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Imaging through Altantic Margin basalts: An introduction to the sub-basalt mini-set

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The 2005 EAGE annual conference in Madrid featured a novel session, convened and chaired by the authors of this introduction, dedicated to sub-basalt imaging. Novelty lay in the structure of the session: three oral talks, three parallel posters delivered in the same room spanning the coffee break; three more oral talks and a moderated discussion at the end. The session captured the flavour of a genuine workshop with good discussion from the floor and an audience that was ready to chat around the posters with their cups of coffee. The co-chairs were encouraged to capture as many of the papers as possible for a mini-thematic set and while fewer papers than had been hoped have ended up in the set, this introduction sets the context for the following three papers, acknowledges the contributions of all the presenters in the session with a summary of their key results and selectively comments on recent developments in the topic.

The inexorable rise in the price of oil over the past few years, together with diminishing access to fresh reserves has encouraged the quest for 'unconventional' hydrocarbons, such as heavy oil, tar sands, coal-bed methane and gas hydrates. Hydrocarbons below basalt may arguably be an example of 'conventional' oil – mobile fluids in sedimentary traps – beneath an unconventional overburden, an overburden which presents challenges to imaging from severe scattering losses by impedance contrasts and rough surfaces, geometrical spreading, strong multiples and velocity heterogeneity. And yet, if it were possible to see through the glass even a little less darkly, it may be that the rocks beneath the Faroes basalts, extruded at the time of continental breakup under the influence of the Iceland mantle plume, would be as prospective as their counterparts on the basalt-free, UK flank of the Faroes-Shetland Trough. After all, the extensive basalt flows that make up the Faroes part of the North Atlantic Igneous Province are contemporaneous or more recent than the proven reservoir rocks in Foinaven and Marjun.

The opening paper of the session (Colombo *et al.* 2005) endeavoured to set the sub-basalt imaging problem into a geological context and to use geological models prior to a joint inversion problem. Their paper explored the complexities of the velocity structure of basalt layers as derived from the mechanisms of lava flows emplacement. The resulting basalt layers are far from being uniform homogenous bodies and cannot be described by simple, blocked velocity structures. Colombo *et al.* (2005) identified as a key issue for sub-basalt imaging, the accurate estimation of the basalt velocity structure, a theme that was repeated by other speakers including Gallagher and Dromgoole (2005). Colombo *et al.* (2005) recognised the difficulty of deriving reliable velocity models for basalts using conventional inversion techniques based on seismic data alone. For this reason they proposed a velocity model building workflow where geological knowledge and seismic observations are joined together by means of a combination of inversion methods and forward modelling techniques. The most plausible geological model consistent with the measured seismic data was used to re-image seismic data using pre-stack depth migration (PSDM) to obtain an improved and geologically-consistent seismic image.

A recent paper from the same author (Colombo and De Stefano 2007) approaches the problem of reconstruction of complex velocity fields by means of multiple geophysical measurements and simultaneous joint inversion within a PSDM workflow. The problematic resolution from noisy, sub-basalt seismic data is complemented by other remote sensing data such as gravity and magnetotelluric (MT) measurements. Velocity model building is then performed by simultaneous joint minimisation of residuals in seismic travel-time (both first breaks and common image point gathers) and residuals in gravity and MT data. Initial applications of PSDM-joint inversion to real data in Oman (Colombo *et al.* 2007) suggest that the workflow might successfully address complex velocity model building problems such as are found in basalt.

Hobbs *et al.* (2005) agreed that complementary remote sensing may be a way to place constraints upon the seismic

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velocity model and offered an approach to study the issue using models in which the ground truth is known. The group have computed both 2D and 3D synthetic geophysical datasets to evaluate sub-basalt processing, inversion and interpretation strategies. The data include raw seismic shot gathers, potential field and MT data. Hobbs *et al.* (2005) introduced the datasets and showed not only that modelling can produce realistically challenging, constrained data but that it can also provide insights into the sensitivity of the various geophysical techniques to the parameters of the model. One key result was an insight into how a seismic wave interacts with heterogeneous basalt flows. A snapshot of the wavefield crossing a basaltic interval vividly showed strongly scattered high frequencies becoming trapped between the sea surface, the seafloor and the supra-basalt interfaces. By contrast, the low frequencies remain as a reasonably coherent wavefront and may subsequently be processed to an image. Further results included the sensitivity to the basalt and sub-basalt geology of potential field and MT data, and processing/integration strategies that can recover the primary information. The audience was challenged to test their inversion strategies on the multiple datasets, which would be made available on application to the authors. In a later SEG paper, Jegen *et al.* (2006) rise to their own challenge and test their joint inversion on the synthetic datasets. Provided care is taken in developing relationships between P-wavespeed, resistivity and density, and judicial use is made of relative weighting to avoid small misfits in one data-type from swamping significant misfits in another data-type, Jegen *et al.* (2006) show that the joint inversion of seismic traveltimes, gravity and MT data gives a better-defined velocity model than do the seismic data alone. Sensitivity in one dataset may be used to offset uncertainty in another.

Returning to the EAGE session, Hobbs *et al.* (2005) also introduced the fundamental question for a sub-basalt workshop: how do you know that a given event is truly sub-basalt? Perhaps the best you can say is that the event is below top basalt, an issue which was to be another *leitmotif* of the session and is addressed in different ways by two of the following papers Spitzer *et al*. (2005, 2008) and Gallagher and Dromgoole (2005, 2008). The former used step-backs visible on long-offset ocean bottom seismometer (OBS) data, beyond the 12 km streamer aperture used in the iSIMM low-frequency seismic acquisition (White *et al.* 2002), to demonstrate the existence of a low-velocity zone beneath the high-velocity basalt flows. Full waveform OBS synthetics, computed from the streamer velocity model, matched the observed step-backs, showing consistency and complementarity of the OBS and streamer data types. An interpretation of sub-flow hyaloclastites, putative sediments and possible basement was supported by comparison with velocities from the Lopra-1/1A borehole on the Faroe Islands (Christie *et al.* 2006a), the stratigraphy of prograding basalt foresets in the Faroe-Shetland Trough (Kjørboe 1999) and deeply buried sediments in the iSIMM tie-well, 206/1-2.

Gallagher and Dromgoole (2005, 2008) supported the low-frequency theme, perhaps first propounded by Mack (1997) in the context of Atlantic margin basalts, but asserted the importance of a good geological model to guide picking of the correct velocity trend, having first removed as many of the multiples as possible using velocity-independent demultiple methods. Convincing examples were shown of the improvement of reflectivity below top basalt and the following paper (Gallagher and Dromgoole 2008) shows the further improvement afforded by a proprietary beam migration in bringing out deep, coherent events. Gallagher and Dromgoole (2005) pick a base basalt event conforming to the geological model and knowledge of the basalt interval velocities. Following an extensive campaign of low-frequency 2D and 3D acquisitions, the Brugdan prospect was drilled by Statoil and partners in 2006: well 6104/21-1 in Faroes Licence area 006 was the first sub-basalt penetration in Faroes waters. The results remain embargoed at the time of writing, but although it is known that only gas shows were found, the well must surely form a major stratigraphic control point for seismic data in the area and its analysis is likely to lead to better imaging below the basalt (Gallagher and Dromgoole 2007).

Over coffee, three poster presentations covered a variety of topics. Shaw *et al*. (2005, 2008) reminded everyone about the attenuating properties of basalt flows from an integration of borehole and log data from the Glyvursnes and Vestmanna boreholes on the Faroe Islands. This is consistent with the highly attenuative nature of basalts reported from a third Faroes borehole, Lopra-1/1A (Christie *et al.* 2006a), and from hole 164/07-1 in Rockall Trough which also penetrated a thick Tertiary basalt sequence (Maresh *et al*. 2006). While scattering losses are significant, Shaw *et al.* (2008) suggest that not all the loss observed on the Faroes borehole VSP data could be explained in this manner and so other loss mechanisms are discussed in the paper published here.

In the second poster, Murphy *et al*. (2005) presented experiences gained from using the Bell Geospace gradio-gravimeter for regional prospecting in the Faroe-Shetland Basin. The instrument, developed from de-classified military technology, measures the gradient of the gravity vector in all three spatial dimensions, resulting in a 9-element tensor, of which 5 elements are independent. More sensitive to shallow density contrasts than conventional gravity measurements, the gradio-gravimeter is able to locate dykes, sills, igneous centres, basalt edges and basement highs with a depth of investigation estimated from the spatial wavelength of the signal. While short wavelength anomalies arise from sources within and above the basalt, long wavelength anomalies may indicate Mesozoic fault blocks which can control syn-rift traps. As another potential field measurement which may be used in joint inversion with seismic data, constraining the PSDM velocity model, or simply as a support for regional screening and play high-grading (Rohrman 2007), Murphy *et al.* (2005) show that high resolution 3D gradio-gravimetry has a rôle to play in sub-basalt imaging and characterisation.

The final poster by Jupp *et al.* (2005) presented a depth migration tool-kit which is tailored for imaging beneath heterogeneous, high-velocity layers such as basalt. Beginning with wavelet manipulation for the highly mixed-phase, bubble-tuned airgun array signatures, trialled in the Faroes region for their low frequency content and deep penetration (White *et al.* 2002; Lunnon *et al.* 2003; Christie *et al.* 2006b; Gallagher and Dromgoole 2007), the tool-kit also includes primary velocity-independent demultiple steps such as surface multiple attenuation and high resolution Radon demultiple to deal with the strong multiple generators found in the Faroes. An initial velocity model is derived from 3D pre-stack time migration and then updated by creating high density Kirchhoff PSDM gathers and analysing them for residual moveout. The model is further refined by using grid tomography on key horizons picked at the top of and within the basalt sequence. More physically meaningful velocities result from the process, together with greater detail on the rugosity of the top basalt, than from NMO-based velocity analysis. Because rugose surfaces can result in multi-pathing, a wave-equation migration is performed in the shot domain, based on explicit extrapolation of both the up- and down-going wave-fields. Jupp *et al.* (2005) showed good examples of improved 3D imaging based upon the workflow described in the paper.

In an oral paper after the poster mini-session, Droujinine *et al.* (2005) demonstrated the power of linear, parabolic or generalised Radon transforms in separating primary, multiple and mode-converted arrivals using their different moveout parameters in the Radon domain. Using two case studies; one from the Slyne Trough near to the Corrib field (a successful example of sub-basalt exploration and production: Dancer *et al.* 2005) and one from the Erlend Volcano north of the Shetland Islands, Droujinine showed how judicious interpretation of events in the Radon domain could enhance selected modes, allowing improved migration in either time or depth domains (Droujinine 2005). In the Slyne Trough data, a comparison of PP and mode-converted depth sections showed that the latter imaged coherent events deeper below the shallow volcanics than the former, a result which has been reported elsewhere (e.g. Emsley *et al.* 1998; van der Baan *et al.* 2003), but which has not seen universal applicability (Hanssen *et al.* 2003).

Finally, Ziska and Morgan (2005) brought us back to the 5.5 km (or more) stratigraphic thickness of basalts proven on the Faroe Islands with an assertion that good quality air-borne and ship-borne magnetic data can be valuable in unravelling some of the basalt secrets. Because the ratio of remanent magnetisation to induced magnetisation in Faroes basalts varies from 0.8 to 48, the magnetic signature of the Islands and neighbouring areas is dominated by the palaeomagnetic imprint. An elongated positive magnetic anomaly is observed around Suðuroy, the location of the Lopra-1/1A borehole. The anomaly can be correlated to lava flow outcrops on Suðuroy that have positive remanent magnetisation in an otherwise negatively magnetised basalt section. Two positively magnetised units of 400 m and 180 m thickness sandwich a 500 m negatively magnetised unit, and the composite has a characteristic magnetic signature which can be matched by modelling. Ziska and Morgan (2005) show that the same signature is consistent with seismically-interpreted seabed outcrops of the basalts northwest of the island, thereby correlating the magnetic and seismic structures. Due to differential uplift and erosion, the upper 3 km of the basalt sequence outcrops on the Faroes and surrounding seabed, allowing direct observation of the palaeomagnetic polarity reversals which enables onshore basalt stratigraphy to be interpreted in the offshore seismic data using the magnetic signatures. In some places, the basalts are thought to overlie basement directly, while in other locations there may be a sedimentary sequence between the two and the paper ended with some speculation regarding the depth of basement below total depth of the Lopra borehole. The magnetics suggest that the well may be located to the east of a basement high, perhaps on the downthrown side of a basement fault. From the final Lopra VSP, Christie *et al.* (2006a) observed a sharp decrease in impedance some 167 m below total depth which was therefore unlikely to be basement but which was interpreted as most probably another basalt bed. It remains the million-dollar question: what lies beneath?

REFERENCES

van der Baan M., Kerrane T., Kendall J.-M. and Taylor N. 2003. Imaging sub-basalt structures using locally converted waves. *First Break* **21**, 29–36.

Christie P., Gollifer I. and Cowper D. 2006a. Borehole seismic studies of a volcanic succession from the Lopra-1/1A borehole in the Faroe Islands, northern North Atlantic. *Geological Survey of Denmark and Greenland Bulletin* **9**, 23–40.

Christie P.A.F., Lunnon Z.C., White R.S. and iSIMM Team. 2006b. iSIMM experience with peak- and bubble-tuned sources for generating low frequencies. 68th EAGE meeting, Vienna, Austria, Extended Abstract, A034.

Colombo D., Carbonara S. and Pellegrino S. 2005. Bringing geology in the sub-basalt seismic imaging problem. 67th EAGE meeting, Madrid, Spain, Extended Abstracts, G033.

Colombo D. and De Stefano M. 2007. Geophysical modeling via simultaneous joint inversion of seismic, gravity and electromagnetic data: application to pre-stack depth imaging. *The Leading Edge* **26**, 326–331.

Colombo D., Mantovani M., De Stefano M., Garrad D. and Al Lawati H. 2007. Simultaneous joint inversion of seismic and gravity data for long offset pre-stack depth migration in Northern Oman. 2007 Annual Meeting, Canadian Society of Exploration Geophysicists, Expanded Abstracts, 191–195.

Dancer P.N., Kenyon-Roberts S.M., Downey J.W. and Baillie J.M. 2005. The Corrib gas field, west of Ireland. In: *Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference* (eds A.G. Doré and B. Vining), pp. 1035–1046. Geological Society of London.

Droujinine A., Buckner S., Cameron R., Pajchel J. and Hitchen K. 2005. Multi-wave-type sub-basalt imaging. 67th EAGE meeting, Madrid, Spain, Extended Abstracts, G037.

Droujinine A. 2005. The attribute-based generalized discrete Radon transform. *Journal of Seismic Exploration* **14**, 155–196.

Emsley D., Boswell P. and Davis P. 1998. Sub-basaltic imaging using long offset seismic data. 60th EAGE meeting, Leipzig, Germany, Extended Abstract, 1–48.

Gallagher J.W. and Dromgoole P. 2005. Seeing below the basalt, offshore Faroes. 67th EAGE meeting, Madrid, Spain, Extended Abstracts, G038.

Gallagher J.W. and Dromgoole P.W. 2007. Exploring below the basalt, offshore Faroes: a case history of sub-basalt imaging. *Petroleum Geoscience* **13**, 213–225.

Gallagher J.W. and Dromgoole P.W. 2008. Seeing below the basalt, offshore Faroes. *Geophysical Prospecting*, in press.

Hanssen P., Ziolkowski A. and Li X.-Y. 2003. A quantitative study on the use of converted waves for sub-basalt imaging. *Geophysical Prospecting* **51**, 183–193.

Hobbs R., Cherrett A., Jegen M., Harrop N., Martini F. and the SIMBA group. 2005. 2D and 3D synthetic data for evaluating strategies for subbasalt exploration. 67th EAGE meeting, Madrid, Spain, Extended Abstracts, G034.

Jegen M.D., Heincke B. and Hobbs R. 2006. Joint inversion of MT, gravity, and seismic data applied to sub-basalt imaging. 76th SEG meeting, New Orleans, USA, Expanded Abstracts, 784–789.

Jupp R., Syed Y., Grimshaw M., Bell T., Micklewright I., Jones N., Gallagher J.W., Dromgoole P. and Brenne E.O. 2005. A 3D seismic depth-processing toolkit for sub-basalt imaging. 67th EAGE meeting, Madrid, Spain, Extended Abstracts, P501.

Kjørboe L. 1999. Stratigraphic relationships of the Lower Tertiary of the Faeroe Basalt Plateau and the Faeroe-Shetland Basin. In: *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference* (eds A.J. Fleet and S.A.R. Boldy), pp. 559–572. Geological Society of London.

Lunnon Z., Christie P. and White R. 2003. An evaluation of peak and bubble tuning in sub-basalt imaging: modelling and results. 65th EAGE meeting, Stavanger, Norway, Extended Abstracts, C01.

Mack H. 1997. Seismic response of Tertiary basalt flows in the northeast Atlantic – a modelling study. 59th EAGE meeting, Geneva, Switzerland, Extended Abstracts, B017.

Maresh J., White R.S., Hobbs R. and Smallwood J.R. 2006. Seismic attenuation of Atlantic margin basalts: observations and modelling. *Geophysics* **71**, B211–B221. doi:10.1190/1.2335875

Murphy C.A., Mumaw G.R. and Zuidweg K. 2005. Regional target prospecting in the Faroe-Shetland Basin area using 3D-FTG gravity data. 67th EAGE meeting, Madrid, Spain, Extended Abstracts, P503.

Rohrman M. 2007. Prospectivity of volcanic basins: Trap delineation and acreage de-risking. *Bulletin of the American Association of Petroleum Geologists* **91**, 915–939.

Shaw F., Worthington M.H., White R.S., Andersen M.S., Petersen U.K. and SEIFABA Group. 2005. Seismic attenuation in Faroe Island basalts. 67th EAGE meeting, Madrid, Spain, Extended Abstracts, P502.

Shaw F., Worthington M.H., White R.S., Andersen M.S., Petersen U.K. and SEIFABA Group. 2008. Seismic attenuation in Faroe Islands basalts. *Geophysical Prospecting*, in press.

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 EAGE meeting, Madrid, Spain, Extended Abstracts, G035.

Spitzer R., White R.S., Christie P.A.F. and iSIMM Team. 2008. Seismic characterisation of basalt flows from the Faroes Margin and the Faroe-Shetland Basin. *Geophysical Prospecting*, in press.

White R.S., Christie P.A.F., Kusznir N.J., Roberts A., Davies A., Hurst N., Lunnon Z., Parkin C.J., Roberts A.W., Smith L.K., Spitzer R., Surendra A. and Tymms V. 2002. iSIMM pushes frontiers of marine seismic acquisition. *First Break* **20**, 782–786.

Ziska H. and Morgan R. 2005. Can paleomagnetism be used as a mapping tool in basalt provinces? 67th EAGE meeting, Madrid, Spain, Extended Abstracts, G039.