Wide azimuth imaging and azimuthal velocity analysis using offset vector tile prestack migration

Alexander Calvert,[1*] Edward Jenner,[1] Robert Jefferson,[1] Robert Bloor,[1] Nicola Adams,[2] Rosemarie Ramkhelawan[2] and Chris St. Clair[3] make the case for the application of vector offset binning to many of today's wide azimuth surveys. They say the approach is a natural complement to the surface-fitting method for azimuthal anisotropy analysis and used together allow efficient post-migration analysis for velocity anisotropy, providing insights into subsurface fracturing and stress.

The industry is acquiring increasing numbers of wide azimuth surveys. In soft rock settings, such as the Gulf of Mexico, the objective is usually to improve illumination and imaging of obscured or structurally complex targets (e.g., Michell et al., 2007). In hard rock settings, the presence of significant azimuthal velocity anisotropy can actually degrade the image quality of wide azimuth surveys when ignored (Williams and Jenner, 2001). If the anisotropy is measured and corrected for, the result is not only an improved image, but also valuable information related to the fracture and stress characteristics of the overburden and reservoir. Knowledge of fracture densities and orientations in tight rocks, where fractures are the dominant source of porosity and permeability, may allow improved well positioning and performance. Understanding of the principal stress orientation may also permit more efficient planning and prediction of well fracturing.

Traditional signal processing techniques often smear or ignore this azimuthal information and it is certainly lost in poststack or common offset prestack migration. Increasingly, more care is being taken to preserve and use this information through imaging to produce migrated azimuthal attributes for interpretation. In this paper we review field data experiences preserving, measuring and correcting for azimuthal velocity effects with prestack vector offset imaging.

Measuring azimuthal velocity anisotropy

The presence of azimuthal velocity anisotropy results in an elliptical variation of the measured NMO velocity with azimuth (Grechka and Tsvankin, 1998). When caused by a single set of aligned vertical fractures, the fast NMO velocity direction is orientated along the fracture strike and the slow direction perpendicular to fracture strike. A number of approaches are currently being used in the industry to analyze for azimuthal velocities. These fall into three broad categories:

- *Sectoring* (e.g., Lynn, 2007). NMO velocity analysis is performed independently on azimuth sectored migrated subsets of the data, and then an azimuthally varying elliptical velocity is fit to these velocities. Lynn (2007) has suggested that sectoring approaches may suffer from accuracy issues related to the instability of independent velocity analysis and the limited data points available for velocity fitting. To obtain usable images the design of land surveys often requires large sector sizes (60^0, 45^0, or 30^0) providing few velocity points for ellipse fitting.
- *Scanning* (e.g., Sicking et al., 2007). Azimuthal velocity perturbations from an isotropic or VTI background model are scanned over a 2D grid of test parameters (e.g., fast orientation and % anisotropy). This approach is attractive when applied in conjunction with an azimuthally anisotropic migration, but requires compute intensive migration scanning and layer stripping with an inherent trade off between precision and compute time/cost.
- *Surface-fitting* (e.g., Jenner et al., 2001). An azimuthal NMO ellipse is simultaneously fit to the measured travel times as a function of offset and azimuth. A valuable feature of the surface-fitting method is that it does not require the data to have any particular distribution as long as the offset/azimuth space is sufficiently sampled to constrain the anisotropic velocities.

Measured elliptical NMO velocities should be converted to interval parameters using a generalized form of the Dix equation (Grechka et al., 1999). Attempting to determine interval parameters as a function of azimuth directly from picked NMO velocities using conventional Dix will result in an incorrect answer unless the anisotropy is weak or

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one is fortunate enough to measure the velocities close to the principal directions of the interval of interest.

Sectoring and scanning approaches have historically been applied to migrated data whereas surface-fitting approaches have predominantly been applied to unmigrated data. None of these approaches is inherently limited to either of these domains. Although surface-fitting has been applied to migrated data (Kappius, 2006), it has been more widely used for pre-migration analysis owing to the low fold and irregular design of many land surveys which makes them unsuitable for sectoring using prestack migration. As survey densities continue to increase, they become more suitable for prestack migration and post migration analysis. When possible, azimuthal velocity analysis after migration is preferred because structural dip can potentially bias measurements on unmigrated data resulting in artifacts that can be difficult to distinguish from anisotropy.

Summary of offset vector tiling (OVT)

The concept of using vector offset bins was proposed almost simultaneously and independently by Vermeer (e.g., 2002) under the name offset vector tile (OVT) and by Cary (1999) under the name common offset vector (COV). Until recently the approach has experienced limited usage perhaps related to the limited availability of surveys perceived to be suitable and awareness of the value of azimuthal information. The approach consists of defining vector offset migration bins (vs. the standard scalar offset bins) with the two vector offset components aligned along the CMP grid axes. For a number of standard survey designs, the vector offset bin dimensions can be chosen such that each bin defines a single fold cube over the survey area populated with traces of similar offset and azimuth.

To understand how these bin dimensions are chosen, it is useful to view an orthogonal land survey as a collection of single fold sub-surveys each acquired by a source-receiver line pair (Figure 1a and 1b). These sub-surveys are often referred to as ‘cross-spreads’. Traces from adjacent CMPs within a cross-spread have similar offsets and azimuths (Figure 1c&d). Selecting traces that fall within a range of inline and crossline offset defines a rectangular ‘tile’ of CMPs. If these vector offset ranges are chosen such that the tile width perpendicular to the shot lines matches the shotline spacing and the tile width perpendicular to the receiver lines matches the receiver line spacing, the corresponding ‘tile’ from an adjacent cross spread will be located next to the original tile with no gap or overlap (Figure 1e). If the shot and receiver station and line spacings are regular, collecting all of these tiles from all of the cross-spreads that make up the survey results in a volume of single fold data with similar offsets and azimuths (Figure 1f).

Selection of the appropriate vector offset ranges to produce a tile with the required dimensions is best explained by starting in 2D. Consider a 2D survey with shots spaced every ΔS into a static spread of regularly spaced receivers. The CMPs from a shot located at x=0 recorded by receivers located from $0 <= x < 2\Delta S$ will fall in the range $0 <= x < \Delta S$. The CMPs from the next shot located at $x=\Delta S$ from the same offset range are located at $\Delta S <= x < 2\Delta S$. They lie next to the CMPs from the previous shot with no gap or overlap. This relative CMP positioning will be true for all subsequent shots located at $n\Delta S$. Selecting data with an offset range equal to twice the shot spacing selects a single fold data subset with no gaps in CMP coverage. This is the standard approach for offset binning 2D data to obtain single fold ‘common’ offset profiles (perhaps ‘similar’ offsets might be more accurate). To extend to 3D, if the shots have the same x coordinates but are now arbitrarily displaced in the y-direction, as they would be for a shot line orthogonal to the receiver line, the CMPs still have the same x-coordinates so the optimal vector offset range parallel to the receiver line is twice the shot line spacing. Similarly the appropriate range for the vector offsets parallel to the shot lines is twice the receiver line spacing.

Although originally conceived for orthogonal survey designs, the OVT approach can be extended to survey designs

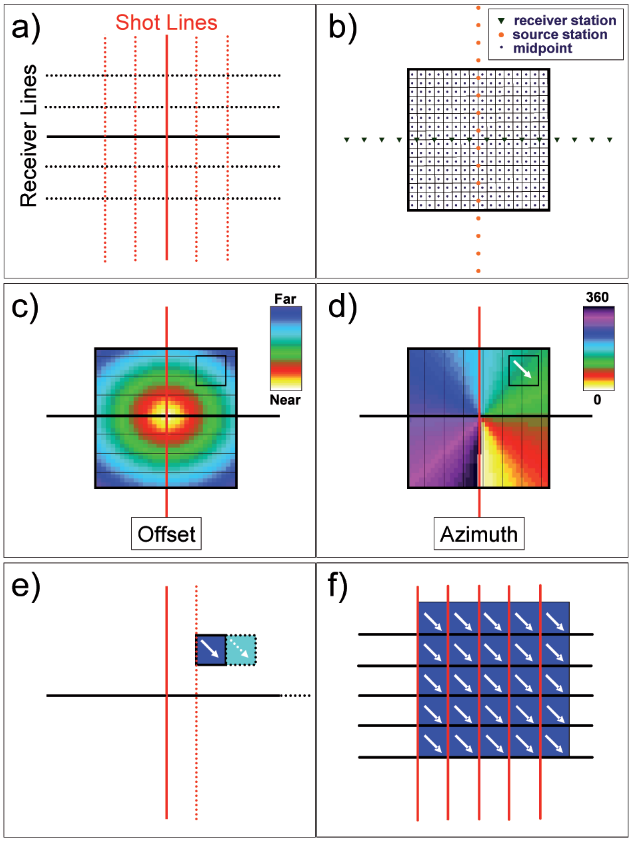

Figure 1 An orthogonal land survey may be viewed as the sum of subsurveys acquired by each ‘cross-spread’ (a source-receiver line pair) (a). CMPs from a well behaved cross-spread fall on a single fold grid (b). Offsets increase progressively from the source-receiver line intersection. A rectangular ‘tile’ of CMPs have similar offsets (c) and azimuths (d). If the tile size is chosen to match the source and receiver line spacing, the same tile from the cross-spread associated with the adjacent shot line (dotted and cyan) will lie adjacent to the first tile (e). Collecting all the tiles from all the cross-spreads results in coverage of the full survey area with single fold data that has similar offsets and azimuths (f).

that exhibit 2D periodicity along the CMP grid axes (e.g., slant designs). For non-orthogonal designs the required vector offset ranges will not be twice the perpendicular distance between shot and receiver lines but twice the repeat period of the geometry along the CMP grid axes. The tiles defined by vector offsets in non-orthogonal geometries may not be rectangular. For example, the tiles for a slant design will be parallelograms but still tessellate.

In summary, the OVT approach is a natural extension of the binning used for 2D surveys to 3D. It uses a Cartesian coordinate system of vector offsets aligned appropriately with the survey CMP grid. Conventional sectoring attempts to use a polar coordinate system of offset and azimuth for bin definition which inherently cannot fit the 2D periodicity of most land survey designs (Figure 2). Such polar coordinate binning schemes will inevitably produce holes and/or overlaps requiring careful fold compensation to minimize migration artifacts and potentially reduce attribute quality. See Vermeer (2002) for a more detailed review of the theory and applications of cross-spreads and vector tiling.

Azimuthal velocity analysis after OVT Migration

The CIP gathers produced by OVT prestack time migration (PreSTM) are quite different from conventional offset gathers. In OVT gathers, scalar offsets are not linearly sampled and often duplicated so they cannot be processed or analyzed with tools that assume a constant offset spacing. This may also be a reason why the industry has historically favoured sectored migrations. Sectored migrations are usually parameterized to produce gathers with regularly spaced offsets within the sectors allowing standard scalar offset velocity analysis tools to be applied to each sector. Fortunately the surface-fitting approach, developed to deal with arbitrary offset/azimuth distributions in unmigrated data, is directly applicable to the OVT binning scheme. A similar workflow to that for pre-migration analysis may be used but the nominal OVT centre offset and azimuth now define the geometry of each trace.

In an effort to understand the practical differences between sectored and OVT migration on azimuthal attributes, both migration approaches were applied to a reasonably dense survey in Canada (210 m receiver line spacing, 240 m shot line spacing at a 45^0 slant). Apart from some gaps in shot coverage, the slant design survey is very regular with excellent data quality over relatively flat structure. Figure 3 shows the fast and slow NMO velocity difference derived by surface-fitting both the sectored and OVT PreSTMs. Both approaches identify similar first order anomalies but also contain subtle differences. It is important to emphasize that as surface-fitting was used to obtain both results this is a comparison of the impact of the migration differences alone. We expect that application of the full sectored approach described above, including independent velocity analysis of sectors, would result in more significant differences. The standard error estimate, which accounts for both data distribution and misfit, implies that the OVT result is significantly more constrained. Examination of the velocity fit to the data confirms the increased scatter of the sectored result. As Figure 2 illustrates, the sectored migration has many CIP locations that did not contain a trace before migration. During migration these locations are populated by swinging data in

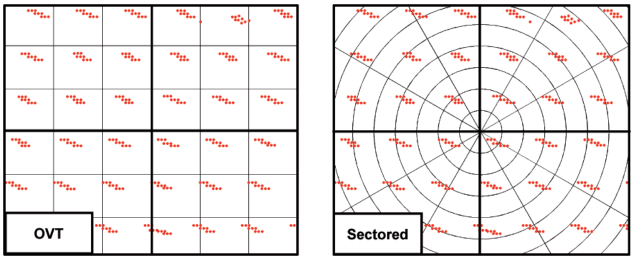

***Figure 2** The vector offset locations (red dots) of traces from nine adjacent CMPs drawn from a slant design survey in Canada illustrating the natural 2D periodicity of the vector offset sampling. An OVT binning approach (left) naturally fits the data distribution unlike a sectored binning scheme (right).*

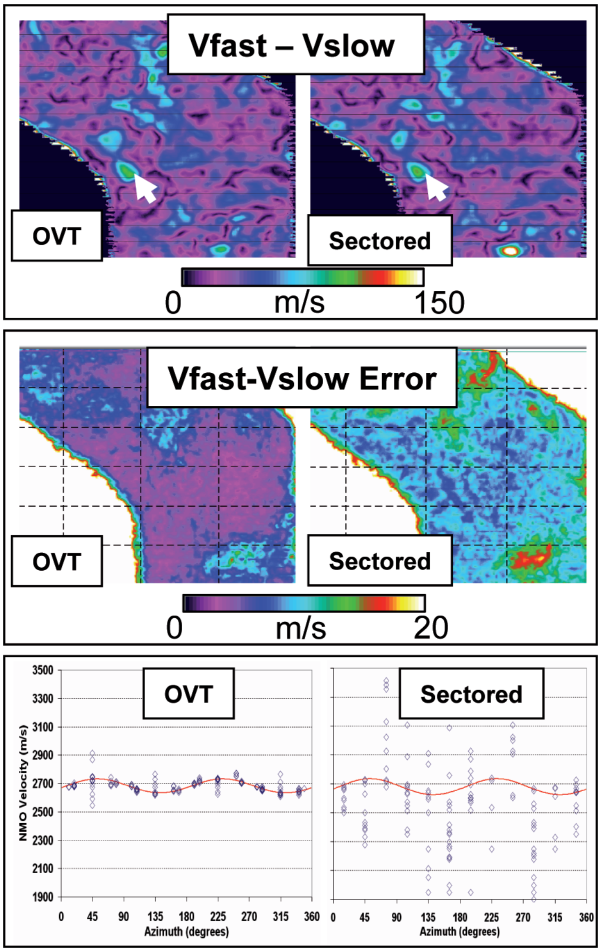

***Figure 3** Vfast-Vslow anisotropy results (top) and associated standard error estimate (middle) from post migration surface-fitting of OVT (left) and sectored (right) PreSTMs. Although similar, the OVT result appears better constrained. The velocity fit to the data at a higher anisotropy location (top, white arrow) suggests less migration noise is present in the OVT result (bottom).*

from nearby traces resulting in subtle timing errors even for flat events. These observations are expected to be true in general but differences may diminish with increased survey density.

Including azimuthal anisotropy in migration

Once the azimuthal velocities have been determined, the data can be remigrated with a model and travel-time calculation that includes azimuthal anisotropy effects (Kappius, 2006). These azimuthal travel-times are calculated by using the appropriate velocity for the source to image point and image point to receiver azimuths. Figure 4 shows azimuth (0–180^0) sorted gathers from applying this workflow to another dataset acquired in Wyoming, USA. Some of the events imaged using an isotropic PreSTM velocity model contain a consistent variation in timing with azimuth which can be corrected for with an azimuthal RMO derived using surface-fitting. The azimuthal RMO partially corrects the gathers but some azimuthal residual moveout remains. However, when the data are remigrated using the same azimuthally anisotropic velocity field that was used for the azimuthal RMO, the resulting gathers are flatter than the RMO result. This result was unexpected. Our explanation and hope is that the inclusion of azimuthal effects in migration results in subtle improvements in relative positioning of the wide azimuth prestack images, resulting in gathers that more accurately represent the relative timing and amplitude of events as a function of offset and azimuth.

Some practical aspects

The OVT approach fundamentally assumes a regular survey geometry with consistently spaced and parallel shot and receiver lines. In practice, obstructions or exclusions often require significant deviations from this ideal. We have found that the OVT approach is surprisingly robust even in the presence of significant but randomly distributed survey irregularities. In these situations additional steps need to be taken to compensate for fold variations and to remove large pre-migration gaps that are populated by migration swing. Consistent or progressive differences in line spacing are problematic. This situation will probably most often arise when attempting to merge two or more surveys with different line spacings or orientations. These surveys cannot be imaged using a single set of OVT parameters. The surveys either need to be imaged separately with different OVT parameters or some form of regularization needs to be applied to transform the surveys to a common acquisition grid. A simplistic approach is to do this by trace borrowing and trace header manipulation but higher dimensional regularization and interpolation (e.g., Liu and Saachi, 2004) is a better solution.

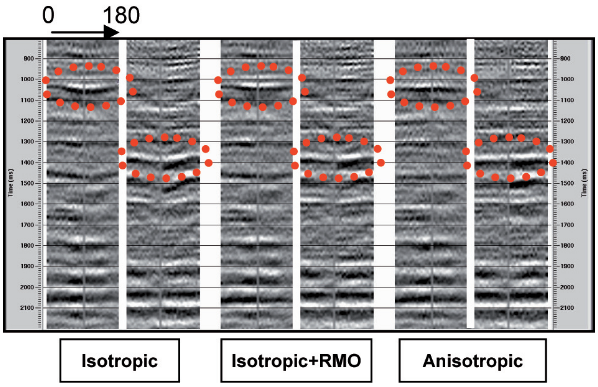

***Figure 4** Example pair of azimuth sorted gathers (0-180 degrees) from isotropic OVT PreSTM (left), OVT PreSTM + azimuthal RMO (middle) and OVT PreSTM using the same azimuthal velocities used for the azimuthal RMO (right). The fast direction is approximately N-S. Note slight further gather flattening by accounting for azimuthal velocities in PreSTM.*

Even if the survey is very regular, the line spacings and associated vector offset ranges can be so large that using the standard OVT binning scheme described above may produce only a few unique scalar offsets for velocity analysis. It is valuable to understand that although the tile must have certain dimensions, there is no constraint on the absolute location of the tile. One can define overlapping or random brick patterns of tiles to broaden the range of available offsets or even focus on a particular azimuth of interest.

A first step to assessing the suitability of a survey for azimuthal analysis using OVT migration is to determine the nominal fold for offsets less than or equal to the depth of interest. As azimuthal NMO analysis is usually constrained to approximately this offset range, where moveout is approximately hyperbolic, this is the approximate number of unique non-overlapping tiles available for analysis. The number of tiles required to obtain a robust result will depend on the data quality. Thirty to 40 unique tiles should provide sufficient statistics for inversion of event travel-times for three anisotropic velocity parameters but we continue to test increasingly sparse surveys to understand where these limits lie practically.

Cross-spread gathers and OVT volumes also offer an opportunity for data conditioning and regularization before migration. Both data subsets, when sorted by inline and crossline, produce 3D volumes with adjacent CMPs sampling the subsurface with similar offsets and azimuths. The progressive variation in offset and azimuth in a cross-spread gather make them a suitable domain for applying 3D algorithms such as F-Kx-Ky for coherent noise attenuation or FXY deconvolution for attenuation of incoherent noise. FXY has also proven very effective for attenuating incoherent noise in OVT volumes. Even though the full dataset is wide azimuth, perhaps leading one to believe that 5D interpolation is required for prestack interpolation, lower dimensional interpolation (2D or 3D) can be effective if the data is sorted to cross spreads or OVT volumes. Missing stations result in the loss of a single line or line segment of CMPs in these domains, so even simple 2D interpolation can be quite effective. OVT volumes also offer one further opportunity when large acquisition holes are present. As source-receiver reciprocity is rarely a bad assumption for P-wave data, traces can be shared between reciprocal tiles to fill holes. If the survey is particularly ill-behaved, we have even found it advantageous to stack traces from reciprocal tiles after apply residual NMO to the nominal tile offset.

The examples shown have all been drawn from onshore prestack time imaging projects where azimuthal anisotropy can be significant. OVT has also been proven very effective for isotropic depth imaging and velocity model building for wide azimuth marine streamer surveys (e.g., Michell et al., 2007). Areas of ongoing research include extending the techniques described in this paper to increasingly irregular surveys and more challenging imaging environments.

Conclusions

OVT and cross spreads offer many practical opportunities for today's modern wide azimuth surveys. PreSTM using vector offset binning provides data well suited to azimuthal analysis when used in conjunction with surface-fitting. The resulting attributes appear better constrained than those produced by conventional sectoring. The azimuthal analysis results can be used for a further migration including azimuthal anisotropy in the travel-time calculations that may produce additional improvement in gather flatness and stack quality. OVT appears effective for a greater variety of survey geometries than perhaps previously thought. Sorts into cross-spread and OVT gathers also offer many opportunities for data conditioning and regularization prior to migration.

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