Numerical modelling of seismic reflection in basalt terrains

Eric Battig
University of Queensland
Now at *MIM Exploration*
enbatt@mim.com.au

Steve Hearn
University of Queensland and *Velseis Pty Ltd*
steveh@velseis.com.au

SUMMARY

We have used numerical modelling to improve understanding of seismic reflection in basalt covered regions. Our models are based on hydrocarbon prospects in the Denison Trough (Queensland, Australia).

Reflectivity modelling has been used to assess the influence of a range of model and source parameters. Models that include a single near-surface basalt layer generally result in relatively noise-free reflection signals, provided the basalt is reasonably attenuative. Reflection quality is poorest for models with buried high-velocity basalts, or for multi-layered basalts interspersed with lower-velocity material. Such models result in strong reverberatory noise, apparently propagating between the surface and basalt, or within the multi-layered basalts. In these situations, reflection strength is significantly improved if the source can be positioned below the basalt.

Finite-difference modelling permits analysis of models incorporating lateral variations in basalt geometry. Shot records generated with this approach exhibit basalt-related features seen routinely in real field data. Simple stacking of the finite-difference records indicates that reasonable sections can be obtained in areas of near-surface, or thin, basalts. Poorer stack quality is associated with thicker, buried basalts although deeper reflectors may be imaged by undershooting the basalt.

Key words: Seismic, modelling, basalt, reflectivity, finite-difference.

INTRODUCTION

The problem of obtaining acceptable imagery in regions of basalt (or other high-velocity) cover is well documented (e.g. Papworth, 1985; Samson et al., 1995; Hanssen and Li, 1999; Wombell et al., 1999) The presence of such anomalous features in the near surface can result in pseudo-structure due to velocity pull-up. In addition, strong noise energy may be generated, swamping the weaker reflection events. A number of the studies noted above have proposed various mechanisms for such noise (scattering, reverberation, wave-guide effects, mode conversion). The precise cause no doubt varies from case to case. The present modelling study is aimed primarily at improving understanding of such basalt-related noise effects, with specific reference to geological models relevant to the Denison Trough (Queensland, Australia). This is an area of considerable interest to hydrocarbon explorers. In the adjacent Bowen Basin, similar basalt-related problems are impacting on high-resolution 3D seismic reflection, which has emerged as the primary geophysical tool for coal mine development (e.g. Peters and Hearn, 2001).

REFLECTIVITY MODELLING

The reflectivity technique (e.g. Kennett, 1983, Mallick and Frazer, 1987) has been used for the bulk of the modelling tests carried out in this study. The main program used was ERZSOL (written by B.L.N. Kennett), which computes the full seismic response of a horizontally stratified medium. Subject to the restriction of horizontal layers, the reflectivity algorithm provides a computationally efficient approach to examining the influence of a wide range of model parameters. We have analysed the effects of basalt velocity, thickness, burial depth, layering, and *Q* factor. The recording geometry and model parameters are relevant to current petroleum exploration in the Denison Trough. A detailed discussion of the many models considered is given in Battig (2000). Here we show a few representative examples and report the main conclusions.

In this paper we will not list detailed parameters of all models referred to. However, as an indication, Table 1 lists the parameters for our reference model, which is broadly designed on typical basalt-free lithologies from the Denison Trough. The quality factor (*Q*) estimates are from VSP analyses, discussed further below. Other models are developed from this reference.

Layer	*Thickness* (m)	V_P (m/s)	V_S (m/s)	ρ (g/cc)	Q_P	Q_S
1	5	1500	860	1.92	200	100
2	130	2200	1270	2.12	200	100
3	150	2400	1385	2.17	200	100
4	200	2800	1615	2.23	200	100
5	300	3200	1850	2.33	200	100
6	600	4000	2310	2.46	200	100
7	700	5500	3170	2.67	200	100

Table 1: Reference model parameters.

Figure 1 shows the vertical component synthetic shot record corresponding to the reference model. The basalt-free model results in a relatively noise-free record, and a number of reflection events are visible.

In the Denison Trough basalts can be outcropping or buried, thick or thin, and single or multilayered. P-wave velocities typically span the range 3000 m/s to 4500 m/s. Most noise problems are found to occur for higher velocity basalts, which provide greater contrasts on reflecting boundaries. We now illustrate the effect of some of these variations, by adding basalt features to the basic reference model and examining the corresponding shot records.

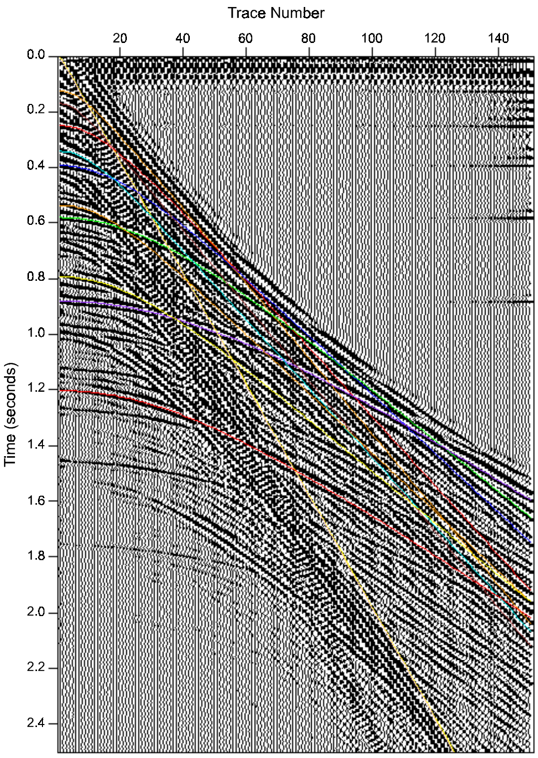

Figure 1. Vertical component shot record corresponding to the reference model in Table 1. The far offset is 4.5 km, and a shallow explosive source is used. The coloured overlays are theoretical travel-time curves used during the study for event identification. Examples are: dark blue - P reflection base Layer 4, green - P reflection base Layer 5, yellow - PS conversion base Layer 5, purple - P reflection base Layer 6, red - PS conversion base Layer 6. Numerical noise is visible at the top and top-right of the record.

Near-Surface Basalt Models

The noise generated in near-surface basalt depends on the attenuation properties of the basalt. Figure 2 shows the synthetic obtained when a near-surface high-velocity basalt layer (V_P = 3750 m/s, V_S = 2170 m/s, ρ = 2.5 g/cc, thickness = 50 m, depth = 4 m) is added to the reference model. In this case the basalt has been assigned a *Q* factor equal to that in the sediments (Q_P = 200, Q_S = 100). The record exhibits much more coherent noise than for the basalt-free model (Figure 1). It is, however, likely that the basalts in the Denison trough are considerably more attenuative than the surrounding sediments. By spectral-ratio and pulse- broadening analyses of VSP data, Battig (2000) found that *Q* values in the basalt layers were an order of magnitude lower than in the surrounding sediments, consistent with similar *Q* analyses carried out on basalts elsewhere (Tompkins and Christensen , 1999; Pujol and Smithson, 1991).

Figure 3 shows the synthetic corresponding to the case of a highly attenuative basalt. The horizontally propagating noise associated with the basalt has now been heavily attenuated. This analysis suggests that near-surface basalts are not likely to generate noise problems, provided they are reasonably attenuative. This appears to be case in the Denison Trough.

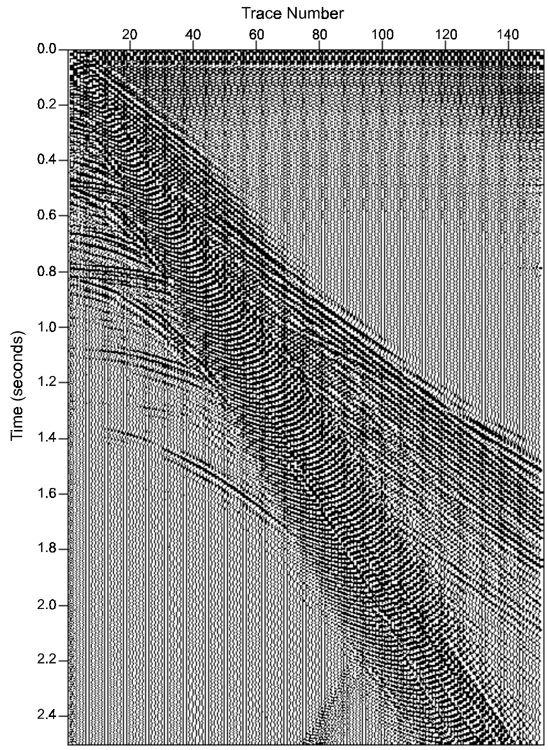

Figure 2. Shot record after addition of a near-surface basalt layer (V_P = 3750 m/s, V_S = 2170 m/s, ρ = 2.5 g/cc, thickness = 50 m, depth = 4 m, Q_P = 200, Q_S = 100) to the reference model.

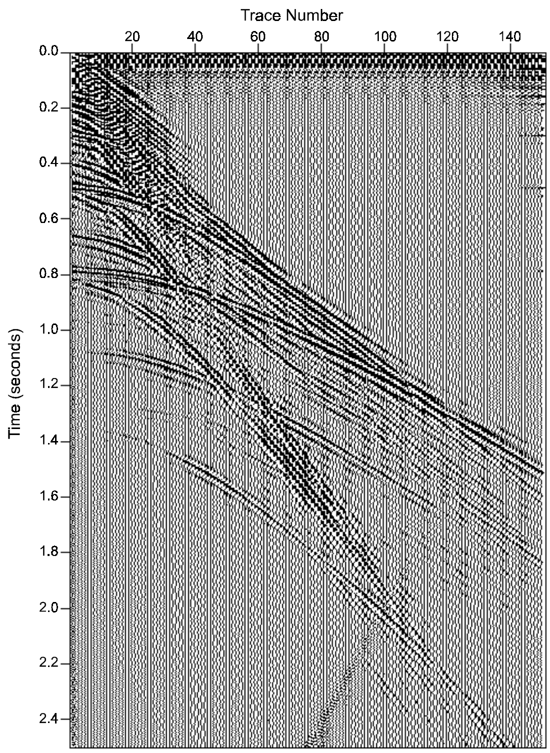

Figure 3. Shot record after addition of a low-*Q*, near-surface basalt layer (V_P = 3750 m/s, V_S = 2170 m/s, ρ = 2.5 g/cc, thickness = 50 m, depth = 4 m, Q_P = 20, Q_S = 10) **to the reference model.**

Buried Basalt Models

For the synthetic of Figure 4 , the reference model has been modified with a buried high-velocity basalt layer (V_P = 4500 m/s, V_S = 2600 m/s, ρ = 2.29 g/cc, thickness = 80m, depth = 50m). The refractions off the top of basalt (e.g. around Trace 40, Time = 0.4 s) exhibit character typical of real field records. Strong reverberatory noise obscures much of the reflection energy, particularly at shorter offsets. Since we have again assumed a highly attenuative basalt, it appears that this strong coherent noise must be propagating in the zone above the basalt. The good contrast provided by the high-velocity basalt provides an effective waveguide between surface and basalt. Although not shown here, our modelling suggests that similar wave-guide noise problems are to be expected in the case of multilayered basalts interspersed with lower-velocity layers.

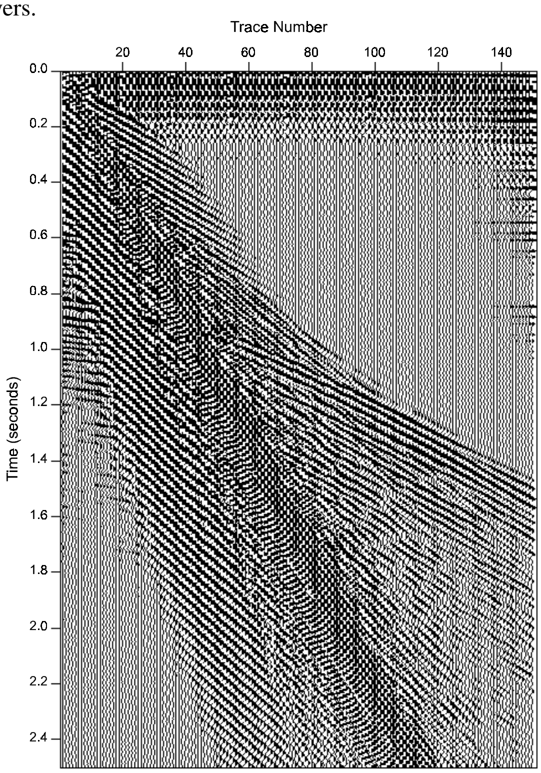

Figure 4. Shot record for a buried high-velocity basalt layer (V_p = 4500 m/s, V_s = 2600 m/s, ρ = 2.54 g/cc, thickness = 80m, depth = 55m). A shallow explosive source is used.

Our tests suggest that positioning the source within the basalt layer does not significantly reduce reverberatory noise. However, marked improvement is seen if the source is below the basalt. Figure 5 shows the synthetic for the same model as in Figure 4 (high-velocity buried basalt) but with a sub-basalt source. The dramatic improvement in record quality indicates that the reverberatory noise is predominantly source generated. That is, the upgoing waves do not appear to generate significant reverberations in the zone between surface and basalt. A real example of the improvement in record quality achieved by using a sub-basalt source has been given by Peters and Hearn (2001) in the context of Bowen Basin coal reflection.

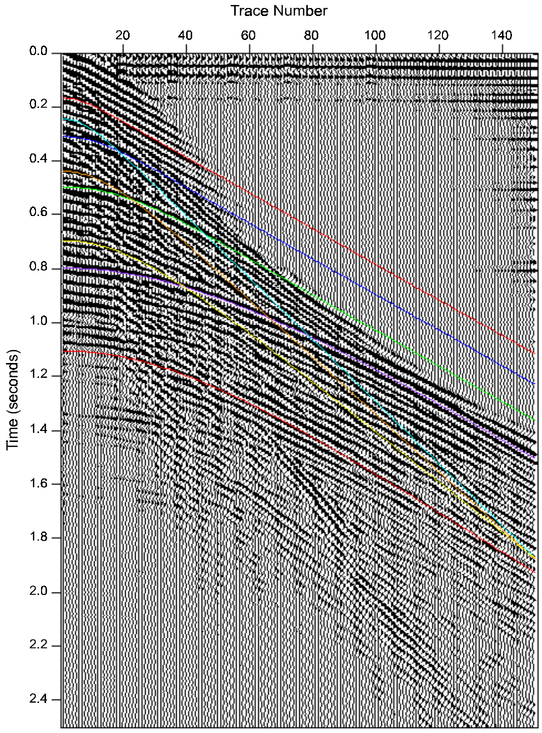

Figure 5. Shot record for the same high-velocity basalt model as for Figure 4, but with the explosive source placed below the basalt.

FINITE-DIFFERENCE MODELLING

Reflectivity is an excellent approach to modelling in situations where lateral continuity is a realistic assumption. Finite-difference modelling (e.g. Kelly et al., 1976) requires significantly more computation, but can handle models of any complexity. We have used the SUFDMOD2 program from the Seismic Unix package. This is an acoustic finite-difference algorithm using explicit second-order differencing. Note that in contrast to the reflectivity algorithm, this does not account for mode conversions or anelastic attenuation. In the context of the above discussion, this latter point is something of a limitation for basalt modelling. However, subject to these restrictions, useful deductions can still be made.

Here we show one example which continues the analysis of the more problematic buried basalts. A numerical seismic survey was shot across the model of Figure 6, which includes three isolated, buried-basalt bodies of different depth extents. Figure 7 shows one field record for a shot point at 2370m (near the left-hand edge of basalt body *C*). Field records of such complexity are not uncommon in the Denison Trough. The right half of the record exhibits strong refractions propagating along the top of the basalt, as well as later guided reverberatory energy. The influence of basalt *B* is seen to the left of the shot, as a displacement of the first arrivals, as well as reverberatory and diffraction noise later in the record. The thin body *A* has minimal affect on this record. Figure 8 shows a simple stack obtained across this model. The disruptions in the reflections underneath basalt *A* are in fact caused by wide-angle traces travelling through basalt *B*. (These distortions are not seen on a short-offset stack.) The deeper reflectors have been imaged beneath basalt B by undershooting with wide-angle traces (no image on a short- offset stack), although the thick basalt causes significant pull-up. The image beneath the thinner basalt *C* is predominantly due to rays travelling through the body (similar quality is seen on a short-offset stack).

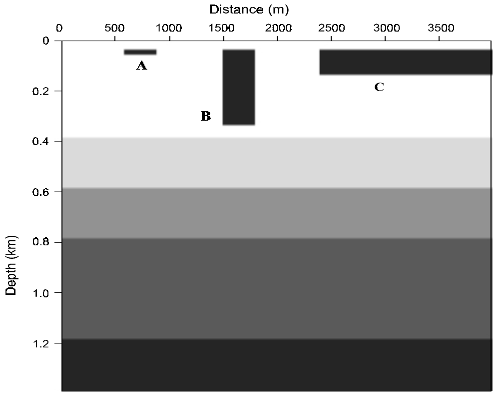

Figure 6. Buried-basalt model used in finite-difference modelling. The basalt P velocity is 4500 m/s. The background model has layer velocities of 1500 m/s, 2000 m/s, 3000 m/s ,3750 m/s and 4500 m/s, top to bottom.

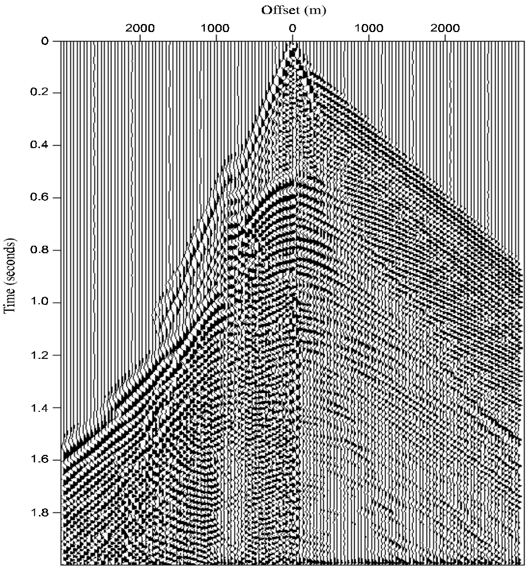

Figure 7. Finite-difference record corresponding to a shot point at 2370 m in Figure 6 (near left edge of basalt C) .

CONCLUSIONS

Reflectivity modelling based on Denison Trough geology suggests that significant reverberatory noise is to be expected from high-velocity buried basalts, associated with the wave-guide between the surface and basalt. Similar waveguide effects are expected in multi-layered basalts. Near-surface basalts should be less problematic, provided they are reasonably attenuative. Noise is reduced if the source is positioned beneath the basalt layer, consistent with practical experience. Finite-difference modelling is an effective tool for predicting effects of basalt bodies of arbitrary shape and size. Finite-difference shot records exhibit features commonly seen on real data, and the resultant stacks assist in the understanding of such concepts as ray-path distortion, basalt undershooting and velocity pull-up.

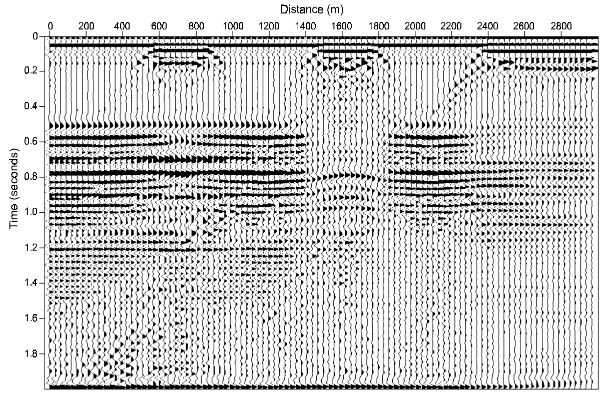

Figure 8. Simple stacked section produced from finite-difference shot records generated every 30m across the model in Figure 6. The primary reflectors from Figure 6 occur in the range 0.5 s to 1.2 s. No multiple attenuation has been applied.

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