Interpretational Variability of Structural Traps; Implications for Exploration Risk and Volume Uncertainty

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Abstract

Defining the size and shape of hydrocarbon traps is a critical component in estimating the economic value of potential and existing oil and gas fields, and is therefore a key business risk. Structural traps, defined by fault and fold geometries, form the most common type of hydrocarbon traps; the size estimates of which are based on interpretation of sub-surface data, most notably seismic imagery. Interpretation of seismic image data is uncertain, as the sub-surface images have limited resolution, quality; and in 2D datasets the imagery is spatially limited and the interpretation requires interpolation between images. Here we present data from top reservoir maps created by eight interpretation teams, each of which interpreted a grid of 2D seismic sections at a regular spacing of 1km, over a 220km\textsuperscript{2} area. The resultant maps are compared for interpretation variability. Fault statistics have been generated for each map and compared to analogue datasets to aid in the identification of anomalous interpretations, and to create a likelihood rank for each map. The structural traps identified by each team are compared, and the two largest traps are assessed for their potential trapped hydrocarbon volume. An initial volume and a corrected volume, accounting for potential fault seal breach by reservoir-reservoir juxtaposition across the trap-defining faults, are calculated. The integrated analysis of the multiple interpretations: 1) captures the
interpretational uncertainty, 2) determines the likeliness (or risk) of each interpretation being valid, when compared to analogue datasets, and 3) assesses the impact of each interpretation on the economic viability of potential prospects (defined by structural traps).

**Introduction**

The ability to derive an accurate representation of the subsurface, in order to define and identify potential hydrocarbon structural traps, is a critical part of the exploration process. As discoveries are matured and developed, although the uncertainties tend to reduce as more data is acquired, significant structural uncertainty can remain and be critical to the commercial viability of the field. e.g. the detail of how key faults are connected can have enormous impact on flow rates and is critical for the effective placement of injectors and producers.

Typically identification of a trap is completed by acquiring and then interpreting seismic data to determine the sub-surface geometries defined by horizons, faults and folds. In simple terms the aim is to define the containers into which buoyant fluids may have migrated and then become trapped. Away from controlled experiments (e.g. Bond el al. 2007), the only unambiguous test of how good we are at doing this is to review the success or failure of completed exploration and appraisal wells. Petroleum companies use dry well analysis and look-back studies to assess how accurate they have been at predicting success; and in the case of failure, the accuracy of predicting the reason for failure (Uman et al. 1979; Rose, 1987; McMaster, 1997; Otis and Schneidermann, 1997; Alexander, 1998 and Ofstad et al. 2000).

Although these sorts of data tend not to be readily available in the public domain, McMaster (1997) published the results of data collected by Amoco comparing the results of 380 exploration wells drilled over a seven year period. Dry well studies in this case show that defining the trap was the most common reason for failure (N.B. there was no distinction
between structural and stratigraphic traps). An earlier case study published by Uman et al. (1979) indicated that incorrect structural interpretation was observed to be the principal cause of dry holes (43%) and this risk was only correctly anticipated in 23% of cases (Uman, et al. 1979, Rose, 1987). The anticipation of failure due to lack of reservoir and hydrocarbon migration was more accurate with a percentage accuracy rate of 79% and 50% respectively. Detailed analysis of exploration well results drilled in Norway over a ten year period (1884-94) conducted by Ofstad et al (2000) found that on average the reasons for failure was approximately equal, between lack of trap, reservoir and charge. The accuracy of predicting the trap as the reason for failure was again the least accurate; anticipated to have been 46%, post drill analysis showed it to be 26% (Reservoir; pre-drill 32%, Post-drill 27% and Charge; predrill 37%. Post-drill 29%) (N.B. the categories used in these two studies were slightly different; Ofstad (2000), did not contain a specific category for structure, the structural component was included in the trap category). Intriguingly, although the discrepancy is similar to that identified by Uman, et al. (1979) the results are reversed, over-prediction as opposed to under-prediction. Despite this both studies are consistent in that they suggest that the structural component of predicting the success, or failure is the most difficult to predict correctly.

Given that prospects are defined by top reservoir structure maps, there is potentially enormous value associated with being able to distinguish, in a structural geological sense, between ‘good’ and ‘bad’ seismic interpretations. This, we would argue, is more far reaching than just identifying maps that are seen as more or less ‘risky’ and that poor structural interpretations may completely fail to define a valid trap or conversely may define prospects that are overtly compartmentalized. In this paper we review a set of prospect-defining, top reservoir structure maps generated by teams of interpreters from an identical dataset. We define how structurally variable they are and look at possible ways of assessing their
structural integrity. We then go on to assess the trapped volume associated with the principal (largest) prospects defined by each map and investigate the relationships between structural interpretation, trap risk and variations in trapped hydrocarbon volume.

**Background**

In a controlled experiment, Bond et al. (2007) demonstrated how a single synthetic seismic section could be interpreted in many different ways, and investigated how this came about. Their study showed the influence of personal bias on structural interpretation and demonstrated how incorporation of a kinematic understanding of the section being interpreted could be linked to greater success at deriving a valid solution (see also, Bond et al. 2012).

Our study is similar in that it assesses a set of alternative interpretations of seismic data, however it is different in a significant number of ways. Firstly it is based on real seismic data that involved the interpretation of a grid of orthogonal 2D lines and secondly it does not focus on a single cross-section interpretation, rather it is the final top reservoir structure maps, derived from multiple section interpretations that were examined. The dataset consisted of a good-quality, 2D seismic data grid with a regular spacing of 1 km, covering an area of approximately 220 km². Eight alternative interpretations of the same surface are considered. The methodologies employed to construct each map were identical, and consisted of interpreting the 2D seismic lines and then transferring the location of structural data (faults and folds) and horizon data (depth in two-way travel time (TWT) of the top reservoir surface) onto a gridded map. Hand drawn maps were then constructed, which involved choosing which 1D fault points to link together to form a hard-linked fault network, and then drawing contours to define the geometry of the horizon (Figure 1). The completed maps were then depth-converted (N.B. there were no depth conversion anomalies in the data). Interpreters, all
from industry, had the same purpose in mind, to map and identify potential prospects for hydrocarbon exploration.

For reasons of confidentiality, the underlying seismic data and the actual maps cannot be shown, however an accurate geoseismic section and a much simplified generic map are shown in Figures 2 and 3. For the most part the interpreted structures consist of relatively simple, linked, listric normal faults. The interval containing the mapped horizon (annotated as top reservoir in Figure 2) is uniform in thickness and the deformation at this level was related to a single, late pulse of tilting and extension. This event reactivated an underlying fault system which propagated upwards to create fault offsets observed at the top reservoir level.

For this reason, comparisons between individual vertical sections show a relatively consistent set of interpretations. Variability and therefore uncertainty is related to how the cross-section data was interpreted in map view to create a top reservoir structure map (Figure 1).

The structure, shown diagrammatically in Figure 3, can be described in terms of two domains. Over the southern two thirds of the map area, the interpreted faults define a series of curved (listric) normal faults. Towards the north, the structure changes and the curved faults give way to a set of oblique to orthogonal faults that link with a larger, more linear, fault that trends NNW-SSE.

The eight map interpretations present an opportunity to compare and contrast a significantly greater number of alternatives than would ever be available as a result of standard industry practice. Companies may, on occasion, feel the need to approach a complex structure by carrying multiple working hypotheses of a mapped structure; and in partnerships, each party may undertake their own mapping and debate the merits of the each other’s maps. Most of the time however, in the authors’ experience, there is a tendency to settle on a single, prospect-defining, top reservoir map at an early stage.
In order to facilitate accurate comparisons and detailed analysis, the hand drawn maps were digitally captured in a GIS format. This step made it possible to make detailed spatial and statistical comparisons of the interpreted structure. It also enabled accurate area calculations to be made of any traps defined on the maps. These calculations have allowed us to document the differences and discuss the significance of these with regards the number and size of potential traps. As this study is based on real seismic data which is inherently imperfect, it could be argued that ultimately there is no correct answer. If, however, we can differentiate structurally between the maps, or individual traps defined by the maps, and relate these to prospectivity, then from an industry perspective this potentially allows us to demonstrate how structural geology can be used to reduce uncertainty and provide quantifiable value.

**Defining Variability**

Geometrical data extracted from the interpreted maps allows quantitative analysis of the variability to be undertaken. In this section we consider 6 different parameters, based on fault population statistics, to compare the eight map interpretations with each other and analogue data of ‘known’ natural populations. The parameters considered are: fault linkage, total number of faults, mean fault length, fault length distributions (cumulative frequency), fault length-maximum displacement relationships, and number of fault intersections.

1. *Fault linkage - Overlay analysis of hard linked fault interpretations*

Simply by overlaying the maps and conducting a visual inspection it is immediately apparent that the consistency of the fault patterns differs across the maps (Figure 4), with some identifiable zones where the interpreted fault pattern, across the eight interpretations, is distinctly less consistent. These zones represent areas where each team has managed to interpret an almost unique fault pattern. The reason for these differences appearing to be related to the number of choices available. Figure 5 shows the seismic grid used for
constructing the map. The seismic grid is colour-coded by the number of fault cuts for each cell. A red fill, for example, indicates that the cell has greater than four 1D cuts available to be linked to form a 2D fault cut. The greater the number of 1D cuts, the greater potential there is of connecting faults in different ways with different orientations to generate alternate interpretations. The areas where a higher degree of variability is apparent in Figure 4 coincide with zones where three or more, high-choice, red cells are juxtaposed, extending the fault linkage choices over a larger area (Figure 5).

2. Fault Populations - Total number of faults and mean fault length

A basic parameter for the assessment of fault population is the number of faults interpreted on each map (Figure 6A). The average number of faults (F) for all eight maps is 33. The degree of variability is considerable, Map 4 stands out as an interpretation with a particularly high number of faults (F = 53) and at the other end of the spectrum, Map 6 has less than half this number with only 20 faults interpreted (Figure 6A). The graph shown in figure 6B suggests that the number of faults that appear on the maps is inversely linked to fault length, i.e. maps with high fault counts tend to have shorter faults and vice-versa. A likely explanation for this variation is that an interpretational preference for fewer longer faults or shorter more numerous faults. The above count only considers discrete individual fault lines, faults that are linked by branch points are described later.

The summed total of fault lengths for each map with respect to the total number of faults interpreted is shown in Figure 6C. The relatively high fault count associated with Map 4 (53) is associated with a considerably larger sum total fault length of 24,277 m, over 40,000 m longer than the next highest. A positive correlation between summed fault lengths and the total number of faults is apparent (Figure 6C). This relationship appears to be a product of how the faults are linked within the grid system (Figure 1A & Figure 6D). This principal is
demonstrated by comparing the two hypothetical interpretations shown in Figure 6Di and 6Dii which show two alternate interpretations of 4 fault cuts on a small grid. One interpretation has linked the fault cuts to form two faults, the second, which is equally valid has four, one for each fault cut. Comparison of total length of the two- and four-fault solutions with respect to the number of faults shows the four-fault interpretation has a total line length that is 40% longer (Figure 6Div). Essentially, interpreting fewer faults is more efficient with regards to the length of fault you need to connect the fault cuts together. The relationship however is complicated by a number of other geometrical factors, such as the trends imposed on the faults, how they intersect and bisect each other and also how the interpreter chooses to terminate them (Figure 7Di-iii).

3. Fault lengths - cumulative frequency

Significantly more detail regarding individual fault populations and on how they vary is shown by cumulative frequency plots of fault lengths. Data extracted from field studies have shown that fault populations are consistent with a power law distribution (Cladouhos and Marrett, 1996; Davy, 1993; and Scholz et al. 1993). Plotted on a log-log scale graph, such distributions define a straight line, the slope of which is defined by the function C (Cladouhos and Marrett, 1996). Potentially these plots could be used not only to define the variability of the fault populations but also discriminate between them by relating them to natural analogues. The individual trends of each map are shown in Figure 7A, together with analogue data (adapted from Cladouhos and Marrett, 1996). All of the maps show little correlation with the straight line prediction for small fault lengths. This phenomenon has been well documented by a number of publications regardless of the sampling techniques used (e.g. Childs et al. 1990; Gauthier and Lake, 1993; Stewart, 2001 & Torabi and Berg 2011). This “truncation effect” is caused by under-sampling of the small fault population (Torabi & Berg 2011). With regards this dataset the small fault population interpreted on the seismic lines
would have been limited by the resolution of the seismic (the smallest visible faults had offsets of around 5 milliseconds or approximately 3-6 m), this would have been the same for all teams. The maps, however, display significant variation and this is a product of how the faults have been interpreted (Figure 7). Maps 1, 3, 4 and 5 have similar truncation points of around 2 km, the truncation points displayed by the remaining maps (2, 6, 7 and 8) are longer at ~6 km. Essentially the second group have fewer smaller faults compared to the first group (Figure 7A). At the long end of the fault spectrum, the trends displayed by the maps also drop away from the power law curve. This tendency is similarly well documented in publications (e.g. Torabi and Berg 2011) and is related to the limitations in the data set caused by size of the study area with respect to the length of the larger faults. Faults that extend beyond the mapped area will be foreshortened and too short to maintain a power law trend at the long end of the spectrum. Maps 1 and 5 stand out as having particularly good correlations to a power law curve at the long end of the fault spectrum (Figure 7A and 7B).

The trends displayed at the two ends of the fault length population and how they relate to analogue data enable the maps to be grouped with regard to how well they fit power law curves. Trends A and B are similar at the short end with similar truncation points of around 2 km, however they are very different at the long end; Trend A drops off the curve at around 8 km while Trend B remains almost parallel up 25-30 km. Trend C stands out as having a low end truncation point of around round 6 km, and a long end similar to that of Trend A (~ 8 km) (Figure 7C).

Based on the above observations one could argue that the fault populations associated with Trend B (Maps 1 & 5) show a better relationship to natural analogue populations, and as such may well be a more accurate reflection of reality.

4. Fault length - maximum displacement ($d_{\text{max}}/L$ ratio)
Fault population statistics often also take into account fault length - displacement relationships. These are often plotted on log-log scale graphs of fault length / maximum displacement (d_{max}/L ratio; Cowie & Scholz, 1992, and Schultz et al. 2008). Graphs for each map, together with an analogue fault dataset (Schultz et al. 2008) are shown in Figure 8. It is worth remembering that with regards the input data this extraction is not only a function of how faults have been joined together, but also of how the horizon contours have been drawn, and importantly how they have been interpreted to intersect and relate to faults.

A general relationship displayed by all the maps, with respect to the analogue data, is that the maximum displacements are smaller than would be expected for the fault lengths that have been interpreted (i.e. they sit to the right of the global dataset in Figure 8). The reason for this is almost certainly due to the mapped horizon being located towards the shallower part the reactivated faults; in other words, the maximum throw on the faults is located deeper within the stratigraphy, requiring the mapping of older horizons to properly define this (Figure 2). A best-fit line defining the long axis of the distribution for each map is shown on Figure 8. The angle this forms with respect to the global dataset varies for each map and provides an alternative way of defining the interpretational variability between the maps. The best fit lines from the maps are consistently steeper than that defined by the global dataset, the only exception being Map 5 which is broadly parallel. The angular difference, however, varies considerably and is compared in Figure 9. In this figure the trend lines have been placed so they diverge from a single point so as to emphasise the angular relationships between them.

Where the map trend is parallel or at a low angle to the analogue data, although d_{max}/L ratios are on the low side (as described above), the relationship remains consistent across the whole fault population (Maps 2, 5, & 8 and to a lesser extent 1 & 7). Where the angle is particularly pronounced (Maps 3, 4 & 6), shorter fault lengths are progressively associated with lower d_{max}/L ratios. If we take the fault population defined by Map 6, two of the shortest faults (4...
and 8 km in length) both have maximum displacements of 5 m. Global analogue faults of comparable displacement have lengths ranging from 150 to 900 m. By way of comparison, the Map 5 interpretation has almost an order of magnitude lower $d_{\text{max}}/L$ ratios for faults of roughly the same length. Some caution is required in using $d_{\text{max}}/L$ ratio data to discriminate between datasets, as analogue data is itself a varied and complex set of data derived from numerous sources (Schultz et al. 2008). Considerable variation has been observed and the accuracy and consistency of data recording has come into question (Kim and Sanderson, 2005). The relationships above, however, suggest that some of the smaller faults interpreted on Maps 3, 4 & 6 and to a lesser extent on Maps 1 & 7 may be excessively long given their relatively modest displacements.

5. Fault Intersections

The distribution of fault intersections (branch points) for all teams is shown on the inset map in Figure 10. If the interpretation teams had consistently linked the same faults in the same place, some degree of clustering would be apparent. Although some clusters can be observed (A, Figure 10) the intersection points generally display linear trends distributed along the major faults (B, Figure 10). However, over significant portions of the map the distribution appears to be relatively random. Although, there are no apparent trends to the distribution of branch points associated with the eight maps, the exercise highlights the degree of variability that exists between the multiple interpretations.

The degree to which fault populations have been linked together can be gauged by measuring the relative number of X, Y and I nodes (Figure 10). These intersections (or network topology) have been used to understand both fault and fracture connectivity (Manzocchi 2002, Nixon 2013, Sanderson & Nixon 2014). In the context of this analysis, topology is potentially a critical factor for creating multi-fault structural traps (also known as Complex
Traps; Beha et al., 2012). A topology graph showing the % of X, Y and I nodes is shown in Figure 10. I and Y nodes account for most of the connections. Five of the maps have a more or less equal proportion of I and Y nodes, however, Maps 6 & 2 stand out for having a high percentage of Y nodes, in particular Map 6 where the Y nodes total 77 %. At the other end of the spectrum, Map 7 has the lowest number of Y nodes at 37 %. Again these statistics are illustrating interpretational preferences, in this case relating to how aggressively the fault population is linked together; the significance of this is discussed below.

Linked Fault Systems and Structural traps

The development of a curved, listric fault on a dipping surface, where the fault dips in the direction of the slope is a common occurrence in gravity-driven extensional systems (e.g. Niger Delta, Roudby and Cobbold 1996). The combination of the bedding dip and fault curvature creates an ideal scenario for a fault-bounded structural trap into which any hydrocarbons migrating up-dip could accumulate (Figure 3). If we take a simple case and consider a single reservoir of uniform thickness surrounded by impermeable shale, in order to complete the trap, the fault must have sufficient offset of the reservoir and juxtapose the down-thrown hanging-wall against an impermeable lithology in the footwall, i.e. the fault must possess a throw which is greater than the thickness of the reservoir (Hubert, 1953; Smith, 1980; Færseth et al. 2007). This scenario described above is shown in Figure 11A for a single curved fault where it is assumed that the throw on the fault decreases symmetrically towards the fault tips. In the lower diagram the trap size (dashed line) has been adjusted to account for where the offset has become too small to form a trap. Two scenarios involving a two-fault system are shown schematically in Figure 11B and C. In one case, the faults are linked to form a trap, in the other they remain unconnected. The impact on the trap size is
obvious and is a key feature of a number of traps defined by the maps considered here. If multiple reservoirs were present, faults would have to seal by way of an impermeable gouge or smear on the fault where reservoirs overlap (e.g. see Yielding et al. 1997; Yielding, 2015 this publication). Regardless of this complication, trap sizes would be equally impacted by the way the faults are linked in Figure 11 B & C.

The relationship between the number of “linked fault” traps and the % of “Y” nodes is shown in Figure 12. If traps that are dependent on fault linkage are considered independently, Map 6 is clearly anomalous with almost twice as many traps as the other teams. Map 6 also stood out as having the least number of faults (Figure 6), having faults that were overly long with respect to their maximum displacement (Figure 8) and with a significantly larger percentage of “Y” nodes (Figure 10). When these observations are taken together, Map 6 appears to be the product of an interpretation team that tended to draw long faults and critically, linked a high proportion of them together. Interestingly, the graph in Figure 12 also shows that there is no clear relationship between the lower percentages of “Y” nodes associated with the other maps and the number of “linked fault” traps. The reason for this is probably two-fold, firstly the generation of a linked fault trap may be dependent on a few critical branch points, and these may have been made regardless of the number of links. Secondly the number of traps is dependent on other factors such as fault length.

**Screening and Trap Inventory**

An assessment of the potential prospectivity on a map by map basis is revealed by showing the amount of “trapped area” defined by each team (Figure 13). The “trapped area” is essentially the surface area mapped to either a spill point or a fault termination (upper diagrams of Figure 11; note this does not account for reservoir offset). Again Map 6 is clearly an outlier, associated with a high number of traps, and not surprisingly it displays a
significantly greater trapped area than the other map interpretations. In terms of size, three traps stand out; A, B and E. Traps A and B are both single-fault traps, while Trap E is formed by linkages between the large fault that extends off the map to the east, and one of the more oblique-trending faults in the northern half of the map (Figures 3 & 13). The actual fault interpreted to make this link varied from team to team and this is reflected in the variable size of the area of Trap E (Figure 13). At the low end of the spectrum, Map 4 stands out as having a very small gross trapped area and the principal reason for this is the absence from this inventory of Trap A, which is associated with the largest area (Figure 13). On Map 4, the fault that defines this trap is much shorter than on the other maps, and this is consistent with the bias apparent in Figure 6 for mapping significantly more faults that are relatively short when compared with the other maps.

In order to account for potential fault seal issues resulting from the lack of separation of the reservoir across the fault (Figure 11), a second column (α) for each map is shown in Figure 13, where all traps that have a maximum throw of less than 20 meters (the thickness of the reservoir) have been ‘filtered out’. The impact on Map 6 is the most dramatic as it effectively removes all of the extra traps generated by the greater degree of fault linkage when compared to the other maps. In percentage terms, the impact on the trapped area of Map 4 was also dramatic, removing over half the area and reducing its inventory down to a single trap.

In Maps 2, 3 & 5, Trap E is removed completely on the basis of there being no reservoir juxtaposition, i.e. in these maps the maximum displacement defined by the contours on the maps was smaller than those on the other map interpretations, dropping below the twenty meter threshold.

The Principal Traps; detailed analysis & volume assessment
If we assume that other, non-structural elements of the petroleum system are homogeneous across the study area, the largest traps, consistently defined by the interpretation teams as Traps A & B, would be the most attractive in economic terms. Defined by a single, listric fault, these traps are associated with the development of a fault-related fold or rollover anticline (Crans, et al. 1980; White et al. 1986; Xiao and Suppe, 1992). The recognition of this fold on the seismic data, and the subsequent mapping of its 3D geometry in the form of horizon contours, is a critical factor in terms of defining both the integrity and size of the traps. These traps are assessed in more detail below.

As the dataset was comprised of 2D seismic, the interpreted cross-section lines typically become a series of plotted points on a map (Figure 1). The cross sections depicted in Figure 14 A and B are not geo-seismic sections, but represent cross sections drawn as part of the interpretation to create Maps 1 and 8. The cross-sections display solutions that honour the data, and show faults with a normal offset that are equally valid based on the known data points. The difference between the two solutions is in the interpretation and representation of the hanging-wall anticline geometry. The impact from an economic perspective is that the interpretation with the fold (Figure 14B) has significantly increased separation of the reservoir across the fault. Figure 15 shows schematic line drawing maps of the eight interpretations of Trap A; depicted are the main fault that defines the trap and any associated folds, as defined by the interpreted contours. Three of the eight teams did not interpret an anticline associated with the fault.

The impact of not interpreting an anticline is assessed by generating a series of Allan-type (fault separation) diagrams (Allan, 1989) of the faults that define Traps A and B. In Figure 16 (Trap A) and Figure 17 (Trap B), two graphs are defined for each map; to the left, the data points are spaced evenly and the footwall and hanging wall cut off values are shown. To the
right, the data points are separated on the Y axis by the distance between the observations, the X-axis shows the magnitude of reservoir separation. A red intersection line has been drawn to show the point at which the fault throw drops below 20 m and the integrity of the trap is compromised. This is the point at which, according to the map, the reservoir sands are in contact across the fault. If the maps shown in Figure 15 are cross referenced with the suite of graphs shown in Figure 16, the impact of not defining the fold on the effective size of the trap is clear. Trap A, as it is defined on Maps 7 and 8, is greatly reduced in size and would have a reduced value in any economic evaluation. To illustrate the impact of the variability described above, the combined volume that would be attributed to Traps A & B was used as input into a simple deterministic volume calculation (Figure 18). This basic calculation multiplies the Area of the trap/closure by the Gross Reservoir Thickness to calculate a gross volume of reservoir rock (GRV, or Gross Rock Volume). The other volumetric input parameters (Net-to-Gross reservoir, Porosity and Hydrocarbon Saturation) are multiplied through as fractions to give the net pore space occupied by hydrocarbons (In-Place Resources; it is assumed that the structure is filled down to the spill point with hydrocarbons). Finally, a recovery fraction (Recovery Factor, RF) is used to arrive at the final volume of recoverable oil (Recoverable Resources, Millions of Barrels (MMbbl)). The authors would like to stress that this is done purely for the purpose of being able to show comparative volumes. In reality, exploration targets should always be assessed using input distributions with appropriate ranges for each volume parameter to derive a probability distribution for the resultant volumes, i.e. a stochastic/probabilistic approach (Capen, 1976; Capen, 1992; Rose, 1999; Rose and Citron, 2000). Note that in order to keep the calculation as simple as possible, only a single fluid phase is considered here (oil) and changes in volume associated with the transition from the subsurface have not been factored in.
In Figure 18, the graph of ‘initial’, uncorrected volume consists of a bar for each team, which details the total predicted recoverable oil volume from Traps A and B. The corrected volume graph (Figure 18 – right), shows the impact of accounting for the more detailed assessment of the fault throws shown in Figures 16 & 17.

**The Use of Fault Population Statistics to Screen Interpretations**

In the first part of this paper we presented statistics that demonstrated significant variability in the structures defined by each map (Figures 4 to 10). The significance of the variability, with regards to petroleum exploration, was made clear by calculating the potential closure area associated with structural traps (Figure 13). The results show that the degree of uncertainty is considerable, ranging from just over 50 km$^2$ to 230 km$^2$. For traps, where the throw of the fault was greater than the thickness of the reservoir, the area ranged from 26 km$^2$ to 143 km$^2$.

The ratio in both cases is around 1:5. In percentage terms, maps from each end of this spectrum would be inputting areas into volume screening which differ by 500 %. If the two end members are omitted (Maps 4 & 6) the ranges displayed are much narrower with ‘unfiltered’ and ‘filtered’ ratios of 1:1.9 ratio of 1:1.5 respectively.

From a commercial perspective this is quite disconcerting, particularly as a company would almost certainly not have a suite of maps with alternative interpretations to consider. As such, they would have no frame of reference as to where in the interpretation spectrum their map, (upon which they were basing their investment), was located in the range of possible outcomes. As a geoscientist making commercial considerations, it would be prudent to contemplate the reliability of a recommendation based on a single top-reservoir map, given the statistical variation we have considered here.

We must consider the outliers (in terms of trapped area) to see if they display any particularly anomalous structural traits, both with respect to the other maps and with respect to analogue
data. The high trap area associated with Map 6 stands out, as do many of the fault statistics for this map. Map 6 has the:

1. Lowest number of faults and highest mean fault length (Figure 6),
2. Displays a trend line with one of the highest variations in slope with respect to the analogue data in Maximum Displacement vs. Fault Length log-log scale graphs (i.e. faults that have the smallest throws have significantly larger fault lengths if compared to the analogue data; Figure 8), and
3. Critically, of all the maps, the faults on this map are significantly more connected with a $N_{c/b}$ ratio (average number of faults per branch) of just over 1.8, the maximum possible being 2. This has resulted in the definition of a high number of traps defined by linked faults (Figure 12).

The low trap area defined by Map 4 is down to the omission, from this map’s prospect inventory, of Trap A. This trap was mapped by all teams and also consistently had the largest area (Figure 13). When compared to the other maps, Map 4 stands out as having a higher fault count and a low mean fault length (Figure 6). It also stands out as being notably anomalous with respect to the statistics for two analogues: fault-length frequency, and maximum displacement vs. fault length (see Table 1), but is not as conspicuous as Map 6. In the case of Map 4, it is possible that the difference in the interpretation that caused this trap to be omitted from the map may be too subtle to be captured by the gross statistics of the interpretation.

An attempt has been made to use the statistical comparisons of the interpreted maps to the various analogues. A qualitative scheme has been adopted, scoring each map’s relationship to three key analogue datasets as: particularly anomalous, anomalous, or good (Table 1). Using this relatively simple system, each map has then been ranked from 1-4...
based on these judgements. Although this approach clearly highlights that there may be a
problem with Map 6, it also suggests that Map 3 may be similarly flawed, however this
map does not stand out as being particularly anomalous with regard to trap area (Figure
13). This suggests that, as noted above, some structural features that have a high impact
on area are too subtle to be reflected by gross statistics. A larger dataset may well indicate
if, on average, this approach may be applicable. Based on this study, a better approach
may be to use any anomalous relationships compared to the analogues as simply ‘warning
flags’ that there may be problem and that a review of the interpretation may be
appropriate using further geometric, kinematic and mechanical techniques. At the other
end of the spectrum, we note in Table 1 that two maps (Maps 1 & 5) have no anomalous
flags i.e. they are judged as having a good statistical fit to the three analogue dataset
comparators. In the following section we discuss how these observations relate to the
more detailed analysis of Traps A & B, the primary prospects.

Discussion – Volume Uncertainty and Risk

The detailed comparison of the two volumetrically biggest prospects (Traps A & B) focuses
on the actual geometry and offset of the reservoir unit across the fault. The traps are
dependent not only on the geometry of the interpreted faults but also of the geometry of the
interpreted contours. Figures 15, 16 and 17 show there is substantial variation between the
eight map interpretations. To properly describe the variation and the business impact that this
may have, we need to talk both in terms of Risk (i.e. the chance that the trap may or may not
exist; including consideration of fault seal issues) and in terms of Uncertainty (i.e. the size of
the trap and the range in potential volume outcomes). Risk needs to be considered as Traps A
and B were not identified by all the maps.
Specifically, Map 4 did not define Trap A; and in Maps 4 and 8, although they defined Trap B, the contouring was such that there was no separation of the reservoir across the fault and therefore no effective trap (Figures 15, 16 and 17). Does the fact that these teams failed to map these traps suggest there is a chance (or risk) that the trap does not exist on any of the maps? Or alternatively can we argue that the maps that failed to define the traps are so poor that they can be discounted in a risk sense (i.e. there is no chance that they are correct) and for these teams poor mapping has led to a missed opportunity. In this case we would argue the latter, and would base this on the clearly anomalous offset patterns displayed by Allan diagrams that define Faults A and B in Figures 16 and 17.

Much of the uncertainty in volume arises from the recognition, and then definition by contouring, of a rollover anticline (Figures 14, 16 & 17). The nature of the data is such that the interpreters had to recognise this trend from the sections, then make sure this geometry was captured as the contours were drawn. The impact of understanding the relationship between listric fault geometry and associated folding is obvious in terms of value when the initial and corrected volumes for Trap A in Maps 7 & 8 are compared. The level of uncertainty is demonstrated by calculating and comparing firstly the trap area for each map, and secondly by undertaking volume analysis on the two largest traps. In the second calculation, three of the maps (Maps 4, 7 & 8) fared poorly; Map 7 predicting 25 MMbbl (60% reduction), Map 8 only predicting 4.2 MMbbl (91% reduction) and Map 4 predicting no volume at all (Figure 18).

In terms of risking the interpreted reservoir maps, QC checks such as those identifying anomalies in offset patterns across faults, including reservoir offset (as a fault seal risk), are vital. But the use of fault statistics analogue datasets may also play a role in discriminating between and risking multiple interpretations. Interestingly, of the remaining five maps that meet the interpretation criteria (i.e. ones that do not have anomalous fault offset patterns),
Map 1 predicts the highest volume, and was one of two maps (Map 1 & 5) that had the best relationship to our three key analogue metrics.

In the context of 3D seismic datasets and the merits of software interpretation versus traditional hand contouring techniques, the results of this paper may appear not to be directly relevant. However, the authors believe that many of the interpretational issues that arise in this exercise are also common products of interpretations undertaken in industry software packages, as evidenced by Freeman et al. (2010); and are found equally in the interpretation of 3D seismic volumes. For 3D seismic volumes this is partly the result of common interpretation methodologies in which key surfaces are interpreted from 2D grids of selected lines, to construct a template for the full 3D interpretation. Variation will always arise because fault connectivity and lateral and vertical extent (length and displacement) still require interpreter choice. In some cases poor results often also arise because interpreter choice is devolved, to some degree or another, to automated procedures embedded within the code of the interpretation package being utilised, which may not adequately handle imperfect seismic data.

The data presented here give an intriguing insight into volume variability and trap risk and uncertainty associated with converting a 2D seismic grid of cross-section interpretations into a top reservoir map. The results are particularly insightful as the structures displayed on any one line section appear comparatively simple to interpret, yet when used to make an interpretation across a seismic survey, they can yield starkly different map products. Differences between the initial section interpretations, therefore, do not necessarily highlight the ultimate impact on structural trap geometry, and hence potential hydrocarbon volumes.

Conclusions
The results of this interpretation exercise raise questions, as to the efficacy of using single interpretations of seismic datasets to create single deterministic models from which trap size and hydrocarbon volumes may be calculated. In our example, based on real data, the uncertainty in potential trap volumes for the two largest traps identified varied from 66.4 (Map 1) MMbbl to no volume at all (Map 4). Such uncertainty could have a substantial impact on economic evaluations of prospectivity in a commercial Exploration and Production context.

As advocated by Freeman et al. (2010) we propose that empirical rules, such as Allan diagrams of fault displacement-offset patterns and fault length-displacement characteristics, (the latter based on global analogue datasets) can be used judicially to flag-up erroneous or unlikely interpretations. In detailed studies this may be undertaken quantitatively, but here we found a qualitative ranking was a useful indicator as to which map interpretations were most extreme, or biased; and hence of potential greater risk to subsequent project economics. In combining screening of the map interpretations using fault population statistics with assessment of trap volume, both the uncertainty in potential hydrocarbon volume can be established as well as a risk ranking. This additional step provides a clear indication of the business risks associated with different interpretations.

In an ideal world, more interpretational scenarios should be developed from individual seismic datasets throughout the oil and gas industry. But considering the context of financial and workforce/skills constraints, we would at least recommend the use of simple statistical checks on fault populations and attributes as an initial interpretation quality control, and the consideration of alternative interpretations if these quality checks highlight anomalies. In addition, rather than simply using a generic uncertainty range to calculate volumes, we would recommend direct consideration of the impact of interpretation decisions on volume inputs e.g. fault connectivity, fault extent, fault population, size of roll-over anticline etc. Seismic
interpreters should be aware of their interpretation choices, how these feed into risk analysis and volumetric uncertainties within the structural model, and ultimately the business impact of their decisions. If we can cast our minds back to the introduction and the look back data described by Uman et al (1979) and Ofstad (2000), the high levels of inaccuracy associated with defining traps is consistent with the findings of this study.

We would like to acknowledge and thank Frank Peel and Seb Turner for taking time to review this paper. Also thanks to Marguerite Fleming for perpetual encouragement.

Tables

Table 1. Qualitative scoring of each interpreted map (1-8), against three key analogue datasets.

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<th>Map 1</th>
<th>Map 2</th>
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<th>Map 7</th>
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Table 1. Qualitative scoring of each interpreted map (1-8), against three key analogue datasets. The scoring categories are: particularly anomalous relationship = XX, anomalous relationship = X, good relationship = blank. Each map has then been ranked from 1-4.
Figure Captions

Figure 1. Examples of the interpretation methodology n.b. the two maps shown are for representation purposes only and have been extracted from different areas of the original map and may have been rotated. A. Fault interpretation; connecting fault intersection points or “fault-cuts” to form a fault map. Fault intersection points are in determined from interpretation of the 2D seismic data (seismic grid outlined in grey). B. Horizon interpretation; contouring using posted horizon time data at the 2D seismic grid intersection points (n.b. there are different ways of posting horizon data, here horizon data has been posted at intersection points).

Figure 2. Geoseismic cross section. The section shows part of a structural ‘dip line’ of the faulted reservoir interpreted during the study. Top reservoir is annotated and the reservoir interval is outlined in black.

Figure 3. Generic map (A) showing the style of the fault system, towards the south faults are more curved forming large listric faults. Towards the north, although the faults can be traced down to the same detachment, the faults are less curved in map view and display more varied strike direction. (B) The change in the character appears to be linked to a change in the dip of the underlying detachment.

Figure 4. Clip out detail of the 8 fault interpretations considered in this study superimposed. Areas A and B show parts of the map where the variation is visually more variable and less variable respectively.
Figure 5. Colour-coded seismic grid showing “fault-cut” density. Seismic grid colour coded with the average number of fault intersections for each intersection box (hot colours – high density, cool colours – low/no density). Dashed polygon outlines are of areas of high fault interpretation variability (as shown in Figure 4A).

Figure 6. Fault length statistics for each map interpreted. A. Graph showing the number of faults interpreted by each interpretation team. B. Mean fault length plotted against the number of faults for each map. C. Total length of interpreted faults plotted against the number of faults on each map. D. Illustration of alternate interpretations of a simple grid with 4 fault cuts, see text for discussion.

Figure 7. Fault-length frequency. A. Fault length frequency profile for each map. Each graph shows the point data together with a trend line, orange lines show best fit slopes (C) for natural fault populations (adapted from Cladouhos and Marrett, 1996). B. Grouped trend profiles (map numbers grouped are shown in the white box for each graph), with best fit slopes (C) shown in white dashes. C. Trend comparison for each of the three groups.

Figure 8. Maximum displacement vs. fault length log-log scale graphs. White circles (Series 1) = global dataset; black circles (Series 2) = map team data, Global dataset courtesy of Badleys Geoscience. Thick dashed lines = global dataset trend, double line = specific map trend (M1–M8).
Figure 9. Graphs comparing maximum displacement vs. fault length trends across the eight map interpretations. A. Trend comparisons for groups of maps overlaid. B. Same data moved to diverge from a single point to show the angular relationships; thick-dashed line is the global dataset trend (Schultz et al. 2008), other lines are for the specific map trends (M1 to M8).

Figure 10. Fault Topology. Triangle diagram depicting the % proportion of “X”, “Y” and “I” intersection nodes (see explanatory diagram) for each map interpretation (Triangular diagram plotted courtesy of the Tri-plot program by Graham and Midgley, 2000). Inset map shows the distribution of fault intersection nodes (branch points) for all the map interpretations. Some clustering of nodes occurs (e.g. A) indicating that fault intersection points are common across the interpreted maps. More common are linear trends of intersection nodes (e.g. B) along faults.

Figure 11. Schematic diagrams of cross-fault separation of a hydrocarbon reservoir. A simple dipping surface is cut by A., a single curved fault; B., Two connected faults; and C., Two unconnected faults. In each scenario a schematic trap accounting for displacement gradients, reservoir separation & cross fault communication is shown with spill points annotated in red.

Figure 12. Graph showing the relationship between the % of fault linkage and the number of linked-fault traps generated. The percentage of Y nodes (which have the potential to create linked-fault traps), for each map interpretation is plotted against the number of interpreted linked-fault traps.
Figure 13. Assessment of potential hydrocarbon traps resulting from each map interpretation.  
A. Map showing the approximate position and size of the structural traps defined by the maps (the number shown next to each letter indicates how many times it appeared on one of the maps). B. Graph showing trap area (km$^2$), multiple numbers for some traps indicate where the trap was shown to be compartmentalised, together with a second bar (alpha) the area for traps which had a maximum fault throw of > 20 m (ensuring reservoir separation across the fault traps).

Figure 14. Grid spacing and reservoir horizon interpretation across a fault. A., with no hanging wall anticline interpreted. B., with hanging wall anticline interpreted (both interpretations honour the data points).

Figure 15. Schematic maps of the eight interpretations. The line drawings show the location of the Trap A Master Fault and the location of the associated anticline (as defined by the contours) made by each team.

Figure 16. Graphs of reservoir displacement across the fault defining structural Trap A for each map interpretation. Each map interpretation has two graphs: Graph 1 (left) an Allan-type diagram showing footwall and hanging-wall depths; Graph 2 is based on the same data but shows fault throw against fault length. The black line of the graph highlights the 20 m throw mark, and the red line denotes the point along the fault at which trap integrity may be breached.
Figure 17. Graphs of reservoir displacement across the fault defining structural Trap B for each map interpretation. Each map interpretation has two graphs: Graph 1 (left) an Allan type diagram showing footwall and hanging-wall depths. Graph 2 is based on the same data but shows fault throw against fault length. The black line of the graph highlights the 20 m throw mark, and the red line denotes the point along the fault at which trap integrity may be breached.

Figure 18. Deterministic recoverable volume (MMbbl) calculation for Traps A and B. Initial volume = no correction for any variation in fault throw. Corrected volume; same traps but corrected for each maps throw profile.

References


Rose, P.R., 1999, Taking the Risk out of Petroleum Exploration; The Adoption of Systematic Risk Analysis by International Corporations During the 1990s., The Leading Edge, February, pp 192- 199.


A Fault Interpretation

- Fault Intersection Point (showing throw direction)
- Anticline

**Interpreted structure**
- Fault Trend (2D fault cut)
- Fold Trend

B Horizon Contour Interpretation

Top Reservoir point depth posted at grid intersection points and interpreted contours. Units = meters. (n.b. faults have already been interpreted on this map)

Figure 1
Figure 3

A

- Anticline
- Fault Trend
- Break in slope of the underlying detachment
- Detachment surface

B

- Strike of listric faults more linear (NW-SE trend) some oblique faults
- Listric faults more curved in strike direction

Detachment surface
Figure 4.
Figure 5.
Figure 6
Figure 7
Figure 8.
Figure 9.
Figure 10

Map 1
Map 2
Map 3
Map 4
Map 5
Map 6
Map 7
Map 8

(N_{c/b}) = \text{Average number of connections per branch}

\begin{align*}
N_{c/b} &= 1 \\
N_{c/b} &= 1.2 \\
N_{c/b} &= 1.4 \\
N_{c/b} &= 1.6 \\
N_{c/b} &= 1.8 \\
N_{c/b} &= 2
\end{align*}

Analogue Data (Nixon, 2013)

Devon, UK Data (outcrop)
- Hartland Point
- Westward Ho!

Alaska Data (seismic)
- SAG (Sag River Sandstone)
- KUP (Kuparuk River Sandstone)
Dipping Surface

A. Single Curved Fault

B. Two connected Faults

C. Two unconnected faults

Fault related structural traps

Cross fault reservoir separation

Figure 11
Figure 12.
Figure 13
Figure 14.
Fault

Folds

Figure 15
Figure 16
Figure 17
Gross interval 20m
N:G 0.80
porosity 0.25
HC Saturation 0.70
Recovery Factor 0.50

Figure 18