

1. INVESTIGATOR(S)/AWARD HOLDER(S): Professor N Kuszniir (Principal Investigator) Dr P Christie (Co-Investigator) Dr AM Robers (Co-Investigator) Professor RS White (Co-Investigator.)

AWARD HOLDER: University of Liverpool

2. TITLE OF RESEARCH PROJECT:

Mapping and modelling heterogeneous stretching and volcanism on the NW European Atlantic margin.

3. OBJECTIVES:

We will develop a new rifted margin model from quantitative models of mantle flow melt generation and transport previously applied to Ocean ridges. Incorporating continental rheology as an initial condition. The model will predict heterogeneous stretching, subsidence and thermal history for volcanic and non-volcanic continental margins and will be applied and tested on the NW European margin. Seismic surveys using state-of-the-art streamer technology and OBS will be made in the Faroes-Shetland and Hatton-Rockall Basins and adjacent margins to provide data to test the new ridge margins

4. ACHIEVEMENTS OF THE RESEARCH: A new quantitative model of rifted continental margin formation has been developed and successfully tested. The model describes continental lithosphere thinning processes leading to breakup and sea-floor spreading initiation, and may be used to predict margin structure, margin subsidence and heat flow history, and the location of the ocean-continent transition. The new model of rifted margin formation is implemented in a software package, SfMargin, which has been distributed to NERC Ocean Margins iSIMM hydrocarbon Industry partners. The deep water regions of rifted continental margins are the current exploration frontier for oil and gas exploration. The determination of the location of the ocean-continent transition at rifted margin, and their subsidence and heat flow history present major scientific and technical challenges to the hydrocarbon industry. SfMargin provides a major scientific and technical advance in understanding and investigating rifted continental margins. The new margin formation model (SfMargin) has now been used operationally for hydrocarbon Industry research project partners on several deepwater ocean margin exploration targets. We have developed successful new ways of imaging sediments and basement rocks through overlying igneous layers and have for the first time imaged lower-crustal igneous intrusions on a rifted continental margin. This was achieved by careful design of low-frequency seismic sources capable of deep penetration, by use of state-of-the-art seismic reflection equipment provided by our industry partner Schlumberger WesternGeco, and by deployment of 90 multicomponent ocean bottom seismometers (OBS) - the most ever deployed on a profile across a continental margin. We have shown the benefit of integrating reflection and OBS data in developing models from seabed to Moho, impacting both academic and industrial objectives for the project. Our seismic profiles are now the best in the world across a rifted continental margin and, as such, are becoming standard references for work elsewhere. Our seismic designs have subsequently been used by a number of major oil companies for multi-million pound surveys across similar geological settings in both the UK and overseas. A new methodology has been developed for the inversion of satellite gravity data to map crustal thickness variation and predict the location of the ocean-continent transition (OCT) at rifted

continental margins. The new method incorporates a lithosphere thermal gravity anomaly correction for both oceanic and stretched continental margin lithosphere and may be used without a priori information of the location of the OCT from magnetic Isochron data. This new method of gravity inversion with embedded thermal correction provides an improved estimate of rifted continental margin crustal thinning and an improved (and isochron independent) prediction of OCT location. The new gravity inversion method of OCT mapping has been successfully applied to the Arctic Ocean (to produce the first set of comprehensive crustal thickness maps of that ocean), the northern N. Atlantic and operationally for a number of rifted margins targets for hydrocarbon industry research project partners.

Publications from this NERC Research Grant and Related Work

University of Liverpool and University of Cambridge - iSIMM Project

NERC LINK Ocean Margins Programme

Grant number NER/T/S/2000/01021 (Split Research Grant)

Peer-Reviewed Papers and Expanded Abstracts

1. Spitzer, R., White, R. S., Christie, P. A. F. & iSIMM Team. Contrasting expressions of volcanic flows in the Faroes margin and hinterland, *Geophysical Prospecting*, In Review
2. Kusmir, N.J. & Karner, G.D., Application of a new model of continental breakup and rifted margin formation to the Newfoundland and Iberian Margins. *Proceedings of NSF Rifted Margins Modelling Workshop*, ed. Kamer. G.D., Columbia University Press, In Review.
3. Healy, D. & Kusznir, N.J., Early kinematic history of the Goban Spur rifted margin derived from a new model of continental breakup and sea floor spreading initiation. *Proceedings of NSF Rifted Margins Modelling Workshop*, ed. Karner, G.D., Columbia University Press, In Press.
4. Maresh, J., and White, R.S., (2005). Reply to 'Seeing through a looking glass ...' by D.O. Larsen, *First Break*, 23(9), 75-76.
5. Lumon, Z.C., Christie, P.A.F., and White, R.S., (2005). Reply to 'Air gun arrays for sub-basalt exploration' by F. Avedik, *First Break*, 23(8), 83-84.
6. Spitzer, R., White, R.S., Christie, P.A.F., and iSIMM Group, (2005). Detailed insights into intra- and sub-basalt structures of the Faroe-Shetland Basin. 67th Mtg.: Eur. Assn. Geosci. Eng., Madrid, Exp. Abs. G035.
7. Spitzer, R., White, R.S.? and iSIMM Team, (2005). Advances in seismic imaging through basalts: a case study from the Faroe-Shetland Basin. *Petroleum Geoscience*, 11(2), pp. 147-156.
8. Maresh, J. & White, R. S. (2005). Seeing through a glass, darkly: strategies for imaging through basalt, *First Break*, 23(5), 27-33.
9. White, R.S., Spitzer, R., Christie, P.A.F., Lumon, Z., Maresh, J. & iSIMM Working Group, (2005). Seismic imaging through basalt flows on the Faroes shelf. In: *Faroe Islands Exploration Conference: Proceedings of the 1st Conference*. Eds: Heri Ziska, Thomas Varming & Dorete Bloch, *Annales Societatis Scientiarum Faeroensis, Supplementum 43*, Tdrshavn, 1 1-3 1.
10. Hoare, R., Schearer, P., Langridge, A., Saragoussi, E., Christie, P. & iSIMM Team, (2005). Imaging sub-basalt with deep towed seamer: a case study from the Faroe Islands. In: *Faroe Islands Exploration Conference: Proceedings of the 1st Conference*. Eds: Heri Ziska, Thomas Vanning & Dorete Bloch, *Amles Societatis Scientiarum Faeroensis, Supplementum 43*, Tdrshavn, 168-175.
11. Roberts, A.W., White, R.S., Lunnon, Z.C., Christie, P.A.F., Spitzer, R. & iSIMM Team, (2005). Imaging magmatic rocks on the Faroes margin. In: *Dod, A.G. & Vining, B.A.*

(eds) *Petroleum Geology: North-West Europe and Global Perspectives-Proceedings of the 6th Petroleum Geology Conference*, 755-766.

12. Kusmir, N.J., Hunsdale, R., Roberts, A.M. & iSIMM Team, (2005). Timing and magnitude of depth-dependent lithosphere stretching on the S. Lofoten and N. Vsring continental margins offshore mid-Norway: implications for subsidence and hydrocarbon maturation at volcanic rifted margins In: Dore, A.G. & Vining, B.A. (eds) *Petroleum Geology: North-West Europe and Global Perspectives-Proceedings of the 6th Petroleum Geology Conference*, 767-783.

13. Smith, L.K., White, R.S., Kusmir, N. J. & iSIMM Team, (2005). Structure of the Hatton-Rockall Basin and adjacent continental margin. In: Dore, A.G. & Vining, B.A. (eds) *Petroleum Geology: North-West Europe and Global Perspectives-Proceedings of the 6th Petroleum Geology Conference*, 947-956.

NERC Reference: NER~lISi2000!01021

14. Christie, P., Langridge, A., Spitzer, R., White, R., Lunnon, Z., Roberts, A.W. and the iSMM working group, (2005). iSIMM demonstrates the benefit of high-fidelity, lowfrequency acquisition in sub-basalt imaging. Ea. Abs. 559 presented at 6th PETROTECH Conference, Delhi, India.

15. White, R.S., Spitzer, R., Christie, P.A.F., & iSIMM Team, (2004). Seismic imaging through basalt flows on the Faroe shelf. Petex, 24 November 2004, [hnp://www.pesgb.org.uk/pesgb/S3/petex-abstr~~-WesPh2OShetlan&.asp](http://www.pesgb.org.uk/pesgb/S3/petex-abstr~~-WesPh2OShetlan&.asp).

16. Spitzer, R., White, R.S., and Christie, P.A.F., & iSIMM Group, (2004). Sub-basalt imaging - integration of surface and ocean bottom data 66th Mtg.: Eur. Assn. Geosci. Eng., Paris, Exp Abs. D042.

17. Healy, D., Kusmir, N.J. & Yielding, G., (2004). An inverse method to derive fault slip and geometry 6om seismically observed vertical stratigraphic displacements using elastic dislocation theory. *Marine and Petroleum Geology*, doi: 10.1 016/j.marpetgeo.2004.05.002.

18. Christie, P., Langridge, A., Bengt, L., White, R., Lunnon, Z., Roberts, A. & iSIMM team (2004). Looking beneath the Faroes basalts: Can the iSIMM experience be applied to the deepwater Norwegian Sea? (expanded abshact). Norwegian Peboleum Society Seminar 7235, Kristiansand, Norway, 15-1 7 March, 2004.

19. Kusmir, N.J., Hunsdale, R. & Roberts, A.M. (2004). Timing of depth dependent sketching on the Lofoten continental margin: pre-breakup or post-breakup. *Basin Research* 16 (2), 279-296.

20. Tsikalas, F., Kusmir, N.J. & Faleide, J.I. (2004). Crustal architecture and depthdependent lithosphere stretching of the northern Vsring and Lofoten segments of the Norwegian margin: along strike variation across the Bivrost Transfer System. *Bollettino di Geofisica Teorica ed Applicata*, 45 (no. 1 supplement), p. 275-280.

21. Christie, P., Langridge, A., White, R., Lunnon, Z., Roberts, A.W. and the iSIMM team, (2004). iSIMM looks beneath basalt for both industry and university research. Ext. Abs. 87 presented at 5th Petroleum Geophysics Conference, Hyderabad, India.

22. Davis, M. & Kusmir N.J., (2004). Depth-Dependent Lithospheric Stretching at Rifled Continental Margins. In: *Rheology and deformation of the lithosphere at continental margins*, Proceedings of NSF Rifted Margins Theoretical Institute. ed. Kamer, G.D., Columbia University Press, 92-1 36.

23. Spitzer, R., White, R.S., and Christie, P.A.F., (2003). Enhancing sub-basalt imaging using parabolic tau-p transformation. *The Leading Edge*, 22(12), 1184-1201.

24. Lunnon, Z., Christie, P., and White, R., (2003). An evaluation of peak and bubble tuning in subbasalt seismology: modelling and results from OBS data. *First Break*, 21(12), 51-56.

25. Spitzer, R., White, R.S., and Christie, P.A.F., (2003). Improvement of sub-basalt imaging using parabolic tau-p transformation. 73rd Ann. Internat. Mtg: Soc. of Expl. Geophys., Dallas, Exp. Abs. SPI.1.
26. L u ~ o n Z., , Christie, P., and White, R., (2003). An evaluation of peak and bubble tuning in sub-basalt imaging: modelling and results. 65th Mtg.: Eur. Assn. Geosci. Eng., Stavanger, Exp. Abs. COI.
27. Christie, P., Gollifer, I., and Cowper, D., (2005). Borehole seismic studies of a volcanic succession 60m the Lopra-I/IA borehole in the Faroe Islands, NE Atlantic. In press, Geology of Denmark Survey.
28. White, Robert S., Smallwood, John R., Flidner, Moritz M., Boslaugh, Brian, Maresh, Jennifer, & Fmehn, Juergen, (2003). Imaging and regional distribution of basalt flows in the Faroe-Shetland Basin. *Geophysical Prospecting*, 51,215-23 1.
29. White, R.S., Christie, P.A.F., Kusznir, N.J., Roberts, A., Davies, A., Hunt, N., Lunnon, Z., Parkin, C.J., Roberts, A.W., Smith, L.K., Spitzer, R., Surendrq A., and Tymms, V., (2002). iSLMM pushes frontiers of marine seismic acquisition. *First Break*, 20(12), 782-786.
30. Davis, M. & Kusmir N.J., (2002). Are buoyancy forces impomt during the fonnation of rified continental margins? *Geophysical Journal International*, 149,524-533.
31. Lumon, Z., Roberts, A.W., Christie, P., White, R., Kusmir, N. and Roberts, A., (2002). integrated Seismic Imaging and Modelling of Margins: an overview (extended abstract). *Journal of Conference Abstracts*, 7(2), 170-171.
32. Christie, P., Gollifer, I., and Cowper, D., (2002). Borehole seismic results 60m the Lopra Deepening Project, (extended abstract). *Journal of Conference Abstracts*, 7(2), 138-139. *Conference Abstracts*
33. Kusmir, N. J. & Healy, D. Modes of Continental Lithosphere Deformation and Thinning Leading to Continental Breakup and Sea-floor Spreading Initiation. *EOS Trans. AGU*, 86, Abstract T52B-06.
34. Hurst, N.W. & Kusmir, N.J. Mapping the Ocean-Continent Transition at Rifted Margins using Satellite Gravity Inversion Incorporating a Lithosphere Thermal Correction. *EOS Trans. AGU*, 86, Abstract T12C-03.
35. Fletcher, R.J., Kusnir, N.J. & Roberts, A.M. Tertiary Formation of the Faroes-Shetland Basin, NE Atlantic Margin, by Failed Continental Breakup. *EOS Trans. AGU*, 86, Abstract T52B-06.
36. Chappell, A.R. & Kusmir, N.J. Evidence for a Slow Spreading Ocean Ridge in the Southern Rockall Trough From Satellite Gravity Inversion and Seismic Data. *EOS Trans. AGU*, 86, Abstract T41 E-1345.
37. White R.S., Christie P.A.F., Kusmir N.J., Roberts A.M., Eccles, J., L w o n Z.C., Parkin C.J., Hurst N.W., Roberts A.W., Smith L.K., Spitzer R., & iSIMM team, (2005). The ocean-continent transition at the North Atlantic continental margins. *EOS Trans. AGU*, 86, Jt. Assem. Suppl., Abstract T41A-03.
38. Parkin. C.J., White., R.S. & Kusmir, N.J., (2005). Mantle plume temperature variations immediately following continental breakup of the northern Nonh Atlantic. *EOS Trans. AGU*, 86, Jt. Assem. Suppl., Abstract V51A-13.
39. Kusmir, N.J., Kamer, G.D., Tymms, V., Healy, D., Roberts, A.M. & iSIMM team, (2005). Predicting structure and location of the ocean-continent transition at rifted margins using a new model of continental breakup and rifted margin formation. *EOS Trans. AGU*, 86, Jt. Assem. Suppl., Abstract T41A-04.
40. Kamer, G.D. & Kusmir, (2005). Application of a new model of continental lithosphere breakup and sea-floor spreading initiation to the Woodlark Basin western Pacific. *EOS Trans. AGU*, 86, Jt. Assem. Suppl., Abstract T51A-02.
41. Hurst, N.W. & Kusmir, N.J., (2005). Crustal thickness mapping of the rifted margin

ocean-continent transition using satellite gravity inversion incorporating a lithosphere thermal correction. EOS Trans. AGU, 86, Jt. Assem. Suppl., Abstract T53A-04.

42. Tymms, V. & Kusmir, N.J., (2005). Modelling of continental lithosphere breakup and rifted margin formation in response to an upwelling divergent flow field incorporating a temperature dependent rheology. EOS Trans. AGU, 86, Jt Assem. Suppl., Abstract T53A-10.

43. Chappell, A.R. & Kusmir, N.J., (2005). Crustal structure in the southern Rockall Trough from satellite gravity data: evidence for sea-floor spreading. AGU, 86, Jt. Assem. Suppl., Abstract T53A-05.

44. Healy, D., & Kusmir, N. J., (2005). Kinematics of lithosphere breakup deformation at the Goban Spur rifted continental margin. European Geosciences Union, EGU05-A- 06603.

45. Fletcher, R.J., Kusmir, N. J., & Roberts, A.M., (2005). Tertiary development of the Faroes-Shetland Basin: Intracontinental rifting or failed continental breakup? European Geosciences Union, EGU05-A- 08516.

46. Chappell, A. R., & Kusmir, N. J., (2005). Crustal thickness mapping using satellite gravity data: Implications for the formation of the southern Rockall Trough. European Geosciences Union, EGU05-A-07953.

47. Tong, C. H., White, R. S., Christie, P., Lunnon, Z. & iSIMM Working Group, (2005). Oceanographic study of the Faroe-Shetland channel using seismic reflection data. European Geosciences Union, EGU05-A-09191.

NERC Reference: I.iEfi~liS~2i)t'O!O!021

66. Kusmir, N.J. & Kamer, G.D., (2004). A kinematic fluid-flow model of continental lithosphere deformation leading to continental lithosphere breakup and rifted continental margin formation. EOS Trans. AGU, 85(47), Jt. Assem. Suppl., Abstract T41E-1272.

67. Shillington, D.J., Kusmir, N.J. & Holbrook, W.S., (2004). Mapping variations in oceanic and continental crustal thickness using satellite gravity data on the Newfoundland rifted margin. EOS Trans. AGU, 85(17), Jt. Assem. Suppl., Abstract T41B-04.

68. Hurst, N.W., Kusmir, N.J., Roberts, A.M. & White, R.S., (2004). Predicting rifted continental margin subsidence history from satellite gravity derived crustal thinning: application to North Atlantic margins. EOS Trans. AGU, 85(17), Jt. Assem. Suppl., Abstract T41B-02.

69. Kusmir N.J. & Tymms V., (2003). Modelling sea floor spreading initiation and depth dependent stretching at rifted continental margins. EOS Trans. AGU, 84, 1342.

70. Hurst, N. W., Kusznir, N. J. & R. S. White, (2003). North Atlantic rifted margin crustal thickness and crustal thinning from satellite gravity data. EOS Trans. AGU, 84, 1341.

71. Kusznir, N.J., Hunsdale, R. & Roberts, A.M. (2003). Timing and magnitude of depthdependent

lithosphere stretching on the Lofoten continental margin: implications for subsidence and hydrocarbon maturation at volcanic rifted margins. 6th Petroleum Geology Conference, London, October 2003, Program & Abstracts p.47.

72. Smith L.K., Parkin C.J., White R.S., Kusmir N.J., Christie P.A.F., Roberts A.M., Spitzer R., Hurst N.W., Lunnon Z.C., Roberts A.W. & Tymms V., (2003). Mantle plume influence on the Hatton-Rockall Basin and adjacent continental margin. 6th Petroleum Geology Conference, London, October 2003, Program & Abstracts, p.54.

73. Tymms V., Hurst N.W., Kusmir N.J., White R.S., Roberts A.M., Christie P.A.F., Lunnon Z.C., Parkin C.J., Roberts A.W., Smith L.K., & Spitzer R., (2003). Model development and testing of rifted continental margin formation. 6th Petroleum Geology Conference, London, October 2003, Program & Abstracts, p. 53.

74. White R.S., Kusmir N.J., Christie P.A.F., Roberts A.M., Hunt N.W., Lunnon Z.C., Parkin C.J., Roberts A.W., Smith L.K., Spitzer R. & Tymms V., (2003). Rifting and Magmatism on the North Atlantic Continental Margins. 6th Petroleum Geology Conference, London, October 2003, Program & Abstracts, p.41.

75. Kusmir, N.J., Hunsdale, R., & Roberts, A.M. (2003). Timing of depth dependent stretching on the Lofoten continental margin: pre-breakup or post-breakup? *Geophys. Research Abstracts*, 5,02218.
76. Healy, D. & Kusmir, N.J. (2003). Elastic dislocation models of listric normal faults. *EOS Trans. AGU*, 84,1437.
77. Tymms, V., Kusmir, N.J., White, Roberts, A.M., Christie, P.A.F. & the iSIMM Team (2003). Modelling sea floor spreading initiation and rifted continental margin formation. *Geophys. Research Abstracts*, 5,02547.
78. Roberts, A.W., White, R.S., Kusmir, N.J., Christie, P.A.F., Robens, A.W. & iSIMM Team, (2003). Crustal structure from the Faroes shelf to the Norwegian Basin. *Geophys. Research Abstracts*, 5,01454.
79. White, R.S., Kusznir, N.J., Christie, P.A.F., Roberts, A.W., Hurst, A.N., Lunnon, Z.C., Parkin, C.J., Roberts, A.W., Smith, L.K., Spitzer, R., Tymms, V., Davies, A. & Surendra, A., (2003). Influence of the Iceland plume on North Atlantic continental margins. *Geophys. Research Abstracts*, 5,01224.
80. White, R.S., Kusmir, N.J., Christie, P.A.F., Roberts, A.M., Spitzer, R., Lunnon, Z., Roberts, A.W., Surendra, A., Hurst, N., Parkin, C.J., Smith, L.K., and Tymms, V., (2002). iSIMM (Integrated Seismic Imaging And Modelling Of Margins): the North Atlantic volcanic continental margin. Poster presented at Seismix 2003, Taupo, New Zealand, 6-10th January 2003.
81. Kusmir, N.J., Roberts, A.M., & Hunsdale, R. (2002). Timing and Magnitude of Depth-dependent Lithosphere Stretching on the Lofoten Segment of the Norwegian Rifted Continental Margin. *EOS Transactions AGU*, 83(47), Fall Meet. Suppl., Abstract T52C-1209.
82. White, R.S., Kusmir, N.J., Christie, P.A.F., Roberts, A., Lunnon, Z., Roberts, A.W., Hurst, N., Smith, L.K., Parkin, C.J., Surendra, A., and Davies, A., (2002). iSIMM (Integrated NERC Reference. NEK~IS;2000!01021 Seismic Imaging and Modelling of Margins): Seismic acquisition on the Faroes Shelf, Hanon Bank and adjacent continental margins. *EOS Transactions AGU*, 83(47), Fall Meet. Suppl., Abstract T52C-121 I.
83. White, R.S., Kusmir, N.J., Christie, P.A.F., Roberts, A., Davies A., Hurst A.N., Lunnon Z., Parkin C.J., Robert., A.W., Smith L.K., Spitzer R., Surendra A., & Tymms V., (2002). iSTMM: Integrated Seismic Lmaging and Modelling of Margins. *Ocean Margins LINK First Workshop*, DTI Conference Centre, 19th November 2002.
84. White, Robert S., Smallwood, John R., Fliedner, Moritz M., Maresh Jennifer, & Fmehn, Juergen, (2002). Imaging and regional distribution of basalt flows in the Faroe-Shetland Basin (extended abstract). *Journal of Conference Abstracts*, 7(2), 199-200.
85. Roberts, A.W., Lunnon, Z., White, R., Christie, P., Kusmir, N. and Roberts, A., (2002). integrated Seismic Lmaging and Modelling of Margins - the OBS surveys. Abstract for Geological Society of London Meeting on Frontier Exploration of Volcanic Margins, Burlington House, London, 17-18 September 2002.
86. Lunnon, Z., Roberts, A.W., Christie, P., White, R., Kusmir, N. and Roberts, A., (2002). integrated Seismic Imaging and Modelling of Margins - the towed streamer surveys. Abstract for Geological Society of London Meeting on Frontier Exploration of Volcanic Margins, Burlington House, London, 17- 18 September 2002.
87. Healy, D., Kusmir, N.J. & Yielding, G., (2002). An invene method to determine fault slip and geometry from seismically observed subsurface vertical stratigraphic displacements using elastic dislocation theory, *EOS Trans. AGU*, 83, 1373.