The Use of Low Frequencies for Sub-Basalt Imaging

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Summary

Large areas of passive ocean margins are covered by basalts which conceal sediments that may contain large accumulations of hydrocarbons. These basalts are extremely heterogeneous and scatter the seismic energy of the conventional seismic reflection system. We propose to modify the system to emphasize the low frequencies, using much larger air guns, and towing the source and receivers at about 20 m depth. The rationale for this approach is supported by synthetic seismograms over a realistic 1-D earth model. In the summer of 2001 we plan to obtain data over basalt in the North-East Atlantic using a suitably-modified system.

Introduction: Why is Sub-Basalt Imaging Important?

Large areas of passive ocean margins are covered by basalts which are often opaque to conventional seismic reflection surveys. For example. the North East Atlantic margin, larger than the UK sector of the North Sea, is a vast, relatively unexplored area, and holds the promise of very large hydrocarbon accumulations. However, most of the area is covered by Cenozoic flood basalts that overly the deeper Mesozoic and Palaeozoic sediments, which may contain the source and reservoir rocks for hydrocarbons. These basalts are highly heterogeneous, and have many different geometrical characteristics and physical properties. This causes an enormous problem for seismic waves to "see through" the basalt using conventional towed streamer technology (e.g. Longshaw et al., 1998), and hence the deep geology of the NE Atlantic Margin is poorly understood. The key to unlock the huge potential of the margin is to characterize the basalt and find better seismic methods to image beneath it.

Seismic Properties of Basalts

Most studies of the seismic response of the basalt assume a flat homogeneous layer. In some cases, the basalt has been characterised as a massive high-velocity slab. This characterisation is over-simplified for reliable seismic modelling. Even in a simple setting, basalt is often interbedded with thin layers of other lithologies, such as claystone and siltstone (e.g. Gatliff et al., 1984). Mack (1997) performed a 1D seismic modelling experiment to assess the effects of thin bedded basalt on seismic waves. He concluded that it is important to design the acquisition system to focus more on low frequencies

Previous Work on Sub-Basalt Imaging

Various innovative seismic methods have been employed for sub-basalt imaging, and these include wide-angle seismic surveys, long streamer (up to 12km) and two-boat seismic acquisition, and multi-component ocean-bottom surveys (see the extensive list of references in Richardson et al., 1999). So far, all these efforts have had limited success. Several fundamental problems arise for seismic wave propagation through basalt, due to the intrinsically heterogeneous nature of the basalt. These may include scattering and absorption from rough interfaces and joints, etc. and interference effects from interbedded units of basalt and sediment. In addition to all these effects, there are always serious sea surface and 'interbed' multiples that sometimes completely mask the reflections from below.

Wide-angle seismic survey, which avoids the scattering problem to some extent, in most cases gives results related only to the large scale interval velocity of the basalt and not to the reflectivity below (Shipp et al., 1999). For some years it appeared that locally-converted waves, which avoid the multiple problem to some extent, could offer a 'seismic window for success' (Emsley et al., 1998). However, the success of the technique is very model-dependent. From an intensive study of real and synthetic data, Hanssen et al. (2000) concluded that locally-converted shear waves are difficult to utilise for imaging below the basalt.

Low-Frequency Seismic Wave Response

It has been known for many years that the elastic transmission response of a sequence of thin layers is low-pass (e.g. Ziolkowski and Fokkema, 1986). Also modelling wave propagation in heterogeneous media reveals that for seismic waves with a wavelength about an order of magnitude longer than the scale of the heterogeneity (Ebrom et al., 1990), the heterogeneous medium can be represented by an equivalent homogeneous anisotropic medium (Liu et al., 2000). Field studies of basalts in the NE Atlantic Margin indicate that although in most areas the basalts are very heterogeneous, the heterogeneous features often have scale lengths in the ranges of tens of metres (Gatliff et al., 1984), which is approximately an order of magnitude less than the seismic wavelength for low-frequency waves with 10 Hz or less. Therefore, the use of low frequency seismic waves may avoid the problem of thin layering and heterogeneity, and may provide the basis for reflection seismic energy to penetrate through basalt. This innovative idea has never been tested for imaging through basalt in a setting like the Atlantic Margin. However, a 1991 survey in the Indian Ocean has revealed the potential of this technology (Figure 1). If this technology is proved to be successful in the Atlantic Margin it will open a completely new area and market for the seismic method.

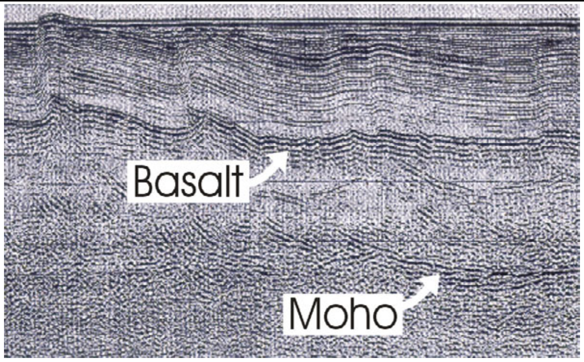

Figure 1. An example from the Indian Ocean using low frequency waves to image the Moho The data were acquired in 1991 using large air guns (2 x 2000, 2 x 1000, and 4 x 500 cu. in.) as described in Chamot-Rooke et al. (1991). The guns were towed at 15 m, and the cable was at 22 m. The sea-floor reflection is at 6.5 s and the Moho reflection is at 10.5s.

Modelling of Sub-Basalt Reflections

To check the applicability of this approach to the basalts of the North Atlantic margin, we have generated some synthetic seismograms using the full waveform OSIRIS code from Ødegaard A/S and a realistic model of the basalt. Figure 2 shows a log in well 209/9-1 through Palaeocene basalt (Stoker et al., 1993). It is clear that the basalt is extremely heterogeneous. We have followed in Mack's (1997) footsteps and have modelled the effect of such a composite basalt layer overlying a single deep reflector. Figure 3 shows the model.

Figure 4 shows an offset-dependent synthetic seismogram, omitting the sea surface to enable the primary reflections to be seen. The centre frequency of the source time function was 35 Hz. Figure 5 shows the response for the same configuration, but with a centre frequency of 10 Hz. The lower frequency response of Figure 5 clearly shows less scattering in the composite basalt layer and a much higher amplitude reflection from the sub-basalt interface at 3.5 s.

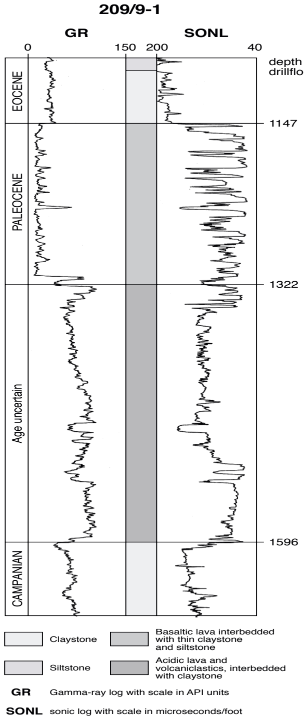

Figure 2 Well logs from basalt north of Shetland

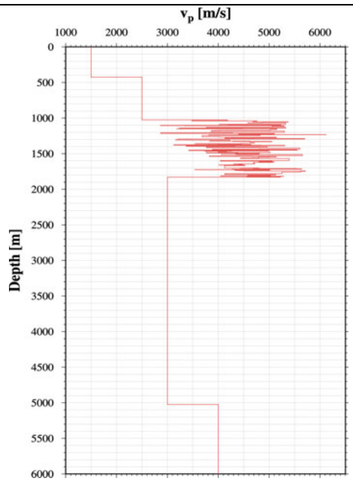

Figure 3 1-D earth model for synthetic seismograms showing a very heterogeneous basalt layer 1000-1820 m and a sub-basalt interface at 5000 m

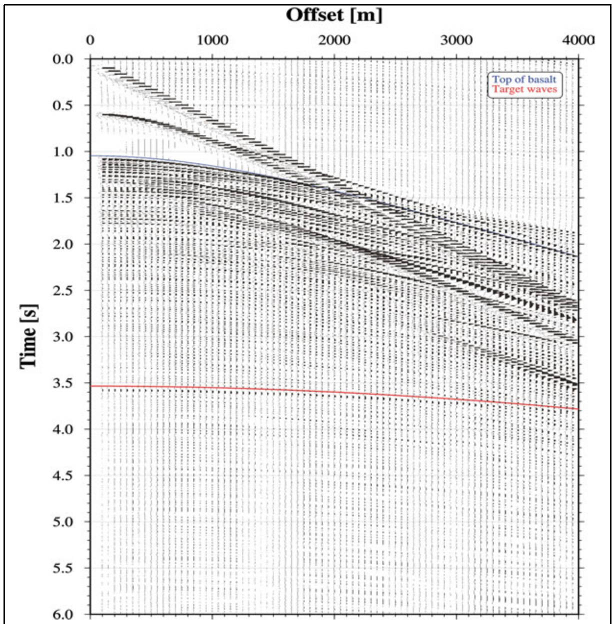

Figure 4 Offset-dependent synthetic seismogram for model of Figure 3 with 35 Hz source signal. The reflection at 3.5 s is barely visible

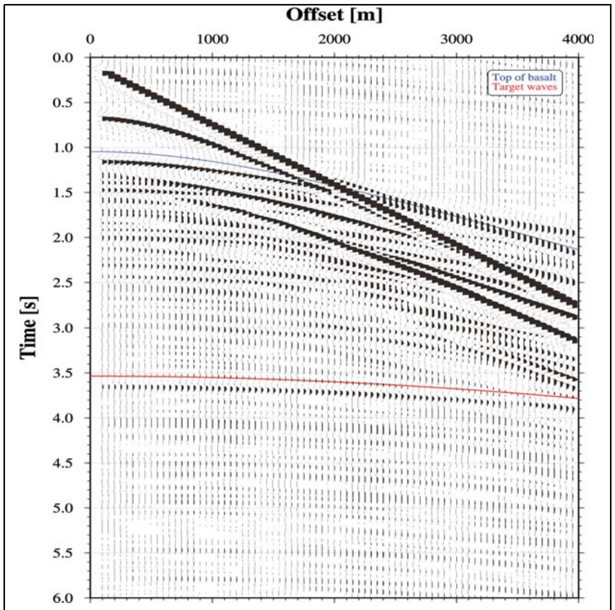

Figure 5 Offset-dependent synthetic seismogram for model of Figure 3 with 10 Hz source signal. The reflection at 3.5 s is clearly visible

Low Frequencies: Source and Receiver Depth

In conventional seismic reflection surveying, the source and receiver cable depths are typically about 5 m below the sea surface. In the vertical direction the sea surface reflection effect at the source is of the form:

$$R_s(\omega) = 2\sin(\omega D_s \cos\theta / v_w) , \qquad (1)$$

in which D_s is the depth of the source, θ is the angle of incidence, and v_w is the velocity of sound in water. At the receiver the expression is identical, except that D_r, the receiver depth, replaces D_s. The system response is optimised for a given bandwidth by putting the source and receiver at the same depth D, when the combined response becomes

$$R_c(\omega) = 4\sin^2(\omega D\cos\theta / v_w) . \qquad (2)$$

For example, at normal incidence, $\theta = 0$, and the response is greater than unity over the bandwidth $\pi v/(6D) < \omega < 5\pi v/(6D)$. For the source and receiver cable depth at 5 m this effect boosts the amplitude of reflected waves in the bandwidth 30-120 Hz. By placing the source and receiver cable at a depth of 15 m, for example, the optimum bandwidth is shifted to 10-40 Hz. In practice it may be better to tow the source and receiver even deeper, say 20 m. This would give an optimum bandwidth of 7.5-30 Hz.

Low Frequencies: the Air Gun Source

In a normal air gun array the largest gun has a volume of not greater than about 6.4 l (400 cu. in.). At a depth of 5 m, and a pressure of 135 bar (2000 psi), a 6.4 l gun emits an air bubble which oscillates with a period of about 130 ms, corresponding to a fundamental frequency of 7.7 Hz. The bubble oscillation period is given by the well-known modified Rayleigh-Willis formula:

$$T = k\frac{P^{\frac{1}{3}}V^{\frac{1}{3}}}{\left(P_{atm} + \rho g D\right)^{\frac{5}{6}}} \qquad (3)$$

in which P is the gun pressure, V is the gun volume, P_{atm} is atmospheric pressure, ρ is the density of water, g is gravitational acceleration, D is the depth of the gun, and k is a constant. From the bubble period for one gun of known volume, pressure, depth, and bubble period, it is possible to determine the constant, and hence determine the bubble period of any gun of known volume, pressure and depth. For example, a 6.4 l gun at a depth of 15 m would have a bubble period of about 85 ms, corresponding to a fundamental frequency of about 11.7 Hz. The guns are already operated at close to the maximum safe pressure, so the only parameters that can be adjusted are the depth and volumes of the guns.

If a conventional air gun array is put at 15 m, instead of its normal depth of 5 m, the frequency of oscillation of every bubble in the array is increased by about 50%. In order to obtain low frequencies, say down to 5 Hz, we must use much bigger air guns (since the period is proportional to the cube-root of the volume), say 32 l (2000 cu. in.). Using the Rayleigh-Willis formula, we can calculate that a 2000 cu. ins. air gun at 15 m and 135 bar (2000 psi) would have a bubble period of about 145 Hz, corresponding to a fundamental frequency of about 7 Hz.

In summary, the air gun array must be re-designed, using air guns at least five times bigger than conventional guns, probably about 2000 cu. ins., and towed at a depth no shallower than 15 m. The receiver cable must be towed at about the same depth. We note that these large air guns are commercially available.

Conclusions

Large areas of passive ocean margins are covered by basalt that may conceal enormous reserves of hydrocarbons. Various innovative seismic methods have been employed for sub-basalt imaging, but they have had limited success. The passive ocean margin basalts are very heterogeneous and scatter high frequencies more than low frequencies. To increase the probability of obtaining detectable sub-basalt reflections it is essential to design the seismic reflection system to emphasize the low frequencies. The source and receiver must be towed deep (about 20 m) and much larger air guns must be used than have been used so far: at least a factor of 5 increase in volume.

We are planning to implement these ideas in an experimental survey to be conducted in the summer of 2001. A proposal has been submitted to the UK Natural Environment Research Council and to oil companies. If our proposal is funded, some results may be available for presentation at the meeting.

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