Characterizing the Near-Surface with Common Offset Seismic Refraction Attributes

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Abstract

Refraction attributes can be readily computed from multi-fold seismic data using the standard algorithms of the generalized reciprocal method (GRM), a common offset refraction (COR) modification of the GRM, and the refraction convolution section (RCS). A seismic attributes is any measure that helps to better visualize or quantify features of interest in seismic data.

The accuracy of the time model attribute derived with the COR GRM algorithm is comparable to that computed with the standard multi-fold GRM model. However, the COR GRM seismic velocity model is a smoothed version of the standard GRM model.

The refraction attributes computed from the head wave amplitudes include the multi-fold head coefficient, and a COR equivalent with the amplitude product. Although the COR amplitude product for each offset is of comparable accuracy to the multi-fold head coefficient, it also includes a residual geometric spreading component. The geometric spreading coefficient, which is generally assumed to be two, varies from less than one to up to four.
The attribute derived from the RCS is bandwidth in octaves.

The COR GRM algorithms are applied prior to the parameterization of the traveltime data into individual layers. The COR GRM presentations facilitate the efficient quality control and interpretation of large sets of multi-fold data. Furthermore, the algorithms can be applied to single ended refraction data, which are recorded with marine and land streamers.

The regolith can be characterized with the refraction attributes of seismic velocity and RCS spectra, as well as the combined attributes of scaled density ratio and P-wave modulus. The seismic attributes can be employed as starting models for traveltime or full waveform inversion, or integrated with borehole and other geophysical data, using multivariate geostatistics. The larger suite of refraction attributes can facilitate more comprehensive characterization of the near-surface for exploration and natural resource management.

**Key words:** seismic, refraction, attributes, GRM, RCS, COR

### Introduction

**Characterizing the regolith**

The regolith is the surficial blanket of material including weathered rock, sediments, soils and biota that forms by the natural processes of weathering, erosion, transport and deposition. It has complex architecture and may vary in thickness from a few centimetres to hundreds of metres. It hosts or hides valuable mineral deposits, we live on it, we grow our food in it, it is the foundation of many major engineering works, and much of our water supplies are stored in it. It underpins our economic, social and infrastructure systems.

The regolith occurs everywhere. Modern regolith processes are principally climate-controlled, except in areas with active tectonics. Thus similar weathering processes occur at similar latitudes, such as in North America, Europe and Russia, and in South
America, Southern Africa and Australia. The regolith may be modified by
geologically recent events such as large-scale glaciation in North America, Europe,
and Russia, or desertification in North Africa and Middle East. In Australia,
prolonged deep weathering over the last 10 to 250 million years, on a predominantly
stable continent of antiquity, has created a unique regolith.

Regolith architecture and the processes that act within it, have important applications
in the fields of exploration and natural resource management. Existing models have
largely been built around surface mapping and a range of airborne geophysical
techniques including hyperspectral, radiometric, magnetic and electromagnetic
methods. Bore hole datasets have also been employed, but are often limited in
spatial coverage, while seismic methods are considerably less common.

**Refraction attributes**

In the standard approach to the inversion of near-surface seismic refraction data,
usually only the traveltimes are inverted to produce a model of the seismic velocities.
The thickness of the weathered layer can be important in many geoscientific
investigations, such as statics corrections for processing seismic reflection data,
while seismic velocity is often used as a measure of rock strength for geotechnical
site characterization.

The regolith can be characterized with a more comprehensive suite of refraction
attributes, using models of both the standard attribute of seismic velocity, as well as
various combinations to derive models of the scaled density ratio and the P-wave
modulus. A seismic attribute is any measure that helps to better visualize or quantify
features of interest in seismic data (Chopra and Marfurt, 2007).

The major objective of this study is to extend the methods for deriving refraction
attributes from the relatively small volumes of data that are characteristic of many
gеotechnical investigations (Palmer, 2010c, 2010d), to the considerably larger
volumes of multi-fold common midpoint (CMP) seismic reflection data, that are
routinely recorded for petroleum and mineral exploration. The refraction attributes
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are computed from the head wave traveltimes, amplitudes and full waveforms using novel adaptations of the generalized reciprocal method (GRM) (Palmer, 1981, 2009b, 2010a), for deriving common offset refraction (COR) attributes with multi-fold data, in addition to the standard GRM algorithms and the refraction convolution section (RCS) (Palmer, 2001a, 2001b, 2009a).

Three major roles for COR refraction attributes are proposed. They are (i) detailed starting models for tomographic inversion, (ii) detailed characterization of the near surface, and (iii) the quality control and parameterization of large sets of data, irrespective of the method of inversion.

Refraction attributes can be used to derive detailed starting models for either traveltime or full waveform inversion. Generally, the final traveltime tomogram is very similar to the starting model Palmer (2010a, 2010b, 2010e). Therefore, if detailed refraction tomograms are the objective, then detailed starting models are required. This study demonstrates that the refraction tomograms obtained with starting models derived with the standard GRM, the COR GRM, and the COR GRM which includes velocity gradients in the weathering, are considerably more detailed than those generated with smooth vertical velocity gradients, which are the default starting model with many standard implementations of refraction tomography.

This study also demonstrates that reductions in the spatial resolution of refraction tomograms can result from even moderate numbers of iterations of the inversion routine to quite detailed starting models. It provides further confirmation that refraction tomography is essentially a smoothing process which rarely, if ever, improves the spatial resolution of the starting model. Since they frequently exhibit considerably better spatial resolution than the model-based inverted results, it is concluded that refraction attributes constitute useful parameters in their own right with which to characterize the near surface, especially where geostatistical methods are employed.

Finally, refraction attributes can facilitate the efficient quality control and parameterization of large sets of multi-fold seismic refraction data, irrespective of whether the method of refraction inversion employs traveltimes or full waveforms.
Refraction attributes can be especially useful in confirming whether vertical velocity gradients occur in the near surface.

**Backus-Gilbert appraisal**

Much of the current theory on the inversion of geophysical data had its genesis with the three landmark publications of Backus and Gilbert (1967, 1968, 1970). They showed that linear inverse problems can have either a single unique solution or infinitely many solutions. In the latter case, Backus and Gilbert (1967, 1968) showed that it is possible to generate linear combinations of the data, which represent unique averages of the model. This process is known as appraisal, whereas model-based inversion, such as refraction tomography, is known as construction.

The GRM inversion algorithms constitute a version of Backus-Gilbert appraisal, because they consist of simple linear combinations of the traveltime data. Few, if any, other geophysical methods share this unique and fortuitous coincidence. Accordingly, the GRM traveltime and amplitude attributes (which have been linearized with logarithms), are unique and useful parameters with which to both characterize the near surface, and to monitor the quality of any subsequent inversion processes, whether using traveltimes or full waveforms.

The methodology is applied to regional seismic reflection data recorded across part of the Palaeozoic Lachlan Fold Belt in south-eastern Australia (Jones and Drummond, 2001). The analysis focuses predominantly on the Wirrinya traverse 99WR-HR1, which is ~17 km in length and which was recorded with 240-channel split spreads using 10 m bunched receivers along the eastern portion of line 99AGS-L1. Where appropriate, these results are compared with those computed along line 99AGS-L1, which is ~47 km in length, and which was acquired with 40 m end-to-end arrays consisting of twelve receivers. Stations 1076 to 2776 on line 99WR-HR1 correspond with stations 1000 to 1425 on line 99AGS-L1.

**Common Offset Seismic Refraction Methods**
COR GRM time models

Common offset seismic sections have been usefully employed in the processing of seismic reflection data (Fulton and Darr, 1984). While they have also been employed to a lesser extent with the processing of seismic refraction data (Coppens, 1985), their wider application has yet to be fully exploited. This study employs common offset refraction (COR) GRM methods to generate additional useful sets of attributes with which to characterize the regolith.

The COR GRM time model algorithm, which is shown in equation (1), using the symbols in Figure 1, is essentially the same as the standard GRM version. The difference is that only a single value is computed with each source separation for the receiver midway between the two sources, that is $FG = GR$.

$$t_G = \frac{1}{2}(t_{FG} + t_{RG} - t_{FR})$$ (1)

With most high fold CMP data, it is possible to average all traveltimes, such as the traveltime from the source at F to the receiver at G, with the traveltime from the source at G to the receiver at F. To a reasonable approximation, this use of reciprocity can accommodate the effects of extended receiver arrays and any offsets or uncertainties in the source location, as can often occur with surface sources. Furthermore, the application of reciprocity in this study successfully accommodates the crooked line geometry, including two sections which are 220 and 500 metres in length and which have 90° changes in azimuth (Palmer, 2009a, Figure 1). Finally, the COR GRM time model algorithm generates useful results with single ended data, as is usually acquired with marine and land streamers.
Figure 2 presents a histogram of the COR GRM time model for source separations from the minimum of 20 m up to the maximum of 1200 m in increments of 20 m, that is, in multiples of twice the station spacing. For the small source separations of 20 m and 40 m, the time model is representative of the surface soil layers. Between stations 1075 and 1900, Tertiary alluvium occurs, and a time model of approximately 10 ms, computed with a source separation of 40 m, is appropriate. Between stations 1900 and 2775, weathered Palaeozoic metasediments occur, and a time model of approximately 5 ms computed with source separations of 20 m and 40 m, is appropriate.

As the source separation increases, the traveltimes are representative of deeper refractors, such as the sub-weathered zone. However, there is an intermediate source range where the traveltimes are from different layers and the computed values are meaningless because they are intermediate between the true time models of the different layers. They are recognized as the uncorrelated low count values in Figure 2.

The clustered time model values, which range from approximately 10 ms to 75 ms, are representative of the base of the weathering, and have been computed with source separations greater than approximately 260 m. These values exhibit very little variation, with the average standard deviation being less than 2 ms at each station. With the increasing source separation, there is an increase in the depth of investigation. Figure 2 demonstrates that lateral changes in the time model are more significant than any vertical changes caused by vertical velocity gradients in the sub-weathered zone. Alternatively, any vertical velocity gradient would represent a
change in depth to the base of the weathering of less than 4 m (less than ±2 ms at an average seismic velocity of ~1000 m/s in the weathering).

Figure 3 presents the multi-fold short wavelength GRM time model (Palmer, 2009a, Figure 2) and the COR GRM time model which has been averaged over the range of source separations of $300 \text{ m} \leq \Delta VP(20 \text{ m}) \leq 1200 \text{ m}$. The average difference is 1.4 ms and the standard deviation is 1.2 ms. Figure 3 demonstrates that the COR GRM time model is usually sufficiently accurate for most applications of the seismic refraction method, such as statics corrections for seismic reflection data.

Figure 4 presents a COR GRM time model generated from data recorded in an arid region of North Africa. It demonstrates that several interfaces can be detected, including a thin surface layer at approximately 10 ms, the base of the weathering at approximately 50 ms, and a carbonate reservoir at approximately 250 ms. The arrivals from the base of the weathering, which indicate a large sand dune near station 1250, exhibit considerable scattering characteristic of cycle skipping. Figures 2 and 4 demonstrate the usefulness of the COR GRM time model for rapidly and conveniently assessing the large volumes of data characteristic of multi-fold seismic...
data, prior to their parameterization into the various layers and subsequent processing or inversion.

**COR GRM seismic velocities**

The COR GRM refractor velocity analysis algorithm, which is shown in equation (2) using the symbols in Figure 5, employs a novel four-term modification of the standard GRM velocity analysis algorithm. As with the COR GRM time model algorithm, *only a single value* is computed with each source separation for the receiver midway between the four source locations.

\[
V(G) = \frac{2BC}{\left(t_{BC} + t_{AD} - t_{CD} - t_{AB}\right)} \text{ where } AB = BC = CD
\]  

(2)

Like the COR GRM time model, the accuracy of individual times can be improved through averaging with the appropriate reciprocal values. Furthermore, the algorithm is also effective with single ended traveltime data. In contrast to the COR GRM time model algorithm however, the COR GRM velocity analysis algorithm is computed with a total source separation AD which increases in increments of three times the station spacing.
Figure 6 presents a histogram of all the single fold COR GRM refractor velocity function for total source separations from 30 m to 1200 m. An alternative presentation of the COR GRM seismic velocities, which shows the individual values computed with each source separation (Palmer, 2009a, Figure 9), indicates that the seismic velocity in the weathered layer is approximately 1000 m/s.

As the source separation is increased, eventually the traveltimes are representative of the sub-weathered zone. However, there is an intermediate range where the arrivals are from different layers, and the computed seismic velocities are meaningless, because they are intermediate between the true seismic velocities. These values are recognized by the low counts in Figure 6.

With the increasing source separation, there is an increase in the depth of investigation. The range of source separations from 600 to 1200 m in Figure 6 demonstrates that the seismic velocities are approximately 5000 m/s in the sub-weathered zone, and that lateral changes in the seismic velocities are more significant than any vertical velocity gradients. In fact, most of the variation at each station can be attributed to the greater averaging or smoothing with the larger source separations. Figure 6 shows that the base of the weathering occurs where the seismic velocities are within approximately ±200 m/s of the mode, which is ~5000 m/s. The abnormally high values in the vicinity of stations 1800 and 2100 are caused by 90° changes in azimuth (Palmer, 2009a, Figure 1).
Figure 7 compares the averaged COR GRM refractor velocities with the seismic velocities computed with the standard GRM velocity analysis algorithm over a 1 km section of the traverse. In general, the two sets of seismic velocities are comparable. Nevertheless, the COR GRM seismic velocities exhibit significantly less spatial resolution, as would be anticipated with their computation over considerable larger intervals of the refractor. (The extreme seismic velocities of ~10,000 m/s near station 1630 computed with the standard GRM algorithms are attributed to out-of-plane side swipes.)

The average wavelength of lateral variations in the COR GRM seismic velocities is approximately 550 m. This distance is still greater than the maximum interval of 400 m over which the seismic velocity is averaged with the maximum source separation of 1200 m. Accordingly, it can be concluded that the lateral variations are still largely representative of the subsurface geology even though they may lack the spatial resolution achievable with the standard GRM refractor velocity analysis algorithm.

Figure 8 presents the COR GRM seismic velocities from the traverse in North Africa. The seismic velocities which can be recognized are ~800 m/s in the weathered layer, ~2,500 m/s for the sub-weathered zone and ~4000 m/s for the carbonate reservoir.

**Seismic Velocities in the Weathering**

Figure 9 presents four models of the seismic velocities in the weathered layer. The first model of seismic velocities has been computed with the COR GRM algorithm.
using a source separation of 60 m (Figure 6). The second model of seismic velocities has been computed from the differences in the traveltimes over a distance of 20 m for the receivers which are two and four stations from the source. To a reasonable approximation, this approach compensates for the usual uncertainties in source location and offset. These two models of the seismic velocities employ the traveltimes which have propagated within the weathered layer only.

The third and fourth models of seismic velocities have been computed with the GRM average vertical velocity (Palmer, 2009b, Equation A7), which employs the optimum XY value, the time model of the base of the weathered layer (Figure 3) and the seismic velocity in the subweathered zone: **No traveltimes through the weathered layer are used.** Using a presentation similar to that in Figure 10 below, it can be shown that the optimum XY value systematically varies from ~20 m over the Tertiary alluvium between stations 1075 and 1900, to ~10 m over the weathered Palaeozoic metasediments between stations 1900 and 2775. The seismic velocities computed with this laterally varying optimum XY value are consistent with those obtained with the first two methods which use the traveltimes through the weathered layer. This consistency indicates that vertical velocity gradients are not significant in the weathered layer.

However, with a great majority of seismic surveys acquired for deep exploration targets, the station spacing is frequently too large to compute seismic velocities either directly from traveltimes which propagate through the weathered layer, as is shown with the first two methods above, or from detailed optimum XY values, as is...
shown with the third method. The alternatives include special weathering and uphole surveys.

Nevertheless, the fourth model of seismic velocities computed with the GRM average vertical velocity in Figure 9 demonstrates that useful seismic velocities can still be derived with an approximate optimum XY value, in this case, 20 m. Figure 10 presents the seismic velocities computed with the standard GRM algorithms applied to the Lachlan data acquired with 40 m arrays for the interval which corresponds with stations 1596 to 1716 for the Wirrinya traverse. An optimum XY of ~20 m can be recognized clearly in Figure 10.

It can be concluded that where the base of the weathering is sufficiently irregular to facilitate the determination of either detailed or approximate optimum XY values, then the computation of average vertical velocities with the GRM can be useful. However, where the base of the weathering is reasonably featureless, then the interpolation of widely spaced seismic velocities derived with either uphole or weathering surveys can be an acceptable alternative.

**Tomographic Inversion of Velocity Models**

**Smooth vertical velocity gradient starting model**

The traveltime data, which were acquired with 10 m and sometimes 20 m source separations, were edited to a uniform 20 m source interval for tomographic inversion. This operation reduced the number of traveltimes from ~305,000 to ~195,000.
Nevertheless, each model still required more than two days to process through twenty iterations. By comparison, most sets of data for geotechnical investigations consist of less than one thousand traveltimes and require only a few minutes for the same number of iterations.

![Figure 11](image)

Figure 11 presents the smooth vertical velocity gradient starting model and wavepath eikonal travelt ime (WET) (Schuster and Quintus-Bosz, 1993) tomogram. This starting model, which is the default with most implementations of refraction tomography, emphasizes the vertical resolution of many layers, whereas the inversion algorithms of the GRM emphasize the lateral resolution of individual layers. The RMS misfit error is 10.98 milliseconds after twenty iterations.

It is not a straight forward task to identify the base of the weathering. The usual approach is to select the region where the largest vertical gradients in the seismic velocities occur. However, the seismic velocities essentially increase monotonically with depth and it is difficult to identify any distinctive regions with converging contours. Figure 6 indicates that the region in the vicinity of the 4000 m/s to 5000 m/s contours is a reasonable approximation.

The WET tomogram in Figure 11 does not exhibit many lateral changes in the seismic velocities in the sub-weathering. Apart from the artifacts caused by 90° changes in azimuth at stations 1800 and 2100, the only other obvious changes are between stations 2400 and 2774.
Standard GRM starting model

Figure 12 presents the three GRM-based starting models. Figure 13 presents the three corresponding WET tomograms, obtained after five iterations.

The top image in Figure 13 presents the WET tomogram derived from the starting model which uses the seismic velocities in the sub-weathering derived with the standard GRM, using a 15 m XY value, the seismic velocities in the weathering shown in Figure 9, and the time model shown in Figure 3. The RMS misfit error is 7.32 ms after five iterations and 6.86 ms after twenty iterations.

There are few ambiguities in recognizing the base of the weathering. There is a large increase in seismic velocities over a change in depth of approximately five metres, which is consistent with the estimated variation in depths, due to increasing source-to-receiver offsets. It contrasts with the difficulties with the WET tomogram generated from the smooth vertical velocity gradient starting model in Figure 11.
The application of WET tomography has smoothed the seismic velocities in the sub-weathering. Although there does appear to be some reduction in spatial resolution with WET tomography, nevertheless, the spatial resolution of the GRM WET tomogram is still better than that for the COR GRM WET tomogram. This result is consistent with smaller average wavelength of 150 m for the GRM starting model.

**COR GRM starting model**

The centre image in Figure 13 presents the WET tomogram derived from the starting model which uses the seismic velocities in the sub-weathering computed with the COR GRM averaged over the range $480 \, \text{m} \leq \Delta V_P(30) \leq 1200 \, \text{m}$, the seismic velocities in the weathering shown in Figure 9, and the time model shown in Figure 3. The RMS misfit error is 7.32 milliseconds after five iterations.

As with the standard GRM WET tomogram, there are few ambiguities in recognizing the base of the weathering. Both the standard GRM and the COR GRM WET tomograms in Figure 13 indicate significant thicknesses of the regolith at stations 1300, 1950 and 2450 where the elevated topography and the occurrence of limited “outcrop” might indicate otherwise.
The application of WET tomography has smoothed the seismic velocities in the sub-weathering. However, the wavelength remains much the same as the starting model, indicating that the spatial resolution has not been reduced significantly. The lower resolution COR GRM seismic velocities in the sub-weathering would be adequate for most reflection statics applications (Palmer, 2009c). As with other studies, there are very few significant visual differences between the WET tomograms and the GRM starting models.

**Hyperbolic velocity function**

The hyperbolic velocity function (Slichter, 1932; Healy, 1963; Berry, 1971; Aki and Richards, 2002, p.422) is the maximum vertical velocity gradient which is consistent with linear traveltime graphs. In the absence of either a priori information, such as the GRM average vertical velocity in Figure 9, or a posteriori information, such as uphole surveys, sonic logs or borehole tomography, the hyperbolic velocity model is a more useful measure of uncertainty than either simplistic comparison of misfit errors or standard descriptions of the undetected layer problem (Merrick et al, 1978), except where velocity reversals occur (Palmer, 2010a). It generates the *maximum* depth model which is consistent with the traveltime data.

The hyperbolic model has been included for completeness, even though Figures 6 and 9 indicate that vertical velocity gradients in the weathering are unlikely on this profile. Figure 12 shows the starting model obtained by approximating the seismic velocities in the weathering with the hyperbolic velocity equivalents, together with the COR GRM model of the seismic velocities in the sub-weathering. It effectively represents a combination of the starting model in Figure 11 with the top image in Figure 12, and demonstrates that the GRM and vertical velocity gradients are not necessarily mutually exclusive as stated by Rohdewald et. al. (2010).

The major effect of the incorporation of velocity gradients with the tomogram in Figure 13 (misfit error of 7.23 ms after five iterations), has been to increase the depth to the base of the weathering by ~25% (Palmer, 2010a). Although there is some
uncertainty in recognizing the base of the weathering, that situation is consistent with the use of vertical velocity gradients in the weathering. If vertical velocity gradients are considered to be applicable, then the modeling in the WET tomogram at the bottom of Figure 13 exhibits significantly better resolution and geological verisimilitude than the WET tomogram in Figure 11, which represents the default with standard implementations of refraction tomography.

**Resolution versus misfit errors**

Many implementations of refraction tomography frequently recommend increasing the number of iterations from the default, commonly twenty, to fifty or one hundred, in order to improve resolution and reduce artifacts, even if the RMS error does not decrease (Rohdewald et al, 2010). Figure 14 confirms that there is minimal significant change in the RMS misfit errors for the standard GRM tomograms after five iterations.

![Figure 14](image)

However, Figure 15 demonstrates that the resolution is systematically reduced after five iterations. Both the spatial resolution of seismic velocities in the sub-weathering is reduced and the width of the transition between the weathering and sub-weathering is increased with more iterations. Other studies with smaller volumes of data (Palmer, submitted) demonstrate that the tomograms generated after one and two hundred iterations are virtually identical to those generated with the smooth vertical velocity gradient starting model, such as that in Figure 11.
Figures 13 and 15 demonstrate that refraction tomography is effectively a smoothing operation which rarely, if ever, improves the spatial resolution of the seismic velocities in the sub-weathering. This study employs the GRM-based WET tomograms generated after only five iterations because they represent the optimum compromise between maximizing resolution and minimizing misfit errors.

Common Offset Amplitude Attributes

COR amplitude products

The standard model of the head wave amplitude for plane homogeneous layers is shown in equation (3), where $A$ is the amplitude, $K$ is the head coefficient, $F(t)$ is the source function, $r$ is the source-to-receiver distance, $\alpha$ is the coefficient of inelastic attenuation, and $n$ is the geometric spreading coefficient which is usually assumed to be 2 in the far field.
\[ A = \frac{KF(t)e^{-\alpha r}}{r^n} \] (3)

Geometrical spreading dominates the observed head wave amplitudes. The shot records for the Wirrinya survey can exhibit more than 60 db variation in amplitudes between the near and far receivers. To a reasonable approximation, the multiplication of the forward and reverse amplitudes largely compensates for geometrical spreading (Palmer, 2001a). In addition, the amplitude product minimizes the effects of any lateral inhomogeneities in the sub-weathered region, in a manner similar to the addition of traveltimes with the time model in equation (1).

The COR amplitude product is computed in a manner analogous to the generation of the COR GRM time model. The COR amplitude product, shown in Figure 16, is presented with a logarithmic scale in order to accommodate the large dynamic range which is a result of the residual geometric spreading. Figure 16 also shows a geometric mean for source separations from 200 m to 1200 m.

Figure 17 presents the relative head coefficients computed with multi-fold inversion of the head wave amplitudes for the 10 m bunched receivers (Palmer, 2009c, Figure 14) and the 40 m arrays, and the mean of the amplitude products for the 10 m bunched receivers. Figure 18 presents a cross plot of the head coefficients computed with the 10 m bunched receivers averaged over 40 m with those for the 40 m arrays. Figures 17 and 18 demonstrate excellent correlation between the relative head coefficients computed with different methods and with different sets of coincident data.
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The major source of “noise” with the relative head coefficient is variations in the surface soil composition, rather than variations in receiver coupling (Palmer, 2006). Figures 17 and 18 demonstrate that the spatial averaging of the 40 m end-to-end arrays effectively minimizes the effects of lateral variations in soil composition and any minor variations due to receiver coupling.

Integrating the seismic velocity and head coefficient

The head coefficient K, which is the refraction analogue of the Zoeppritz transmission coefficient in reflection seismology, can be an extremely useful attribute, because it is a function of the ratios of the seismic velocities and the densities in the weathered and sub-weathered regions. Palmer (2001b) demonstrates that the head coefficient is approximately proportional to the ratio of the specific acoustic impedance in the weathered layer to that in the sub-weathered region, viz.
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\[ K \propto \frac{\rho_1 V_1}{\rho_2 V_2}. \]  \hspace{1cm} (4)

Layer 1 overlies layer 2 while \( \rho \) is density and \( V \) is compressional wave velocity. Palmer (2006, Figure 16), demonstrates that the head coefficient and the seismic velocities can be employed to compute a ratio of the densities in the weathered layer and the sub-weathered zone with equation (5), viz.:

\[ \frac{\rho_2}{\rho_1} \propto \frac{1}{K} \frac{V_1}{V_2}. \]  \hspace{1cm} (5)

Figure 19 presents the scaled density ratio computed with equation (5), using the smoothed head coefficients in Figure 17, the seismic velocities in the weathering shown in Figure 9, and the averaged COR GRM seismic velocities in the sub-weathering, shown in Figure 12. In general, there are increases in the scaled density ratio in the vicinity of elevated topography at stations 1300, 1950 and 2450.

The seismic velocity of P-waves is related to the bulk modulus \( k \), the shear modulus \( \mu \), and the density \( \rho \), in isotropic media (Sheriff and Geldart, 1995, Table 2.2), by:

\[ V = \sqrt{\frac{k + \frac{4}{3} \mu}{\rho}}. \]  \hspace{1cm} (6)

Equations (4) and (6) can be rearranged and generalized to form:
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\[ P - \text{wave modulus} = \rho_2 V_2^2 \propto \frac{1}{K} \rho_1 V_1 V_2 \]  \hspace{1cm} (7)

Figure 20 presents the P-wave modulus in the sub-weathered region in arbitrary units, computed from the seismic velocities in the weathered layer shown in Figure 9, the COR GRM seismic velocities in the sub-weathered region shown in Figure 12, and the head coefficient, shown in Figure 17. Equation (7) suggests that the P-wave modulus, which accommodates the effects of density, is probably a more representative measure of rock strength for geotechnical site characterization than the commonly employed seismic velocity.

![Figure 20](image)

**COR amplitude ratios**

The COR amplitude ratios can be inverted to derive \( \alpha \), the coefficient of inelastic attenuation where the geometric spreading coefficient is assumed to be 2. Alternatively, the COR amplitude ratios can be inverted to derive \( n \), the geometric spreading coefficient where the inelastic attenuation is ignored. Both parameters are shown in Figure 21 for the range \( 600 \text{ m} \leq \Delta VP(30 \text{ m}) \leq 1200 \text{ m} \).

The results in Figure 21 are of questionable significance. The average value of the geometric spreading coefficient is 1.77 and the standard deviation is 0.48, whereas the theoretical value is 2 with plane homogeneous refractors in the far field. One possible explanation is the occurrence of vertical velocity gradients, for which theoretical studies suggest that the geometrical spreading coefficient is less than 2 (Červený and Ravindra, 1971, p.242). However, neither the COR GRM time nor seismic velocity models support this explanation.
Furthermore, the situation is not improved with the alternative computation of $\alpha$, the coefficient of inelastic attenuation, principally because the majority of values are negative. Note that all values of $\alpha$ have been scaled by a factor of 1000 to facilitate the comparison in Figure 21.

The close correlation between the two sets of graphs in Figure 21 indicates that the standard model for the head wave amplitude in equation (3) is inadequate where there are inhomogeneous refractors. Initial observations indicate that large variations in the amplitude ratios correlate with major lateral changes in the seismic velocities in the refractor. Furthermore, there can be a correlation with the GRM time model, as shown in Figure 22. However, no alternative theoretical models are currently available to adequately describe these results.

The significance of amplitude ratios with irregular and inhomogeneous refractors is the subject of ongoing research.
Attributes Derived from the RCS

The RCS is generated by the convolution of individual pairs of forward and reverse traces. The convolution operation adds traveltimes and multiplies amplitudes, and hence generates the same time model of the refractor as that obtained with the time model algorithm of the GRM, as is shown in Figure 23.

![Stacked RCS](image)

Figure 23

The inelastic attenuation through the weathering at each source point and through the sub-weathering is the same for all convolved traces for a given pair of forward and reverse sources. Therefore, any variations in the waveform of the convolved traces can be attributed to variations in the weathered and unweathered regions below each receiver.

Figure 24 shows the spectral analysis of the Wirrinya stacked RCS. The regolith has attenuated much of the high frequency content of the single 12-140 Hz sweeps generated with a single 30 tonne vibrator, with the Tertiary alluvium between stations 1100 and 1900 generally having a greater effect than the weathered Palaeozoic meta-sediments between stations 1900 and 2700. Also, there is a reduction in the low frequency signal over the weathered Palaeozoic meta-sediments.
Figure 25 presents the spectral analysis of the RCS generated over the same interval of the coincident Lachlan traverse using the data recorded with the 40 m arrays and using the same range of source-to-receiver offsets as the Wirrinya traverse. These data were acquired with three in-line 30 tonne vibrators generating three 10 second 6-90 Hz sweeps with a 10 m moveup and a 40 m vibrator point (VP) interval. Figures 24 and 25 exhibit many similarities, such as those between the Tertiary alluvium and the weathered Palaeozoic metasediments, even though there are significant differences between the acquisition parameters for the two sets of data.

Figures 23 and 24 demonstrate the effects of the regolith on the seismic waveform. The region between stations 1500 and 1650 in Figure 24 is of particular interest because the significantly larger high frequency attenuation corresponds with an increase in the depth of the regolith and higher seismic velocities in the sub-weathering. This region may represent more porous unconsolidated Tertiary alluvium and therefore more favourable conditions for groundwater.
The RCS spectra provide a useful attribute for the weathered layer. Frequently, it can be the only attribute in addition to the time model, where the use of large station spacings, which are employed for deep exploration targets, do not facilitate the computation of representative seismic P-wave velocities in the weathered layer.

Discussion

Velocity models and spatial resolution

Figures 11 to 14 demonstrate that the final tomogram is usually very similar to the starting model, and that refraction tomography essentially smoothes rather than improves spatial resolution. Therefore, if a high resolution tomogram is the objective, then it is essential to employ a high resolution starting model.

The WET tomogram derived from the common default starting model consisting of smooth vertical velocity gradients, exhibits minimal spatial resolution of the seismic velocities in the sub-weathering. In addition, there is considerable uncertainty in identifying the base of the weathering. By contrast, the GRM-derived WET tomograms exhibit significantly better spatial resolution of the seismic velocities, there is little ambiguity in identifying the base of the weathering, and the RMS misfit errors are smaller (7.3 ms versus 11.0 ms). Furthermore, the spatial resolution of the standard GRM tomogram using a 15 m XY value is better than that of the COR GRM tomogram.

The COR GRM time and seismic velocity models can provide a convenient method for validating the default use of smooth vertical velocity gradient starting models with many standard implementations of refraction tomography. Although the deep and prolonged weathering along the Wirrinya traverse might suggest that vertical velocity gradients are a reasonable expectation in the sub-weathering, the COR GRM time and seismic velocity models demonstrate that lateral variations in both depth and seismic velocity are more significant than any vertical variations. Nevertheless, the hyperbolic velocity model provides a convenient method of incorporating velocity
gradients with the GRM, in order to provide a complete range of possible models for validation with a posteriori methods.

The GRM average vertical velocity also provides a useful indication of the occurrence or otherwise of vertical velocity gradients, as well as velocity reversals or seismic anisotropy in the weathering. In this study, the good correlation between the horizontal seismic velocities derived from the traveltimes in the weathered layer and the GRM average vertical velocities derived from the traveltimes in the subweathering support the occurrence of reasonably uniform seismic velocities in the weathering.

Furthermore, the GRM inversion algorithms can avoid the generation of velocity artifacts, as often occurs with the use of tau-p (Barton and Barker, 2003) and smooth vertical velocity gradient starting models (Palmer, 2010a, 2010b). These artifacts occur principally because no distinction is made between true seismic velocities and apparent seismic velocities due to dip. This study demonstrates that the COR GRM seismic velocity algorithm overcomes this problem through the use of forward and reverse traveltimes in the inversion algorithm. Accordingly, the COR GRM seismic velocity algorithm can be viewed as a more accurate and a more convenient alternative to the tau-p inversion algorithm.

However, COR GRM seismic velocities can lack the detailed lateral resolution of the standard GRM algorithm, where the seismic velocities in the subweathered zone are quite variable, as occurs with the data used in this study. Accordingly, it is essential to employ the standard GRM algorithms, where detailed resolution of the seismic velocity and P-wave modulus in the subweathered zone are required, as is usually the case with most geotechnical investigations.

Other studies (Palmer, 2009a), demonstrate that the reflection statics corrections, which are computed from the standard GRM time model, are comparable to those derived with standard delay time methods, together with one application of residual statics. Furthermore, the resolution of the COR GRM seismic velocities is usually adequate for routine statics corrections. It can be concluded that the COR GRM time
models and seismic velocities are well suited to the routine computation of reflection statics with multi-fold data.

Density models

Gravity methods, particularly the recently developed airborne gravity gradiometer, are currently enjoying increasing application in mineral and petroleum exploration. The models of the scaled density ratios can be usefully employed in the processing of any coincident gravity data. In those hard rock provinces where regional seismic reflection profiles have been recorded to assist mineral exploration, such as the Lachlan data used in this study, the scaled density profiles can facilitate the derivation of more representative rock densities through their use as starting models for the inversion of any coincident gravity data.

Alternatively, the scaled density profiles can be employed to strip away the gravity effects of the weathered layer, in a manner similar to the application of statics corrections with seismic reflection data, in order to enhance the detectability of any deeper gravity targets. This may be especially useful in many arid regions, because this study shows that significant thicknesses of the regolith can occur where the elevated topography and the occurrence of “outcrop” might indicate otherwise.

In many investigations, the variations in the thickness of the low density weathered layer can mask the response of deeper targets. For example, although the seismic results support a large increase in the density of the massive sulphide ore body at Mt Bulga (Palmer, 2006, 2010d), the gravity anomaly is masked by a corresponding increase in the thickness of the low density weathered layer.

Geotechnical and environmental applications

It is anticipated that the P-wave modulus will prove to be a more representative measure of rock strength for geotechnical site characterization than the commonly employed seismic velocity, because it accommodates the effects of density. In fact, it can be argued that this is self evident, given the validity of equation (7).
The RCS spectra provide another useful attribute for the weathered layer, in addition to the time model. Frequently, it can be the only other attribute which can be computed, where the use of large station spacings, which are routinely employed for deep exploration targets, do not facilitate the derivation of representative P-wave seismic velocities in the weathered layer from the traveltime data.

A prerequisite for the computation of the COR GRM time and amplitude attributes is suitable multi-fold data, such as that routinely recorded for petroleum and mineral exploration. However, the methods described in this study are not readily applicable to most geotechnical and environmental investigations because those data are frequently acquired with static spreads using under-capitalized and inefficient field operations (Palmer, 2008). This study demonstrates the superior characterization of the near surface through the use of suitable multi-fold data acquired with more efficient refraction operations.

Conclusions

Seismic refraction attributes can be readily computed from the traveltimes, amplitudes and full waveforms obtained from multi-fold seismic data, using the standard algorithms of the generalized reciprocal method (GRM), a new common offset refraction (COR) modification of the GRM, and the refraction convolution section (RCS). The time model attribute obtained with the COR GRM algorithm is of comparable accuracy to that computed with the standard multi-fold GRM algorithm, whereas the COR GRM seismic velocity model is a smoothed version of the standard GRM model. Nevertheless, the COR GRM velocity algorithm avoids the generation of artefacts as often occurs with the tau-p algorithm and accordingly, it can be viewed as a more accurate alternative. The amplitude attributes include the multi-fold head coefficient, the COR amplitude product, and the COR amplitude ratio. The attribute derived from the RCS is spectral bandwidth.

The refraction attributes can be usefully employed to generate detailed starting models for traveltime and full waveform inversion of seismic data. The resolution of
the refraction tomograms generated with the standard GRM, the COR GRM, and the COR GRM with vertical velocity gradients is significantly better than that for the tomogram generated with the default starting model consisting of smooth vertical velocity gradients. Furthermore, the misfit errors for the GRM-based tomograms are less.

The GRM-based starting models generated acceptable tomograms after five iterations, whereas the default starting model required twenty iterations. This improved efficiency can be useful, especially where multiple starting models are tested with large volumes of data, as was the case in this study.

There can be significant reductions in the spatial resolution of tomograms generated from even quite detailed starting models with only moderate numbers of iterations of refraction tomography. It provides further confirmation that refraction tomography is essentially a smoothing process which rarely, if ever, improves the spatial resolution of the starting model. Since they frequently exhibit considerably better spatial resolution than the refraction tomograms, it is concluded that refraction attributes constitute useful parameters in their own right with which to characterize the near surface, especially where geostatistical methods are employed.

The COR GRM algorithms can facilitate the efficient quality control and parameterization of large sets of multi-fold data, when applied prior to the inversion of the traveltime data using any method. The refraction attributes can validate the use of vertical velocity gradients, which are often employed as the default starting model with many implementations of refraction tomography.

The refraction attributes of seismic velocity and RCS spectra, as well as the combined attributes of scaled density ratio and P-wave modulus can be employed to characterize the regolith. It is concluded that the larger suite of refraction attributes can facilitate more comprehensive characterization of the near-surface for exploration and natural resource management, especially with multivariate geostatistics.
Acknowledgements

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Characterizing the regolith with refraction attributes

Derecke Palmer

Equations

\[ t_G = \frac{1}{2} \left( t_{FG} + t_{RG} - t_{FR} \right) \]  

\[ V(G) = \frac{2BC}{t_{bc} + t_{bd} - t_{cd}} \text{ where } AB = BC = CD \]  

\[ A = K F(t) e^{-\alpha r} / r^n \]  

\[ K \propto \rho_1 V_1 / \rho_2 V_2. \]  

\[ \frac{\rho_2}{\rho_1} \propto \frac{1}{K} \frac{V_1}{V_2}. \]  

\[ V_p = \sqrt{\frac{k + \frac{4}{3} \mu}{\rho}} \]  

\[ \text{P-wave modulus} = \rho_2 V_2^2 \propto \frac{1}{K} \rho_1 V_1 V_2 \]
Figure Captions

Figure 1: Schematic summary of the ray paths used to compute the common offset refraction (COR) time model.

Figure 2: Histogram of COR GRM time models computed with source separations of $20 \leq VP(20 \text{ m}) \leq 1200 \text{ m}$ for the Wirrina traverse.

Figure 3: Comparison of multi-fold GRM time model and mean COR GRM time model for source separations of $300 \leq VP(20 \text{ m}) \leq 1200 \text{ m}$.

Figure 4: Histogram of COR GRM time models computed with source separations of $50 \leq VP(50 \text{ m}) \leq 4000 \text{ m}$ for a traverse in North Africa.

Figure 5: Schematic ray paths used to compute the common offset refraction (COR) seismic velocity.

Figure 6: Histogram of COR GRM seismic velocities computed with source separations of $30 \leq VP(30 \text{ m}) \leq 1200 \text{ m}$ for the Wirrina traverse.

Figure 7: Comparison of standard GRM with mean COR GRM seismic velocities for source separations $480 \leq VP(30 \text{ m}) \leq 1200 \text{ m}$ in the sub-weathering for stations 1600 to 1700 for the Wirrina traverse.

Figure 8: Histogram of COR GRM seismic velocities computed with source separations of $75 \leq VP(75 \text{ m}) \leq 3975 \text{ m}$ for a traverse in North Africa.

Figure 9: Comparison of the seismic velocities in the weathered layer computed from the near trace traveltimes with the GRM average vertical velocity.

Figure 10: The GRM seismic velocities computed for $-20 \leq XY(20) \leq 60 \text{ m}$, using traveltimes for the Lachlan traverse recorded with 40 m arrays.
Figure 11: The smooth vertical velocity gradient starting model and WET tomogram.

Figure 12: The starting models derived with the standard GRM, the COR GRM and the COR GRM with hyperbolic velocity gradients in the weathering.

Figure 13: The WET tomograms derived with the standard GRM, the COR GRM and the COR GRM with hyperbolic velocity gradients in the weathering after five iterations.

Figure 14: The RMS misfit errors for the WET tomographic inversion of the standard GRM starting model.

Figure 15: WET tomograms for five, ten and twenty iterations, demonstrating systematic smoothing of the seismic velocities in the sub-weathering and widening of the transition between the weathering and sub-weathering.

Figure 16: The COR amplitude products.

Figure 17: A comparison of the scaled head coefficient for the 10 m and 40 m data with the geometric mean of the COR amplitude products for the 10 m data.

Figure 18: A cross plot of the scaled head coefficient for the 10 m data averaged over 40 m against the head coefficient for the 40 m data.

Figure 19: The scaled density ratio in the subweathered zone computed from the head coefficients and the COR GRM seismic velocities.

Figure 20: The P-wave modulus in arbitrary units computed from the head coefficient and the COR GRM seismic velocities.

Figure 21: The geometric spreading and the inelastic attenuation coefficients computed from the COR amplitude ratios.
Figure 22: A cross plot of the geometric spreading coefficient against the GRM time model.

Figure 23: The stacked RCS and the GRM time model.

Figure 24: Spectral analysis of the first few cycles of the stacked Wirrinya RCS.

Figure 25: Spectral analysis of the first few cycles of the stacked Lachlan RCS for the same range of source-to-receiver distances as the stacked Wirrinya RCS.
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