Tectonophysics 508 (2011) 22–33

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

# The composition and structure of volcanic rifted continental margins in the North Atlantic: Further insight from shear waves

Jennifer D. Eccles [a],*, Robert S. White [a], Philip A.F. Christie [b]

[a] Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Madingley Rise, Cambridge CB3 0EZ, UK
[b] Schlumberger Cambridge Research, High Cross, Madingley Road, Cambridge CB3 0EL, UK

ARTICLE INFO

*Article history:*
Received 14 January 2009
Received in revised form 17 December 2009
Accepted 7 February 2010
Available online 12 February 2010

*Keywords:*
Volcanic rifted continental margin
North Atlantic Igneous Province
Ocean Bottom Seismometers
Seismic tomography

ABSTRACT

Imaging challenges caused by highly attenuative flood basalt sequences have resulted in the understanding of volcanic rifted continental margins lagging behind that of non-volcanic rifted and convergent margins. Massive volcanism occurred during break-up at 70% of the passive margins bordering the Atlantic Ocean, the causes and dynamics of which are still debated. This paper shows results from traveltime tomography of compressional and converted shear wave arrivals recorded on 170 four-component ocean bottom seismometers along two North Atlantic continental margin profiles. This traveltime tomography was performed using two different approaches. The first, a flexible layer-based parameterisation, enables the quality control of traveltime picks and investigation of the crustal structure. The second, with a regularised grid-based parameterisation, requires correction of converted shear wave traveltimes to effective symmetric raypaths and allows exploration of the model space via Monte Carlo analyses.

The velocity models indicate high lower-crustal velocities and sharp transitions in both velocity and Vp/Vs ratios across the continent–ocean transition. The velocities are consistent with established mixing trends between felsic continental crust and high magnesium mafic rock on both margins. Interpretation of the high quality seismic reflection profile on the Faroes margin confirms that this mixing is through crustal intrusion. Converted shear wave data also provide constraints on the sub-basalt lithology on the Faroes margin, which is interpreted as a pre-break-up Mesozoic to Paleocene sedimentary system intruded by sills.

## 1. Introduction

Volcanic rifted continental margins represent an important subgroup of large igneous provinces (LIPs). Fig. 1 shows the global distribution of these LIPs and other ‘hotspot’ related volcanism (Coffin and Eldholm, 1994). LIPs cause important additions of igneous material to the crust and potentially important fluxes of heat and volatiles from the mantle (Self et al., 2008). Theories to explain the diverse geological, geochemical and geophysical observations made at LIPs are still controversial with the relative role of mantle temperature, active or passive upwelling and mantle composition actively debated (e.g., Sheth, 1999; Holbrook et al., 2001; Foulger et al., 2005; White et al., 2008).

At volcanic rifted margins, continental break-up was accompanied by the extrusion and intrusion of large volumes of dominantly basaltic magma (Menzies et al., 2002). Such margins are characterised by seaward dipping reflector (SDR) sequences. These represent flood basalt sequences that flowed landward away from the transiently uplifted rift but underwent dip reversal as further stretching, loading and subsidence occurred (Mutter et al., 1982; Planke and Eldholm, 1994; Spitzer et al., 2008).

The early Tertiary North Atlantic Igneous Province (NAIP; Fig. 1) contains >1 million km$^3$ of extruded lava (Eldholm and Grue, 1994). Flood basalts flowed up to 150 km outward from the subaerial axial rift (Spitzer et al., 2008) and are more than 7 km thick on the Faroe Islands (Passey and Bell, 2007). Localised extension in the North Atlantic region had been initiated in the Devonian (Dean et al., 1999), with further rifting in the Permo-Triassic as the super-continent Pangea broke-up (Glennie, 1995). More significant regional extension occurred in the Cretaceous with reactivation of pre-existing Caledonide thrusts (Dean et al., 1999). Thus significant pre-breakup depocentres existed between northwest Europe and Greenland which were later buried beneath the Tertiary flood basalt flows. The locus of rifting had shifted westward due to strengthening of the mantle beneath the stretched crust by conductive cooling (Newman and White, 1997) and proceeded to full continental break-up in the Paleocene (Smallwood and White, 2002).

While in many regions seismic reflection imaging of the crust provides structural and morphological control, at volcanic rifted margins the blanketing basalt flows reduce the efficiency of this technique. Although mafic crystalline rocks have low intrinsic attenuation (e.g., Nakamura and Koyama, 1982), the cyclic nature of the basalt flow sequences, with rough

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* Corresponding author. Institute of Earth Science and Engineering, University of Auckland, Auckland 1142, New Zealand. Fax: +44 1223 360779.
*E-mail addresses:* j.eccles@auckland.ac.nz (J.D. Eccles), rsw1@cam.ac.uk (R.S. White), pafc1@slb.com (P.A.F. Christie).

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doi:10.1016/j.tecto.2010.02.001

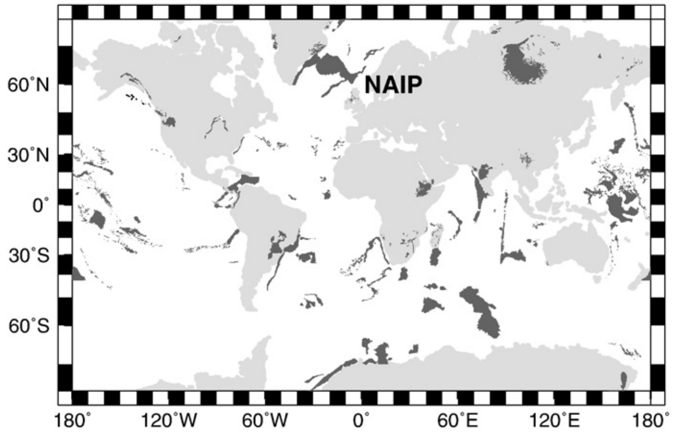

**Fig. 1.** Global distribution of large igneous provinces (shaded in black), including continental flood basalts, volcanic rifted continental margins and oceanic plateaus, and hotspot related volcanism. Compilation by Coffin and Eldholm (1994). The North Atlantic Igneous Province (NAIP), the subject of this study, is labelled. Volcanic rifted continental margins are thought to represent up to 70% of the Atlantic Ocean's passive margins (Clift, 1999; Planke et al., 1999).

surfaces, high velocity massive flow cores and low velocity fractured or vesicular flow margins and interbedded sediments, leads to high effective attenuation. This is due to scattering, complex multiples and mode conversion (Pujol and Smithson, 1991; White et al., 2003; Maresh et al., 2006). Seismic wave induced fluid flow within pores and micro-cracks has also been suggested as a contributor to the high attenuation of basalt sequences (Shaw et al., 2008). Attenuation can be described by the Quality Factor ($Q$; Scheirer and Hobbs, 1990), with high attenuation indicated by the low values (15–40) of effective $Q_P$ measured for basalt sequences (Rutledge and Winkler, 1989; Maresh and White, 2005; Christie et al., 2006; Maresh et al., 2006; Shaw et al., 2008). The frequency-dependent nature of the attenuation is illustrated by Fig. 2. The basalt flow sequences significantly attenuate the high frequencies, with the amplitude of frequencies above 15 Hz typically below the level of noise. Shear (S-) waves have slower velocities through the basalt and $Q_S$ is estimated to be 4/9 $Q_P$ (Lay and Wallace, 1995), leading to the even greater attenuation of the high frequency energy observed for converted S-waves (Fig. 2).

The integrated Seismic Imaging and Modelling of Margins (iSIMM) project specifically tailored data acquisition to the sub-basalt problem. Seismic data were collected across two margins in the North Atlantic (Fig. 3): the Faroes margin (Profile 1) in the region of most voluminous magmatism and, further to the south, the Hatton Bank margin (Profiles 2 and 3) close to a previous classic transect (Fowler et al., 1989; Spence et al., 1989). Large (6360 in.$^3$) airgun arrays were towed at ~ 18 m depth to produce a low frequency source. There is a trade-off between increased low frequency energy generated by interference of the primary with the sea-surface ghost, which lowers the first notch in the frequency domain as the source is towed deeper (Lunnon et al., 2003), and increased high frequency energy with increased ambient water pressure (i.e., increased tow depth) following the Rayleigh–Willis relation (Christie et al., 2004). The peak frequency of the iSIMM source was 9–11 Hz (Lunnon et al., 2003).

Long offset acquisition enabled more effective velocity analyses to be made and sub-basalt reflectors to be identified. The deployment of 170 ocean bottom seismometers (OBSs) allowed the wide-angle elastic wavefield to be directly recorded at the seabed. Arrivals are observable to source–receiver distances of up to 180 km. Wide-angle compressional (P-) wave arrivals have previously allowed joint refraction and reflection traveltime tomography of these profiles to be carried out (Parkin and White, 2008; White et al., 2008; White and Smith, 2009; Roberts et al., 2009). The value of long offsets has also been demonstrated by the multichannel seismic (MCS) reflection data collected by towed streamers; WesternGeco collected coincident MCS data across the Faroes margin (Profile 1) using a 12 km single-sensor streamer (WesternGeco, 2002), which resolved structure never

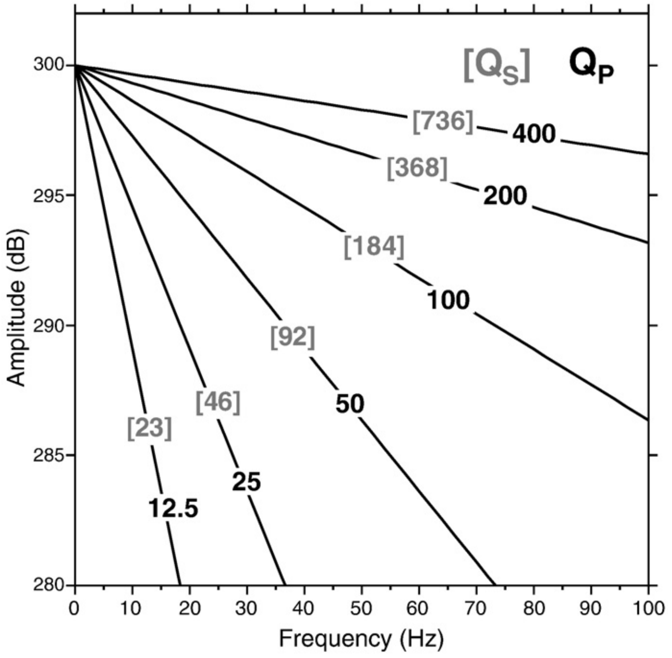

**Fig. 2.** Frequency-dependent effect of variable $Q_P$ (black) and $Q_S$ (grey) on amplitude calculated (Maresh et al., 2006) by two-way transmission through a 1 km thick basalt layer with a P-wave velocity of 4 km/s and Vp/Vs ratio of 1.84 (Christensen, 1996). Geometrical spreading is not considered. The seismic source for this simple model is assumed to have an amplitude of 300 dB (estimated from the direct arrival) across all frequencies.

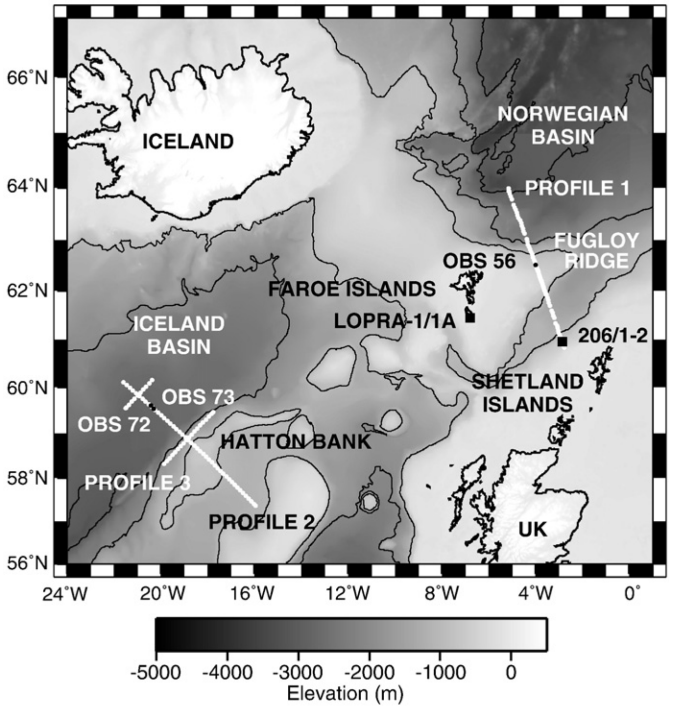

**Fig. 3.** Location map of iSIMM profiles in the North Atlantic region. Bathymetric contour interval is 500 m. OBS deployed across the Faroes and Hatton Bank margins are shown by white circles, example instruments OBS72 and OBS73 from Profile 2 and OBS56 from Profile 1 are highlighted in black. Important boreholes on the Faroes Islands (Lopra-1/1A; Christie et al. (2006)) and Faroe–Shetland Trough (206/1-2) are shown by black squares.