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Estimation of Uncertainties in Fault Lateral Positioning on 3D PSDM Seismic Image - Example from the NW Australian Shelf

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SUMMARY

We present a two-step sequence to estimate uncertainties in lateral positioning of fault planes on 3D PSDM seismic images.
The first step provides an approximate evaluation of what causes the uncertainties, how uncertainties are distributed in 3D space and what to expect within our target zones. At this step we create a qualitative 3D volume of lateral fault position uncertainties that depend on complexity of the overburden and the seismic acquisition parameters.
In the second step we focus on a single fault of practical interest. Based on the results of the first step we modify the existing 3D PSDM anisotropic velocity model by introducing additional anomalies that cause maximal changes to the lateral position of the fault on seismic image. Then we iteratively re-migrate a small sub-volume around the fault and check the PSDM images and residual moveout. We assess how far the velocity changes can move the image of the fault and still satisfy the available seismic data. The second step gives more reliable quantitative uncertainty estimations for a single location within the general uncertainty volume produced in the first step.
We use a real multi-azimuth 3D seismic dataset from the North-West Australian shelf to illustrate this sequence.

Introduction

Depth-velocity models that we create in seismic data processing always have some level of uncertainty. This is due to two groups of effects.

Firstly: real seismic data have limited bandwidth and signal/noise ratio; reflectivity on some geological boundaries can be too weak and illumination is restricted by the acquisition parameters. These factors lead to errors (or uncertainties) in our velocity estimations.

Secondly: we use certain mathematical models to process the seismic data. These models describe major wave propagation effects, however reality is more complex than our models and this results in additional errors.

The first type of depth-velocity uncertainty is caused by "technical" errors occurring in depth-velocity estimation with a given processing model while the second type is caused by problems within our processing model itself.

It is important to understand how these uncertainties affect results of seismic data interpretation. In this paper we present how we evaluate velocity related uncertainties in lateral fault positioning.

Uncertainties in imaging PSDM velocity models and lateral fault positioning.

Faults are important components of geological models. Migrated seismic images are the major source of information about fault spatial locations. Errors in overburden velocities can move the seismic image of a fault away from its true position. Many of our targets in the NW Australian shelf are fault bounded traps. Understanding fault uncertainty has important implications for drilling as it impacts well trajectory and planning and ultimately well cost.

A fault can be picked on a seismic image either based on terminations of seismic events displaced by the fault or, in some cases, using the reflection of the fault plane itself. In this paper we deal with faults as determined by the terminations of seismic events. Images of the terminations are formed by diffracted and reflected waves with the major part of the relevant seismic energy traveling in near vertical direction. We analyze how these images can be moved laterally by possible velocity errors in the overburden. This analysis is fully applicable to any localized detail on a seismic image but, in the majority of geological settings, it is most important for the faults. Fault plane reflections, which we often see on seismic images, are formed by seismic energy that has traveled longer distances along rays with high angles. They are more affected by velocity and anisotropy variations in the overburden than events terminating against the faults. In general, their positions on seismic images are less reliable than the terminations. We do not include the fault plane reflections in our analysis.

Figure 1A illustrates how a seismic image can be moved laterally by a shallower velocity anomaly. There are some rules that describe this effect:

A. A velocity anomaly size should be comparable with the area covered by rays forming the image point (F on figure 1A). Smaller velocity anomalies will turn only a part of the rays, which affects the clarity of the image without the lateral movement. This depends on the acquisition direction and parameters.

B. The lateral image displacement (LD on figure 1A) is proportional to the distance between the velocity anomaly and the target (D on figure 1A). As a result, shallower anomalies are more "dangerous" than the deeper ones.

C. In the North-West Australian shelf, and in many other regions, the majority of velocity anomalies have elongated shapes (like channels, bars etc.). Azimuthal relationships between the axis of a velocity anomaly, a fault plane direction and the acquisition direction are important for the uncertainty of the fault position. Figure 1B gives an example. Sea floor channels create strong velocity gradients in direction across the channels (along the red arrow). This may cause significant lateral movements of seismic image along this direction. The position of the fault AA on the seismic image can change dramatically but the fault BB is not affected as it would move along its own plane.

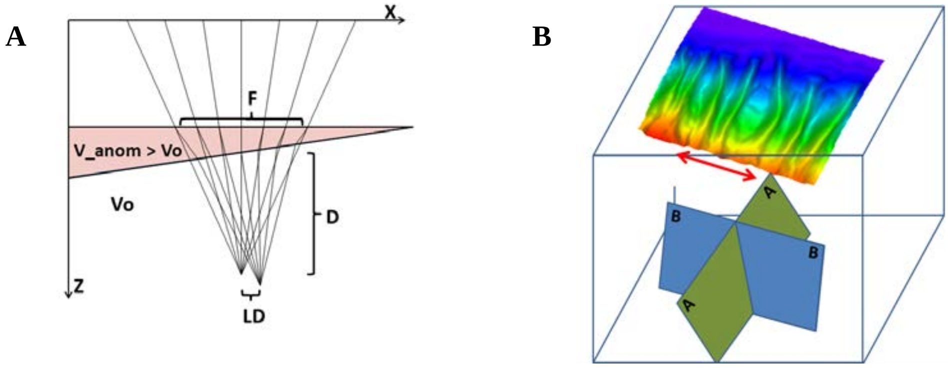

Figure 1 *(A) Ray diagram for a velocity anomaly causing lateral image displacement, (B) Faults potentially affected by velocity variations associated with a rugose sea floor. See text for details.*

Step 1. Qualitative evaluation of lateral uncertainties in 3D seismic images.

Usually PSDM velocity modelling starts with a smoothed initial model (figure 2A). All small scale details are introduced later based on seismic data moveout (figure 2B). After creating the final velocity model (figure 2C) we want to evaluate uncertainties associated with this model. The transformation of localized variations of seismic moveout (figure 2B) into localized velocity anomalies (figure 2C) is always affected by the two types of errors/uncertainties mentioned in the introduction. Stronger velocity/moveout anomalies lead to higher uncertainties.

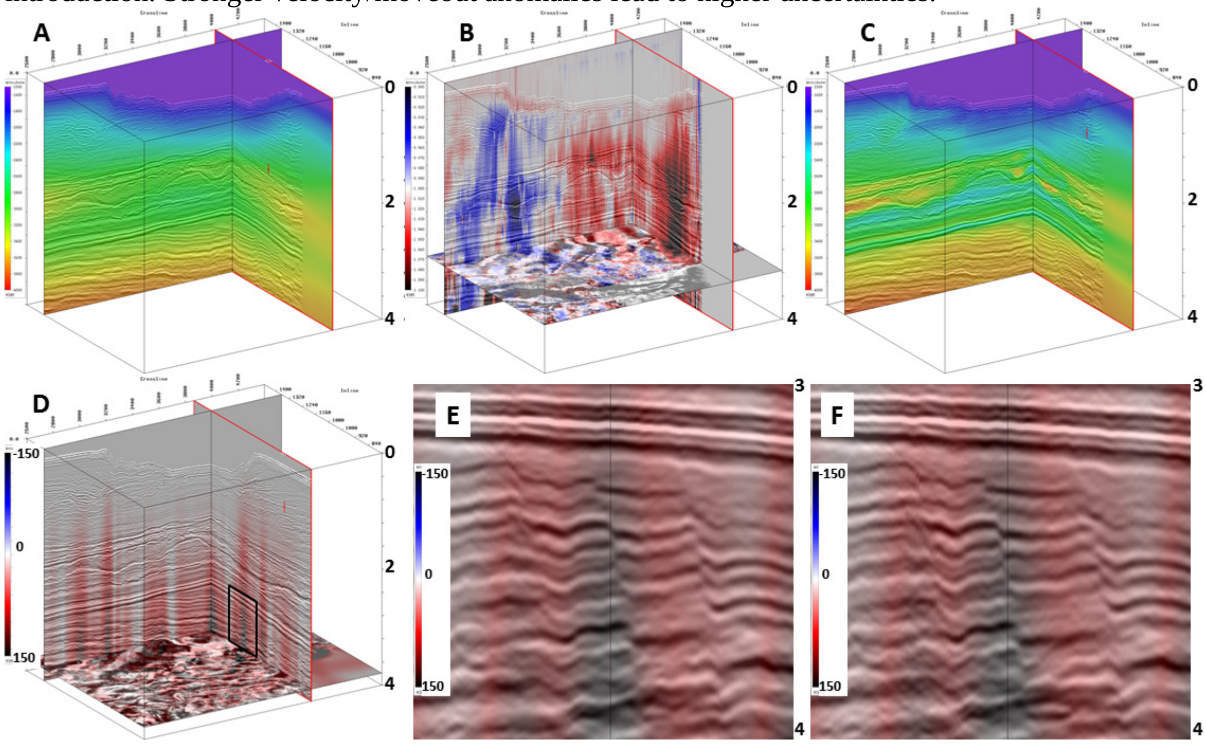

Figure 2 *(A) initial velocity model; (B) residual moveout picked after PSDM with the initial velocities; (C) final PSDM velocity model; (D) uncertainty in lateral fault positions (absolute values); (E) zoomed 3D PSDM image (area marked on D); (F) the same shifted laterally by predicted values of lateral uncertainty. The black line marks the same location on both images. The fault at depth 3500m moves laterally by approximately 100m. Data courtesy Chevron Australia Pty Ltd.*

We apply a spatially and azimuthally variable smoothing to the final PSDM model to extract velocity anomalies that can potentially cause lateral movements of the seismic image. We run the ray-tracing for the image rays from the surface to the bottom of the model with and without those velocity anomalies to see how each point of the 3D seismic image can be moved laterally (figure 2D).

At this step we have not yet produced a reliable quantitative assessment but rather an approximate evaluation of what causes the uncertainties, how uncertainties are distributed in 3D space and what to expect within our target zones. The uncertainty volume (figure 2D) illustrates the rules A-C that we discussed earlier. We calculate the lateral uncertainty as a vector with X and Y components; figure 2D shows the absolute values but, as discussed earlier, the direction is also important.

In order to help visualise and present these uncertainties, we can laterally shift each sample of the 3D PSDM seismic volume by predicted uncertainty values and compare the modified seismic cube to the original one (figures 2E-F). It is difficult to see and analyse the difference on static side-by-side displays (like figures 2E-F) but when presented on a workstation screen such comparison quickly gives an idea of what these uncertainties can mean for the interpretation results. At this stage, the image comparison ignores vertical shifts and defocusing effects inevitably associated with velocity changes in the overburden.

Step 2. Quantitative analysis for a fault of practical importance.

In practice, our attention is focused on a limited number of faults where understanding their uncertainties has practical importance, for example, faults near a future well trajectory or faults that can change volumetric estimations or development plans. We apply a detailed quantitative uncertainty analysis for such faults. Each fault is analysed separately. Based on the results of step 1 we identify intervals (or geological bodies) in the overburden that cause maximum uncertainty for the target fault. Then we try to move the seismic image of the fault by introducing additional lateral velocity variations within these intervals of the overburden. Our objective is to find out how far the velocity variations can move the image of the fault and still satisfy available seismic data.

We create several alternative velocity models and re-run PSDM for each model within a limited area around the fault. We cannot allow any noticeable increase in the residual moveout on PSDM gathers, as this would indicate that the given modifications of the velocity model are not acceptable. The best way to minimize changes in the moveout is to simultaneously update both vertical velocity and anisotropy. Such simultaneous velocity and anisotropy updates for localized anomalies can preserve residual moveout within the anomalies but still cause changes in residual moveout at deeper intervals (Artemov and Birdus, 2014). When we change the velocities to shift the fault image laterally, it inevitably causes some vertical movements on the seismic image. So, trying to move the fault laterally, we check the following: (a) residual moveout should stay within the original level at all depth intervals; (b) vertical movements on the seismic sections should be acceptable; (c) the sharpness of the seismic image should not deteriorate; (d) velocity and anisotropy models should stay geologically plausible. Working this way, we evaluate both types of uncertainty that were mentioned in the introduction: (1) "technical" errors should not increase residual moveout above the existing level and (2) possible changes in processing model (in our case related to velocity-anisotropy uncertainty) should be geologically plausible.

We applied this analysis to the main bounding fault of a major gas field in the NW Australian shelf (figure 3). The fault is positioned beneath the rugose shelf break and complex overburden. The uncertainties in the fault lateral position are primarily caused by shallow velocity variations (area marked by yellow ellipse on figure 3A). The area was recently covered by MAZ seismic data (three narrow azimuth surveys with 60 degrees difference in the acquisition direction) and the MAZ 3D PSDM project was completed in 2013.

We did quantitative uncertainty analysis for two acquisition directions: near-orthogonal (figure 3) and near-parallel to the fault plane. We determined that the uncertainty in the lateral fault position at a target depth of 3000m was 30m for the near-orthogonal and 90m for the near-parallel acquisition directions. In our case, the uncertainty range was controlled by the increase in residual moveout at deeper intervals (marked by the green ellipse on figure 3F) and geologically unacceptable changes in the anisotropy model that we had to make to preserve the moveout in the shallow section (the yellow ellipse on figure 3E). These results confirmed that the tolerance we were using for well placement in the vicinity of faults was acceptable, i.e. larger than the uncertainties in the fault position.

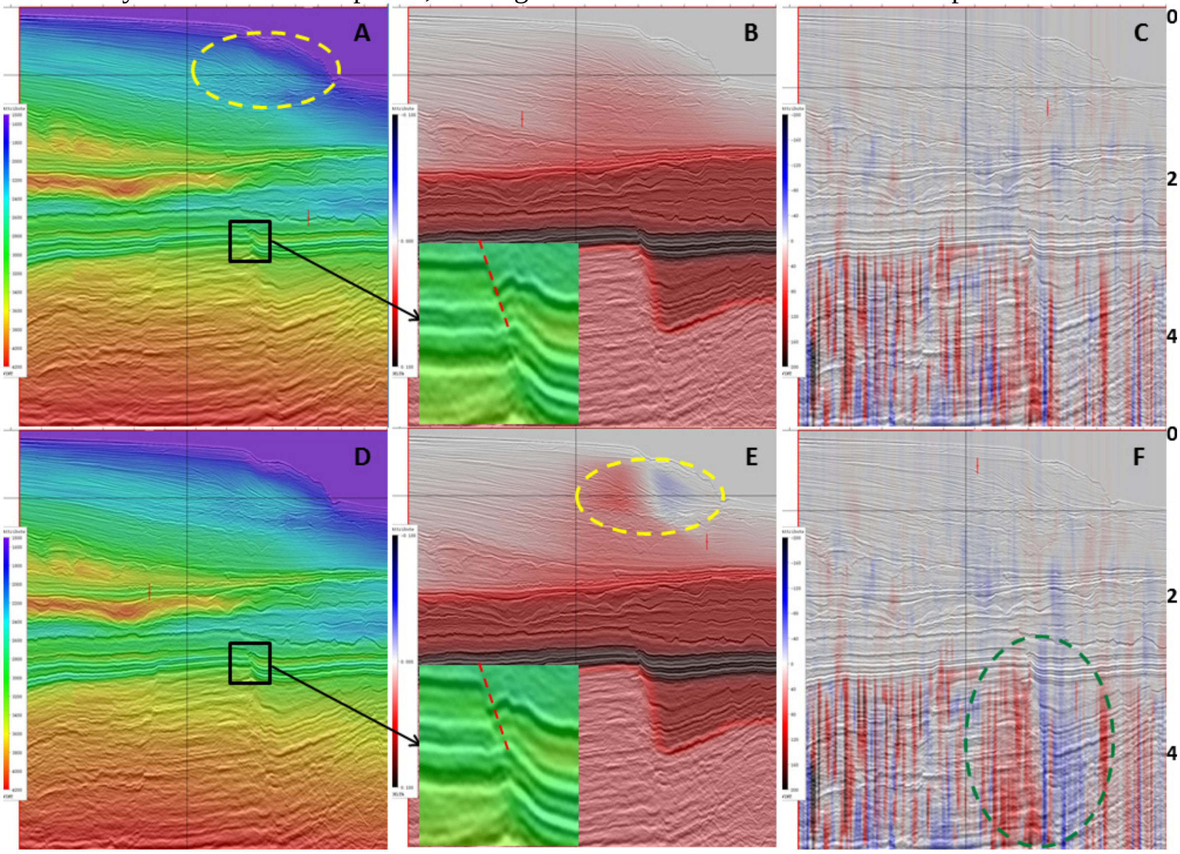

Figure 3 *Attributes used for the quantitative analysis. The upper row corresponds to the final production 3D PSDM model. The lower row corresponds to the model modified to produce maximal lateral shift for the target fault image (approximately 30m in this case of the acquisition orthogonal to the fault). A, D – velocity models overlaid on corresponding PSDM images; B, E – anisotropy δ; C, F – residual moveout. Data courtesy Chevron Australia Pty Ltd.*

Conclusions

The presented workflow estimates uncertainties in lateral fault positioning on 3D PSDM images in two steps: general qualitative analysis for the whole 3D PSDM volume and then detailed quantitative study for selected faults of practical interest. We demonstrate its successful application to the main bounding fault of a major gas field in the NW Australian shelf.

Acknowledgement

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References

Artemov. A., Birdus, S. [2014] Reducing geologically significant structural uncertainties in anisotropic depth-velocity modeling in settings typical for the North-West Australian shelf. 84th Annual International Meeting, SEG, Extended Abstracts.