Maximising the lateral resolution of near-surface seismic refraction methods*

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Abstract. The tau-p inversion algorithm is widely employed to generate starting models with most computer programs, which implement refraction tomography. This algorithm emphasises the vertical resolution of many layers, and as a result, it frequently fails to detect even large lateral variations in seismic velocities, such as the decreases which are indicative of shear zones. This study demonstrates the failure of the tau-p inversion algorithm to detect or define a major shear zone which is 50 m or 10 stations wide. Furthermore, the majority of refraction tomography programs parameterise the seismic velocities within each layer with vertical velocity gradients.

By contrast, the Generalized Reciprocal Method (GRM) inversion algorithms emphasise the lateral resolution of individual layers. This study demonstrates the successful detection and definition of the 50 m wide shear zone with the GRM inversion algorithms. The existence of the shear zone is confirmed by a 2D analysis of the head wave amplitudes and by numerous closely spaced orthogonal seismic profiles carried out as part of a later 3D refraction investigation. Furthermore, an analysis of the shot record amplitudes indicates that a reversal in the seismic velocities, rather than vertical velocity gradients, occurs in the weathered layers.

The major conclusion reached in this study is that while all seismic refraction operations should aim to provide as accurate depth estimates as is practical, those which emphasise the lateral resolution of individual layers generate more useful results for geotechnical and environmental applications. The advantages of the improved lateral resolution are obtained with 2D traverses in which the structural features can be recognised from the magnitudes of the variations in the seismic velocities. Furthermore, the spatial patterns obtained with 3D investigations facilitate the recognition of structural features such as faults which do not display any intrinsic variation or ‘signature’ in seismic velocities.

Key words: GRM, near-surface, RCS, resolution, seismic refraction, 2D, 3D.

Introduction

Limitations of tomography with 1D inversion algorithms

In recent years, refraction tomography (Zhu et al., 1992; Stefani, 1995; Lanz et al., 1998; Zhang and Toksöz, 1998), also known as tomographic inversion, has been widely employed to process near-surface seismic refraction data. Refraction tomography is one example of model-based inversion, in which an initial starting model is systematically updated through iteratively comparing the modelled response with the field data. Frequently, it is possible to obtain consistency between the data and a wide range of quite disparate starting models. It is now generally recognised that non-uniqueness is a fundamental reality with the inversion of virtually all sets of geophysical data (Oldenburg, 1984; Treitel and Lines, 1988), including near-surface seismic refraction data (Ivanov et al., 2005a, 2005b). The most common source of non-uniqueness is the choice of the inversion algorithm used to generate the starting model.

The 1D tau-p algorithm (Barton and Barker, 2003), is the default in virtually all refraction tomography programs, because it is commonly considered that this algorithm can achieve automatic parameterisation of the traveltimes graphs into the various layers. The parameterisation of the traveltimes graphs is often considered to be a major source of uncertainty in the processing of seismic refraction data.

The tau-p algorithm emphasises the vertical resolution of many layers, which in most refraction tomography programs, are parameterised with vertical velocity gradients. However, virtually any standard velocity function can be fitted to most traveltime data with acceptable accuracy (Hagedoorn, 1955; Palmer, 1986, pp. 169–175; Palmer, 1992), because the arrivals used to derive the seismic velocities in each layer usually propagate within only a relatively thin section of the upper part of each layer. Less than 30% of the upper section of each layer is usually sampled (Palmer, 1986), with reasonable vertical velocity gradients in which the increases are less than a few metres per second per metre.

This incomplete sampling is the major reason for the well known undetected layer problem, whereby layers, which are below a minimum thickness in relation to the seismic velocities of the surrounding layers, are not detected as first arrivals. Palmer (1986, pp. 124–129), using the analysis of Merrick et al. (1978), demonstrates that the number of undetected layers is more significant than the seismic velocities within those layers.

The hyperbolic velocity function (Slichter, 1932; Healy, 1963; Berry, 1971; Aki and Richards, 2002, p. 422), represents the limiting case in which the maximum vertical velocity gradient, or equivalently, a multiplicity of undetected layers can exist in the region above the main refractor. As a result, traveltime graphs consisting of linear segments can represent either constant...
velocity layering or vertical hyperbolic velocity gradients. The most common result of model parameterisation with vertical velocity gradients is that the depth to the main refractor is increased, often by ~50%.

Figure 1 illustrates the ambiguity. Although the ray paths suggest complete sampling of the first layer, the reality is that the traveltime graph represents signals which only propagate along the upper region of the first layer, and which therefore, have minimal sampling of that layer.

Frequently, ray path coverage diagrams are presented as a validation of the outputs of refraction tomography. However, such ray path trajectories are an inevitable consequence of the vertical velocity function selected to represent each layer, rather than the true seismic velocities in the subsurface. Minimal penetration occurs where constant velocity layering is employed. Alternatively, complete sampling of the layer can occur where vertical velocity gradients are used, as is shown in Figure 1. Because the fundamental task of determining a unique vertical velocity function in each layer is not achievable from the traveltime data alone, it follows that it is not possible to derive a true or unique ray path coverage for each layer. Accordingly, it can be concluded that, being *circulus in probando*, ray path coverage diagrams can be of very limited usefulness in validating the results, in most cases.

Another major short coming with the majority of refraction tomography programs which employ the tau-p algorithm is the failure of the algorithm to detect large lateral changes which are representative of shear zones with low seismic velocities. This study demonstrates this deficiency with a major shear zone which is 50 m wide. However, even larger shear zones in excess of 100 m wide, such as that at Welcome Reef (Palmer, 1980) are not detected with the tau-p algorithm (Palmer, 2007). Since the detection of shear zones of any size is an important objective of most seismic refraction surveys carried for geotechnical, environmental or groundwater investigations, it can be concluded that the inability of the tau-p algorithm to define or even to detect major shear zones indicates that it is unsuitable for the great majority of near-surface applications.

### The 2D inversion algorithms of the reciprocal methods

Alternative inversion algorithms include the 2D algorithms of Hagiwara’s method (Hagiwara and Omote, 1939), the ABC method (Nettleton, 1940), the plus-minus method (Hagedoorn, 1959) and the conventional reciprocal method (CRM) (Hawkins, 1961), all of which are mathematically identical, and the generalized reciprocal method (GRM) (Palmer, 1980, 1986, 2006; Palmer et al., 2005). The CRM is a special case of the GRM in which the XY separation in equations 1 and 3 is zero.

While the CRM and the GRM generate much the same time structure model of the refractor (see Figure 12), and therefore, similar depth models, the use of the GRM is indicated where detailed lateral variations in the seismic velocities in the refractor are required. Commonly, the CRM generates artefacts in the seismic velocities where there are irregular (2D) refractors (Palmer, 1986, pp. 63–66; Palmer et al., 2005).

The major objective of this study is to demonstrate that processing seismic refraction data with the 2D GRM inversion algorithms that emphasise lateral resolution, generates more useful results than the 1D inversion algorithms that emphasise vertical resolution. This approach is consistent with the observation that most refracted seismic energy propagates in a predominantly horizontal direction, rather than a predominantly vertical direction as is the case with reflected seismic energy. Furthermore, this approach is supported by the fact that the unique parameterisation of the layering in terms of constant seismic velocities, vertical velocity gradients or velocity reversals is not possible using the traveltimes from those layers.

In addition to the use of traveltime data, this study also employs the head wave amplitudes and the refraction convolution section (RCS) (Palmer, 2001a, 2001b; de Franco, 2005; Palmer and Jones, 2005; Palmer and Shadlow, 2008), in order to extract additional useful information from the field data. The derivation of additional parameters with which to characterise the regolith can promote more effective application of near-surface seismic refraction operations, many of which have exhibited only quite modest innovation in more than half a century (Palmer, 2008).

### The GRM inversion algorithms

The GRM employs two inversion algorithms.

The first, the refractor velocity analysis function $t_V$ (Palmer, 1980, equation 2; Palmer, 1986, equation 8.1), is shown in equation 1, where $t_{FY}$ is the traveltime between the forward shot point at F and the receiver at Y, $t_{RX}$ is the traveltime between the reverse shot point at R and the receiver at X, and $t_{FR}$ is the reciprocal time between the two shot points:

$$t_V = \frac{(t_{FY} - t_{RX}) + t_{FR}}{2}. \quad (1)$$

Equation 1 is illustrated schematically in Figure 2, in which traveltimes that are added are shown as solid lines, those that are subtracted are shown as open lines, and both are shown as broken lines where they cancel. Where detailed lateral resolution of seismic velocities is required, equation 1 is evaluated for a range of XY separations between the reverse and forward receiver positions, and is referenced to the position G, where $XG = YG$.

From Figure 2, it can be seen that equation 1 reduces to approximately the traveltime from the shot point at F to a point in the refractor below the reference point G. Therefore, the gradient

![Fig. 1. Traveltime graphs and ray paths for a hyperbolic vertical velocity gradient in the upper layer.](image-url)
of the line(s) fitted to the points computed with equation 1, using
equation 2, are a measure of the seismic velocity in the refractor,

\[
\frac{d}{dx} t_V = \frac{1}{V_{\text{refractor}}} = \frac{1}{V_n}. \tag{2}
\]

The second is the time model algorithm \( t_G \) (Palmer, 1980,
equation 10; Palmer, 1986, equation 8.6) which provides a
measure of the depth to the refracting interface in units of
time, and which is shown in equation 3:

\[
t_G = \frac{1}{2} \left( t_{FY} + t_{RX} - \left( t_{FR} + \frac{XY}{V_n} \right) \right). \tag{3}
\]

The term \( \frac{XY}{V_n} \), represents the additional traveltime in the
refractor between the stations at \( X \) and \( Y \). This term is
approximated with the difference in the refractor velocity
analysis function in equation 1, which has been averaged over
a range of \( XY \) values, i.e.,

\[
\frac{XY}{V_n} = t_V(Y) - t_V(X). \tag{4}
\]

Equation 3 is illustrated in Figure 3. It shows that the GRM time
model is the average of the reverse delay time at \( X \) and the forward
delay time at \( Y \).

The time model is related to the thicknesses \( Z_i \), and the seismic
velocities \( V_i \), of each layer in the weathering with equation 5,

\[
t_G = \sum_{i=1}^{n-1} Z_i \sqrt{\frac{V_n^2 - V_i^2}{V_n V_i}}. \tag{5}
\]

In many cases however, it is not possible to define all layers
within the weathering because of large station spacings, as
frequently occurs with reflection surveys for deep targets, or
velocity reversals, as frequently occurs in arid and semi-arid
regions. In such circumstances, the multiplicity of layers in
Equation 5 can often be replaced with a single layer of total

\[
Z_G = t_G \frac{V_n V}{V_n^2 - V^2}. \tag{6}
\]

A unique feature of the GRM is the computation of an average
vertical seismic velocity in the weathering where an optimum \( XY \) value can be recovered from the refractor velocity analysis
function, as shown in equation 7 (Palmer, 1980, equation 27;
Palmer, 1986, equation 10.4). The optimum \( XY \) value is selected
where the seismic velocity model is the simplest, that is, the
extreme lateral variations are minimised.

\[
V = \sqrt{\frac{XY_{\text{optimum}} V_n^2}{XY_{\text{optimum}} V_n + 2 t_G V_n}}. \tag{7}
\]

The Mt Bulga case study

The data used in this study were recorded at Mt Bulga, which is
located near Orange in south-eastern Australia, and which is the
site of a small massive sulphide ore body in steeply dipping
to vertical Silurian meta-sediments. The site underwent extensive
investigation several decades ago, and much of the exploration
program is summarised in Whiteley (1986), who also recorded
numerous seismic refraction profiles at the site.

The 2D seismic profile described in this study (Palmer, 2001a,
2001b), was recorded by the author as part of an undergraduate
goephsics students’ field tutorial at the site in the 1980s. A 48
channel seismic recorder and a 5 m receiver spacing were used.
The profile is located some distance away from the ore body on
relatively flat ground in the vicinity of the now-demolished core
shed. Nine shot points, nominally 60 m apart, were recorded.

The traveltime data, which are presented in Figure 4, show that
three layers can be recognised. They are a surface soil layer with a
seismic velocity of 300–500 m/s, a weathered layer with a seismic
velocity of ~1000–1200 m/s for which the upward concave graphs
suggest cycle skipping, and in turn, the occurrence of a velocity
reversal, and a main refractor at the base of the weathering with a
seismic velocity of ~2500–6000 m/s. The traveltime graphs for shot
points 1, 13, 85, and 97 represent arrivals from the base of the
weathering, and since they are very irregular, they suggest that 2D
rather than 1D inversion algorithms would be more useful.

Approximately 1 year later, a 3D refraction survey was
recorded at the same location using the same 48 channel seismic
recorder, in order to study azimuthal anisotropy associated with
the shear zone (Palmer, 2001c). The 3D survey consisted of two separate receiver setups.

The first used two lines of 24 receivers at a 5 m spacing, which were parallel to, and located ~10 m either side of the earlier 2D survey. The in-line station numbers of these two in-lines correspond with those of the 2D profile. Five shot points, 60 m apart, were located along each line. Another four oblique shot points offset 60 m from the end of each line of receivers in the in-line direction and offset 60 m in the cross-line direction were also recorded, making a total of 14 shot points.

The second setup used a series of seven parallel cross-lines which were 20 m apart, and each of which consisted of 12 receivers at a 5 m spacing. The centre of each cross-line coincided with the earlier 2D profile. There were four shot points nominally 60 m apart on each cross-line. These lines were recorded in groups of four by simply rolling through from one end to the other. A total of 27 shot points were recorded in the cross-line direction.

High resolution refractor velocity analysis

An objective methodology

In the standard application of the GRM, a single velocity model—the so-called optimum—is derived first through visually determining the simplest of the refractor velocity analysis functions computed with equation 1 for a range of XY separations and then with manual curve fitting for the evaluation of equation 2 over discrete intervals (Palmer, 1991). However, Sjögren’s (2000) critique of the GRM demonstrates the necessity of employing objective approaches for determining seismic velocities. Despite the fact that the mean-minus-T method is mathematically equivalent to the GRM (Sjögren, 2000: p. 825), and that Sjögren’s Figure 4 is identical to Figure 18 in Palmer (1991), apart from some minor smoothing, nevertheless Sjögren achieves a different model of the seismic velocities in the refractor. Sjögren’s (2000) critique demonstrates the significance of the subjectivity in simple curve fitting, rather than his conclusion that the GRM is somehow defective.

In this study, the seismic velocities are obtained with a simple algorithm which computes a reciprocal of the gradient with equation 2 at each station. The aim is to employ an objective methodology for automatically computing a multiplicity of detailed seismic velocity models in the refractor with a range of XY values. Each of these models can be used as starting models for tomographic inversion, if an evaluation of the significance of non-uniqueness is an objective (Palmer, 2007). Equation 8 is the algorithm employed in this study to compute a seismic velocity \( V_s(G) \) at each station \( G \):

\[
V_s(G) = \frac{\Delta x}{t_v(G + \Delta x) - t_v(G - \Delta x)},
\]

where

\[
t_v\left(G + \frac{\Delta x}{2}\right) = \frac{1}{3} \left(t_v(G + \Delta x) + t_v\left(G + \frac{\Delta x}{2}\right) + t_v(G)\right)
\]

and

\[
t_v\left(G - \frac{\Delta x}{2}\right) = \frac{1}{3} \left(t_v(G) + t_v\left(G - \frac{\Delta x}{2}\right) + t_v(G - \Delta x)\right),
\]

and \( \Delta x \) is the station spacing.

Corrections for variations in the soil composition

The traveltimes include minor variations which originate in the surface soil layers and from minor picking errors. These minor variations, which can be correlated with the short wavelength or residual statics corrections in the processing of seismic reflection data (Palmer and Shadlow, 2008), must be removed before the application of equation 8. Otherwise, they can adversely affect the detailed determination of seismic velocities in the base of the weathering. This study employs a smoothing method based on the GRM (Palmer, 2006). The corrections are shown in Figure 5 and average 0.02 ms with a standard deviation of ±0.88 ms.

Figure 6 shows the refractor velocity analysis function computed with equation 1 for \(-20 \leq XY (5 m) \leq 25\) m after one application of the GRM smoothing corrections to the traveltimes from the shot points at stations 1 and 97. The major effect of the application of the smoothing corrections is that the refractor velocity analysis function is more symmetrical about the optimum \( XY \) value, which an inspection indicates is between zero and 5 m. This study will use a value of 2.5 m, which illustrates the resolution of the optimum \( XY \) value to half the trace spacing. Previous studies (Palmer, 2001a, 2001b, 2003) have used a 5 m value.

Although the application of the GRM smoothing corrections has significantly reduced most of the ‘noise’ from the surface soil
layers, it has not completely removed it. As a result, the application of equation 8 results in seismic velocities which are still erratic and unrealistically high, especially between stations 25 and 49. In that region, the seismic velocities in the refractor are ~6000 m/s, and the increments in the refractor velocity analysis function are less than one millisecond per station. As a result, even small errors of the order of a tenth a millisecond in these times can result in large variations in the seismic velocities computed with equation 8. Although another application of the GRM smoothing corrections would reduce these errors, it could also introduce additional smoothing and a possible loss of resolution.

**Averaging the refractor velocity function**

The approach employed in this study is based on the empirical observation that the refractor velocity analysis function is essentially symmetrical about the optimum value (Palmer, 1980, Figure 26), as is shown in Figure 6. Therefore, averaging the refractor velocity analysis function over a range of $XY$ values centred on the optimum, preserves the shape of the graph, while also reducing any small errors through the averaging process.

Figure 7 presents the seismic velocities computed with equation 8 with $\Delta x = 5$ m, averaged over various ranges of $XY$ values which are centred on an $XY$ value of 2.5 m. For small ranges of $XY$ values, the seismic velocities oscillate about an average, which is better defined where the averaging is applied over larger ranges of $XY$ values. Although the averaging over 10 values, which represents $XY$ values from $-20$ m to 25 m, has been selected as providing optimum smoothing, nevertheless, some values are as large as 8000 m/s which are clearly not geologically reasonable.

Figure 8 shows the seismic velocities obtained with the application of equation 8 to the refractor velocity analysis function which has been averaged over the same range of $XY$ values from $-20$ m to 25 m. However, the window $\Delta x$, over which the seismic velocity is computed is not constant, but instead, ranges from 5 m to 50 m. Furthermore, the two times used in equation 8 are averaged over similar windows, with the centre stations also being the same distance apart as the length of the window. A 30 m value has been selected as providing optimum smoothing without undue loss of resolution. For this value, the two times used in equation 8 have been averaged over seven stations or 30 m intervals, the centre stations of which are 30 m apart.

The unusually high values in the vicinity of station 49 correspond with an inferred out-of-plane artefact in Figure 14, as well as low amplitude products in Figure 17 and in turn, high inverted amplitude products in Figure 19. Furthermore, the 3D results in Figure 22, suggest that the region with the high seismic velocity on cross-line 49 is offset from in-line 19, which is the location of the 2D traverse. Therefore, it can be concluded that the high seismic velocities in the vicinity of station 49 are probably the result of out-of-plane side-swipes and/or diffractions.

One reviewer questioned whether the extensive averaging in Figures 7 and 8 had resulted in an effective reduction in resolution. While it is acknowledged that there may be some loss in detail, it is considered that the need for an objective methodology is more important. Furthermore, it will be noted that the GRM wave eikonal traveltime (WET) tomogram in Figure 13 has recovered much of the short spatial wavelength detail that is not present in the considerably smoothed starting model.

An alternative approach is the novel application of the Hilbert transform described in Chopra and Marfurt (2007, pp. 102–105). This algorithm computes an average of the seismic velocities derived over a range of distances $\Delta x$, such as $5$, $10$, $15$, $20$, and $25$, which are centred on the reference station. The results obtained with this range of distances $\Delta x$, for the range $-20 \leq XY \leq 25$, are comparable to those shown in Figure 7 over a similar range of $XY$ values. Figure 10, which is described below, presents the results computed with $5 \leq \Delta x \leq 30$, for a range of $XY$ values from $-2.5$ to 7.5 m, using averaging windows of nine or 10 $XY$ values.

The development of simple reciprocal gradient operators is the subject of ongoing research. Experience with other sets of data has shown that the averaging achieved with that shown in Figure 7 with equation 8 is generally adequate (e.g. Palmer, 2007,
Figure 4). Nevertheless, further averaging such as that shown in Figure 8, or the Hilbert transform can be employed where the data indicates that it can be useful.

**Determination of the optimum XY value**

The averaging operation can be readily extended to other, non-optimum XY values with the same aim of preserving the shape of the graph, while simultaneously, minimising any noise. Figure 9 presents the seismic velocities in the refractor computed for a range of XY values from –2.5 to 7.5 m, using averaging windows of nine or 10 XY values. Note that the effective XY value is taken as the average of the two extreme values of the range. The seismic velocities are smoothly varying and as a result, the determination of the most probable model of the seismic velocities and the optimum XY value(s) are more convenient than is possible with the graphs in Figures 6 or 7.

Where plane layering is appropriate, equation 1 essentially determines the traveltime from the shot point to a position below the reference point G in equation 1, as is indicated in Figure 2. In Figure 9, the regions at either ends of the traverse and between stations 50 and 60 show much the same values, indicating that plane layering is a reasonable approximation and that the seismic velocities can be determined reasonably accurately. However, that approximation is not valid elsewhere, such as in the vicinity of station 40 where there is a large change in depth as is shown in Figure 13, and as a result, there can be some uncertainty in the determination of the true seismic velocities.

Nevertheless, the total traveltime through the refractor in the vicinity of station 40 remains the same. Therefore, if a low seismic velocity is assigned to one narrow region, then a high value must be assigned to an adjacent region, in order to preserve the total traveltime though the combined regions. For example, if a low seismic velocity is assigned to the region between stations 32 and 40, then a high value must be assigned to the region between stations 40 and 49, as is shown with XY = –2.5 m in Figure 9.

The optimum XY value is selected where the seismic velocity model is the simplest, that is, the extreme lateral variations are minimised. In the vicinity of station 40, the optimum XY value is 2.5 m. Figure 9 shows that the seismic velocities range from 2700 m/s to 6200 m/s.

As described above, the Hilbert transform has also been trialed. Figure 10 presents the results computed with 5 ≤ Δx(5) ≤ 30, for an effective range of XY values from –2.5 to 7.5 m, using averaging windows of nine or 10 XY values. While the determination of the optimum XY value requires more care than is the case with Figure 9, nevertheless a value is 2.5 m can still be recovered. Also, there is more variability in the seismic velocities, which addresses the reservations by one of the reviewers for the loss of resolution, although there are minor concerns that the seismic velocities may be unrealistically high in the vicinity of stations 40 and 49.

**Tomographic solutions**

**Inversion with the tau-p algorithm**

Figure 11 presents the starting model generated with the tau-p algorithm and the tomogram obtained with WET tomography (Schuster and Quintus-Bosz, 1993) through its implementation with the refraction tomography program RAYFRACT. The close similarity between the starting model and the final WET tomogram emphasises the significance of the inversion algorithm used to generate the starting model. The errors are presented in Table 1.

The tau-p tomogram does not demonstrate the existence of any low velocity shear zones. The seismic velocities in the lowest layers are greater than 4000 m/s for the entire traverse and there are no regions with seismic velocities which would be indicative of shear zones. The region between stations 40 and 50 is interpreted as a local increase in the depth of weathering and not as a shear zone because the seismic velocity in the lower part of the tomogram is still 4000 m/s or higher.

**Inversion with the GRM algorithms**

Figure 12 presents the GRM time model for a range of XY values, using the traveltimes which have been corrected for minor variations in the surface soil layers and picking errors and equation 3. As stated previously, there is minimal variation in the time models for a wide range of XY values.

The time structure is converted to a depth model using equation 6, using a seismic velocity of 1000 m/s in the weathering, and a smoothed version of the seismic velocities in the sub-weathering, shown in Figure 9. The depth cross section was first gridded in SURFER with a kriging algorithm, and then used as a starting model for WET inversion with RAYFRACT, and is shown in Figure 13. In this study, the default settings were

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**Fig. 9.** The seismic velocities computed over a range of windows of nine or 10 XY values and centred on XY values for the range –2.5 ≤ XY (2.5 m) ≤ 7.5.

**Fig. 10.** The seismic velocities computed over a range of windows of nine or 10 XY values and centred on XY values for the range –2.5 ≤ XY (2.5 m) ≤ 7.5, using the Hilbert transform with 5 ≤ Δx(5) ≤ 30.
used: no steps were taken to remove any obvious artefacts in the gridded starting model caused by either the gridding or the inversion algorithms. The aim was to assess whether tomography is able to recognise and accommodate artefacts of various types.

Seismic velocities for the starting models for the two intervals between stations 51 and 61, and between stations 69 and 73, where the low seismic velocities occur, are much the same for zero and 5 m $XY$ values as is shown in Figures 8 and 10. Accordingly, the tomogram shown in Figure 13 is similar to that derived with a starting model obtained with a zero as well as a 5 m $XY$ value.

The GRM WET tomogram in Figure 13 shows that two regions in the refractor with low seismic velocities can be recognised between stations 53 and 61, and between stations 68 and 73. These seismic velocities, which are less than 2500 m/s and 40% lower than the lowest seismic velocity in the refractor indicated in the 1D tau-p tomogram in Figure 11, provide very strong evidence for one or more shear zones. Furthermore, the 3D cross-line velocities, shown in Figure 22 below, support the existence of the major shear zone between stations 53 and 61.

By contrast, the tau-p tomogram shows the reverse situation between stations 53 and 61, with an increase in the seismic velocity in the deepest layer together with a decrease in the depth to it.

### Inversion with a velocity reversal

The likely occurrence of velocity reversals is indicated by cycle skipping on the shot records, and it can be recognised with the concave upwards segments in the traveltime graphs in Figure 4. It is supported by a comparison the seismic velocities in the weathering of $\sim$1000 m/s computed from the direct arrivals, with the average vertical velocity of $\sim$450 m/s computed with equation 10 and an optimum $XY$ value of 2.5 m.

Figure 14 shows a tomogram generated by replacing the direct traveltimes with values representative of an average velocity of 500 m/s, in order to accommodate the velocity reversal. This

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**Table 1. Wave eikonal traveltime Tomography Errors.**

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean Unsigned Error (ms)</th>
<th>Relative Misfit Function (ms)</th>
<th>Maximum Unsigned Error (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D tau-p</td>
<td>1.60</td>
<td>2.21</td>
<td>9.16</td>
</tr>
<tr>
<td>GRM $XY = 5$ m</td>
<td>1.24</td>
<td>1.57</td>
<td>8.52</td>
</tr>
<tr>
<td>No Velocity Reversals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRM $XY = 5$ m</td>
<td>3.56</td>
<td>11.58</td>
<td>14.48</td>
</tr>
<tr>
<td>Velocity Reversals</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 11.** The starting model and the wave eikonal traveltime (WET) tomogram obtained with the 1D tau-p inversion algorithm.

**Fig. 12.** The Generalized Reciprocal Method (GRM) time models for the range $-10 \leq XY (5 \, \text{m}) \leq 15$.

**Fig. 13.** The starting model and wave eikonal traveltime (WET) tomogram obtained with the Generalized Reciprocal Method (GRM) inversion algorithms. No account has been taken of the velocity reversal in the weathering.
tomogram still supports the occurrence of a major shear zone between stations 51 and 61. Furthermore, it also indicates the possibility of another narrower low velocity region in the vicinity of station 37. However, the isolated high velocity fragment below station 47, which initially appears to be an artefact, is consistent with this segment being a side-swipe. The orthogonal profiles in Figure 22 support the possibility of a side-swipe.

Figure 14 illustrates some of the benefits of explicitly addressing velocity reversals with lower average vertical velocities. The most obvious is that significantly different geological models, in this case the possibility of another shear zone, can result. Perhaps a more important conclusion is that the use of unrealistically high seismic velocities with vertical gradients can result in a loss of resolution, and in some cases, even a failure to recognise likely out-of-plane events. Furthermore, it demonstrates that 2D refraction tomograms, irrespective of how closely they may fit the traveltime data, do not necessarily generate meaningful results where there are genuine 3D targets.

Velocity reversals are not well accommodated with the majority of refraction tomography programs. The replacement of the observed traveltimes in the overburden with values representative of a velocity reversal, in order to obtain the tomogram in Figure 14, constitutes an elementary, but not necessarily an ideal solution. Figure 14 generally illustrates the importance of determining an accurate parameterisation of the overburden velocities in order to obtain representative depth estimates. In general, the depths shown in Figure 14 are approximately half of those shown in Figure 13, which in turn are approximately half of those shown in Figure 11, in which vertical velocity gradients have been used.

However, detailed conclusions, such as the occurrence of an additional low velocity zone in the refractor in the vicinity of station 37 can be less certain. Often, the 2D analysis of shot amplitudes as shown below, can resolve these ambiguities.

The usefulness of error analyses

Table 1 shows that for comparable settings with RAYFRACT, in this case the default settings of 10 iterations, the GRM results provide more accurate inversion. However, the significance of these errors is questionable. Both the tau-p and the GRM tomograms may contain artefacts, such as the possible out-of-plane events, whereas the errors in the tau-p tomogram can be greatly reduced by simply increasing the number of iterations, without any significant changes in the detail of the final tomogram.

A fundamental tenet of model-based inversion is that the response of the final model should be consistent with the original data. Even though it is of questionable validity, because no account has been taken of lateral variations in refractor velocities, or velocity reversals in the overburden layers, nevertheless the tau-p WET tomogram generated for the Mt Bulga 2D case studies is consistent with the traveltime data. Furthermore, the tomogram which seeks to accommodate the likely velocity reversal has significantly greater errors than the alternatives.

These results demonstrate that simplistic assessments of errors do not necessarily ensure geologically appropriate tomograms, especially where there are velocity reversals. Instead, these results demonstrate that the selection of the inversion algorithm used to generate the starting model, together with appropriate model parameterisation are equally important for effective refraction inversion. In most cases, the final WET tomogram is quite similar to the starting model.

Analyses of head wave amplitudes

Shot record amplitudes

Head wave amplitudes constitute half of the volume of seismic refraction data (the other half being the traveltime data), which are too often overlooked. In many instances, there can be a reluctance to analyse head wave amplitudes because it is considered that there can be significant variations in the coupling, and therefore, significant variations in the outputs between individual receivers. However, Drijkoningen (2000) demonstrates that variations in coupling are generally minimal, whereas Palmer (2006) demonstrates that any short wavelength variations in output are related to variations in the surface soil layers. Irrespective of the source of any variations in output, the application of the GRM smoothing routine (Palmer, 2006) largely removes their effect. The amplitude corrections are shown in Figure 5.

Frequently, an analysis of the gross shot record amplitudes can indicate whether uniform seismic velocities, vertical velocity gradients, or even velocity reversals are appropriate. Figure 15 presents the head wave amplitudes for the offset shot points located at stations 1 and 97. These amplitudes decrease with the source-to-receiver distance and therefore indicate that vertical velocity gradients are not significant in the main refractor. If there were vertical velocity gradients, then the head wave amplitudes would in fact increase with the source-to-receiver distance (Cervený and Ravindra, 1971, p. 242). The short wavelength departures from the geometric spreading, which in this figure is approximated with the reciprocal of the distance cubed, are attributed to local variations in the petrophysical properties of the refractor, and they are examined in a 2D analysis of the amplitudes below in Figure 17.

![Fig. 14. The wave eikonal traveltime tomogram obtained by replacing the measured direct traveltimes with values representative of a velocity reversal with an average seismic velocity of 500 m/s in the weathering.](image-url)
Head wave amplitudes for selected near shot points located within the spread of receivers are presented in Figure 16. They show initially over-scaling of the seismic recorder which is indicative of very high amplitudes, followed by very rapid attenuation, and then the establishment of a second mode of more ‘normal’ amplitude decay with distance. This effect is usually recognised as cycle skipping, also known as shingling, on the shot records, and it is characteristic of velocity reversals (Domzalski, 1956; Whiteley and Greenhalgh, 1979).

This analysis of the shot record amplitudes does not support the default use of vertical velocity gradients shown in Figure 11.

**2D analysis of amplitudes**

In the near field, where most surveys for geotechnical investigations take place, geometrical spreading dominates the observed head wave amplitudes. Palmer (2001a) demonstrates that a 2D analysis of shot amplitudes with the multiplication of the forward and reverse amplitudes effectively compensates for geometrical spreading and that the resulting amplitude products are essentially proportional to the square of the head coefficient, as is shown in Figure 17.

Palmer (2001b) also demonstrates that the head coefficient, which is the refraction analogue of the Zoeppritz transmission coefficient in reflection seismology, is approximately proportional to the ratio of the specific acoustic impedance in the overburden to that in the refractor. Therefore, low seismic velocities in the refractor exhibit high amplitude products, whereas conversely, high seismic velocities in the refractor produce low amplitude products, provided of course that the seismic velocities in the overburden do not exhibit significant lateral variations.

For strong contrasts in seismic velocities, the head coefficient $K$, is given by:

$$K \propto \frac{\rho_1 V_{p1}}{\rho_2 V_{p2}},$$

where $\rho$ and $V_p$ are the density and seismic velocity in a medium.

Since the amplitude product, which has been corrected for near-surface irregularities with the GRM smoothing method (Palmer, 2006), is approximately proportional to the square of the head coefficient, it follows that:

$$V_{p2} \propto \frac{1}{\sqrt{\text{amplitude product}}}.$$ (10)

Accordingly, amplitude products inverted with equation 10 can provide an additional useful attribute which is a measure of seismic velocities.

However, for the detailed attribute analysis of head wave amplitudes, it is necessary to more accurately compensate for the residual geometric spreading component, in addition to the use of the product of the forward and reverse values. Although the geometric spreading is widely assumed to vary as the reciprocal of the distance squared, that function is only applicable after the signal has travelled several wavelengths and is in the far field. In the near field, the geometric component can be considerably larger. Because the great majority of seismic refraction surveys for geotechnical investigations take place in the near field, it is not uncommon to obtain geometric spreading functions which are quite different to the far field approximations, as is shown in Figure 15.

Figure 18 presents the square root of the reciprocal of the scaled amplitude products which have been corrected with the GRM smoothing method (see Figure 5) and which have had the geometric component applied using a range of exponents. As a result, the vertical scale correlates approximately with the seismic velocities in the refractor. In this study, an exponent of six has been judged to have effectively eliminated the residual geometric component.
Figure 19 shows the seismic velocities computed at each station with equation 8 and the reciprocal of the square root of amplitude product, which has been corrected for the residual geometric spreading, using a distance to the sixth power function. The correlation between the seismic velocities and the processed amplitudes is generally very good. Figure 19 does not support the occurrence of an additional low velocity zone in the refractor in the vicinity of station 37. It might be noted that the very large inverted amplitude at station 49 correlates with a probable out-of-plane arrival, as is suggested by Figure 14, and with a high seismic velocity in Figure 10.

The determination of a representative exponent for the geometric spreading is necessary only with the analysis of single fold data and single receiver spreads. With multi-fold data, the inversion routine automatically compensates for both variations in the source parameters and the geometric spreading (Palmer, 2009).

The refraction convolution section

The RCS is generated by the convolution of pairs of individual forward and reverse traces. The convolution operation adds traveltimes and multiplies amplitudes, and hence generates the same time structural model of the refractor as that obtained with the GRM algorithms. Furthermore, the multiplication of the amplitudes largely compensates for the geometrical spreading component, with the result that the RCS amplitudes are approximately proportional to the square of the head coefficient.

Figure 20 shows the RCS generated from the shot records for the offset shot points located at stations 1 and 97 for the Mt Bulga profile, together with the GRM time model superimposed. Figure 20 demonstrates that the time model generated with the RCS is consistent with the time model generated with GRM, and that the amplitudes of the RCS first arrivals are consistent with the results shown in Figure 17.

A major advantage of the RCS is that it facilitates the application of the suite of techniques, generally known as attribute analysis (Chopra and Marfurt, 2007) to near-surface seismic refraction data. The spectral analysis of the RCS in Figure 21, shows that the region in the sub-weathering between stations 51 and 61 with the low seismic velocity, has significantly attenuated the high-frequency components. This reduction in the high-frequency response is consistent with increased fracturing and a reduction in mechanical rigidity in the shear zone.

There is also a smaller reduction in the high-frequency content in the vicinity of station 37. This region also corresponds with lower seismic velocities in Figures 9 and 10, much lower seismic velocities in Figure 14, and an increase in depths of weathering in Figure 13. This region of the sub-weathering may represent low to moderate levels of fracturing but not necessarily to the extent characteristic of a shear zone. However, the combined attributes of increased depths of weathering, lower seismic velocities and reduced high-frequency response indicate that this region may be anomalous, and that it might possibly warrant further exploration, depending on the objectives of any site investigation program. By contrast, there is no indication of any comparable variations in the sub-weathering in the tau-p tomogram in Figure 11.

The major focus of this study has been on the detection and delineation of the major shear zone between stations 51 and 61. Such features are not common at most sites and more often it is...
necessary to define less extreme variations, such as those in the vicinity of station 37. This study demonstrates that the application of detailed attributes derived with the GRM and the RCS can significantly improve the resolution and reliability of routine geotechnical site characterisation with near-surface seismic refraction methods.

Extensions to 3D

The 3D refraction survey was carried out some time after the 2D traverse in order to study azimuthal anisotropy (Palmer, 2001c). The 2D traverse corresponds with in-line 19, whereas the in-line station numbers are essentially the same for both surveys.

Figure 22 shows the seismic velocities in the base of the weathering derived from the seven cross lines and confirms the existence of the low velocity shear zone, along virtually all of cross-lines 53, 57, and 61. Figure 22 adds two additional items of major geological significance.

Although the survey was oriented so that the in-lines would be orthogonal to the known shear zone and the dominant strike direction of the local geological structure, which was inferred to be north–south, the 3D results show that the true strike is closer to NW–SE. A common observation with numerous petroleum exploration and production case studies has been that 3D results can show a rotation of 45°, and even up to 90°, in the dominant strike direction of the faulting, as well as a change from a few faults with large strike lengths to many faults with smaller strike lengths, when compared with coincident 2D results (Ruijtenberg et al., 1992, Figure 2).

Furthermore, there are several significant ENE-striking cross-cutting structures, which are indicated by the lateral changes in the seismic velocities in the refractor. These ENE structures are not readily detectable on any single profile with any orientation, because they do not exhibit the same distinctive low seismic velocity signatures as the major NW–SE shear zone.

Figure 23 presents the cross-line corrected amplitude products processed to reflect seismic velocities with equation 10. This figure is a little more complex, probably because the seismic velocities in the weathered layer vary laterally. Nevertheless, the NW–SE strike of the shear zone can still be recognised, as can the ENE structures. Furthermore, the high amplitude effect previously recognised at station 49 of the 2D traverse can also be seen on cross-line 49 near the intersection with in-line 19.

Discussion

The Mt Bulga and other case studies are compelling demonstrations of the fundamental non-uniqueness of all near-surface refraction inversion. Unless specific measures are taken to address non-uniqueness, the production of a single refraction tomogram which fits the traveltme data to sufficient accuracy does not necessarily demonstrate that the result is correct, or even, the most probable.

The tau-p inversion algorithm is currently used as the default for generating starting models with most refraction tomography programs. However, the Mt Bulga and other case studies demonstrate that the tau-p algorithm is unable to detect even major low velocity shear zones in excess of 10 stations in width, and that 2D rather than 1D inversion algorithms are required where the detailed lateral resolution of seismic velocities in refractors is a primary objective.

In those cases where the reality of non-uniqueness is recognised, the most common approach is to employ a priori information to narrow the range of some model parameters. Normally, only borehole data or other geophysical datasets are considered as suitable a priori information. Unfortunately, such a priori data are commonly not available for geotechnical and environmental investigations in reconnaissance surveys. However, head wave amplitudes, which constitute a major proportion of the refraction data, provide an immediately accessible source of a priori data, which are too often overlooked.

Although it is usually not possible to uniquely parameterise the inversion model in terms of constant velocities, vertical velocity gradients, or velocity reversals using the traveltme data for each layer, the analysis of head wave amplitudes in the shot records can usefully resolve many of these ambiguities. Most refraction tomography programs parameterise the model with vertical velocity gradients, which can result in an over-estimate of depths, and in turn, a loss of resolution in the definition of irregular (2D) refractors as well as a failure to recognise or accommodate out-of-plane (3D) refractors. In this study, both the head wave amplitudes and the GRM average vertical velocity indicate that velocity reversals in the weathering are more

![Fig. 21](image1.png) Spectral analysis of the refraction convolution section generated with SP1 and SP97.

![Fig. 22](image2.png) The seismic velocities computed in the sub-weathering with the Generalized Reciprocal Method for the seven cross-lines 45, 49, 53, 57, 61, 65 and 69.

![Fig. 23](image3.png) The inverted amplitude products for the seven cross-lines 45, 49, 53, 57, 61, 65 and 69.
appropriate at the Mt Bulga site. The 2D analysis of head wave amplitudes can often confirm lateral variations of seismic velocities within individual refractors, such as the sub-weathering layer.

The major advantage of using head wave amplitudes is that the amplitudes and traveltimes are different components of the same seismic signal, and therefore they relate to the same layers and interfaces, and to the same petrophysical property of seismic velocity. Consistency between amplitudes and traveltimes constitutes internal consistency within the seismic data, and it relates to the reliability of the inversion process.

There is a widespread expectation that refraction tomography can significantly improve the resolution of the final result, that is, refraction tomography can reveal features that are not apparent in either the traveltime data or the starting model. However, the close similarity between both starting models used in this study and the respective final WET tomograms demonstrates the importance of the inversion algorithm used to generate the starting model. The tau-p tomogram demonstrates that if the gross lateral variations in the seismic velocity in the main refractor are not included in the starting model, then it is unlikely that they will be generated by the tomographic inversion process. Furthermore, the lateral resolution achieved with the final GRM WET tomogram in Figure 13 in the main refractor is consistent with the resolution in Figures 9 and 10 for an XY value of 2.5 m, and it is significantly better than the heavily smoothed starting model. Therefore, it can be concluded that the gross or long wavelength lateral resolution of the final tomogram is usually comparable to that of the starting model, but that refraction tomography can improve the detailed or short wavelength resolution of the final tomogram.

The emphasis on lateral resolution can be readily extended to full trace processing with the RCS. A major benefit of the RCS is that it conveniently incorporates amplitudes and the time structure model of the refractor within a single presentation. Furthermore, the RCS is ideally suited to the application of the wide range of techniques for post-processing seismic reflection data, generally known as attribute analysis (Chopra and Marfurt, 2007). In fact, the methods for deriving detailed lateral variations in refractor velocities described in this study can be viewed as elementary adaptations of attribute analysis. This study demonstrates that even fundamental processes such as an analysis of frequency content can generate results which usefully contribute to the overall geotechnical model.

The derivation of more detailed geotechnical models of the regolith with innovative methods of data analysis is more effective with data acquired with multi-fold roll-through operations rather than with static receiver spreads. At the present time, most near-surface seismic refraction surveys for environmental or geotechnical applications are carried out by in-house personnel, often with in-house equipment. Frequently, these operations are under-capitalised with inadequate channel counts, and inefficient source procedures (Palmer, 2008). The data acquired with these operations are not well suited to detailed or innovative processing, such as the generation of stacked RCS, and commonly, automatic processing with refraction tomography which requires only minimal technical proficiency, is employed. These operations represent an emphasis on minimal or low cost data acquisition which produces low resolution conventional results, rather than on specialist geotechnical services. The development of detailed and innovative methods of data processing and interpretation will require many geotechnical organisations to determine whether their core business is data acquisition and conventional processing or whether it is specialist geotechnical services.

Conclusions

This study is a compelling demonstration that 2D inversion algorithms which emphasise lateral resolution, provide more useful geotechnical models than 1D algorithms which emphasise vertical resolution. The shear zone at Mt Bulga is a major geological feature. It is 50 m wide and represents 10 station intervals, whereas the seismic velocity of 2500 m/s provides a large contrast with the surrounding meta-sediments in which the seismic velocity is ~6000 m/s.

The 2D GRM inversion algorithm detected both the major shear zone in the 2D profile, as well as several ENE cross-cutting structures that did not exhibit comparable contrasts in the seismic velocities, in the 3D set of data. The existence of the shear zone is supported both by the 2D analysis of the head wave amplitudes, a frequency analysis of the RCS and numerous orthogonal profiles recorded as part of the later 3D survey.

By contrast, the shear zone is neither resolved nor even detected with the tau-p inversion algorithm. It can be concluded that the tau-p inversion algorithm generates low resolution tomograms which are unsuited to the great majority of geotechnical and environmental investigations.

The major conclusion which can be reached with this study is that the acquisition and processing of near-surface refraction seismology should aim to maximise the superior lateral resolution of the refraction method. While it is acknowledged that all seismic refraction operations should aim to provide as accurate depth estimates as is practical, the fact that the refracted signal propagates predominantly in the horizontal direction in a narrow region near the top of a limited number of layers, indicates that lateral resolution is more readily achievable than vertical resolution. Nevertheless, one somewhat paradoxical outcome of the emphasis on lateral resolution is the determination of average vertical velocities above irregular refractors with the GRM.

With an emphasis on lateral resolution, it follows that 3D refraction methods should be more widely adopted as a matter of some importance. The Mt Bulga case study demonstrates that 3D refraction methods can determine of rock fabric with azimuthal anisotropy (Palmer, 2001c), and in turn, fracture porosity, in addition to the accurate definition and orientation of major structures with lateral velocity signatures, such as the NW–SE shear zone, as well as structures without lateral velocity expressions, such as the ENE faults. It is concluded that the development of 3D near-surface seismic refraction methods can significantly advance geotechnical and environmental site characterisation.

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浅層屈折法地震探査における水平解像度の最大化

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要旨: さまざまなインパーソナル・アルゴリズムは屈折波トモグラフィーのプログラムの初期モデルを作るのに広く使われている。このようなアルゴリズムは多層構造の垂直方向の解像度向上を主眼にしているので、剪断波で見られる速度の減少などの大きな速度の速度変化でも検知されないことがある。この論文では、さまざまなインパーソナル・アルゴリズムでは50m（10点）の幅を持つ大きな剪断波が検知できないことを実証する。さらに、屈折波トモグラフィーのプログラムの多くは各層間の速度を、垂直方向の速度勾配としてしか表象しない。

対照的に Generalised Reciprocal Method (GRM)インパーソナルでは、水平方向の解像度を強調する。本論文では、同じ50m幅の剪断波が GRM インパーソナル・アルゴリズムで検知・確定できるものを報告する。ヘッドウェーブ振幅の二次元解析と、のちに三次元屈折法探査の一部として実施された直交する高密度なサイスミックプロファイリングにより、剪断波が確認された。さらにショット記録の振幅解析によると、風化層中の速度は垂直方向の単調に増加しており、速度逆転(高速度層の下に低速度層がある)が存在していることが示された。この研究の主な結論は、屈折法探査は実用的な範囲でできるだけ正確な深度推定を目的にしているが、土木地質や環境への適用という観点では各層の水平方向の解像度を強調した断面のほうが有益な結果をもたらすということである。水平方向の解像度の改善は、地震波速度の変化の大きさによって構造の特徴が認識される二次元のトラバース測深によって得られる。さらに、三次元調査によって得られる空間的パターンは、地震波速度に特異的な変化をもたらすことのない断層のような構造の確認を容易にする。

キーワード : 屈折法, 浅層調査, 分解能, 二次元, 三次元, GRM, RCS

前部 乾燥ば 古教 ばの 水平 解像 ばの 最大 化

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要約: 円形波ニコープループを構成するの大部分のコンピュータープログラムはタワッフル・アラニン・アルゴリズムを用いることにより、地質プロファイルを自動的に生成する。タワッフル・アラニン・アルゴリズムは、解像度の向上を目指すために、静電応答の解像度を向上させるために組み立てた。本研究では、タワッフル・アラニン・アルゴリズムは、地震波の極大値を用いた、2次元の解析プログラムで解析される。これにより、ソースの位置が、円形波インパーソナルが発生する地域を知ることができる。さらに、ソースの位置が、円形波インパーソナルが発生する地域を知ることができる。