

An investigation of statics correction methods for 3D PS-wave seismic reflection

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SUMMARY

In the last decade converted-wave (PS-wave) seismic reflection studies have successfully demonstrated that a more complete geological interpretation can be obtained by integrated interpretation of P-wave and S-wave information, at both the petroleum and coal scales. Full 3D implementation of PS reflection presents particular challenges at the coal scale, because relative offsets and dominant frequencies are both large compared to petroleum-scale reflection.

One of the most difficult steps in the PS processing sequence is estimation of the S-wave receiver statics. Statics are time delays caused by variations in the weathering layer, and changes in source and receiver elevation. These time errors can significantly degrade CMP stack quality, and the final geological interpretation of seismic images. Static errors tend to be much more significant in PS surveys since the S wave travels more slowly through the weathering layer and is therefore more likely to be affected by variations within this layer.

In this presentation we evaluate of a number of different approaches for estimating 3D PS statics solutions. These include a surface-consistent inversion algorithm (analogous to the residual-statics method used in conventional P-wave processing), a so-called 'robust-statistical' method, and PPS refraction analysis. The methods are evaluated using a coal-scale 3D-3C survey acquired in the Bowen Basin. This has been used to examine the comparative performance, and the influence of various algorithmic and geological factors.

The results indicate that the surface-consistent inversion method can fail under some weathering conditions. When this occurs the refraction based method or a robust statistical method are preferred.

Key words: PS wave, Residual statics, Refraction statics

INTRODUCTION

The 2D converted (PS) wave seismic reflection method has been used for hydrocarbon exploration since the mid 1980's (Stewart et al., 2002). In recent years there has been a growing trend towards applying this technique to 3D targets (e.g. Simin et al., 1996; Hanson et al., 1999; Brzostowski et al., 1999). Often, PS-wave reflection has been restricted to

situations where conventional P-wave methods have encountered problems, such as imaging structures in the presence of gas (eg. Macleod et al, 1999). One of the reasons why PS reflection has not been more generally applied is that PS processing is relatively complex and time consuming. A particularly difficult steps in the PS processing sequence is determination of S-wave receiver statics.

Statics are time delays caused by variations in the near surface. These time errors cause traces that are to be combined in the stacking process to be misaligned. This introduces smearing, and hence loss of continuity and resolution on the stacked images. In the case of land seismic surveys acquired with surface sources, the main contributions to the static are the time delays associated with the weathering layer in the vicinity of the source and receiver. In PS reflection, a P-wave source is used. Hence the source static can be derived from the conventional P-wave data, normally acquired in conjunction with the PS survey. On the other hand, the receiver static arises when the reflected S-wave passes through the weathering layer. The S-wave velocity at the surface tends to be considerably lower, and more variable, than the P-wave velocity. Hence the S-wave receiver statics tend to be relatively large, and variable, increasing the complexity of statics estimation.

For shallow high resolution surveys the problem of static errors are further emphasised, because of the importance of higher frequencies. In 2D-PS coal surveys, statics have consistently have been found to have a significant effect on the data quality (e.g. Velseis, 2003, 2007). As part of a recently completed 3D-3C ACARP trial, a number of different PS statics algorithms have been investigated.

3D-3C ACARP TRIAL

The trial consisted of a 1200m x 500m 3D multi-component (3C) survey. The aim of this trial was to assess the feasibility of acquiring and processing coal-scale PS-wave data in conjunction with conventional P-wave data in a 3D sense. The survey was acquired using a Vibroseis (IVI Envirovibe) surface source at a location within the Bowen Basin.

The terrain was generally flat to gently undulating with creek cuttings causing localised elevation variations of up to 3m. The surface soil layers consisted of a brown clayish layer for most of the survey area. The southern third of the survey area consisted of a black soil terrain. This layer had many large cracks and tended to crumble when dug up for geophone placement. An examination of a cutting in the area suggested

that the black soil overlays the brown soil layer having a thickness of 1-2m at the southern end and thinning toward the north. These surface conditions were expected to generate significant variations in the PS statics.

SURFACE-CONSISTENT PS-WAVE STATICS

The standard method of calculating the receiver statics in our coal-scale 2D-PS work is based on the P-wave residual statics approach. In the conventional P-wave technique the static errors are assumed to be a linear function of time errors associated with the source, receiver, structure and offset. For this technique reflection horizons are usually automatically picked on CMP gathers. From this the error on each trace can be attributed to individual parameters, in a surface-consistent manner, using least-squares inversion.

For PS data the conventional technique is difficult to implement since CCP binning requires a good understanding of velocities. However, PS velocities are more difficult to determine due to a lower signal-to-noise ratio and larger statics. Therefore, a modified residual statics method has been developed.

Selected PS reflection horizons are manually picked in the receiver domain. For the 2D case, limited-offset receiver-domain stacks are picked. This allows the general RMS velocity to be calculated as a parameter of the inversion and removes the need for the application of an accurate NMO solution before statics calculation.

PS processing is usually conducted in conjunction with the associated P-wave analysis. Hence the P-wave source static correction can be applied to the PS data before statics calculation. Therefore, the PS static error (δt) can be parameterised into receiver (δt_r), structural (δt_{ccp}), and offset (δt_{off}) contributions.

$$\delta t \approx \delta t_r + \delta t_{\text{ccp}} + \delta t_{\text{off}}$$

In 2D-PS surveying it is common to separate the positive and negative offsets and process these separately. Sometimes this includes calculating separate statics solutions. For the 3D case this corresponds to grouping traces according to source-to-receiver azimuth direction. Therefore the reflection horizons are picked on offset and azimuth limited receiver stacks.

Analysis of azimuth-limited receiver statics solutions for the trial dataset has indicated that the variation with azimuth angle can apparently be large. Figure 1 gives a representative example of this for two azimuth directions on two receiver lines.

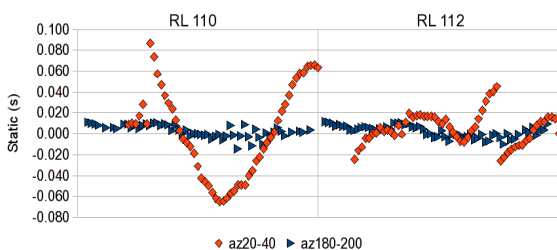


Figure 1: Representative azimuth-limited receiver-statics solutions (using the PS surface-consistent approach).

For low-velocity weathering layers the seismic rays are travelling near vertically in the vicinity of the receiver. This is likely to result in rays from different azimuths travelling through similar paths. Therefore, we would expect the receiver statics to be relatively independent of azimuth. The variations exemplified in Figure 1 seem unlikely. This leads us to question if the method is working as expected.

To determine if the method is working correctly we have also examined azimuths that give similar receiver statics solutions (Figure 2a). If a receiver statics solution was derived using the horizon picks from all these azimuths we would expect the combined solution to have a similar trend to the average of the individual solutions. However, as is demonstrated in Figure 2b the combined receiver statics solution is very different. This is an example of non-uniqueness in the least-squares inversion. In this case it is caused by parameter leakage between the structure and receiver components where some of the error associated with the structure of the reflection is interpreted as a receiver static. This particular leakage is not unexpected in shallow PS reflection, since the reflection point is significantly displaced toward the receiver. This inversion problem suggests that another method needs to be investigated to calculate the statics for this 3D PS dataset.

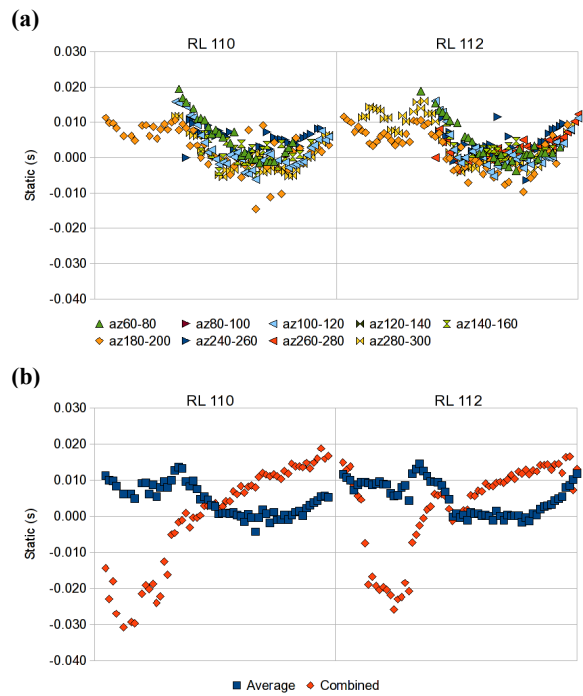


Figure 2: An examination of the variation in receiver statics solution with azimuth. (a) azimuthally limited surface-consistent receiver-statics solutions that display similar properties. (b) comparison of the average solution from the surface-consistent statics in (a) versus a solution incorporating all the input data from each of the curves in (a).

ALTERNATIVE STATIC-CORRECTION METHODS

We have shown that the surface-consistent, residual-static approach may produce errors when the weathering conditions are highly variable. For this investigation we have therefore

investigated two alternative approaches for deriving the receiver static corrections, namely the 'robust statistical' method and a method that uses the PPS refraction event.

When testing new processing methods it is important to compare the results against a reference technique. For our reference, we have applied only the elevation statics to both sources and receivers. This approach corrects for lateral variations in surface elevation, but it assumes a constant weathering profile. The elevation-statics correction is easily implemented and can provide reasonable results if the weathering layer is simple with little variation. Figure 3 shows a stacked section that has been extracted from the 3D volume. The reference elevation statics solution is compared to the other two methods.

Robust Statics

The so-called robust statics method is a simple processing technique that has been developed for this project. It utilises the receiver-domain horizon-picks that were selected for the residual-statics approach. The aim of this approach is to use robust statistical methods (median filters and averaging) to subtract the long-wavelength components from the picks, leaving the short-wavelength receiver statics. A key assumption of this process is that short-wavelength structural terms are cancelled out by the averaging process. This tends to be true if the fold of the data is high, and if we err on the side of caution and only extract the short-wavelength data. It is also assumed that the short-wavelength receiver statics are not azimuthally varying which is reasonable for low velocity weathering layers. The long-wavelength component contains both structural and receiver terms which cannot be separated. Therefore, the main aim of this approach is to improve the stack quality. It may not give a fully corrected structural image. In some situations, it is possible to accommodate for this shortcoming by tying the stacked reflection events to borehole data. Figure 3 allows comparison of the stacked section of Line 110 for the elevation and robust statics methods. The elevation statics solution appears to have better long-wavelength character but the robust statics image has improved continuity of the reflector especially toward the left end of the line (black soil region).

PPS Refraction Statics

A standard method for calculating conventional P-wave statics is to analyse the PPP refraction event. A reversed-spread refraction interpretation allows source and receiver statics corrections to be determined. For P-wave data this is generally the first arrival and is a quite strong event. For PS data the corresponding concept is to pick the PPS refraction (Hean and Meulenbroek, 2011; Meulenbroek and Hean, 2011). This event is generated by conversion of the horizontally travelling P headwave to an upward travelling S wave. Since the S wave is slower than the P wave, the PPS refraction is generally not the first arrival. In addition, the strength of the PPS refraction can be quite variable. These factors often make the PPS wave difficult to identify.

For shallow 2D-PS surveys this technique may be difficult to apply, since there are often not enough picks to give an accurate solution. This is especially true for surface sources where surface waves tend to swamp much of the PPS refraction energy. For high fold 3D surveys even a small number of picks on each record can give a viable number of picks for the statics calculation.

For this investigation we have used the time-term method to extract the receiver statics (Reiter, 1970). This assumes that the time of each refraction pick is a function of a source time (t_s), a receiver time (t_r), and an offset time where the offset time is defined by the distance (d_k) divided by the velocity (v_k) for a number of velocity bins that the ray travels through.

$$t = t_s + t_r + \sum (d_k/v_k)$$

We have used Singular Value Decomposition to separate the individual components.

Solving for these times without constraints tends to give some anomalous velocities which create small errors in the receiver responses. The results have been improved by constraining anomalous velocities to the average velocity. An interesting numerical problem that arose was that the distance and velocity values, measured in m and m/s, are much bigger than the other components and were dominating the solution. To remove this problem it was necessary to normalise the data by using units of km and km/s.

The receiver statics are approximately proportional to a constant multiplied by the receiver time-term. For this investigation the constant has been assumed to be close to one. Therefore, the receiver static is equal to the time-term.

Figure 3 includes the stacked section of receiver Line 110 with the time-term receiver statics correction applied. This PS refraction solution shows a good long wavelength structural behaviour and generally has a slightly improved reflector continuity over the image with elevation statics correction.

CONCLUSIONS

Statics correction is a critical component of shallow 2D and 3D PS reflection. It has been found that the PS surface-consistent statics method may produce incorrect solutions in some statics environments. This is caused by errors in the horizon picking stage which lead to parameter leakage between the receiver and structural parameters. Two alternative statics methods have been examined.

The robust statistics approach produces reasonable event continuity, but the lack of long-wavelength correction can produce errors in structural interpretation. The time-term refraction statics method produced the best statics solution for this dataset. It does require good PPS refraction events and high fold, which may not be available for all datasets.

As with P-wave statics, sequential application of different algorithms may be appropriate.

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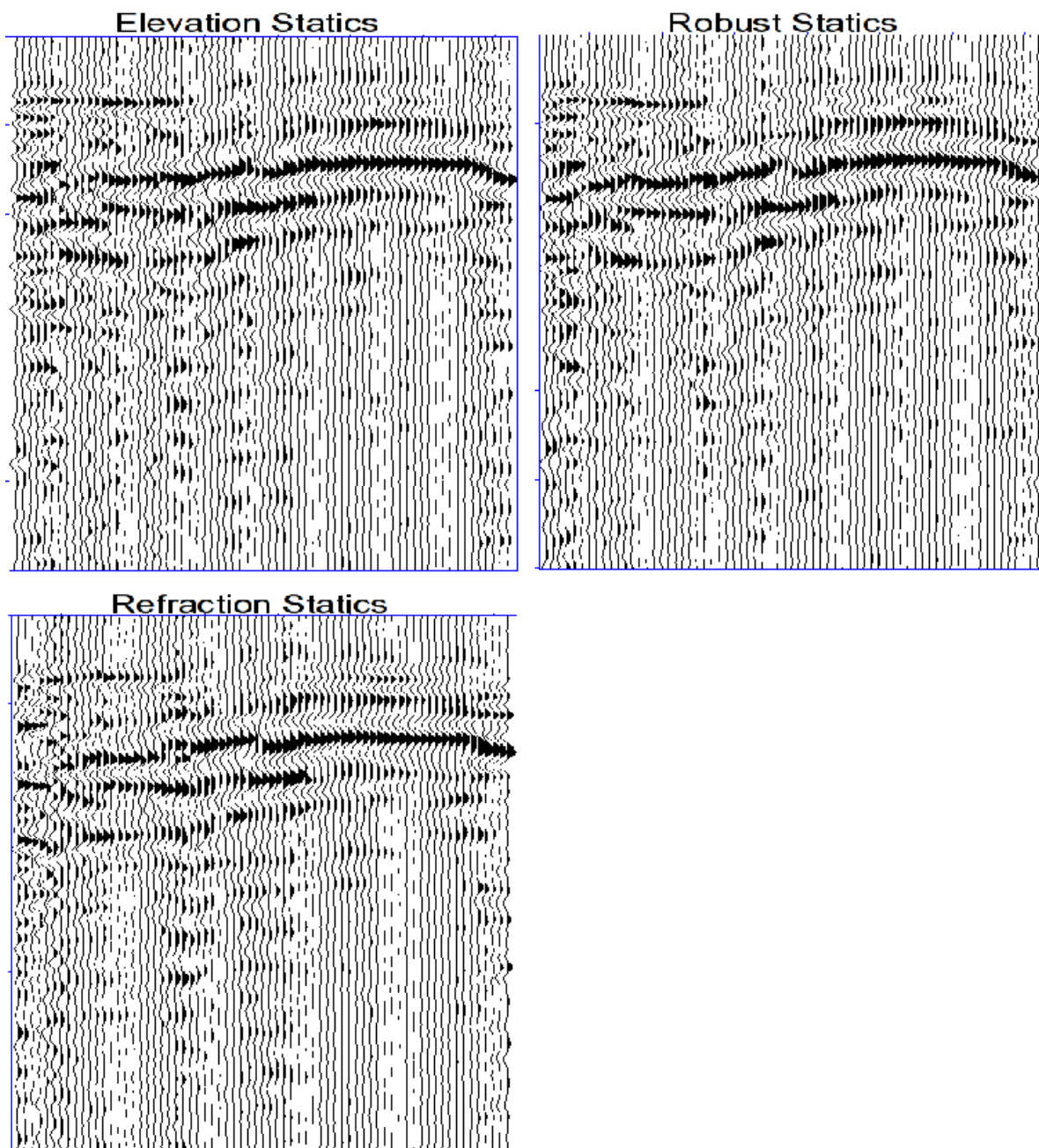


Figure 3: Comparison of representative Receiver Line 110 stacked with elevation statics, robust receiver statics, and time-term PPS refraction statics.