ESTIMATION OF ANISOTROPIC PROPERTIES FROM A SURFACE SEISMIC SURVEY AND LOG DATA

RUIPING LI, MILOVAN UROSEVIC

Department of Exploration Geophysics, Curtin University of Technology, Australia.

ruiping@geophy.curtin.edu.au

Routine P-wave seismic data processing is tailored for isotropic rocks. Such assumption typically works well for small incidence angles and weak anisotropy. However, in the last decade it has become clear that seismic anisotropy is commonplace. Moreover, its magnitude often severely violates the presumptions taken for routine processing. Consequently reservoir characterization may be significantly distorted by anisotropic effects. In particular the intrinsic shale (often sealing rock) anisotropy often has first order effect on AVO gradient. Hence an assessment of the shale properties from surface seismic data may be of the primary importance for quantitative interpretation. There are several inversion approaches which require full set of geological information. In reality we expect to have at least the log and surface seismic data available for such a task. We present here a newly developed hybrid inversion method which is suitable for the recovery of anisotropic parameters of sealing rocks under such conditions. The effectiveness of this approach was successfully tested on seismic data recorded in the North West Shelf, Australia.

1 Introduction

Inversion of surface seismic data for the elastic properties of sealing rocks can impact on the accuracy of the reservoir characterisation. Since shales, which are intrinsically anisotropic, comprise often sealing rocks, an inversion has to at least incorporate recovery of the full set of anisotropic parameters for a transversely anisotropic medium. The shale anisotropy and its variation across an oil or gas field could have first order effect on Amplitude Versus Offset-and-azimuth analysis (AVOaz) [6; 1]. An example incorporating weak shale anisotropy is shown in Figure 1. Shale anisotropy in this case affects reflectivity curve on moderate to far angles. This "deviation" of the reflectivity curve could potentially impact onto our ability to accurately predict fluid type and its distribution across the field. Thus it is clear that before attempting detailed analysis for reservoir properties it is highly desirable to analyze and determine the magnitude of the seal anisotropy. Consequently an assessment of the shale properties from surface seismic data may be of the primary importance for quantitative interpretation of reservoir rocks.

Thomsen [7] derived a convenient five-parameter model to describe seismic wave propagation in a transversely isotropic medium. There are many methods proposed to recover these elastic parameters, for example, the slowness surfaces method [2], the ray velocity field method from VSP surveys [4], the anisotropic moveout method from reflection events [8; 5]. Each of the above inversion method has been tested on field data sets separately provided enough information was available. However, we often have only surface seismic data and log data available for such inversion. In such case the existing methods fail to recover the elastic parameter accurately. For example the slowness method recovers the elastic parameters for an interval layer. The existence of a heterogeneous layer between successive receivers may produce errors in slowness surface determination. Deviation of the borehole, near surface inhomogeneities or topography of the surface also makes calculation of the slowness surfaces more difficult. Because errors in slowness are in inverse proportion to the layer's thickness, errors for a thin interval layer will be larger due to the small time differences involved [3]. Using anisotropic NMO analysis, we may obtain information about overall anisotropy. We still need more constraints to determine the individual layer parameter values. For the ray velocity field method, the elastic parameters for an overall or interval layer may be estimated when the exact values for reflector depths are measured beforehand. Such method uses large number of observations, thereby statistically reducing the errors in the inverted parameters from measurement errors. However, any errors in the depth determination may produce inaccurate velocity field, which result in accumulated errors for the recovered parameters.

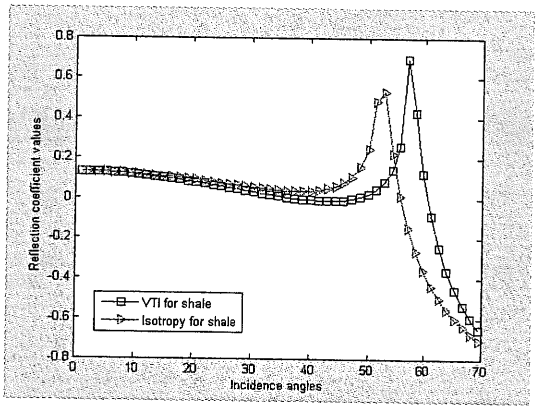


Figure 1. Reflectivity curves for both VTI and isotropic shale sealing an isotropic reservoir rock.

In the absence of suitable information, a new inversion approach which combines positive merits of different methods may be required. We present here a newly developed hybrid inversion which is suitable for the recovery of anisotropic parameters of sealing rocks (shales). The effectiveness of this approach was tested on seismic data recorded in the North West Shelf, Australia.

2 Recovery of elastic parameters using joint inversion method

We first discuss the inversion for the parameters for an overall layer, and then we will show how to recover the interval layer parameters.

2.1 Parameter for an overall layer to a reflector

For a reflection event, we use the anisotropic moveout velocity approximation [8] as below:

$$t^2(x) = \frac{1}{2}\left[t_0^2 + \frac{x^2}{a^2} + \sqrt{\left(t_0^2 + \frac{x^2}{a^2}\right)^2 + 4At_0^2\frac{x^2}{a^2}}\right]. \tag{1}$$

Here, a represents the horizontal velocity. A is a newly defined parameter and its approximate value to the second order expressed in terms of Thomsen's anisotropy parameters ε and δ is [5]:

$$A \approx 2\cdot(\varepsilon-\delta)-(\frac{3}{2f}-1)\varepsilon^2+(3+\frac{1}{2f})\delta^2-(4-\frac{1}{f})\varepsilon\delta\,. \tag{2}$$

Here, $f = 1 - \beta_0^2 / \alpha_0^2$ with α_0, β_0 are the vertical velocities for P and S-waves. To the first order approximation, the A value is the double difference between the anisotropic parameters ε and δ, and A can be called as a dimensionless non-ellipticity parameter. The anisotropic velocity analysis which employs two-parameter (a and A) anisotropic semblance analysis is then implemented. For any set of parameter value of a and A, equation (1) is used to perform moveout corrections. The semblance coefficient S_c is then calculated. The values of the parameter a and A are determined for a specific reflection event when the semblance coefficients S_c achieves its maximum value S_{cmax}.

When we have the exact values for the reflector depth and the vertical velocities, the anisotropic parameters ε and δ can be determined from the recovered parameters a and A using equation (2). From the log data tied with the surface seismic data, the reflector depth and the vertical velocities may be estimated. However, due to the sensitivity of the anisotropy parameters, the accuracy for the inverted parameters ε and δ is inadequate. For the surface seismic survey, the two-way-travel times (TWTs) with different offsets for a specific reflector can also be picked. When the depth of this reflector is known, the velocity values at different travel angles can be inferred. Hence, the ray velocity field method could be applied for the parameter recovery. Combining the above two methods, a hybrid inversion is developed by best-fitting the TWT field with constraints of the parameter a and A values from the anisotropic semblance analysis. Figure 2 gives the program flow for the hybrid inversion.

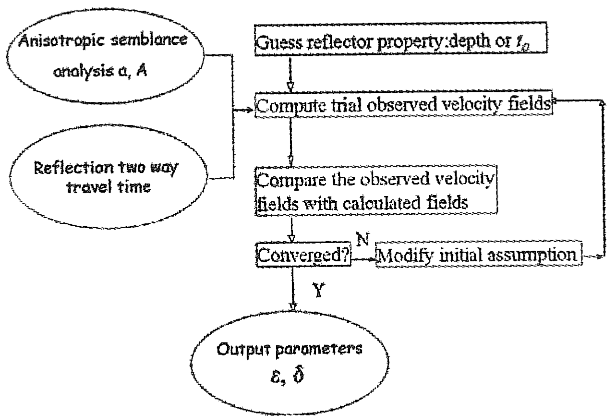


Figure 2. The program flow for the hybrid inversion technique using surface seismic and log data.

2.2 *Parameter for an interval layer between two reflectors*

This approach can be used to obtain apparent elastic parameters for several interfaces such as top and bottom of the shale layer or the top and bottom reservoir interfaces. The parameters ε and δ for the interval layer between these two interfaces are then determined from the measured TWTs for different offsets and the depth values for the interfaces by the ray velocity field method. Subsequently, the slowness surface for this interval layer is built from the measured TWTs for different offsets and the layer thickness. The inverted interval parameters ε and δ from the ray velocity field method are then validated by best-fitting the slowness curves. Figure 3 shows the flowchart for the interval layer inversion program.

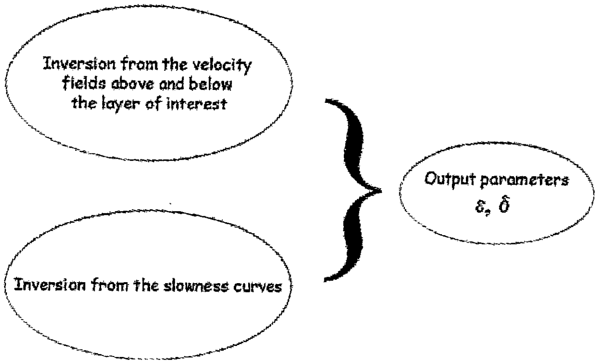


Figure 3. The flowchart for the hybrid inversion technique for the interval layer properties.

The degree of the sealing rock anisotropy has significant effect on the AVOaz reservoir signature. Hence, the inverted anisotropic parameters for the top sealing rocks should play an important part in the reservoir characterization. In the following section, we apply our hybrid inversion to real field data.

3 Field data application

The hydrocarbon field analyzed is located in Exmouth Sub-basin, offshore North-West Shelf, Western Australia. High-quality cross-dipole sonic logs showed significant shear wave splitting (10-15%) over the reservoir interval. To utilize this information for reservoir rock characterization it was first necessary to estimate the anisotropy of the sealing shale and its effect on AVOaz signature.

For a CMP (common mid-point), the anisotropic semblance analysis [9] is applied along the time axis (t_0). For each t_0, the S_c values are computed for a set of a and A values. The parameters a and A are then determined when the semblance coefficient S_c hold its maximum value. Figure 4 shows an example for the reflection event at t_0=*2005 ms*. The corresponding parameters are determined as: a=*2452.5 m/s* and A=*0.16*.

Along the seismic line, the parameter a and A are then determined using the above anisotropic semblance analysis. Figure 5 shows the parameter a and A values for different CMP for the same t_0 value. The stability of the recovered parameters is demonstrated from the figures.

At different t_0, the S_{cmax} values are then compared with the surface seismic section and the log data, as shown in figure 6. The top shale layer is identified as the interval layer between two strong reflection events with local maximum S_{cmax} values. The corresponding parameters a, A for the reflection events on the top and the bottom of the shale layer are also obtained through the anisotropic semblance analysis.

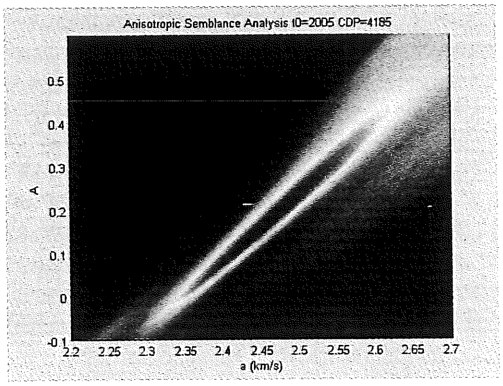


Figure 4. Anisotropic semblance analysis for *CMP=4185* at $t_0=2005\ ms$.

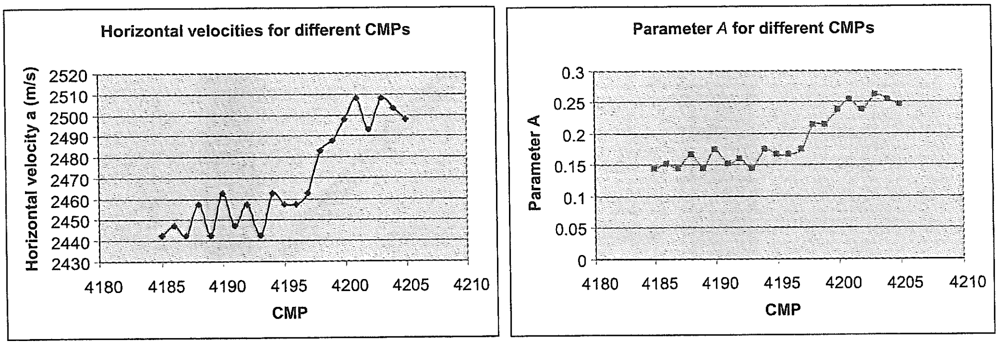


Figure 5. Anisotropy parameter A and horizontal velocity a change along the seismic line (fixed t_0).

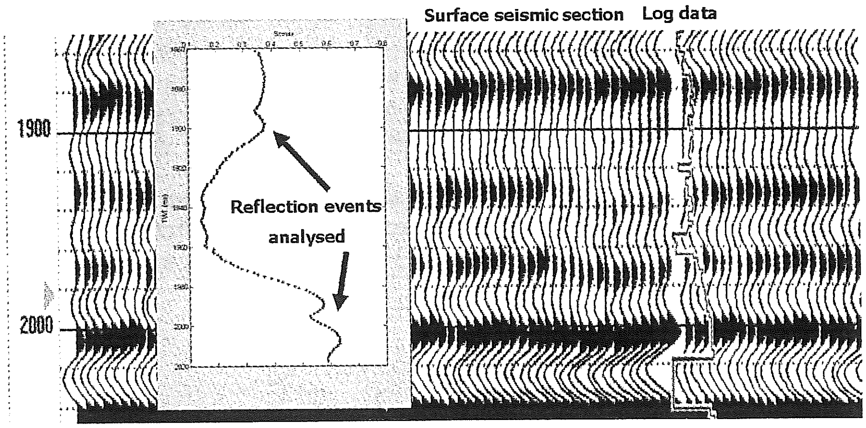


Figure 6. The surface seismic data, log data and the anisotropic semblance analysis.

Even we have the analytical relation between anisotropic parameter A and ε, δ [5], it is still hard to obtain the anisotropic parameters ε, δ directly from parameter A because we lack enough information for the depth or vertical velocity. Making an assumption may cause big errors due to the sensitivity of the anisotropic parameters. The hybrid inversion which combines the ray velocity field method [4] and the anisotropic moveout method is then employed. We first pick the TWTs for different offsets for a reflection event. Then the hybrid inversion program is executed with the input of the TWTs and the recovered parameters a, A as a constraint. For the overall layer above the top of shale, we have $\varepsilon_1=0.175$, $\delta_1=0.086$. The reflector depth and the vertical velocity are also inverted. For the overall layer above the top of reservoir, we have $\varepsilon_2=0.192$, $\delta_2=0.081$. Figure 7 shows the two-way-travel times from the measurements in circles (o) for the top layer. The asterisk (*) denotes the TWTs calculated using the inversion results. Both data sets match very well and the inversion results for the overall layer are quite satisfactory.

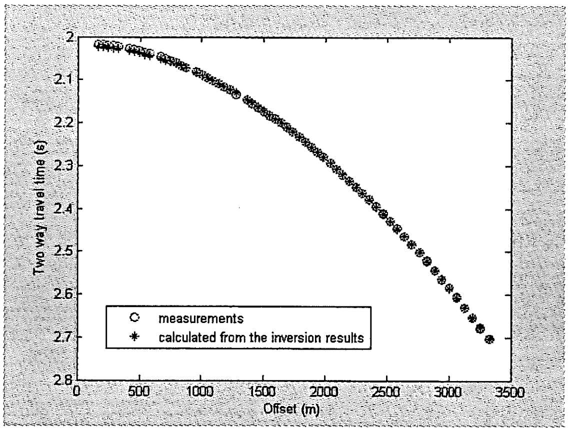
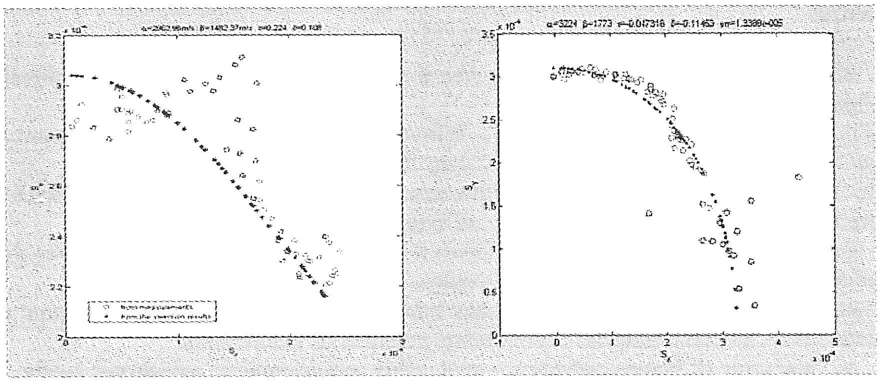


Figure 7. Comparison of the TWTs from the measurements and calculated from the inversion results. Very good agreement between these two sets of data indicates that the inversion is successful.

Subsequently, for the interval shale property, we apply the ray velocity field method based on a two-layer's model [4]. The anisotropic parameters obtained for the shale above the reservoir are: $\varepsilon=0.224$, $\delta=0.108$. Such results are also verified by the slowness surface plot in Figure 8. Notice that the thickness will affect the inversion so that for very thin shale layer at this CMP, the measured slowness surface in figure 8a is of low quality. Figure 8b shows another example with a thicker shale layer in another CMP position.

The anisotropic parameters ε and δ for the overall layer to the top and the bottom of the shale are inverted first. Subsequently, the interval parameters ε and δ for the interval shale layer are then successfully recovered. The inverted anisotropic parameters can then be used in the AVOaz analysis aimed at the reservoir characterization.



(a) Slowness surface for a thin layer

(b) Slowness surface for a thick layer

Figure 8. The comparison of the slowness surfaces from the measurements and calculated from the inversion results.

4 Conclusions

From the log data and anisotropic semblance analysis, the reflection events at different two way travel times are analysed, as well as the horizontal velocities a and the anisotropic parameter A. From a seismic section, the two-way travel times for different offsets for a CMP location are manually picked. With the constraint of the parameter A and horizontal velocity a values, a new hybrid inversion method is developed to recover anisotropic parameters ε, δ, reflector depth and the vertical velocity from the observations of two way travel times for different offsets. As the velocity field at different ray angles can be converted using the inverted reflector depth, verification procedure is carried out. The calculated values of TWT for different offsets using the recovered parameter values should coincide with the log measurements. Apparent differences between the measured and estimated values may suggest misfit of the seismic section with the log data.

After obtaining the apparent average parameter for the top and the bottom sealing layer or reservoir, the interval anisotropy parameters are obtained from the velocity field data using two-layer model approach [4]. From the travel time picks, the slowness surface for the interval layer is also constructed which allows us again to recover the interval anisotropy parameters. These two estimates should match each other.

The application of our new hybrid inversion methods to the field petroleum data suggests that the method is robust and should consequently result in reliable parameter estimates.

5 Acknowledgments

This is a project supported by the Curtin Reservoir Geophysics Consortium (CRGC). We thank CRGC for providing the field data. Thanks also go to Mr. Said Amiri Besheli for his help with the filed seismic data and log data.

6 References

1. Banik, N. C., An effective anisotropy parameter in transversely isotropic media: Geophysics, Soc. of Expl. Geophys., **52** (1987) pp. 1654-1664.
2. Hsu, K., Schoenberg, M. and Walsh, J. J., Anisotropy from polarization and moveout: 61st Ann. Internat. Mtg., Soc. of Expl. Geophys., (1991) pp. 1526-1529.
3. Kebaili, A., Le, L. H. and Schmitt, D. R., Slowness surface determination from slant stack curves, in Rathore, J. S., Ed., Seismic anisotropy: Soc. of Expl. Geophys., (1996) pp. 518-555.
4. Li R., Uren N. F., McDonald J. A. and Urosevic M., Recovery of elastic parameters for a multi-layered transversely isotropic medium: J. Geophys. Eng., **1** (2004) pp. 327-335.
5. Li R. and Urosevic M., Analytical relationship between the non-elliptical parameter and anisotropic parameters from moveout analysis: (2005) being prepared for publication.
6. Ruger, A., Variation of P-wave reflectivity with offset and azimuth in anisotropic media, 66th Ann. Internat. Mtg: Soc. of Expl. Geophys., (1996) pp.1810-1813.
7. Thomsen, L., Weak elastic anisotropy. Geophysics **51** (1986) pp. 1954– 1966.
8. Zhang, F. and Uren, N, Approximate explicit ray velocity functions and travel times for p-waves in TI media: 71th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, (2001) pp. 106-109.
9. Zhang, F., Uren, N., and Urosevic, M., Anisotropic NMO corrections for long offset P-wave data from multi-layered isotropic and transversely isotropic media: 73rd Ann. Internat. Mtg., Soc. Explor. Geophys., Expanded Abstracts, (2003) pp. 133-136.