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Seismic modeling and expression of common fold-thrust belt structures

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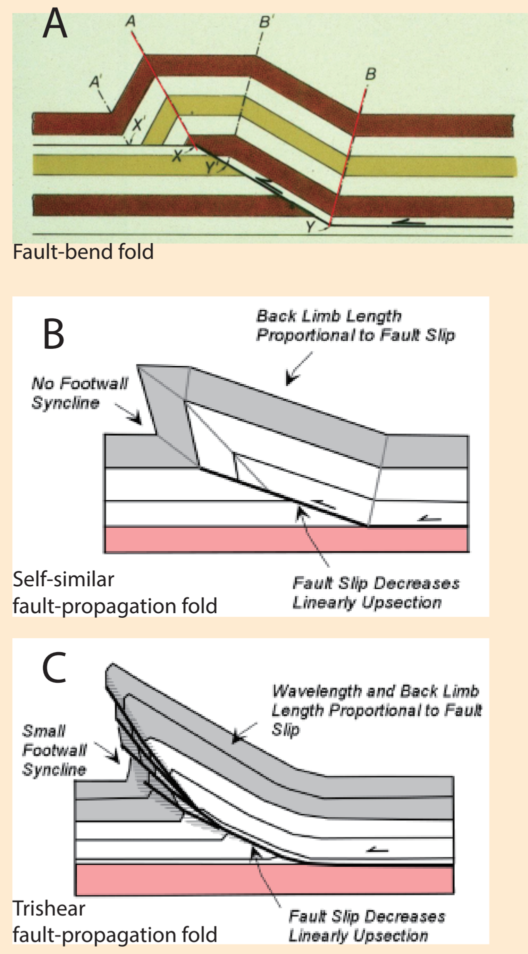
Introduction



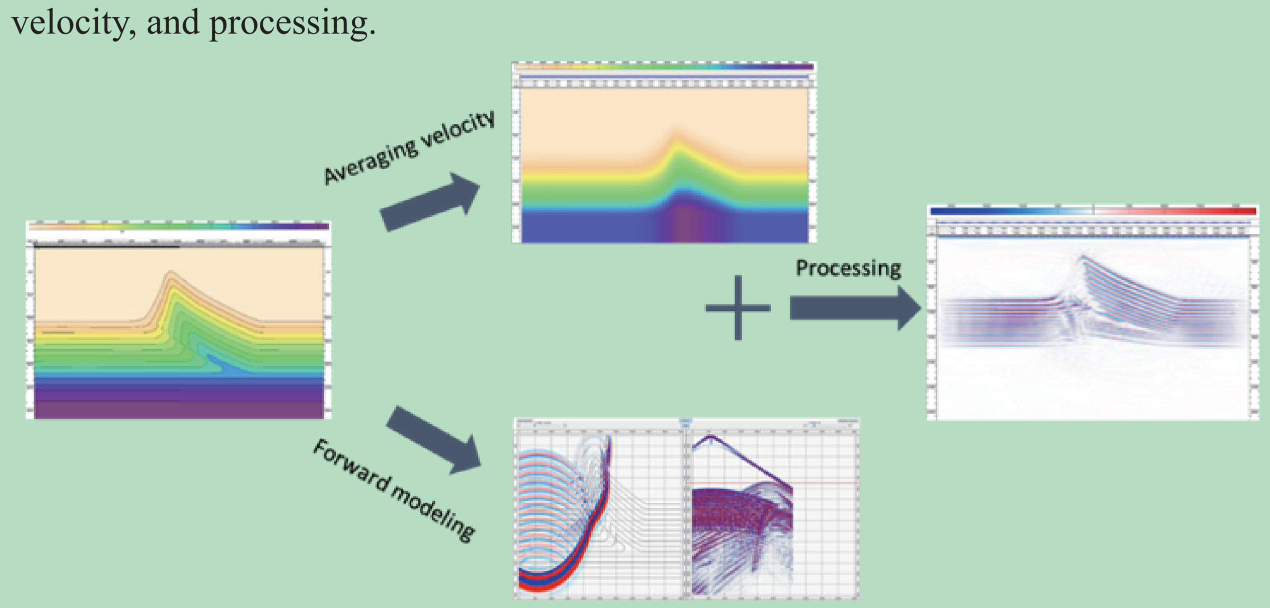
Seismic modeling can be used to understand the expression of common fold-thrust structures in seismic line and depth sections, and to aware of pitfalls in the seismic interpretation of natural structures. Modeling of seismic time sections using pre-stack time migration was conducted for fault-bend folds and fault-propagation folds (self-similar and trishear model). The fault-bend fold model features a gentler front limb compared to other models (Figure A). The self-similar fault-propagation fold model has overturned front limb with constant thickness which is the same as the layer thickness of the back limb and horizontal beddings (Figure B). The trishear fault-propagation fold model features a small footwall syncline (Figure C). The length of the back limb is proportional to fault slip and the front-limb structure is controlled by the propagation to slip (P/S) ratio. Five trishear fault-propagation fold models with various fault slip and P/S ratio were studied.

The velocity model of each structure in depth was built in Tesseral Pro software and the shot gathers were acquired by running the forward modeling. Next, the velocity model is averaged and used for pre-stack time migration. The processing procedure of this study is following a typical 2D seismic processing procedure, however, the velocity picking procedure is replaced by velocity averaging in the softwear to produce a perfect velocity picking senario. The pre-stack time migrated data of each structural model was analyzed afterwards. In terms of trishear fault-propagation fold models, the characteristics of trishear models with increasing fault slip and models with increasing P/S ratio were discussed separately. Moreover, this study involves the analysis of the velocity picking error that might happen in real-life processing case where the velocity of the steep angle beddings is hard to pick.

Methods and Parameters

To study the seismic signature of a common fold thrust belt, the seismic forward modeling method was used. Seismic forward modeling is the seismic forward realization of a given earth model (Fagin, 1991; Alaei, 2012).

A complete workflow of a seismic forward model involves three major parts: forward modeling, averaging velocity, and processing.



The forward modeling starts with building the velocity model in depth. The model is polygon based therefore each velocity variance is bounded by a polygon. A simple velocity polygon will include compression velocity, shear velocity, and density. The velocity models in depth were built in Tesseral Pro program. And the elastic wave forward modeling was conducted in the same program. The shotgathers and wave propagation snapshots are saved and ready for processing and further analysis. The velocity of the layer ranges from 2500m/s to 4300m/s. The velocity increment is 200m/s between two adjacent layers. The detailed parameters of the elastic wave forward modeling are shown in the table.

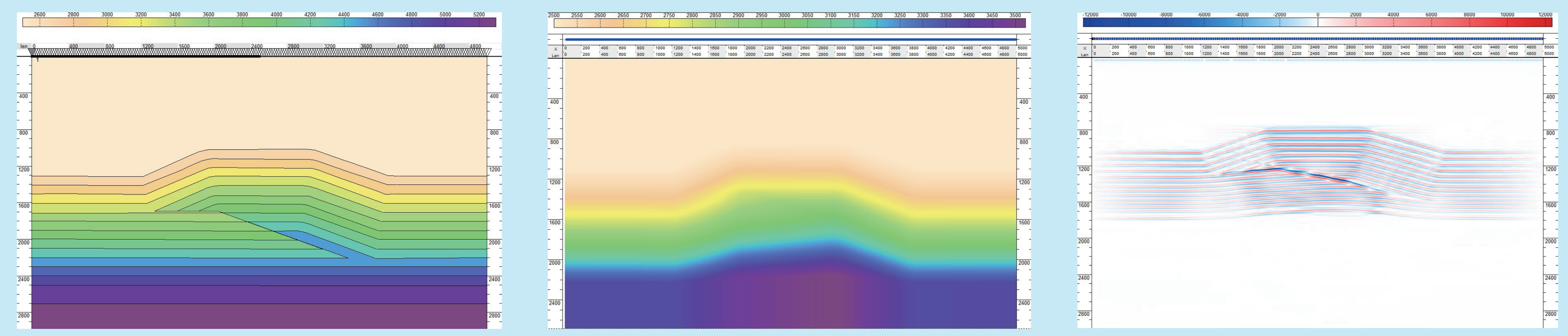
Wave form	Frequency	Source No.	Receiver No.	Source interval	Receiver interval
Ricker	25 Hz	201	401	25 m	12.5 m

The velocity model built at the beginning is in depth domain, however, the migration of the shotgathers needs a velocity model in the time domain. A depth-time conversion of the velocity model wouldn't produce a realistic velocity model for the time migration because the actual velocity picking procedure done in the real case cannot reproduce the actual layering of the underground. Therefore, the velocity is averaged in the time domain which is simulating a perfect velocity picking process.

The shot gathers are processed using pre-stack time migration instead of post-stack time migration. Since we have the averaged velocity model in time for the migration, there is no need to acquire the stacking velocity, therefore, the pre-stack time migration takes fewer steps than post-stack time migration.

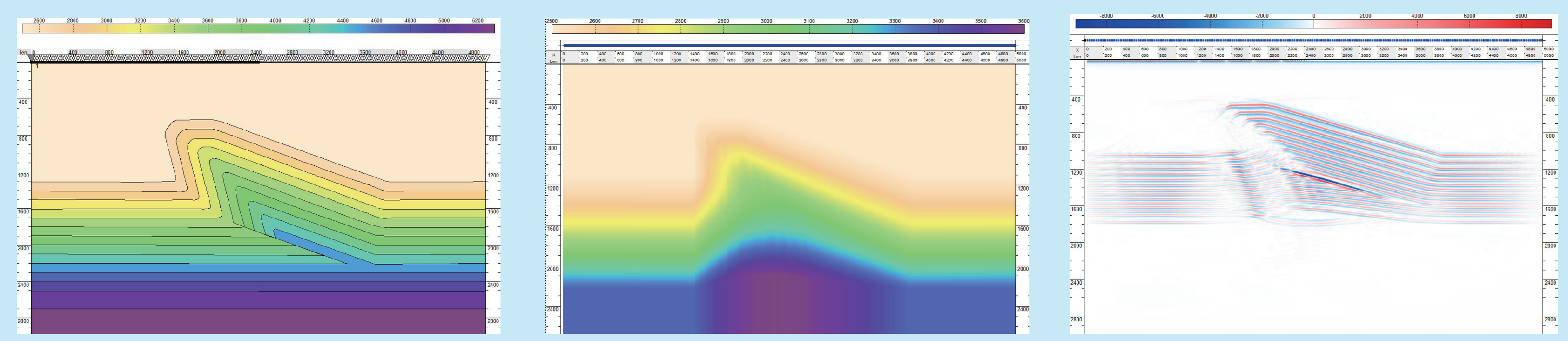
Results and Analysis

Fault-bend fold



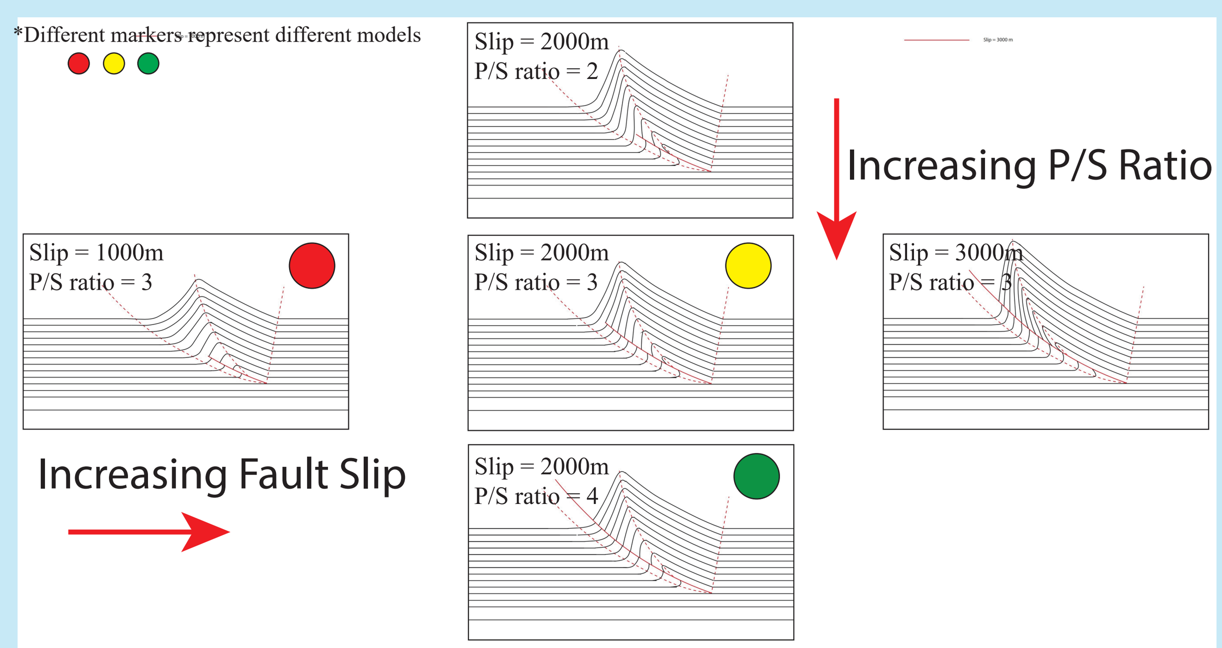
A fault-bend fold is characterized with a detachment connected with another detachment by a thrust ramp (20° in this case). Therefore, it has flat-ramp-flat type of feature for the fault. The key feature that distinguish it from a fault-propagation fold under seismic is the gentle dipping front limb. In the pre-stack time migrated data, the front limb and back limb are well imaged. The pull-up effect is noticeable. It is caused by the lateral average velocity changes for the crest.

Self-similar fault-propagation fold



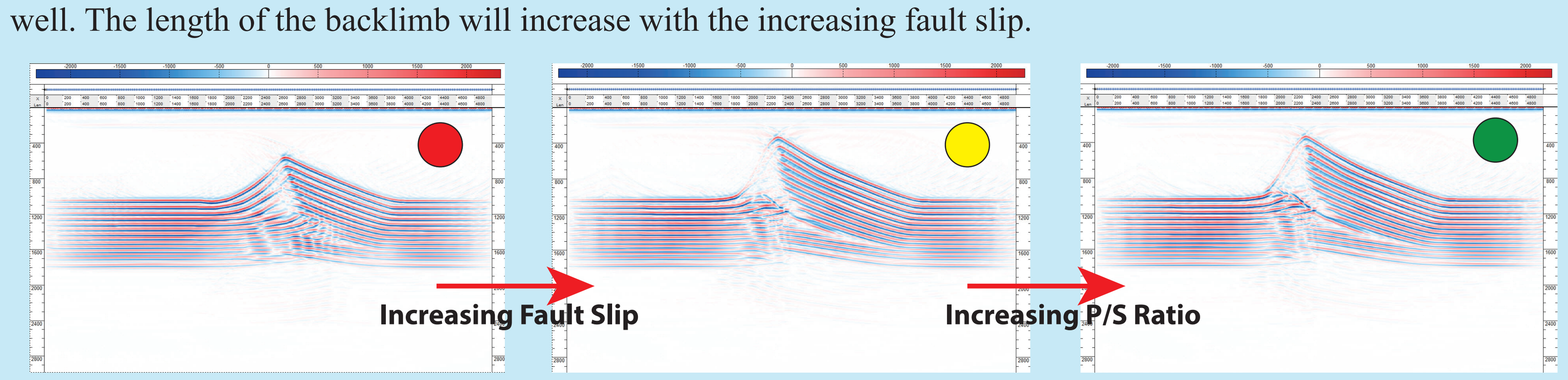
A self-similar fault-propagation fold is featured with an overturned front limb. That makes the imaging of the front limb of the fault-propagation fold structure not good. This "gap" could be easily misinterpreted as a damaged thrust fault zone. Compared to the fault-bend fold, the pull-up effect is more distinct because of higher crest.

Trishear fault-propagation fold



With increasing P/S ratio, the fault length will increase. The dips of the front limbs are decreasing with increasing P/S ratio. The axial surfaces bounding the trishear zone remain the same position. The length of the back limb will remain the same as well.

With increasing fault slip, if the P/S ratio is constant, the fault length will increase and the fault trajectory will be curving up. The front limb will experience thinning with increasing fault slip. The dip of the front limb will increase as well. The length of the backlimb will increase with the increasing fault slip.



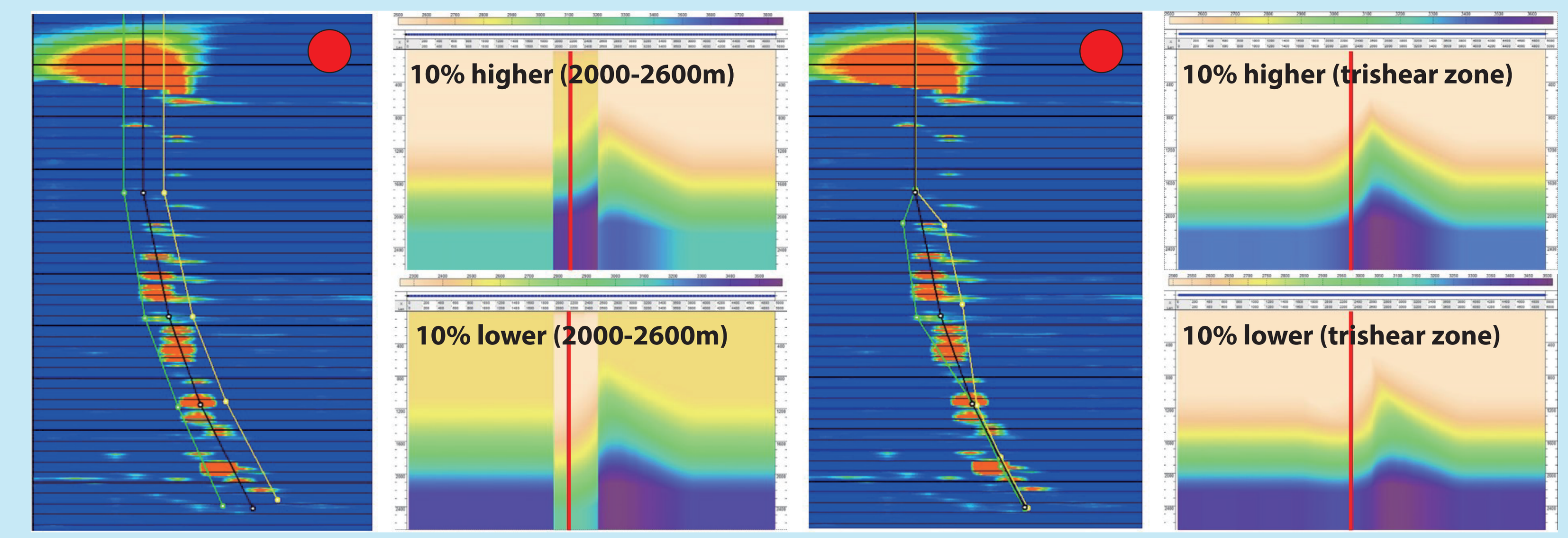
Back limbs are generally imaged better because of the shallow dip. Within the trishear zone (bounded by axial surfaces), as the depth getting deeper, the front limbs are imaged worse and worse because of steeper dip. With increasing P/S ratio, the front limbs can be imaged better because of shallower dips. However, increasing fault slip has an opposite effect.

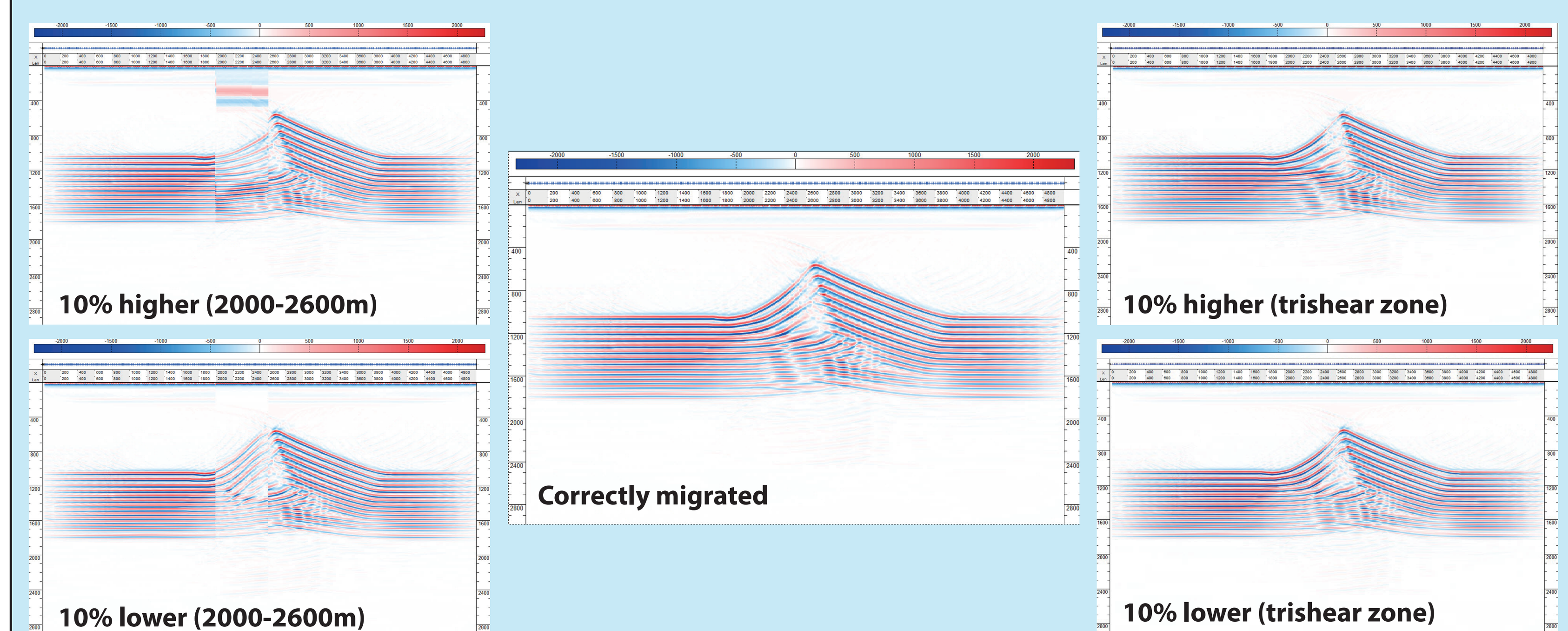
The reflection coefficient is opposite for the fault reflections compared to the bedding reflections because they have opposite velocity contrast. The length of the fault reflectors is long and more continuous with higher fault slip and P/S ratio.

There is a distinct "pull-up" effect under the fold. The cause of this effect is the horizontal velocity differences within the fold. The averaged velocity model is clearly illustrating the velocity changes vertically as well as laterally. The lateral velocity change rate determines the appearance of the "pull-up" effect. In our models, the dip of the bedding controls how fast the velocity is changing laterally. There is no lateral velocity change when the bedding is horizontal, while steeper bedding will cause faster lateral velocity change. Below the back limb, the beddings are gradually pulled up along the lateral increasing of the bedding velocity towards the center of the crest. However, with shorter distance because of the steeper front limb, the pull-up height appears to be more severe. And the highest pull-up effect will move further towards the front as the slip amount increases.

Velocity error effects

Two types of velocity error scenarios are investigated. One type considers that the velocity error happens with traces between 2000m and 2600m (left half). The velocity error is 10% higher (yellow line) or lower (green line) for the whole trace. The other type is that the velocity error only happens within the trishear zone (right half), therefore the velocity error only affects the certain depth where the trishear zone covers.





With higher velocity, the horizons within the edited zone are pushed down clockwise so the dips are shallower than before. The amplitude of the front limb is dimmer than before as well. The effect of the velocity increase on the front limb appears to be bigger than the effect on the horizontal layers underneath it. The front limb horizons look closer and subparallel to the underlying horizontal horizons. Closer to the 2000m boundary, the offset of the horizon is not pronounced compared to much larger offset at the 2600 boundary.

With 10% lower velocity, the front limb horizons are lifted counter-clockwise. The dip of the front limb is steeper. The gap between the front limb slope and the underlying layers becomes larger.

To conclude, the horizontal layers are not affected by the velocity error significantly. The tilted layers like the front limb in our models will be overmigrated when the velocity is higher or undermigrated when the velocity is lower than it supposed to be. The overmigration will cause the dip to be smaller while the undermigration will increase the dip.

The previous example is an extreme case to study the general effect of the velocity error. One of the more realistic scenario is incorrect picking of the velocity caused by the weak signal reception from the trishear zone.

With 10% higher velocity within the trishear zone, compared to the correct migration result, the front limb layers are less parallel. From the front to the back, the front limb exhibits fan shape. The horizons within the trishear zone are pushed down clockwise so the dips are shallower.

The front limb layers reflectors are closer and more parallel to each other for the model with 10% lower velocity in the trishear zone.

The amplitude of the reflections is not obviously affected. Compared to the velocity error band models, the models with trishear velocity error exhibit more continuous horizons between the velocity error zone and surrounding layers. It is also obvious that the averaged velocity model looks smoother laterally.

Conclusions

- The fault-bend fold with gentle fault dip can be imaged quite well after pre-stack time migration.
- The overturn of the frontlimb in the self-similar fault-propagation fold cannot be imaged properly.
- The pull up effect caused by the lateral velocity variance cannot be solved by pre-stack time migration.
- For trishear fault-propagation fold, with lower fault slip or higher P/S ratio, frontlimb has lower dip therefore can be imaged better.
- The length of the fault reflector is longer and more continuous with higher fault slip and P/S ratio in trishear fault-propagation folds.
- The reflection coefficient is opposite for the fault reflection compared to the bedding reflection because of the opposite velocity contrast.
- For the frontlimb reflectors, lower velocity can lead to undermigration while higher velocity will cause overmigration.

References

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Fagin, S. W. (1991). Seismic modeling of geologic structures: Applications to exploration problems. Society of Exploration Geophysicists.