This brief note was written as a contribution to the CSEG Recorder Magazine 'Expert Answers' section.

Q. A common form of anisotropy observed in many geological settings is Transverse Isotropy (TI) where the reference axis or axis of symmetry is normal to the bedding surfaces. For simple layer-cake type models the symmetry axis is vertical and the anisotropy is known as Vertical Transverse Isotropy (VTI). Grain alignments in shales or repeated sequences of finely layered sediments (sand/shale alternation) are the primary causes for such anisotropy. Such anisotropy is usually quantified in terms of Thomsen's parameters, ε and δ ?

Many processing software algorithms are available today to handle such anisotropic effects. However, the difficulty in addressing anisotropy lies in the reliable estimation of parameters.

What are the different methods being used for the estimation of these parameters? You are requested to furnish at least one specific example to show the estimation of the parameters and how their use in processed output led to an improved result or calibration.

Comments on estimation of Thomsen's ε and δ parameters for imaging and 'depthing'

Ian F. Jones (ijones@gxt.com)
Senior Geophysical Advisor, GX Technology.

Although anisotropic data processing and migration have become more common over the past years, the issue of anisotropic parameter estimation still remains contentious. In part, this problem stems from lack of sufficient data. To reliably obtain Thomsen's delta parameter, we need well control, and to estimate the epsilon parameter, we usually require long offsets (offset ~ 2* depth). Occasionally, when we clearly see fault plane reflection energy intersecting sedimentary reflectors, we can also exploit these observations to help define the parameters.

Even when we have good data, correctly tying well markers to the correct seismic even can be ambiguous, and updating a velocity model based on higher-order moveout picks can be incorrect unless the geology is flat lying, or we have a good anisotropic tomographic inversion tool.

In the notes below, we'll briefly consider four scenarios. Migrating with isotropic velocities; converting isotropic migration results to 'true depth', migrating with anisotropic velocities derived from isotropic migration velocities, and migrating with anisotropic velocities derived from scratch. It should be kept in mind that my own experience is primarily marine: dealing with the more complex foothills style of thrusted anisotropic units will bring its own challenges!

Isotropic Model Building

When we build a velocity-depth model for use with isotropic migration, we pick velocities which give-rise to flat CRP gathers. In general, velocities from well logs cannot be used for migration, unless anisotropy is accounted for by the migration algorithm, and the degree (and type) of anisotropy known. The depth obtained in the conventional 'isotropically derived' velocity model will not generally tie well depths.

Well logs measure the vertical component of the velocity field, which tends to be lower than the horizontal component. It is predominantly the horizontal component which is measured from surface seismic data. And it is this measurement which should be used to derive the migration velocity field, in order to collapse diffraction energy when we are running an isotropic migration. Occasionally, the well velocity can be higher than the seismically derived velocity (as in vertically fractured carbonates).

With a conventionally derived velocity-depth model, and isotropic migration code, if we want the resulting image to tie well-depths, we must perform an additional 'depth conversion' step. This conversion from 'geophysical' to 'geological' depth, usually involves converting the result of the isotropic depth migration back to time (using a smooth version of the isotropic model), scaling the interval velocities in the migration model to match the well velocities, then converting the 'time' data back to geological depth, with the well-calibrated velocities.

'Depthing' after Isotropic migration

The question does arise as to whether it is 'safer' to migrate isotropically, and then convert to geological depth (calibrated to the wells) *after* the depth migration. In this case, we would have the trade-off between simplicity in the model building versus potential lateral positioning errors on steeply dipping events.

If the structure is not too complex, and the anisotropy not too pronounced, then 'depthing' after completion of isotropic preSDM may be acceptable (for laterally invariant elliptic anisotropy, epsilon = delta, depthing is an acceptable approximation). However, if the symmetry axis is tilted, this may not be acceptable.

Additionally, we may have a case where we have ambiguity in the parameter determination due to contributions from other factors which affect the depth and residual far-offset moveout but which may be erroneously interpreted as an anisotropic effect (e.g. vertical compaction gradients) Some of the travel time effects resulting from the gradient will be then be erroneously accounted for by incorrect determination of anisotropic parameters. For example, in an isotropic 1D medium in the presence of a strong vertical velocity gradient, preSTM using a straight-ray approximation will give rise to an apparent anisotropy with spurious eta values of about 20%. This is avoided for the most part by using a ray-traced (or curved-ray) preSTM algorithm.

Building an Anisotropic Model (starting from isotropic velocities)

Sometimes we already have isotropic preSDM results, and want to perform anisotropic preSDM with the minimum of additional work. In this case, if the anisotropy is present primarily in one simple thick layer in the overburden, we can approximately adjust the isotropic depth model to be suitable for an anisotropic preSDM. We proceed as follows:

1. Convert the isotropic depth model back to time via vertical stretch using smoothed isotropic velocities: this yields the isotropic 'time' model.

2. Scale the interval velocity in the isotropic 'time' model, by dividing by (1+delta) (thus reducing the velocity for a positive delta)

3. Convert the scaled time model back to depth. This will result in a model with shallower depth horizons and lower velocities (for a positive delta): in this new depth model, the depth horizons should (***by construction***) tie the well depths.

This preserves the vertical travel time, but we commit an error by ignoring the lateral displacement associated with having (erroneously) determined the initial velocity field isotropically.

4. Migrate anisotropically using the anisotropic velocity depth model from (3), and the associated delta values

In figure 1, we see a CRP gather from the isotropic preSDM (top). In terms of conventional model building and CRP velocity analysis, we would be very happy with this result, as the gather is as 'flat' as it can be. However, after creating an anisotropic model by scaling the isotropic model (as described above) and running an anisotropic migration (using delta=10%, on the basis of well mis-ties), we get the picture at the bottom. Here we see that in addition to being 'cleaner', the CRP is also much flatter out to about half the offset range (full offset = 4200m), but then curls-up.

5. We have now tied the well (for this horizon, the isotropic image was 178m too deep), but must estimate epsilon (for many shales, epsilon is typically about 2*delta). In this case, we ran a migration scan over possible epsilon values, some members of which are shown in figure 2.

The images from the isotropic and anisotropic 3D preSDMs are compared in figures 3 & 4 after conversion to time.

In this instance, a migration scanning technique was used to determine epsilon, after delta was measured from well mis-ties. However, if we observe consistent higher-order moveout effects on an horizon, after migrating anisotropically with delta (step 4 above) we can employ a continuous auto-tracker to pick higher order moveout (unfortunately, at high velocity contrast interfaces, we often get supercritical events which confuse the issue).

In the cases where we can employ an autopicker, we would:

- Convert the anisotropically migrated CRP gathers back to time, using the smoothed anisotropic model.

- Back-out the (second order) NMO using the associated RMS velocities if the initial migration used epsilon=0, OR back out higher order moveout with the given eta if a non-zero epsilon was used in the migration in step 4.

- Input these gathers to the continuous higher-order velocity analysis package, and analyse for higher-order moveout by measuring the eta parameter. Recall that it is Alkhalifah's eta parameter that we measure from residual moveout in time gathers. Note that this is a cumulative eta value (also referred to as the 'effective eta'). In order to obtain the interval values of eta, we must perform a Dix-style inversion first. To obtain epsilon for a depth migration, we then use the relationship $\eta = (\varepsilon - \delta)/(1+2*\delta)$ to recover epsilon. It must also be noted that this inversion must account for the fact that the non-anisotropic elements of higher-order moveout have already been corrected (by ray-bending in the migration). In other words, we have solved for the geometric component of higher-order effects with the initial depth migration, and now want to resolve the anisotropic component.

Building an Anisotropic Model (starting from scratch)

In the case of a new project, especially in the presence of good well control, we can commence differently, performing a top-down anisotropic model build.

For very dense well control, we can:
1. Migrate data with the well-derived velocity field (in other words, we are already accounting for an initial estimate of delta).
3. Scan for epsilon and delta values by applying residual moveout to gathers as a function of these two values. We will be correcting the implicit estimates of delta, and obtaining our first estimates of epsilon.
4. Assign the values of epsilon and delta to the depth model
5. Remigrate data and monitor both well-ties and flatness of gathers both laterally and horizontally.

Alternatively, we can run a dense autopicker to recover vertical compaction gradient information and then tomographically invert the picks to update the near offset component of the seismic velocity field. The ratio of the seismically derived velocities to the well-based velocities will be a first order estimate of the delta field (recall that Vnmo = Vvertical $*(1+\delta)$)

For relatively flat data, the delta parameter can be estimated from non-migrated data by employing depth conversion first on the basis of well velocities and then the seismic velocities (where the seismic velocities include vertical compaction gradients). The ratio of these estimates will yield an estimate of the delta field (as above).

There is also the issue of whether we permit lateral variation of the epsilon and delta parameters within a layer. More often than not, we lack the well control and long offset information to justify this, and to-date we have hitherto used fixed epsilon & delta pairs for a given layer (this is not a limitation of software, but more of geophysical justification).

In addition, we have the issue of model representation: to implement anisotropic ray-tracing, we need to carry the dip vector for the surfaces bounding the anisotropic layer (for cases where the anisotropic tilt axis is normal to the layer). Thus for a gridded model, which at GXT we routinely use to carry the vertical velocity field, we need to also supply associated interpreted layers for the dip field. (In a gridded velocity model, the dip field is determined locally whenever a coherent velocity measurement is made, but this is less easy to use for the anisotropic parameterisation, hence layers are also employed.) For a purely layer-based model, this extra complication is not present. In cases where the anisotropic tilt axis is de-coupled from the seismic reflection interfaces (as it can be for some combinations of compaction and deposition), we still need separate ‘surfaces’ to carry the tilt axis information for a layered model.

Background Reading

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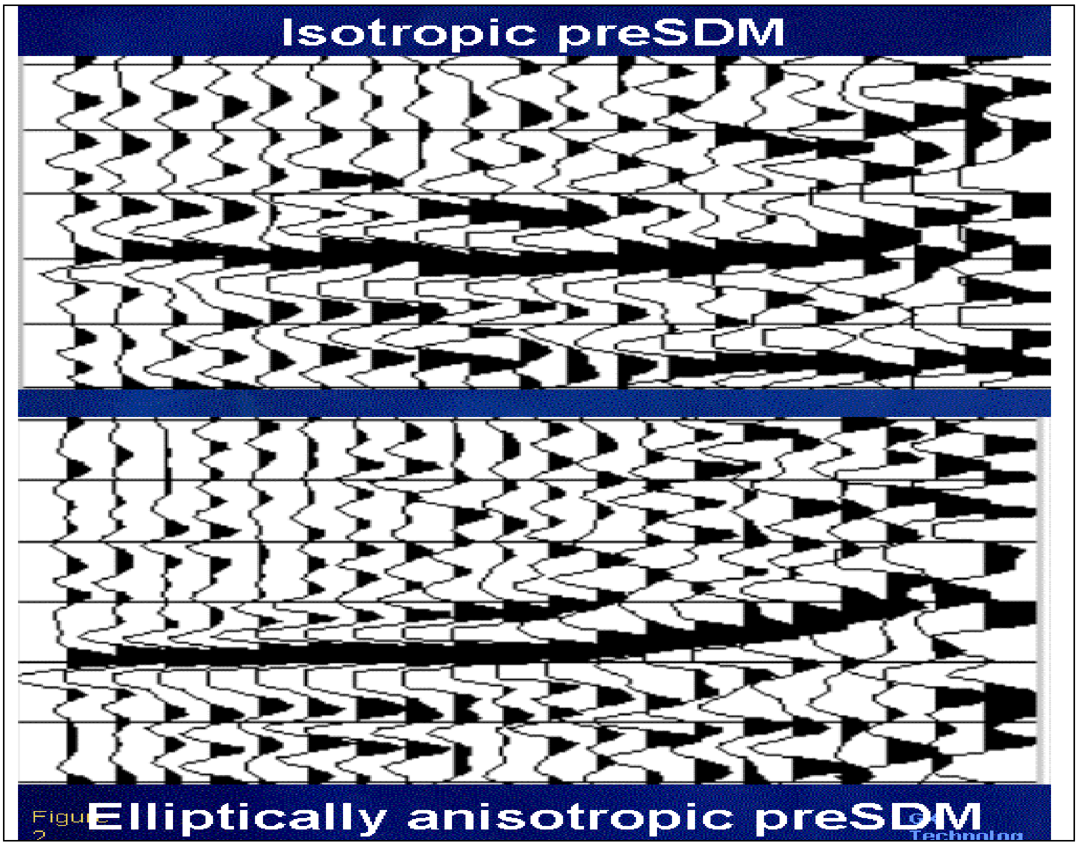

Figure 1

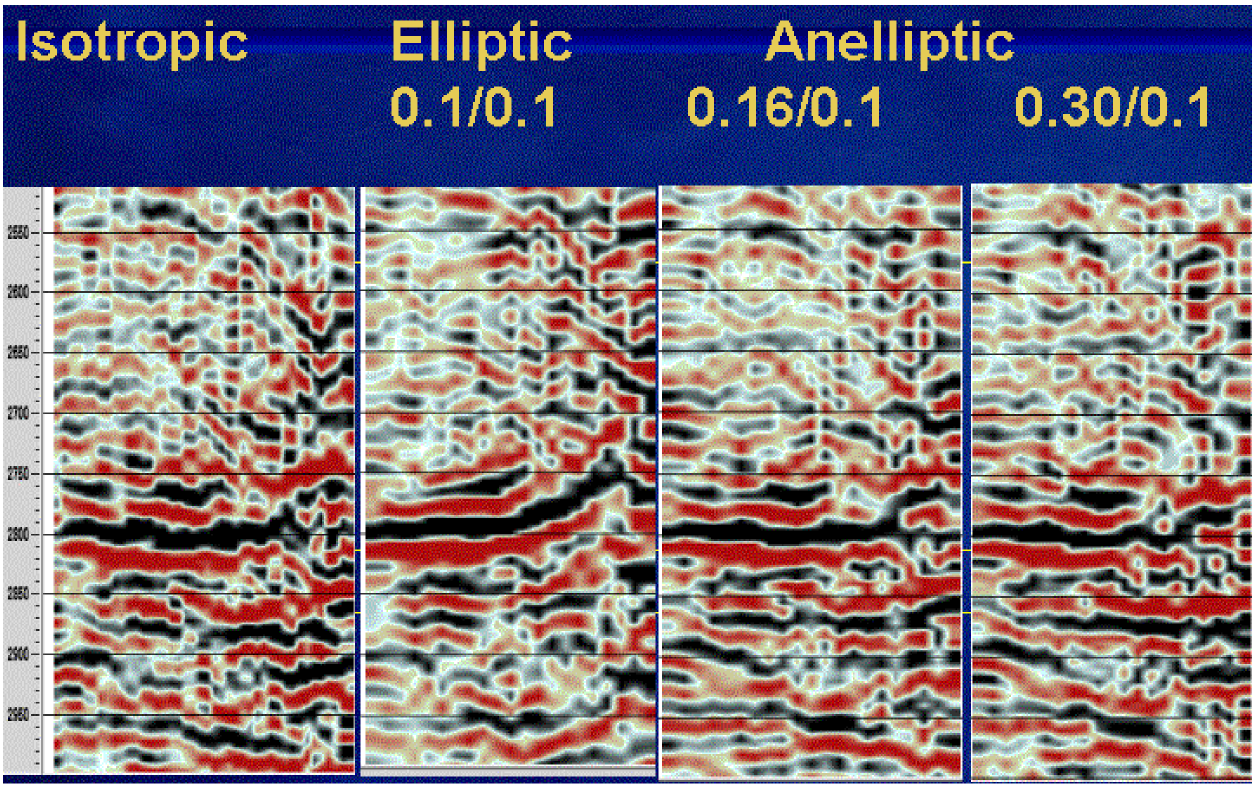

Figure 2: preSDM with different anisotropic assumptions (numbers show epsilon & delta pairs)

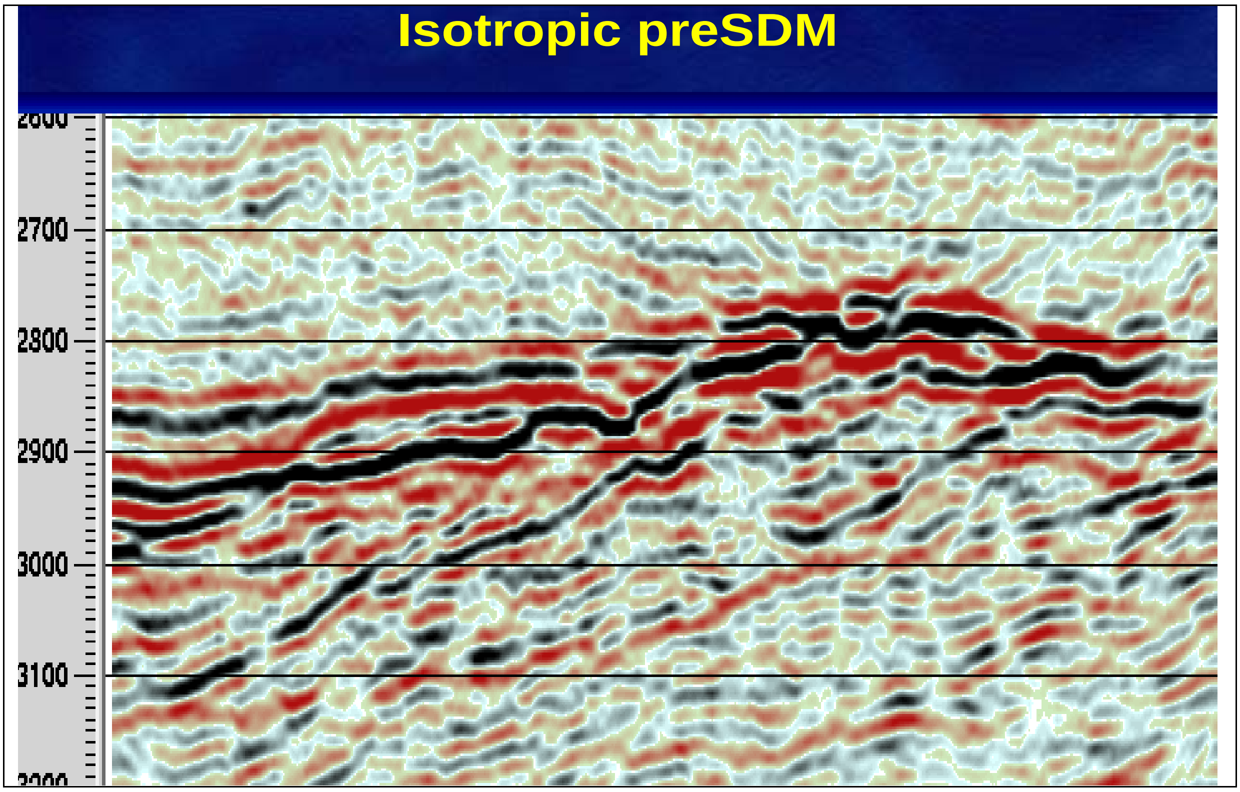

Figure 3: isotropic 3D Kirchhoff preSDM

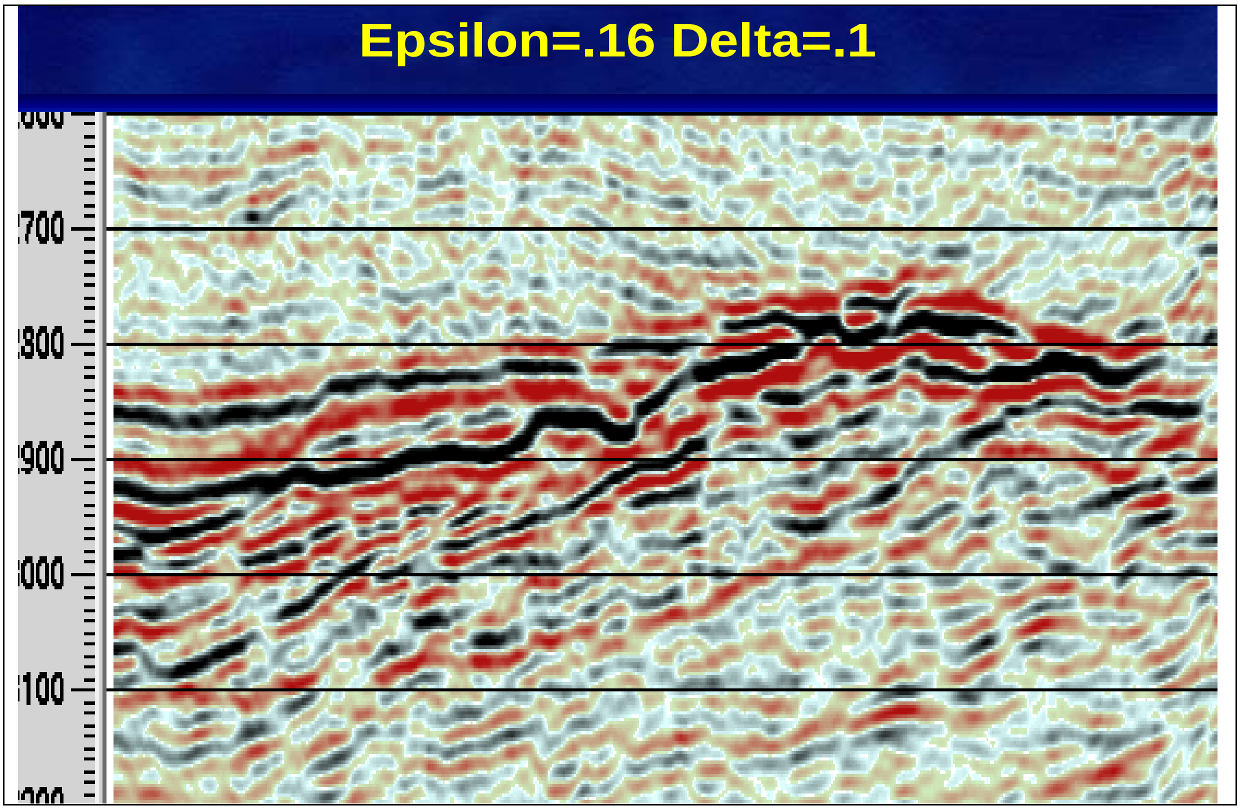

Figure 4: anisotropic 3D Kirchhoff preSDM