A Statistical Approach to Assessing Depth Conversion Uncertainty on a Regional Dataset: Cooper-Eromanga Basin, Australia.

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SUMMARY

Deciding on the most accurate grid based depth conversion method can often be an arbitrary choice made by geophysicists, particularly if previous research is limited. The importance of accurate depth conversion is particularly crucial in the Cooper-Eromanga Basin, where the presence of oil rich, low relief structural traps are questionable depending on the method used. Previous depth conversion studies are limited to local scales, limited well control and a focus on select horizons. To investigate the depth conversion uncertainty on a regional scale, this research performs a comprehensive and regionally extensive depth conversion analysis utilising 13 3D seismic surveys with 73 interpreted TWT grids and 657 wells. Depth conversions were performed using the 4 most commonly used methods; average (pseudo) velocity, time-depth trend, kriging with external drift using TWT, and kriging with external drift to tie stacking velocities to average well velocities.

To manage the large volume of data, a looping script was written to automate the depth conversion process and utilise the cross-validation, or blind-well method (use *n* wells to predict the $n^{th}+1$ well). Statistics on several variables were captured after each loop, with cluster analysis performed on the final data set to test variable significance on depth conversion accuracy. A database of approximately 10000 error calculations found that although the average velocity method is the most accurate at a high level (average absolute error ~24.9 feet), the best method and the expected error changes significantly (tens of feet) depending on the combination and value of the most significant variables. The variables which impacted uncertainty the most were; location (3d survey), formation, distance to the nearest well, and the spatial location of the predicted well relative to the existing well data envelope.

Key words: Cooper Basin; Eromanga Basin; 3D seismic data; depth conversion; velocity modelling.

INTRODUCTION

The introduction of three-dimensional (3D) seismic data has become almost essential for successful hydrocarbon exploration and development; the probability of a successful exploration well within 3D seismic data is >50%, in contrast to ~18% without (Aylor, 1998; Méndez-Hernández, 2003). 3D seismic data can provide an accurate image of the subsurface enabling petroleum companies to interpret and model subsurface structures, stratigraphy, reserves estimates and fluid dynamics. However, since seismic data is acquired in the time domain, an accurate time to depth conversion is essential, particularly in petroleum provinces, such as the Cooper-Eromanga Basin (Figure 1a), where the presence of oil-rich low relief structural traps changes on a local scale and can depend on the depth conversion method being used (Lowe-Young et al., 1997).

The Permian aged Cooper Basin is Australia's largest onshore hydrocarbon province, with the overlying Jurassic to Cretaceous aged Eromanga Basin consisting of low relief structural traps that contain the majority of the oil currently being explored for (Kulikowski et al., 2016a; Lowe-Young et al., 1997; Pokalai et al., 2016). To predict whether low relief structural traps exist within the province, geophysicists must select a depth conversion method that provides minimum error. However, as a detailed study had not been performed, many researchers adopt the most basic methods (Kulikowski et al., 2015; Kulikowski et al., 2016b), or choose to retain seismic data in the time domain (Kuang 1985; Apak et al., 1997; Hillis et al., 2001).

A seismic depth conversion analysis was performed by Hillis et al. (1995) comparing the accuracy of the interval velocity and velocity anomaly (Vo-K) methods; however, their research was restricted to a local study area and performed on two horizons, the Cadna-owie Formation and the Toolachee Formation. They showed that the velocity anomaly method is superior to the interval velocity method; however, these methods are not commonly used in the Cooper-Eromanga Basin. Subsequent research by Rady et al. (2006) and Joraandstad et al. (1999) investigated the depth conversation uncertainty on a local scale using average velocity, interval velocity and stacking velocity methods. These studies both focused on one 3D seismic survey consisting of 15 wells each and with a focus on Jurassic to Cretaceous aged horizons. Their results had contradicting conclusions albeit their research was performed using similar data sets.

To address the limitations in previous studies, this regional, grid-based study uses statistical analysis to examine the four most commonly used depth conversion methods in the Cooper-Eromanga Basin, while also investigating the impact of the most significant variables on depth conversion accuracy.

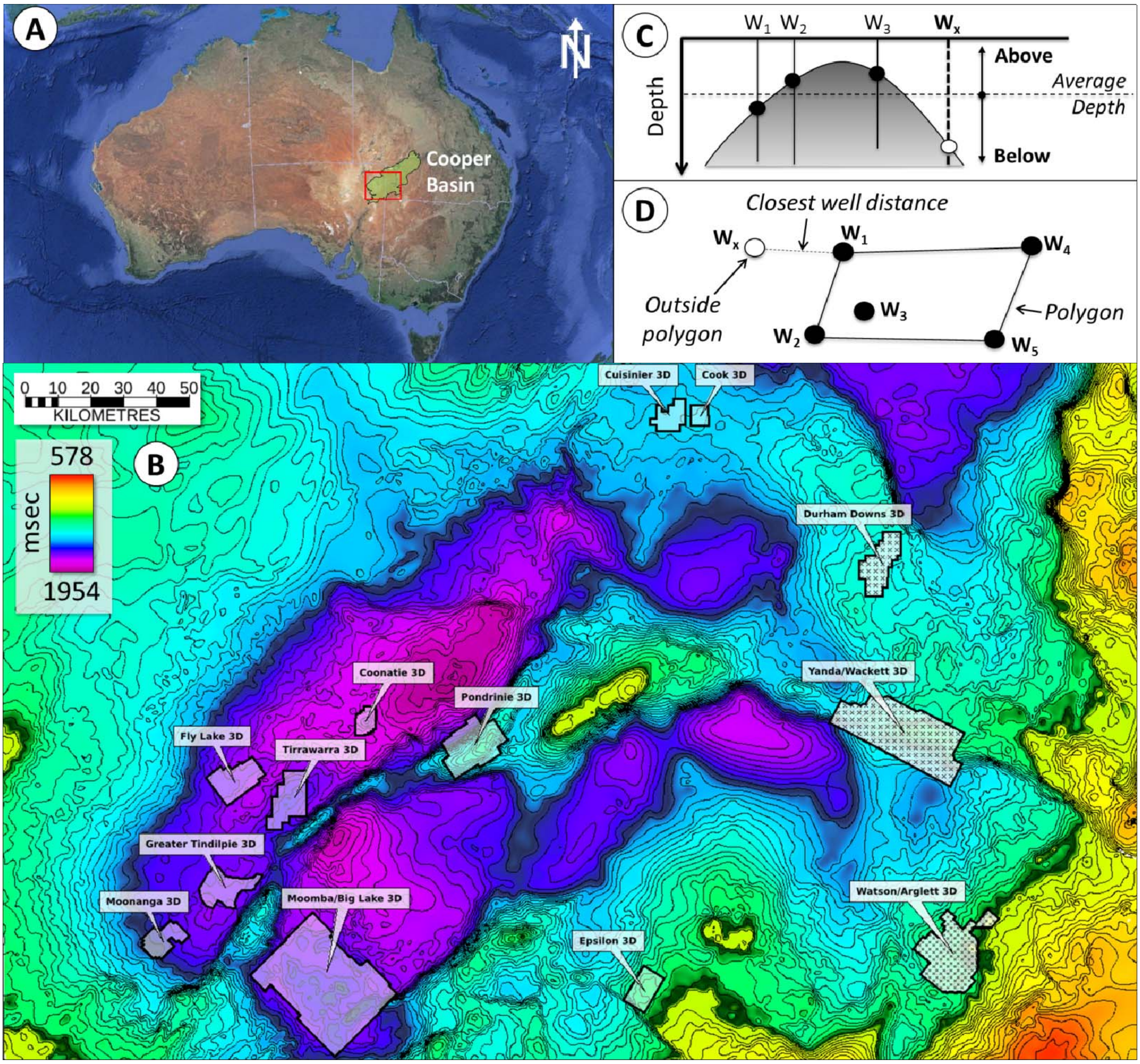

Figure 1: (a) Location map of the Cooper Basin, Australia, with the study area in red. (b) Location map of the 3D seismic surveys used. Surveys with dotted fill lack usable stacking velocities. (c) Schematic of how the *above or below* variable statistic is calculated. This is used as a proxy for crestal or flank well (d) Outer perimeter wells defining the well envelope used to determine the inside or outside polygon variable. Closest and average well distances are also calculated. These variable statistics are used to determine their individual significance on depth conversion accuracy.

DATA SET

Selecting the data for this study required a set of seismic surveys with a good spatial distribution across the study area and a diverse cross section of geological settings. This process used 13 3D seismic surveys, which include Coonatie 3D, Tirrawarra 3D, Fly Lake 3D, Greater Tindilpie 3D, Moonanga 3D, Moomba/Big Lake 3D, Epsilon 3D, Watson/Arglett 3D, Yanda/Wackett 3D, Durham Downs 3D, Cook 3D, and Cuisinier 3D (Figure 1b). These seismic surveys have good Eromanga and Cooper basin reflectors that can be consistently found across the surveys. Of the 73 TWT seismic grids, the majority of interpreted grids come from the Cretaceous aged Cadna-owie Formation, Late Permian aged Toolache Formation, and Middle Permian aged Patchawarra Formation. Other horizons used in this study come from the Namur Sandstone, Murta Member, Birkhead Formation, Hutton Sandstone, top Nappamerri Group, Callamurra Member, Epsilon Formation, Murteree Shale, Tirrawarra Formation and top Basement. Stacking velocity files were available for all 3D seismic surveys, excluding Durham Downs 3D, Yanda/Wackett 3D, and Watson/Arglett 3D (Figure 1b). As such, the KED using stacking and average velocities method could not be performed on these 3 fields. A total of 657 wells were used, ranging in distribution from 6 wells in the Moonanga 3D to 338 wells in the Moomba/Big Lake 3D.

Variogram modelling was also essential for depth conversion methods using kriging with external drift. It should be noted that variograms were defined using all available well data within a given seismic survey, ignoring the fact that the variogram would change and become more defined with increasing well control. To counter this limitation, only fields with greater than 15 wells would be recommended to use kriging based methods. To generate realistic depth conversion scenarios, the inclusion of wells into the looping script is ordered by the drill date.

METHOD

In order to decrease the computational time of performing 4 depth conversion methods (Figure 2) a script was created within *Petrosys* that looped over the 4 methods with an increasing amount of well control per loop. This method is commonly known as the cross-validation method; 3 wells are used in the depth conversion to predict the 4th well, then 4 wells to predict the 5th well and so forth (*n* wells to predict the $n^{th}+1$ well). The error for each loop is calculated by comparing the predicted depth at the location of the $n^{th}+1$ well, with the known depth of the $n^{th}+1$ well. A total of approximately 2500 predicted vs true depth data points, together with an equal volume of variable statistics, were collected for each of the 4 depth conversion methods.

The statistics captured during each loop included; average depth of the wells used in the depth conversion, whether the well to be predicted is up-dip or down-dip from the existing wells, whether the well to be predicted is spatially inside or outside the existing well control envelope, distance between the predicted well and the closest well, and the average distance from the predicted well to the existing wells (Figure 1c & 1d).

To compare the relative significance of the variables on depth conversion error, cluster analysis was performed on the complete data set. Cluster analysis groups data such that within clusters the variability is minimised, and between clusters the variability is maximised (Kaufman & Rousseeuw, 2009). The distance between clusters is calculated using the Euclidean distance equation (Equation 1; where *a* and *b* are two points with dimensions *k*), which has a value of zero when clusters are identical, and a high value when clusters show little similarity. This statistical approach is used to compare the significance of variables and the impact they can have on the time to depth conversion error value, but mostly to assess their individual hierarchal importance (greater Euclidean distance infers more important). These results will provide geophysicists with a better understanding as to which variables have a greater impact on their time to depth conversion accuracy, and which have a relatively negligible effect.

$$Euclidean\ Distance = \sqrt{\sum_{j=1}^{k}\left(a_j - b_j\right)^2} \tag{1}$$

The four depth conversion methods used are described below.

Average (pseudo) Velocity (V_{avg}) Method

The average (pseudo) velocity method is the most commonly used method in the region and has been proven to be an effective method for modelling the earth's velocity (Baerg, 1991). At any given well location, the true depth (Δd feet) taken from the well and the interpreted time (Δt sec) taken from seismic data are known (Figure 2a). This enables a V_{avg} to be calculated by dividing Δd by Δt. This simple arithmetic is re-calculated after each loop. The newly created V_{avg} grid is then multiplied by the interpreted TWT seismic grid to generate a depth grid. To calculate the depth conversion error, the true depth of the well that is being predicted ($n^{th}+1$ well, where n is the number of wells being used for depth conversion) is compared to the depth from the depth grid at the given coordinates.

Time-Depth Trend Method

The time-depth trend method uses a similar relationship to the average (pseudo) velocity method, where depth and time values are obtained from wells and seismic data respectively. However, rather than computing V_{avg}, the points are plotted to find a linear relationship between time and depth (Figure 2b) which is then used to directly convert the TWT grid to depth. This method then requires the resultant depth grid to be tied to the well control by means of a gridded error correction factor. A unique time-depth trend relationship is defined for each loop within the script as well control increases.

KED using a TWT grid as the External Drift Method

Kriging with external drift (KED) is an interpolation method commonly used in gridding, where the primary data set is completely honoured, and a secondary data set is used as a background, or external guide (Figure 2c). This method utilises well depths as the primary data set with the interpreted TWT grid as the external drift. The interpolation technique can be viewed as a weighting system, where the closest wells have a stronger influence on the interpolated value than data from more distant wells. Weightings for KED are calculated through variogram modelling, which is based on the dissimilarity in pairs of data with changing distance (Hudson & Wackernagel, 1994). Generally, as the spacing of data increases the dissimilarity between data increases. This trend continues until at some distance (range) the dissimilarity between points reaches a maximum value (sill) and begins following a near horizontal path. Theoretical variogram modelling was performed using a spherical method.

KED using Stacking and Average Velocities Method

Similar to KED using TWT as the external drift, KED using stacking and average velocities is an interpolation technique with weightings defined through variogram modelling. A velocity value is obtained at each common mid-point in the seismic volume for a given reflector by correcting for the natural move-out effect. Using the densely spaced stacking velocity data for each reflector, a velocity grid is created to guide kriging. This method utilises pseudo average velocity from wells as the primary data set with stacking velocity used in the background to calculate a velocity grid (Figure 2d). The output velocity grid is multiplied by the TWT grid to determine depth. It is important to note that lateral velocity anomalies can have a large impact on the velocity model generated through this method, and geophysicists must have a good understanding of the subsurface geology before solely relying on this method for time to depth conversion.

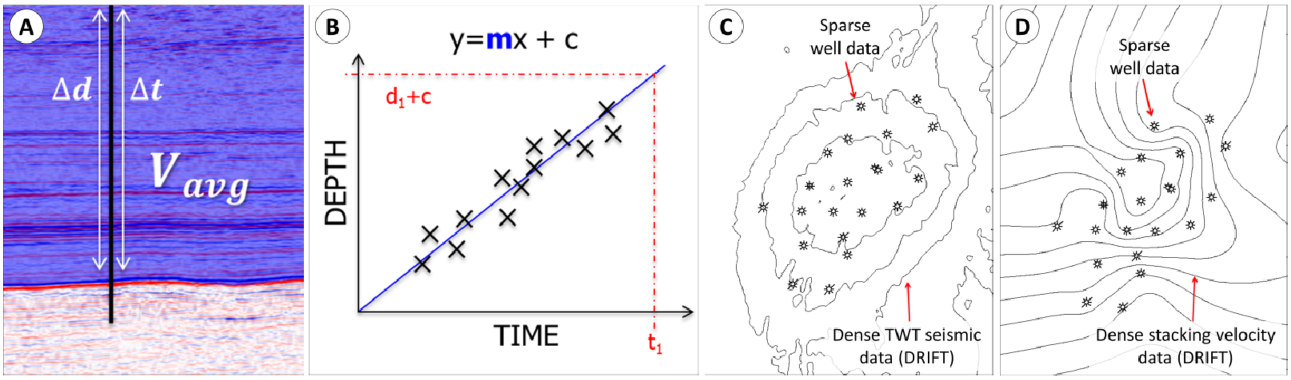

Figure 2: (a) The average (pseudo) velocity (V_{avg}) method uses a uniform velocity from datum to the target horizon. Velocities are obtained dividing measured depth from wells (Δd feet) by the one-way-time from seismic data (Δt sec). (b) Time-depth trend method fits a linear trend through time data plotted against depth. (c) Kriging with external drift using a TWT grid as the external drift honours the well data (depth) completely and interpolates depth using the TWT grid as a structural guide with values based on a variogram model. (d) Similar to (2c), this method uses the average velocity from wells and the stacking velocity grid as a guide with the output velocity grid multiplied by the TWT grid to calculate depth.

RESULTS

To calculate a representative average expected error, the authors use the absolute error value (negative values are multiplied by -1 to give only positive values). Figure 3a shows the absolute average error value for the 4 methods and is split by seismic survey. The average (pseudo) velocity method shows the lowest absolute error value (24.9 feet) and lowest standard deviation (57.3 feet) of the methods. Although the KED using stacking and average velocities method was found to have the largest absolute error value (29.5 feet), the difference between this and the average velocity method is only 4.6 feet. This difference may be significant in very low relief structural traps; however, a more significant error range can be fashioned with a 1 msec error in seismic interpretation or the variance of significant variables.

Testing the importance of variables utilised the cluster analysis technique. Data was split into Cooper and Eromanga basin formations and found a distance between clusters of approximately 9 feet (Figure 3b), inferring that this variable may be more significant than deciding upon the depth conversion method, which has a range of only 4.6 feet. Isolating data into being inside or outside the existing well envelope (Figure 1d) unearthed a significant distance between clusters of approximately 16 feet (Figure 3c). This highlights the importance of the well location relative to the existing well envelope, which is almost twice as significant as isolating data into the Cooper and Eromanga basin formations. Wells being predicted on a crest or flank (above or below) surprisingly had an almost negligible distance between clusters of less than 3 feet (Figure 3d).

The data also formed well shaped clusters based on the seismic survey being depth converted (cluster 1: *Cook 3D, Tirrawarra 3D, Cuisinier 3D, Fly Lake 3D, Coonatie 3D*; cluster 2: *Moomba/Big Lake 3D, Greater Tindilpie 3D, Epsilon 3D*; cluster 3: *Moonanga 3D*; cluster 4: *Watson 3D, Durham Downs 3D*; cluster 5: *Yanda/Wackett 3D*; cluster 6: *Pondrinie 3D*), where the distance between clusters was calculated to be approximately 23 feet. Clustering the data into the 2 main regional groups found a spatial trend, in that all seismic surveys located within the Patchawarra and Nappamerri troughs, as well as the Epsilon, Cook and Cuisinier 3D seismic surveys could be grouped into 1 cluster. Further research into the significance of this cluster should investigate the structural, sedimentological, mineralogical and cementation similarities between the areas covered by these surveys and the potential influence of surface conditions (statics) on depth conversion accuracy.

Reflectors with similar depths were expected to form clusters; however the data did not cluster coherently in this way. The clusters that did form did not appear to be based on depth, since reflectors from the Patchawarra Formation formed clusters with Eromanga Basin reflectors. The distance between these clusters was calculated to be approximately 43 feet and appear to be one of the more significant variables, together with the seismic survey and the well location relative to existing well envelope.

A variable often viewed as being one of the major contributors to depth conversion accuracy is the number of wells present. It would seem intuitive that increasing well control would provide a more accurate depth conversion; however, this relationship is surprisingly not present within the data set (Figure 3e). The number of wells present during depth conversion is plotted against the average absolute error to find a near horizontal trend. Another variable that is considered to be influential is the distance to a known well control, where a smaller distance to a well control would provide more accurate results. This relationship was tested (Figure 3f) and found a strong correlation between depth conversion accuracy and the proximity to well control.

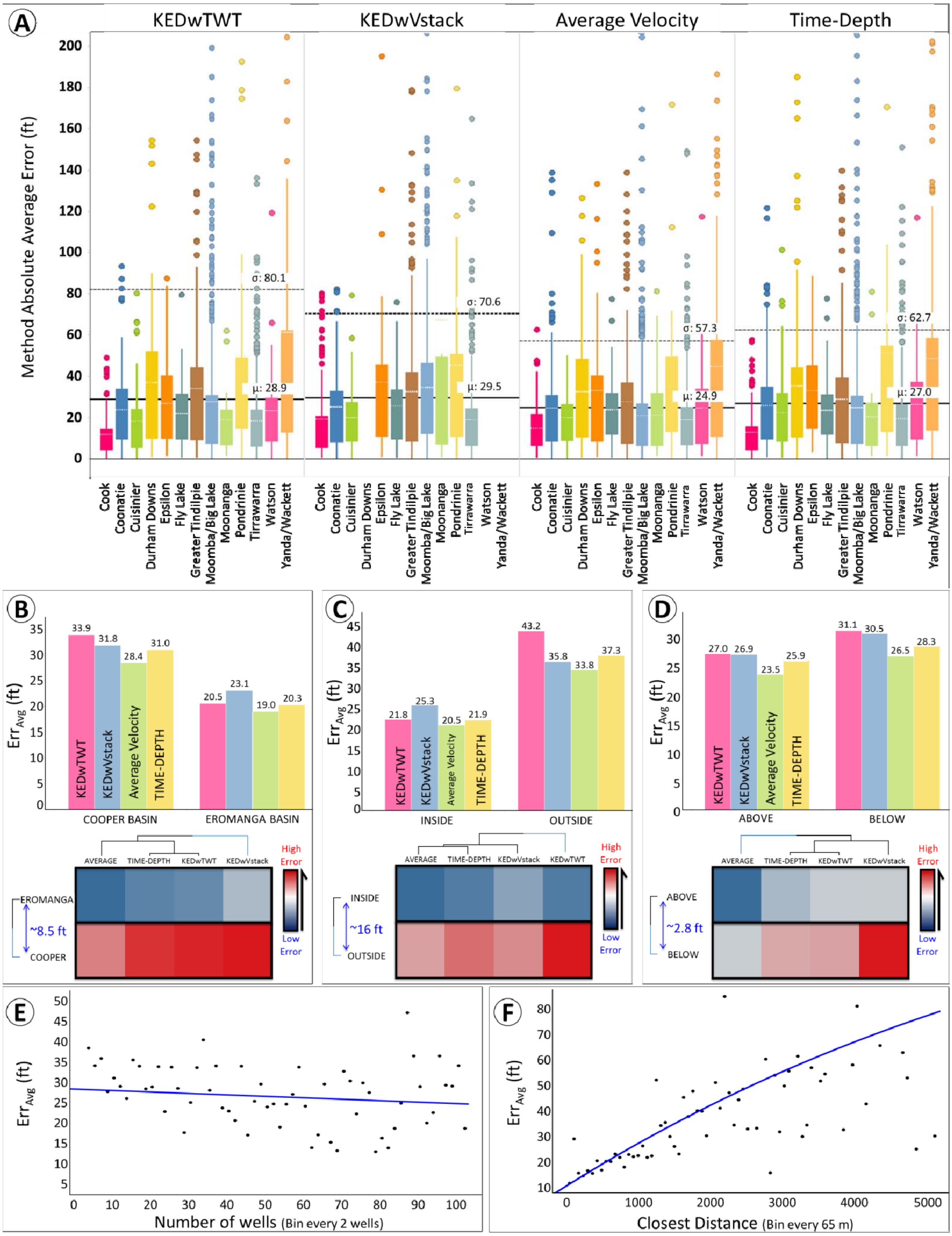

Figure 3: (a) Data split by method and seismic survey showing the absolute average error and standard deviation of each method (expected (+/-) error). (b) Data split by Cooper and Eromanga basin formations with a distance between clusters of 8.5 feet. (c) Data slit by inside or outside the well data envelope (polygon) (Figure 1d) with a distance between clusters of 16 feet. (d) Data split by above or below the average well depth with a distance between clusters of 2.8 feet. (e) Testing the relationship between the number of wells present during depth conversion and the average absolute error. (f) Constraining the relationship between the closest distance to a well control and the average absolute depth conversion error.

CONCLUSIONS

While the average (pseudo) velocity method has the smallest average absolute error on a high level (24.9 feet), the significance of variables such as location, formation, well location relative to the existing well data envelope and closest distance have shown to significantly impact the expected error, as well as the most accurate method. Future depth conversions should therefore use a data specific method rather than taking a blanket approach to depth conversion. Taking a single, 'standard' method approach can result in errors in the range of tens of feet which are large enough to destroy valid structures, or create pseudo ones. Surprisingly, the number of well control points appears to have an insignificant impact on depth uncertainty. It is important to reiterate that accurate seismic interpretation is the most crucial aspect of predicting the true subsurface geology.

This research promotes the creative and innovative use of existing software to investigate problems that have long existed, but that have never been explored due to time requirements for manual handling. This looping script was used to develop a depth conversion decision tree that now allows geophysicists to select the best (lowest prediction error) method for their given data set. This can be replicated and applied to any region around the world with 3D seismic data and well control. Future application would be most beneficial to regions where the most accurate depth conversion method and significant variables have not yet been identified, and also to regions with an uncertain presence of hydrocarbon-rich low relief structural traps.

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