	Sandstone/Claystone	Middle Jurassic (Bathonian)
27/5-1	3	644.5	668.5	Sandstone/Siltstone/Claystone	Middle Jurassic (?Bajocian-Bathonian)
27/5-1	4	1071	1098	Sandstone	Lower Triassic

Table 1: List of samples

## Results

Despite a careful choice of sampled cores on 13 collected samples, only 8 yielded enough apatite for the planned analyses, and two more only enough apatite for fission track analyses. The problem here is that apatite is an accessory mineral and therefore its presence is rarely described in the well reports for each formation. However as it is quite common, the chances of retrieving apatite from certain lithologies are relatively good. Therefore one only knows if there is apatite in a given sample after the separation process, which is time consuming. No analyses were possible for samples 26/28-1 core 5, 26/28-2 core 1, 26/28-4 core 3, and only fission track analyses were possible for sample 26/28-2 core 4 and 27/5-1 core 3. In addition the low amount of apatites recovered from the other samples make the analyses less robust because we were forced to use low quality apatites.

The results for the four studied wells are reported in Table 2 and 3.

Name	Stratigraphic Age	Depth (m)	Ns <sup>1</sup>	<sup>238</sup> U/ <sup>43</sup> Ca <sup>2</sup>	Area (cm <sup>2</sup> ) <sup>3</sup>	FT Age (Ma)	± 2σ (Ma)	# grains	p <sub>(χ<sup>2</sup>)</sub>	MTL (μm)	SE (μm)	SD (μm)	# tracks	Dpar (μm)
26/28-1 core 1&2 core 3 core 4	Upper Jurassic	2261	1070	8.99E-02	7.54E-04	<b>200</b>	<b>20.0</b>	40	<0.01	9.85	0.19	1.88	100	1.71
	Middle Jurassic	2428	532	7.38E-02	5.79E-04	<b>174</b>	<b>24.0</b>	28	<0.01	7.92	0.27	1.90	48	1.63
	Carboniferous	2768	181	2.63E-01	1.30E-04	<b>84</b>	<b>46.0</b>	10	<0.01	10.64	0.66	2.19	10	1.63
26/28-2 core 2 core 10	Middle Jurassic	2094	594	6.09E-02	5.56E-04	<b>244</b>	<b>38.0</b>	33	<0.01	9.83	0.22	1.86	73	1.72
	Middle Jurassic	2185	671	6.55E-02	6.10E-04	<b>182</b>	<b>26.0</b>	36	<0.01	9.12	0.25	2.02	68	1.81
26/28-4Az core 1 core 2	Middle-Upper Jurassic	2058	1166	1.70E-01	4.86E-04	<b>182</b>	<b>28.0</b>	36	<0.01	9.45	0.19	1.90	103	1.65
	Middle Jurassic	2321	401	6.08E-02	5.98E-04	<b>165</b>	<b>32.0</b>	35	<0.01	10.45	0.59	1.88	10	1.73
27/5-1 core 1 core 3 core 4	Middle Jurassic	501	1133	8.31E-02	8.24E-04	<b>231</b>	<b>36.0</b>	36	<0.01	11.37	0.21	2.14	101	1.90
	Middle Jurassic	656	1078	5.10E-02	1.12E-03	<b>214</b>	<b>26.0</b>	39	<0.01	12.07	0.23	2.25	100	2.24
	Lower Triassic	1084	1733	1.12E-01	7.26E-04	<b>270</b>	<b>30.0</b>	39	<0.01	10.77	0.21	2.25	113	1.81

Table 2: Fission track results.

<sup>1</sup>Number of spontaneous tracks.

<sup>2</sup>Sum of the individual grain <sup>238</sup>U/<sup>43</sup>Ca ratios measured by ICPMS and weighted by the counted area.

<sup>3</sup>Counted area.

Sample	U(ppm)	Th(ppm)	eU (ppm)	Th/U	He (nmol/g)	Age (Ma)	± 1σ (Ma)	Ft	Corrected age (Ma)	± 1σ (Ma)	
26/28-1 core1	-1	5.58	8.28	5.77	1.49	1.49E-06	<b>34.0</b>	<b>1.7</b>	0.746	45.6	2.3
	-2	8.82	34.34	9.63	3.89	2.99E-07	<b>3.1</b>	<b>0.1</b>	0.685	4.5	0.1
	-3	9.29	23.15	9.84	2.49	5.36E-08	<b>0.6</b>	<b>0.0</b>	0.656	0.9	0.0
26/28-1 core3	-1	26.86	193.98	31.42	7.22	3.82E-06	<b>9.6</b>	<b>0.1</b>	0.7	13.7	0.1
	-2	22.00	64.55	23.52	2.93	6.57E-07	<b>3.2</b>	<b>0.1</b>	0.716	4.5	0.1
	-3	3.51	129.40	6.55	36.92	3.26E-07	<b>1.7</b>	<b>0.0</b>	0.775	2.2	0.0
26/28-2 core2	-1	0.98	1.37	1.01	1.40	1.54E-08	<b>1.1</b>	<b>0.7</b>	0.683	1.6	1.0
	-2	5.75	69.11	7.37	12.03	8.49E-07	<b>6.6</b>	<b>0.2</b>	0.64	0.0	0.0
26/28-2 core10	-1	12.37	145.41	15.79	11.75	3.18E-06	<b>12.5</b>	<b>0.2</b>	0.846	14.8	0.2
	-2	31.74	502.32	43.54	15.83	5.70E-07	<b>0.7</b>	<b>0.0</b>	0.75	0.9	0.0
	-3	18.22	267.81	24.51	14.70	3.38E-07	<b>0.8</b>	<b>0.0</b>	0.782	1.0	0.0
	-5	27.23	358.20	35.64	13.16	1.81E-06	<b>3.0</b>	<b>0.0</b>	0.712	4.2	0.0
26/28-4Az core1	-1	7.60	37.55	8.49	4.94	1.34E-05	<b>146.5</b>	<b>1.9</b>	0.813	180.2	2.3
	-2	30.09	70.52	31.75	2.34	3.44E-07	<b>1.3</b>	<b>0.0</b>	0.63	2.1	0.0
	-3	10.37	34.74	11.18	3.35	2.67E-07	<b>2.3</b>	<b>0.2</b>	0.603	3.8	0.3
	-4	4.79	13.94	5.12	2.91	2.22E-06	<b>46.8</b>	<b>2.0</b>	0.734	63.8	2.7
26/28-4Az core2	-1	36.08	299.33	43.11	8.30	2.35E-06	<b>4.0</b>	<b>0.1</b>	0.676	5.9	0.1
	-2	50.80	32.37	51.56	0.64	5.35E-08	<b>0.2</b>	<b>0.0</b>	0.729	0.3	0.0
	-3	9.37	59.16	10.76	6.32	9.53E-07	<b>7.3</b>	<b>0.1</b>	0.717	10.2	0.1
27/5-1 core1	-1	8.82	69.24	10.44	7.85	4.92E-07	<b>3.4</b>	<b>0.1</b>	0.615	5.5	0.2
	-2	11.97	83.99	13.95	7.02	1.56E-05	<b>87.0</b>	<b>1.7</b>	0.644	135.1	2.6
	-3	9.80	3.37	9.88	0.34	1.52E-05	<b>245.2</b>	<b>19.8</b>	0.738	332.2	26.8
27/5-1 core4	-1	48.84	102.57	51.25	2.10	5.36E-05	<b>132.6</b>	<b>1.6</b>	0.719	184.4	2.2
	-2	81.75	47.56	82.87	0.58	4.70E-05	<b>91.6</b>	<b>1.7</b>	0.698	131.2	2.4
	-3	28.91	54.19	30.18	1.87	1.75E-05	<b>74.4</b>	<b>1.8</b>	0.654	113.8	2.8

Table 3: (U-Th)/He results

The AHe results are disappointing as none of the samples yielded ages that are reproducible. Thus it is unsafe to use the data for most of the samples. The second problem

is that such an observation is easier to make with AHe data (the method yield multiple ages for the same sample that can be compared with each other) than on AFT (the method uses multiple single grain ages but yields only one "mean" age). But even the AFT data need to be treated with caution. It is likely that some (if not all) of the apatites (which are originally detrital grains) carry detrital AFT age and AHe age components inherited from the original source area, which yields a complicated age profile, particularly when the apatites are partially annealed. The mixing of different sources together with the low quality apatites used are the likely cause to explain the low quality of the dataset.

### **Thermal modeling**

We carried out the thermal modeling, with the results presented above. On the four studied wells, we were unable to obtain constrained models for the three wells located in the Porcupine Basin, 26/28-1, 26/28-2 and 26/28-4Az as the software could not produce any thermal history that respects the data. The quality of the data was not good enough for these three wells and prevents any further interpretation.

For the fourth well, 27/5-1, after a careful selection of a subset of the AHe data (see Cogné et al., 2012 for a description of the selection procedure), we were able to produce a model that fits reasonably the data. However given the small amount of data used to constrain the model and the variable data quality of the whole dataset, we stress here that this model should be regarded as tentative. The thermal history and the associated predictions are shown in Figure 1.

### **Thermal evolution for well 27/5-1**

#### *Parameterization of the model*

Inverse modelling of the AHe and AFT (track length and age) data from the well has been undertaken to extract thermal history information. We used the QTQt software of Gallagher (2012). QTQt employs a Bayesian trans-dimensional Markov Chain Monte Carlo (MCMC) approach (Sambridge et al., 2006; Gallagher et al., 2009). The approach requires a prior probability distribution (a range for the model parameters). A randomly drawn initial model is generated from this distribution and the current model is then perturbed to produce a proposed model. The algorithm then chooses whether or not to replace the

current model by the proposed model or to generate a new proposed model by again perturbing the current model. This process is repeated many times, updating the current model as appropriate. The choice to replace the current model with the proposed model is made in terms of the data fit (likelihood) but also the Bayesian approach adopted here naturally favours simpler models (Gallagher et al., 2009). The output is an ensemble of models, which quantifies the probability of acceptable thermal history models.

In this study the prior is specified as one general time-temperature box ( $75\pm 75^{\circ}\text{C}$ ,  $400\pm^{\circ}\text{C}$ ). A series of discrete time-temperature points are sampled from this to construct a continuous thermal history and the data likelihood is calculated for that model. The vertical profile approach comes from Gallagher et al. (2005). To model the fission track data, we used the individual track counts, measurements of confined length and angle to c-axis, the likelihood function of Gallagher (1995) and the annealing model of Ketcham et al. (2007). The measured AHe ages were modelled using a spherical diffusion formulation, simulating both alpha-ejection and diffusion during the thermal history (Meesters and Dunai, 2002) combined with the radiation damage model of Flowers et al. (2009).

In addition, the following parameters were used to constrain the model. Ages of deposition for the three samples were taken from the core descriptions. The temperatures of deposition was set at  $20\pm 10^{\circ}\text{C}$ . The temperature offset between the samples is given by the geothermal gradient. The closest well with public information on the geothermal gradient is well 27/13-1 (Corcoran and Clayton, 2001). We thus used a value of  $27^{\circ}\text{C}/\text{km}$  and allow a possible variation of  $\pm 5^{\circ}\text{C}/\text{km}$  even though the paleogeothermal gradient also is calculated at  $27^{\circ}\text{C}/\text{km}$  (Corcoran and Clayton, 2001). We also used the geothermal gradient to infer the present day temperature of the sample, while the surface temperature was set at  $10^{\circ}\text{C}$ . The present day temperature is allowed to vary by  $\pm 5^{\circ}\text{C}$ . In addition we used available vitrinite reflectance data for the well to constrain the model (Scotchman and Thomas, 1995; Serica Energy, 2013). We note that the predictions of our model for the vitrinite data are not very good, however because we do not know the uncertainties on the vitrinite data (it was not published) we consider the predicted values reasonable.

27/5-1

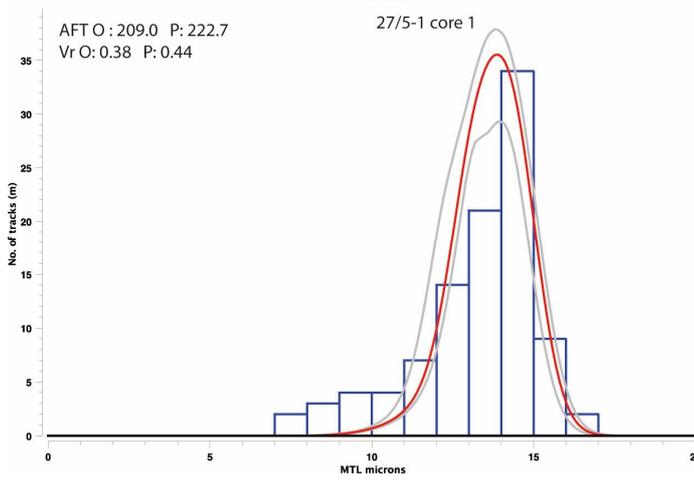
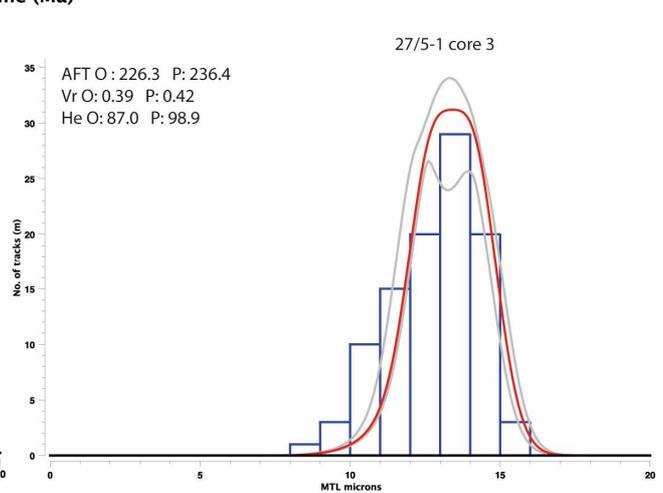
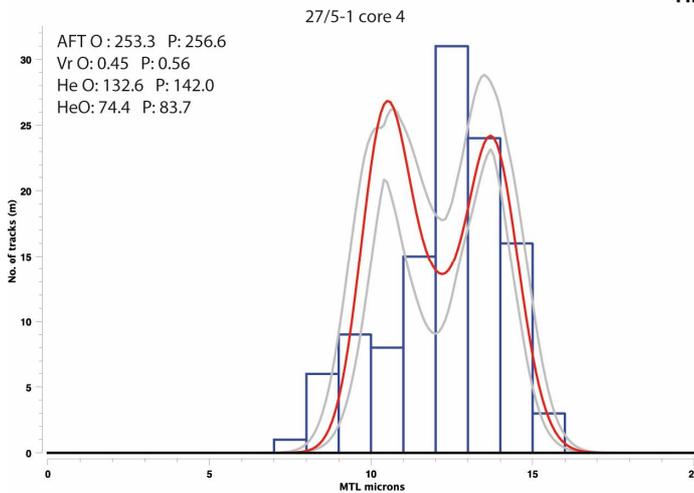
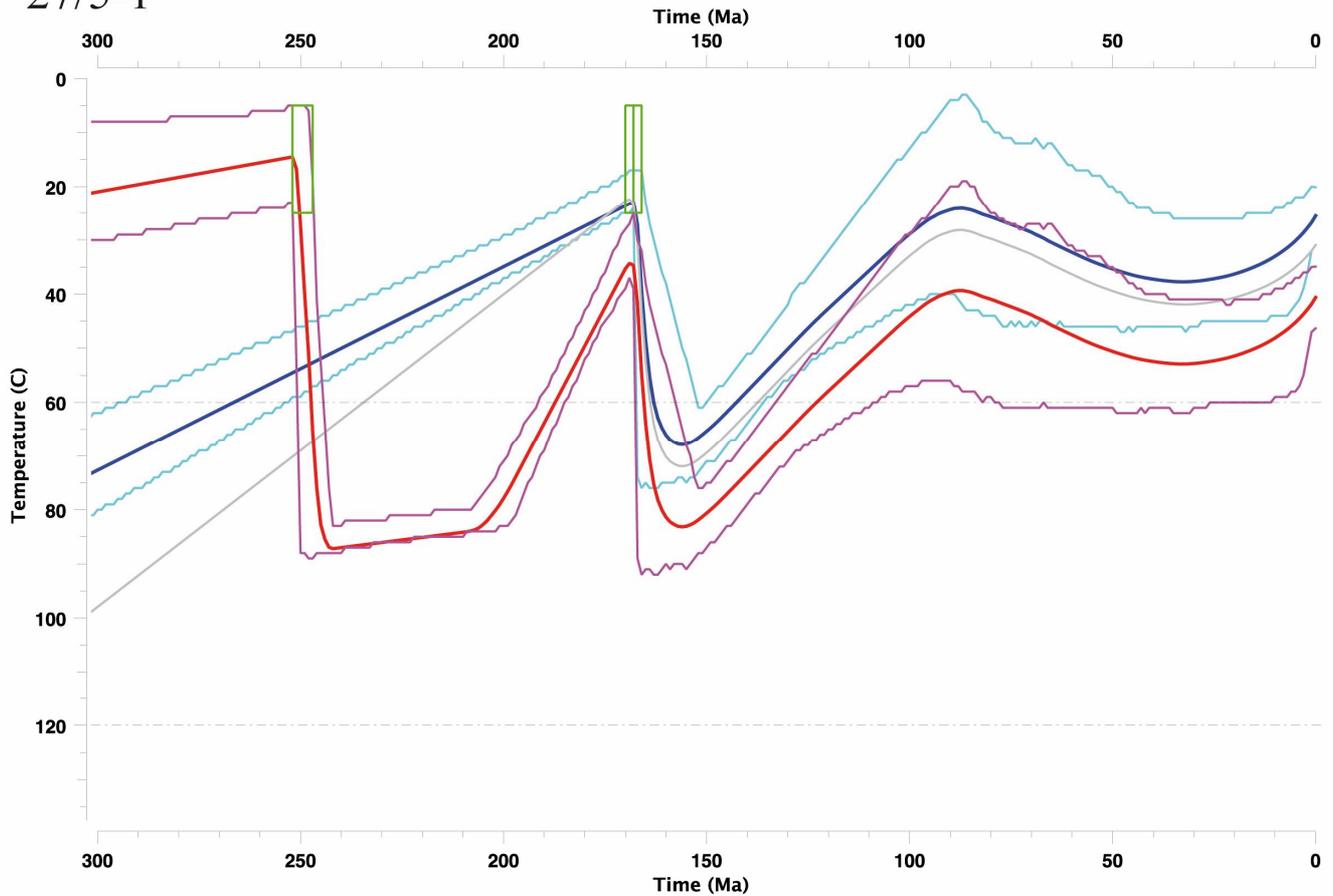


Figure 1: Thermal history for well 27/5-1 and associated predictions. For the thermal history model, the thick dark blue line is the coolest (shallowest sample) of the profile, with its credible interval denoted by thin blue lines. The thick red line is the hottest (deepest sample) of the profile, with its credible interval denoted by thin purple lines. The grey line is the intermediate sample and the dashed horizontal lines are the temperature limits of the PAZ. The green boxes are constraints for the deposition age and temperature. The predictions for all samples are shown. Predicted (red curves with credible intervals denoted by thin grey lines) and observed (blue histogram boxes) track length distributions for the thermal history model are depicted. AFT=Fission Track Age, Vr=Vitrinite reflectance, He=Helium age, O=Observed, P=Predicted.

### *Model results*

Our model indicates a complex thermal evolution. The deepest sample (27/5-1 core 4) was deposited during the Lower Triassic. After deposition we see a rapid heating (c. 7°C/Ma) to a temperature of c. 90 °C. Then the temperature then remains more or less stable until 200 Ma. Following this quiescent period we have a period of rapid cooling that brought the deepest sample to temperatures of about 35 °C at 170 Ma. Then the three analysed samples experienced rapid heating to a temperature of c. 90 °C (in the deepest sample) within 10 Ma. A second period of rapid cooling then occurred between 150 Ma and 90 Ma with a magnitude of 50-60 °C. After 90 Ma the low temperatures obtained make the model under constrained (the techniques used are not sensitive at these low temperature). We can therefore consider the temperatures more or less stable given the confidence interval, or even consider a small pulse of slow heating (as illustrated on the model).

### *Interpretation of the model*

Some features of our model fit well with the previously known evolution of the basin. The period of rapid heating at the end of the Jurassic corresponds to the deposition of Middle to Upper Jurassic sediments during the main period of rifting of Slyne Basin. Dancer et al (1999) report 2.5 km of sedimentation during that period, which corresponds to 67.5 °C of heating (assuming a paleogeothermal gradient of 27 °C/km). Our model indicates a heating phase of about 55-60 °C which is fairly consistent. Thus the Middle - Late Jurassic heating period is likely due to the opening of the rift basin and synchronous deposition. Interestingly this period corresponds well with a significant phase of exhumation (c. 2.5 km) on onshore Ireland (Cogné et al., 2014).

Following this heating period our model indicates a phase of rapid cooling. We interpret this cooling as an evidence of inversion and exhumation of the basin during Early Cretaceous. This is in accordance with the presence of a large unconformity between Late Jurassic strata and Late Cretaceous deposits in the basin (Scotchman and Thomas, 1995; Dancer et al., 1999; Corcoran and Mecklenburg, 2005). With a paleogeothermal gradient of 27 °C/km this 45 °C cooling pulse corresponds to an exhumation event of c. 1.6 km, within the range of previously published values for this episode of inversion of the Slyne Basin (Scotchman and Thomas, 1995; Dancer et al., 1999; Corcoran and Mecklenburg, 2005). Such exhumation is not seen onshore western Ireland (Cogné et al., 2014) and remains quite enigmatic.

The evolution during Late Cretaceous and Tertiary is hard to infer due to the low temperatures reached at 90 Ma. Possible small episodes of heating/cooling, and thus sedimentation/exhumation, could exist and remain undetected.

An interesting feature of our model is the period between the deposition of the deepest analysed samples (Lower Triassic) and the deposition of the Upper Jurassic section. Our model indicates a period of fast heating, following by a quiescent phase and finally a pulse of rapid cooling. A possible interpretation would be to consider a first period of rifting with associated accumulation of sediments during the Lower – Middle Triassic, following by a quiescent phase with a duration of 30 Ma and finally an inversion episode during the Upper Triassic – Lower Jurassic. However the stratigraphic column for Slyne Basin shows that sediment deposition occurred during that interval (Dancer et al, 1999). Nonetheless there is a recognized unconformity before the deposition of Middle Jurassic strata. It is thus possible that an important phase of inversion was not detected before this study. The exact timing of such an inversion episode remains poorly defined, as well as its magnitude for two reasons. First no methods other than thermochronology could detect this inversion episode because it did not exceed the Early Cretaceous inversion phase in terms of its magnitude. Secondly, because our model is not well constrained (due to the variable quality of the dataset) it could be unsafe to infer such an inversion episode based solely on the low temperature thermochronology data.

In summary, our model fits well, and thus reinforces, previous interpretations of the evolution of Slyne Basin from Middle Jurassic up to the present day. For the period between the Lower Triassic to Middle Jurassic the model shows a previously undetected inversion episode, but we currently regard this event as speculative.

### **Suggestions for future low temperature thermochronology work in the Irish offshore**

From the relatively disappointing results from this study, but also from other successful studies that we carried on for private oil companies during the past year, we can suggest a list of recommendations that should be considered for future low temperature thermochronology work on the Irish offshore basins.

We suggest that future studies focus primarily on AFT technique. The AHe technique can yield lots of information and is ideally suited for detecting small scale inversion episodes, but requires high quality, euhedral apatites. From this study we know that these kind of apatite morphologies are very rare in the sandstones that constitute the only suitable apatite-

bearing lithology in the Irish offshore basins. Additionally it appears from the modeling that it is hard to discriminate the AHe age component inherited from the source from the post-deposition history in the AHe data.

As far as possible these fission track studies should be undertaken in conjunction with vitrinite reflectance studies. The addition of vitrinite reflectance data has proven to be successful for some of the studies we undertook for different operators.

The samples given to the lab in charge of the study should be sufficiently large to yield enough high quality apatite grains for analysis. Here we were authorized to take only small samples (i.e. couple of hundred grams). We acknowledge that samples from offshore boreholes are extremely valuable, but this project was partially hindered by the small sample sizes. Good quality apatites lead to good quality data, and we recommend samples of at least 500 g (and in an ideal world around 1-2 kg). For comparison, on onshore sandstones (where sampling is not hindered by availability of material), we sample at least 5 kg.

For boreholes we recommend that no less than five samples are analysed. These samples should ideally be in the range of 40-50°C to 110°C (present day temperature) to cover the range of temperature sensitivity of the AFT system and also to cover a large depositional time range. That implies the present day temperature should be known with a relatively good accuracy (and accessible to the team in charge of the study). Five samples is a minimum limit because of the variable apatite yield encountered in sandstones, and also to yield good thermal history constrains using a vertical modelling approach.

## References

- COGNÉ, N., CHEW, D. STUART, F. M. 2014. The thermal history of the western Irish onshore. *Journal of the Geological Society*, 171, 779-792.
- COGNÉ, N., GALLAGHER, K., COBBOLD, P.R., RICCOMINI, C., GAUTHERON, C. 2012. Post-breakup tectonics in southeast Brazil from thermochronological data and combined inverse-forward thermal history modelling, *Journal of Geophysical Research B: Solid Earth*, 117, (11).
- CORCORAN D.V., CLAYTON, G. 2001. Interpretation of vitrinite reflectance profiles in sedimentary basins, onshore and offshore Ireland. Geological Society, London, Special Publications, 188, 61-90.
- CORCORAN D.V., MECKLENBURGH R. 2005. Exhumation of the Corrib Gas Field, Slyne Basin, offshore Ireland. *Petroleum Geoscience*, 11, 239-256.
- DANCER, P.N., ALGAR, S.T., WILSON, I.R., 1999. Structural evolution of the Slyne Trough. Geological Society, London, Petroleum Geology Conference series 5, 445-453.
- FLOWERS, R.M., KETCHAM, R.A., SHUSTER, D.L., FARLEY, K.A., 2009. Apatite (U-Th)/He thermochronometry using a radiation damage accumulation and annealing model. *Geochimica et Cosmochimica Acta* **73**, 2347-2365.
- GALLAGHER, K., 1995. Evolving temperature histories from apatite fission-track data. *Earth and Planetary Science Letters* **136**, 421-435.

GALLAGHER, K., 2012. Transdimensional inverse thermal history modeling for quantitative thermochronology. *Journal of Geophysical Research* 117, B02408.

GALLAGHER, K., STEPHENSON, J., BROWN, R., HOLMES, C., FITZGERALD, P., 2005. Low temperature thermochronology and modeling strategies for multiple samples 1: Vertical profiles. *Earth and Planetary Science Letters* **237**, 193-208.

GALLAGHER, K., CHARVIN, K., NIELSEN, S., SAMBRIDGE, M., STEPHENSON, J., 2009. Markov chain Monte Carlo (MCMC) sampling methods to determine optimal models, model resolution and model choice for Earth Science problems. *Marine and Petroleum Geology* **26**, 525-535.

KETCHAM, R.A., CARTER, A., DONELICK, R.A., BARBARAND, J., HURFORD, A.J., 2007. Improved modeling of fission-track annealing in apatite. *American Mineralogist* **92**, 799-810.

MEESTERS, A.G.C.A., DUNAI, T.J., 2002. Solving the production-diffusion equation for finite diffusion domains of various shapes: Part II. Application to cases with [alpha]-ejection and nonhomogeneous distribution of the source. *Chemical Geology* **186**, 57-73.

SAMBRIDGE, M., GALLAGHER, K., JACKSON, A., RICKWOOD, P., 2006. Trans-dimensional inverse problems, model comparison and the evidence. *Geophysical Journal International* **167**, 528-542.

SCOTCHMAN, I.C., THOMAS, J.R.W. 1995. Maturity and hydrocarbon generation in the Slyne Trough, northwest Ireland. Geological Society, London, Special Publications, 93, 385-411.