2D Area-Depth analysis

Area-Depth Analysis provides a simple method of validating interpretations and understanding structural evolution. The 2D Area-Depth tool in Move™ is a versatile tool for validating interpretations, predicting detachment depths, predicting displacement, and investigating strain partitioning between faults and folds. In this monthly feature the method is introduced and a simple application of the technique is shown using a compressional example from the Gulf of Mexico. In addition to the simple example, the technique is applicable to multiple tectonic settings, can provide information about strain distributions in complex structural settings (e.g. Groshong et al. 2012) and has been used to validate velocity models (Totake et al. 2017).

Area-Depth analysis

Constrained model building techniques (e.g. geometric fault prediction and depth to detachment calculations) are valuable methods for understanding structural evolution and testing the validity of cross-section interpretations. Such techniques use known geological features to make predictions about unknown features, such as detachment depths, based on physical and geometrical assumptions. A key physical assumption is that material is conserved during deformation (Moretti and Callot 2012).

A simple application of the assumption of material conservation is to assume that bed length remained constant during bed deformation and use the measured deformed bed length (Observed Bed Length ($\boldsymbol{L_0}$) on Figure 1) to calculate the horizontal displacement:

$$Displacement\ (\boldsymbol{D}) = Observed\ Bed\ Length\ (\boldsymbol{L_0}) - \ Width\ of\ Structure\ at\ Regional\ (\boldsymbol{W})$$

Equation 1

If material conservation is true, the volume or area of material displaced by deformation (displaced area in 2D vertical section - ***S***) relative to a pre-deformational geometry must balance with the displaced rock volume or area at the boundary of the system. The pre-deformational geometry is often a horizontal surface known as the regional. In 2D vertical section, the calculated horizontal displacement (***D*** – Equation 1) combined with the displaced area (***S***) can be used to predict the dimensions of a rectangle whose vertical dimension defines the depth to detachment (***H*** - Chamberlain 1910, Groshong 2006), under the assumption that displacement was constant with depth.

$$Depth\ to\ Detachment\ (\boldsymbol{H}) = \frac{Displaced\ Area\ (\boldsymbol{S})}{Displacement\ (\boldsymbol{D})}$$

Equation 2

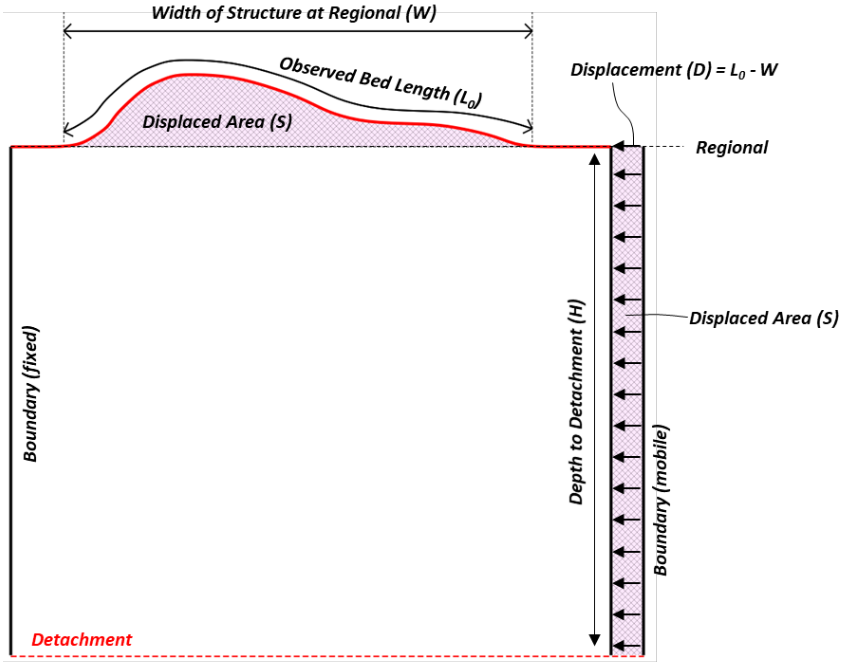

*Figure 1. A simple model illustrating the assumption of conservation of material (Chamberlain 1910). The left boundary of the model is fixed, the deformed bed is indicated with a sold red line, the detachment is illustrated with a dashed red line, the short black arrows indicate displacement vectors, and the displaced area (**S**) is shown in pink.*

A key assumption in this approach is that bed length is conserved during deformation (Groshong 2006). However, folding-related changes in bed length are common (Groshong *et al.* 2012). An alternative approach is to measure the displaced area for multiple horizon interpretations and to plot displaced area against the depth of the regional for each horizon – known as Area-Depth analysis (Groshong 1994, Groshong 2006; Figure 2).

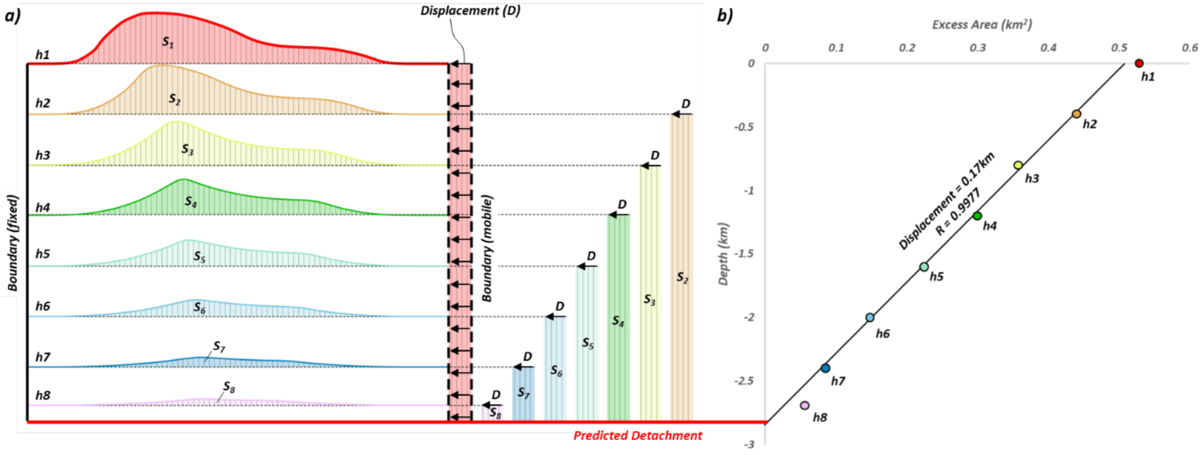

Figure 2. Area-Depth analysis of multiple horizons (h1 to h8). a) The area displaced relative to the regional during deformation shown for multiple horizons (Coloured polygons). b) Area-depth plot based on the relationship between displaced area and depth with best-fit line labelled for displacement and R.

For horizons deformed above a single detachment, it is expected that displaced area increases linearly away from the detachment (Figure 2b) and that the displacement is uniform with depth. Plotting of a best-fit straight line allows the y-intercept to be determined, which represents the depth of the detachment (depth at which no material was displaced); the inverse of the gradient of the best-fit line reveals the displacement (Groshong 2006). Importantly, the technique relies on volume (area in 2D) conservation alone, and is independent of changes in bed length during deformation.

Once an interpretation is made that represents a uniform displacement in each structural domain, results from the Area-Depth analysis (e.g. detachment depth and displacement) can be used to define a structural framework for further interpretation, for example, defining the evolution of displacement through time (e.g. identifying syn-tectonic units), and to assess changes in bed length during deformation (Layer Parallel Strain – LPS).

Worked example

An application of the Area-Depth tool is shown using a 2D seismic section from the Gulf of Mexico (Figure 3a). The data images the frontal thrust of the compressional domain of the Gulf of Mexico gravity spreading deformational system. High-amplitude reflectors are visible, however, uncertainties in the data remain, including the location of the thrust in the fault-propagation fold, the shape of the fault, and the correlation of horizons across the fold (Figure 3b).

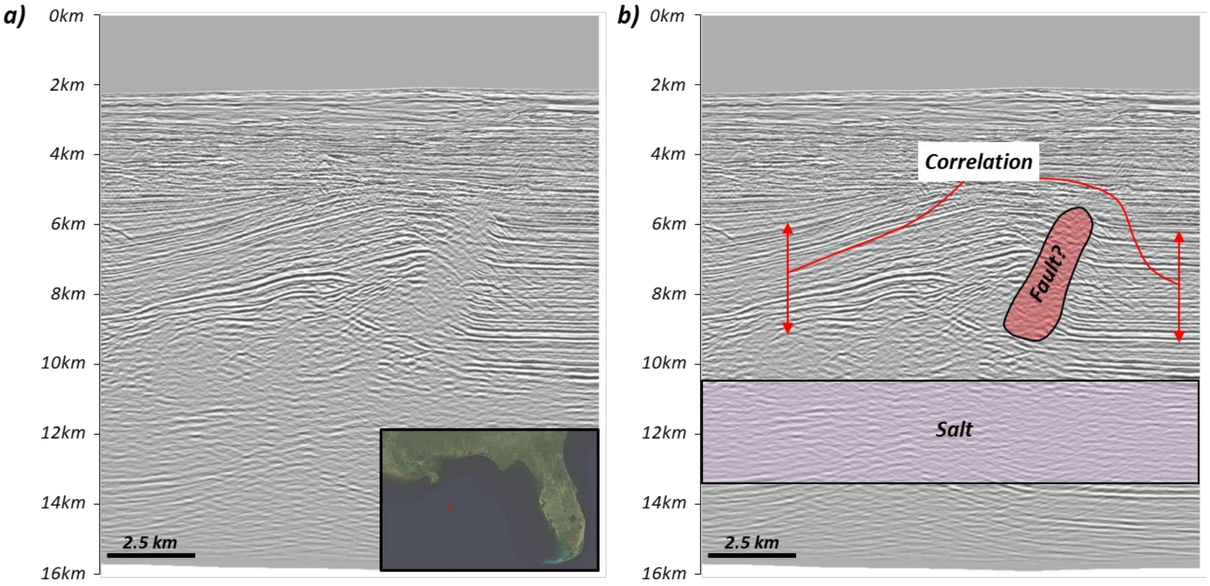

Figure 3. a) Seismic section from the Gulf of Mexico (location map is shown) with grey-scale colour map. b) Uncertainty in the correlation of seismic reflectors shown with red double-headed arrows and solid red line; in the position of the fault is shown by the red polygon; for the expected depth window of the salt shown by the pink rectangle.

An initial interpretation of the data was made, based on correlation of seismic reflector packages alone (Figure 4a). The interpretation included two post-tectonic units (h1 and h2), five syn-tectonic units (h3, h4, h5, h6, and h7), and five pre-tectonic units (h8, h9, h10, h11, and h12). The area-depth analysis of the initial interpretation showed a poor correlation between displaced area and depth in the pre-tectonic units (R = 0.4272; Figure 4b), predicting a detachment depth of 11.4 km, and a displacement of 3.3 km.

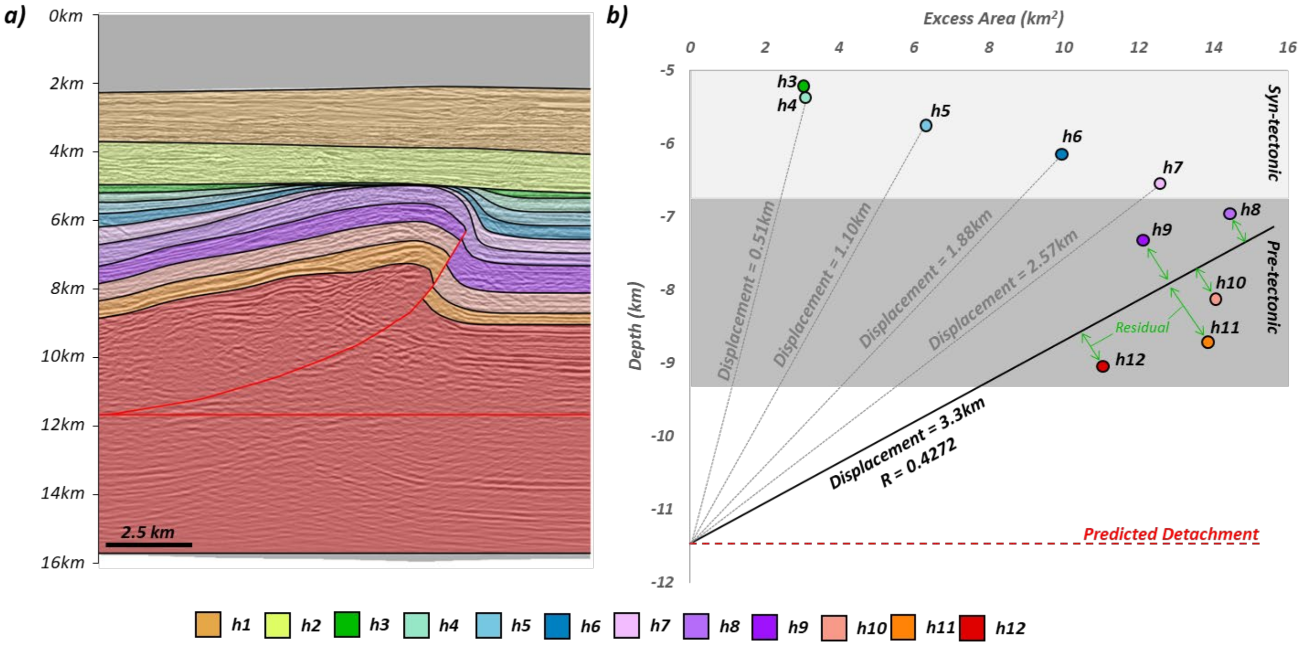

Figure 4. a) Initial interpretation of the seismic section based on correlation of seismic reflector packages. b) The displaced area for each of the horizons (h1 to h12) plotted against the depth of the regionals. The definition of a best-fit line indicated a poor correlation (R=0.4272) in the pre-tectonic units.

The poor correlation indicated that, despite the initial interpretation matching the data and looking sensible, when material conservation was considered, the interpretation of the pre-tectonic units (h8 to h12) represented a non-uniform displacement with depth (see residuals on Figure 4). The poor correlation between displaced area and depth might be associated with the data uncertainty (Figure 3b). To reduce uncertainty and improve the interpretation, geometric fault construction and kinematic forward modelling techniques were used. During this analysis, the correlation of horizons across the fault were found to represent inconsistent displacement and the interpretation in the footwall was updated (Figure 5a). The updated interpretation showed a very good correlation between displaced area and depth in the pre-tectonic units (R = 0.9993; Figure 5b), predicting a detachment depth of 14km, and a displacement of 2 km.

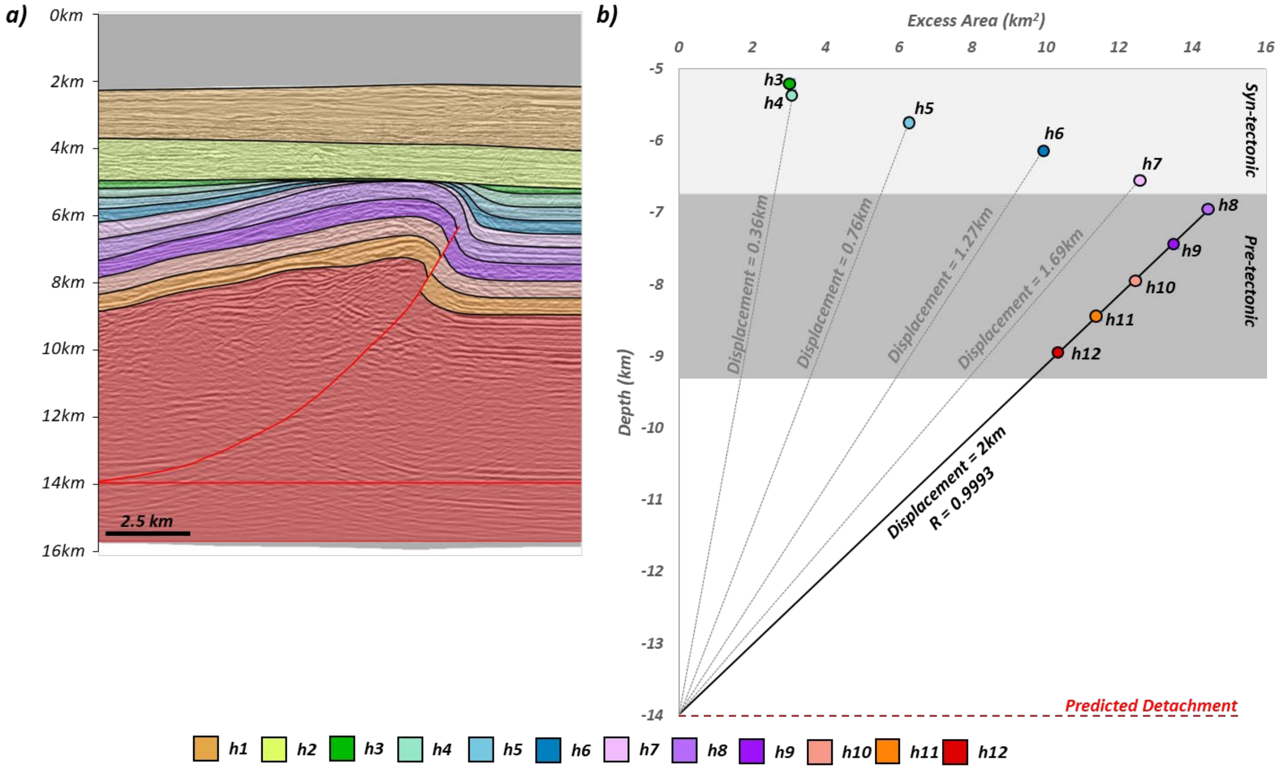

Figure 5. a) The interpretation of the seismic section updated after an initial Area-Depth analysis. b) The updated interpretation plotted on an Area-Depth plot. The best-fit line indicated the correlation in the pre-tectonic units was substantially improved (R=0.9993) by revising the horizon correlations.

Here we have shown the power of the Area-Depth method to identify problems in an interpretation and to guide workflows to remediate those problems. As we have demonstrated, Area-Depth analysis can be used to reveal information not immediately obvious from an interpretation such as detachment depth, displacement, and involvement of layer-parallel-shortening. This analysis can then be used for more sophisticated refinement and analysis of an interpretation, driving re-assessment of fault shape or horizon cross-fault relationships. It can be used to determine the evolution of displacement through time and its control on, for example, development of syn-tectonic units. Please contact us for more information about the implementation of Area-Depth analysis in Move™.

References

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