Sub-basalt imaging
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Sub-basalt: what's the problem?

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What's the problem?

It is clear that imaging beneath both extrusive and intrusive basaltic rocks in deep water sedimentary basins, in areas such as Rockall Trough, is not easy. Conventional seismic reflection profiling performs poorly, and often it fails to image usefully at all. Enhanced seismic acquisition using long offsets, and large, low-frequency sources, and enhanced processing that tries to deal properly with free-surface and interbed multiples, perhaps utilises converted waves, and attempts to derive a velocity field from post-critical data, can improve imaging somewhat. However, the problem appears to be much more difficult than might be expected, and it is not immediately obvious why this should be so.

The conventional explanation is that the basalts prevent penetration of seismic energy. In principle, they can do this either by anelastic attenuation which converts the seismic energy to heat, or by elastic back scattering. Observations of basalts, in wells, in the laboratory, and as propagators of seismic energy in other contexts, together with our understanding of the mechanisms of anelastic attenuation, suggest that anelastic attenuation in deeply buried basalts is unlikely usually to be problematic. Back-scattering of energy, at the intensity required to prevent effective transmission, is likewise difficult to achieve. It requires many layers of intercalated basalt and low-velocity sediment to be effective, and although some areas are likely to contain such layers, many massive flows, pillows and intrusions clearly do not, and these appear to be just as difficult to image beneath.

Seismic observations through and beneath basaltic oceanic crust, of both wide-angle turning rays within the mantle, and near-normal-incidence reflections from the base of the crust, demonstrate that seismic energy can pass easily through basalts that are broadly similar to the rocks in parts of Rockall. Within Rockall itself, wide-angle turning rays from deep beneath the basalt layers are relatively easy to record at offsets of several tens of kilometres. These waves have travelled through the basalts at the same incident angles as those that fail to image properly in conventional reflection surveys. It seems likely therefore, that penetration alone is not the principle problem.

There are other contributory problems that serve to make the problem more difficult to solve – free-surface and strong interbed multiples, lack of reflectivity in the sediments below the basalts, poor weather and sea conditions, and limitations upon the imaging aperture as a result of the large velocity contrast at the top of the basalt – but none of these appears to be adequate alone to explain the difficulty. It is possible that all contribute somewhat, and that the problem is no more than the sum of several unrelated annoyances that together destroy the image.

However, there are a number of datasets, both reflection and wide-angle, that suggest that the problem is principally one of imaging. That is, the velocity contrast between the basalts and the surrounding rocks is sufficiently strong, and the surface is sufficiently rugged, that the transmitted wavefield becomes very significantly disrupted. Near-normal incidence reflections in such a system will not be visible on unstacked data as a result of the other noise and signal limiting problems, they cannot be stacked or migrated using simple velocity models or algorithms, and more sophisticated algorithms and velocity model builders fail because the signal strength pre-stack is too weak and too noisy to begin the iterative model building.

In essence, the problem is identical to that of imaging beneath rugose salt, but with the added complication that the velocity structure within the "salt" is highly variable, unknown, and laterally heterogeneous on wavelength scales.

What's the solution

The solution to this problem is clearly to build a velocity model that is sufficiently accurate to allow proper pre-stack depth migration of the disrupted wavefield. The length-scale of structures at top basalt, and within the basalts, can be small, and both the velocity model and the migration algorithm must properly deal with this. Almost certainly, Kirchhof type migrations are inadequate, and full wave-equation methods will be required, possibly even methods that use the two-way rather than approximate one-way wave-equation.

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The key to applying such methods is to be able to determine a sufficiently accurate and well resolved velocity model. Conventional methods of building migration velocity models cannot reproduce the wave-length lateral resolution that is required. Wave-field tomography, in which a velocity model is sought that explains the entire wavefield at both pre-critical and post-critical distances, can recover wave-length scale velocity variation. Wavefield tomography can also be used to depth migrate the image using the full two-way wave equation.

At present, these methods are being applied successfully in 2D to field datasets, and are able to image successfully beneath basalts in some circumstances. However, in most areas, a full 3D version is required to make progress. We have extended the method to 3D in a small synthetic case study. There are as yet no suitable 3D wide-angle field datasets, and the computational scale of the problem is daunting. It is equivalent to iterative 3D pre-stack depth migration using a two-way rather than one-way wave equation. The problem can be significantly accelerated by operating with data that is sparsely sample in the frequency domain, and by using iterative solvers to deal with the forward problem. However, a practical commercial solution is still several years away.