The United Kingdom Rockall Trough, Northeast Atlantic: An Extinct Young Ocean Basin or a Failed-Breakup Basin?*

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Abstract

We have investigated the crustal structure and crustal type of the United Kingdom Rockall Trough using the Rockall seismic data made available by the UK OGA. The Rockall Trough lies to the west of the UK and Ireland. It is one of several basins formed by high-extension Mesozoic rifting, prior to formation of the Atlantic Ocean (Early Tertiary). Comparable basins of similar age include the Porcupine and Orphan Basins (Ireland and Newfoundland) to the south, and the Møre and Voring Basins (Norway) to the north. An impediment to analysis of the UK Rockall Trough is the extensive post-rift magmatism which masks much of the underlying basin structure. We have interpreted seismic top-basement/base-sediment and used the resulting map as input to an integrated analysis, combining two techniques: (1) 3D-backstripping has been used to investigate subsidence history and the magnitude of lithosphere stretching/thinning, and (2) 3D-gravity-inversion has been used to investigate the magnitude of stretching/thinning, Moho-depth, crustal structure and crustal type and to produce whole-crustal cross-sections.

Our analysis shows that the crustal-basement thickness of the Rockall Trough reduces rapidly from the flanks (20-25 km) into the basin centre (5-10 km), with only a narrow zone of terraces in between. The prediction of thin crust (<10 km) in the basin centre is comparable with published seismic estimates. An important question is whether this thin crust is hyper-extended continental crust or proto-oceanic crust. Our interpretation is that the Rockall Trough formed in a magma-poor extensional environment, probably as the result of time-dependent extension. Extension stopped prior to continental breakup. We therefore interpret the Rockall Trough as a failed-breakup basin, underlain by highly-thinned continental crust, rather than an extinct young ocean basin. We believe this conclusion applies to the other basins of similar age listed above. Our analysis of crustal structure and crustal type allows us to make predictions of heat-flow history for the Rockall Trough. In the basin centre, where thinning-factor is ~0.6-0.8 (β ~3-5), heat-flow history is dominated by cooling of the rift-related transient heat-flow component. On the much less-highly stretched basin flanks, where thinning-factor is ~0.2-0.3 (β ~1.25-1.5), heat-flow history is dominated by the steady-state radiogenic component from relatively thick crust. This has important implications for any future petroleum-systems analysis in the area.
The UK Rockall Trough, NE Atlantic: an extinct ocean basin or a failed-breakup basin?

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Rockall Trough introduction and objectives

We thank the UK OGA for funding the initial 2D pilot-study as part of the 2016 Exploration Licence Competition.

The 3D study presented here was internally funded by Badleys.

Objectives of the study

- Use an interpretation of the OGA Rockall seismic data as input to a quantitative modelling study for the UK Rockall Trough, which predicts:
  - Moho depth
  - Lithosphere stretching/thinning-factor
  - Crustal thickness
  - Possible crustal type
- Assess the likely nature of the crust below central Rockall: proto-oceanic or highly-thinned continental?

- Use the preferred results as input to a model of:
  - Top-basement heat-flow history
1. Seismic interpretation to define regional base sediment / top basement
   • Interpretation within Badleys’ TrapTester™ software
   • Define base-sediment / top-basement, together with any supporting interpretation which helps this objective. Use this to produce a sediment-thickness isochore in TWT

2. Export and depth conversion to define new sediment thickness model
   • Depth convert top basement using the published Winterbourne et al Atlantic-margins time-depth function

3. 3D-Backstripping using new sediment thickness information
   • Provides estimates of subsidence and crustal thinning, plus predictions of possible crustal type
   • Used for QC and independent validity check of the OCTek gravity inversion results

4. OCTek gravity inversion using new sediment thickness information
   • Perform gravity inversion using free-air satellite gravity data and new Rockall Trough sediment thickness information
   • Predicts (i) Moho depth, (ii) crustal thickness, (iii) thinning-factor, (iv) possible magmatic addition and crustal type

5. Heat-flow prediction derived from results of OCTek gravity inversion
   • Uses crustal-thinning estimates from the preferred-case gravity inversion to predict heat-flow history from Jurassic-Cretaceous rifting at 140Ma though to the present-day
• Basement interpreted at the base of observable sediment/stratigraphic fill
• Most readily achievable in north and south of the UK Rockall Trough, where Tertiary post-rift volcanic overprint is least pervasive
• Interpretation model extended from the north and south into the central zone of extensive volcanic cover
• Interpretation uncertainty captured by scaling the resulting sediment thickness within subsequent backstripping and gravity inversion
Seismic interpretation and mapping

**Top Basement TWT, ms**
- Basin centre 7-8s

**Top Basement depth, metres**
- Basin centre 9-10km

**Sediment thickness, km**
- Embedded within regional public-domain data

**Depth conversion**
- *Winterbourne et al*
- Atlantic-margins time-depth function

**Input to 3D backstripping**

**Input to 3D gravity inversion**

*Depth conversion*

Atlantic-margins time-depth function

Depth conversion
Backstripping for water-loaded basement subsidence

2D example

Present-day depth-section with thick sediment fill

Backstripped with no thermal correction, produces profile of basement water-loaded subsidence

3D result

Map of backstripped Top Basement water-loaded subsidence for the UK Rockall Trough

This can be converted to maps of beta-factor or thinning-factor using a modified version of the McKenzie (1978) model, which incorporates magmatic addition at high stretching. See Roberts et al 2013, Pet Geosci
Thinning-factor scales with water-loaded subsidence and it is therefore straightforward to produce maps of thinning-factor from maps of water-loaded subsidence.

Thinning-factor $\gamma$

$\gamma = 1 - 1/\beta$

Beta-factor $\beta$

Model parameters
- Rift age 140Ma
- Initial crustal thickness 35km

Thinning-factor $\approx 0.8$

Thinning-factor assuming no syn-rift magmatic addition

Higher thinning in basin centre

Lower thinning on basin flanks, up to $\approx 0.3$

Anton Dohrn seamount

Max subsidence $\approx 5.3$km

Backstripped Top Basement subsidence, km

Thinning-factor 1.0, oceanic

Lower thinning on basin flanks, up to $\approx 0.3$

Thinning-factor assuming “normal” syn-rift magmatic addition
OCTek gravity inversion method

OCTek gravity inversion using new UK Rockall Trough sediment thickness information

- Perform gravity inversion using free-air satellite gravity data and new information on Rockall sediment thickness
- Predicts (i) Moho depth, (ii) crustal thickness, (iii) thinning/beta-factor, (iv) magmatic addition

Methodology published in multiple papers, since 2007
OCTek gravity inversion results, crustal structure

Model parameters
- Rift age 140Ma
- Reference Moho depth 35km
- Initial crustal thickness 35km

Moho depth ~15km
Deeper Moho on basin flanks, 25-30km
Minimum thickness ~6km

Anton Dohrn seamount
Rosemary Bank seamount

Crustal-basement thickness, km
Thicker crust on basin flanks, 20-25km
**OCTek gravity inversion results, thinning factor**

**Model parameters**
- Rift age 140Ma
- Reference Moho depth 35km
- Initial crustal thickness 35km

**Thinning-factor $\gamma$**

$\gamma = 1 - 1/\beta$

**Beta-factor $\beta$**

Thinning-factor $\gamma$

- Thinning-factor $\approx 0.8$
- Thinning-factor assuming no magmatic addition

- Lower thinning on basin flanks, up to $\approx 0.3$

- Thinning-factor 1.0, oceanic

- Thinning-factor assuming "normal" magmatic addition

- Lower thinning on basin flanks, up to $\approx 0.3$
OCTek gravity inversion results, crustal cross-sections

**Sensitivity to sediment thickness**

- **NW Line-1**
- **NW Line-2**
- **NW Line-3**

Possible magmatic addition

**Continental crustal basement**

**Basin fill**

- **Possible magmatic addition**
- **75% sediment, Top Basement**
- **75% sediment, Moho Depth**
- **100% sediment, Top Basement**
- **100% sediment, Moho Depth**
- **125% sediment, Top Basement**
- **125% sediment, Moho Depth**

**Sensitivity to magmatic addition**

- **NW Line-1**
- **NW Line-2**
- **NW Line-3**

Possible magmatic addition

**Continental crustal basement**

**Basin fill**

**Anton Dohrn volcanic seamount**
Rockall Trough, no syn-rift magmatic addition?

**Westline**
England 1995
England & Hobbs 1997
BIRPS Atlas II 1999
Pearse 2002

Despite the large amount of extension (β>6) there does not appear to be any evidence for oceanic crust at the centre of the trough in the region of the WESTLINE profile.

*England & Hobbs 1997*

- This is an observation we have repeated on the UK Rockall data
- We favour the quantitative solutions with **no syn-rift magmatic addition**
- Probably a result of **time-dependent Jurassic-Cretaceous extension**
- As a consequence we interpret the Rockall Trough as a **failed-breakup basin**
- Underlain by **highly-extended continental crust** rather than proto-oceanic crust
- This solution is used to condition the modelling of heat-flow history

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**OGA line 2015-78**

132/06-1 Basement at 4028m

**OGA line 2014-022**

Anton Dohrn volcanic seamount
Maps of continental lithosphere thinning-factor from gravity anomaly inversion are converted to maps of top-basement heat-flow through time.

**Heat-flow Includes:**
- Transient heat-flow from rift at 140Ma
- Residual radiogenic heat flow from the thinned continental crust
- Long-term steady-state heat loss from the mantle (30mWm$^{-2}$)

**Does not include:**
- Sediment blanketing effects

**Gravity inversion parameters**
- Rift age 140Ma
- Reference Moho depth 35km
- Initial crustal thickness 35km
- No magmatic addition

In this example three cases of initial continental radiogenic heat productivity have been assumed:
- 15mWm$^{-2}$ cold crustal basement
- 30mWm$^{-2}$ typical crustal basement
- 45mWm$^{-2}$ warm crustal basement
Top-basement heat-flow history, 140Ma-present

Heat-flow Includes:
- Transient heat-flow from rift at 140Ma
- Residual radiogenic heat flow from the thinned continental crust, \(30\text{mWm}^2\)
- Long-term steady-state heat loss from the mantle (30mWm\(^2\))

Does not include:
- Sediment blanketing effects

Basin centre dominated by hot transient
Basin flanks dominated steady-state Rad Gen
Syn-rift, 140Ma
Top-basement heat-flow history, 140Ma-present

Top-basement heat-flow history, syn-rift 140Ma to present-day 0Ma, Line1

- **Rad**$_{ini}$ 30 mWm$^{-2}$
- Heat-flow mWm$^{-2}$
- Distance km

1. Basin centre dominated by cooling transient
2. Basin flanks dominated by steady-state Rad Gen

Top-basement heat-flow history, syn-rift 140Ma to present-day 0Ma, Line2

- **Rad**$_{ini}$ 30 mWm$^{-2}$
- Heat-flow mWm$^{-2}$
- Distance km

1. Basin centre dominated by hot transient
2. Basin flanks dominated by steady-state Rad Gen

Basin centre dominated by cooled transient
Anton Dohrn volcanic seamount

Basin flanks dominated by steady-state Rad Gen
Regional context of crustal structure

- **Crustal basement thickness, km**
- **Public-domain sediment thickness**
- **New UK Rockall sediment thickness**
- **Thinning-factor Public-domain sediment thickness**
- **Gravity inversion without ocean isochrons, not accurate in oceanic areas**

**Apparent crustal boundary when public-domain sediment thickness information is used**

**One of a long chain of highly-extended Mesozoic basins cut through by the younger Atlantic Ocean**

**Lundin & Doré 2011**

**No crustal boundary when new UK Rockall sediment thickness information is used**
Rockall Trough conclusions

- We have used seismic interpretation, subsidence analysis (backstripping) and gravity-anomaly inversion to investigate the crustal structure of the UK Rockall Trough.

- From this analysis the crustal structure has been defined by maps of:
  - Top Basement depth
  - Moho depth
  - Thickness of the continental crustal basement
  - Continental-lithosphere thinning-factor

- We favour an interpretation of the UK Rockall Trough with little or no syn-rift magmatic addition (also England & Hobbs 1997) and as a consequence consider it to be a failed-breakup basin rather than an extinct ocean basin.

- Maps of top-basement heat-flow through time have been produced from the results of the gravity inversion. We believe that these should prove useful for future exploration activity.

- Our crustal-modelling and heat-flow results include full sensitivity analysis to:
  - Uncertainty within the initial seismic interpretation
  - Uncertainty within the backstripping and gravity-inversion parameters
  - Uncertainty within the crustal radiogenic-heat productivity

We thank the UK OGA for funding the initial 2D pilot study and for making the Rockall Trough seismic data publicly available.