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Geosteering Using True Stratigraphic Thickness

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Note: This version is somewhat longer than the one published with URTeC. It contains 3 figures that were taken out because of length problems: figures 8, 11, and 12. The text is nearly identical.

Summary

One method used to geosteer horizontal wells is to compare a log trace in the horizontal well, usually a gamma ray log, to the same log in a nearby vertical well (the pilot or template). In this process, the log from the horizontal is squeezed and/or inverted until the character in the well matches the character in the template. Squeezing is necessary because relatively small stratigraphic intervals in the template well will be traversed over much larger distances in a horizontal well. Inversion is necessary because the drill can cover a given stratigraphic interval from bottom to top as well as top to bottom. This technique has been termed "true stratigraphic position" or TSP.

As the name implies, TSP is closely related to true stratigraphic thickness (TST). Indeed, TST can be used in the same manner as TSP. In a geometric sense, TSP uses log correlations to find apparent dips. It is demonstrated here that TST is superior to TSP because it can "look ahead" of the bit, and because it allows the geosteerer to concentrate on features in the drilling well that might not be noticed when the log in the well is squeezed down to the scale of the template.

Display type is important when modeling using TST. Vertical sections can have problems displaying apparent dip and horizons whereas displacement (curtain) sections will properly display both dips and horizons. The source of these display problems with vertical sections is largely from dips whose azimuths are out of the plane of section in places where the borehole has deviated away from the plane of section. Both vector and curtain sections have display problems in areas of high dip or where the borehole is away from horizontal. In those cases, vector sections, which are constructed from dip-normal vectors combined with stratigraphic distances, are much better and displaying the structure.

A common complaint about gamma ray logs from horizontal wells is that they have a "jittery" appearance. This is sometimes an unfair criticism, however, because they sample the stratigraphy at a much higher effective rate than the template wells, giving them a jittery appearance when squeezed down to the template scale. One approach is to stretch, invert, and fault the template log to fit the log in the horizontal log. For example, inversion of the log character when the drill travels up section will cause a "mirroring" or "reflection" effect on logs. Markers that might not even be present in the template log can clearly show a mirror effect on the horizontal log, while the same mirroring is missed when the log is squeezed down to template scale. Taking the idea one step further, it is possible to take a log in a horizontal well, convert it to TST and use it as a template, either to correlate with deeper parts of the same well or to use as a template for other wells using markers that may not even exist in vertical wells.

Introduction

Figure 1 is a forward model illustrating typical relationships between a pilot log and a log in a horizontal well. The trace in the horizontal log has been stretched and/or inverted relative to the pilot. The inverted part of the log is caused by the bit traveling up section, or from older to younger beds. It creates a typical pattern in horizontal wells known as "reflection" or "mirroring".
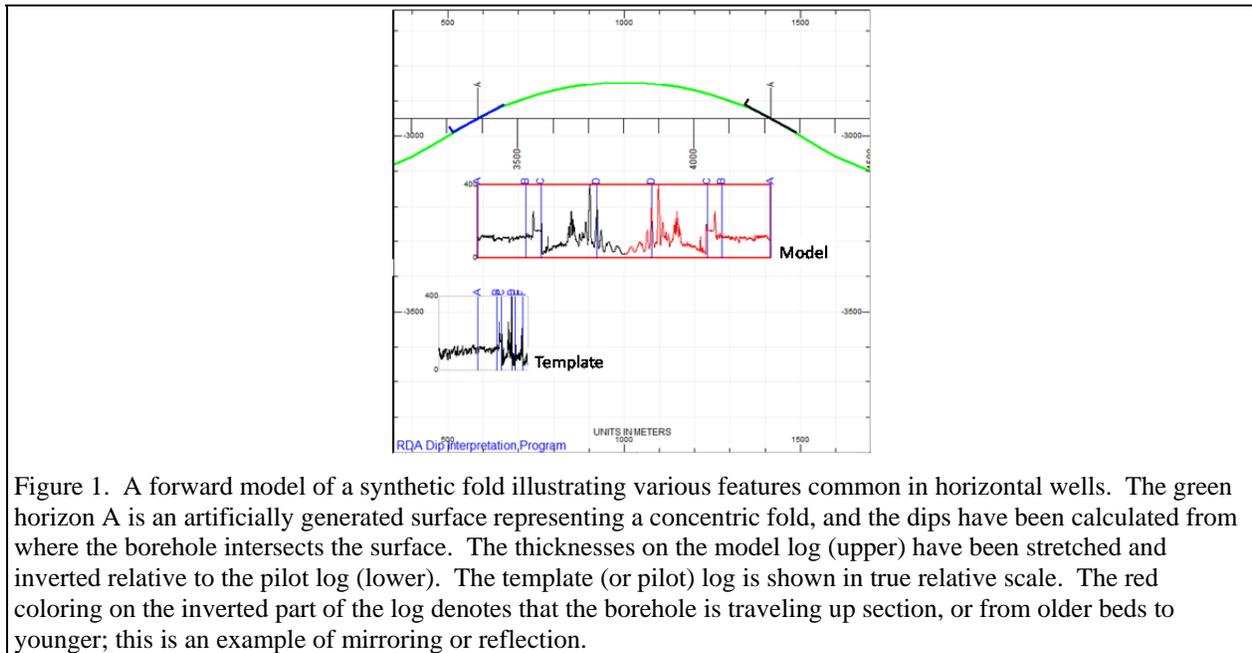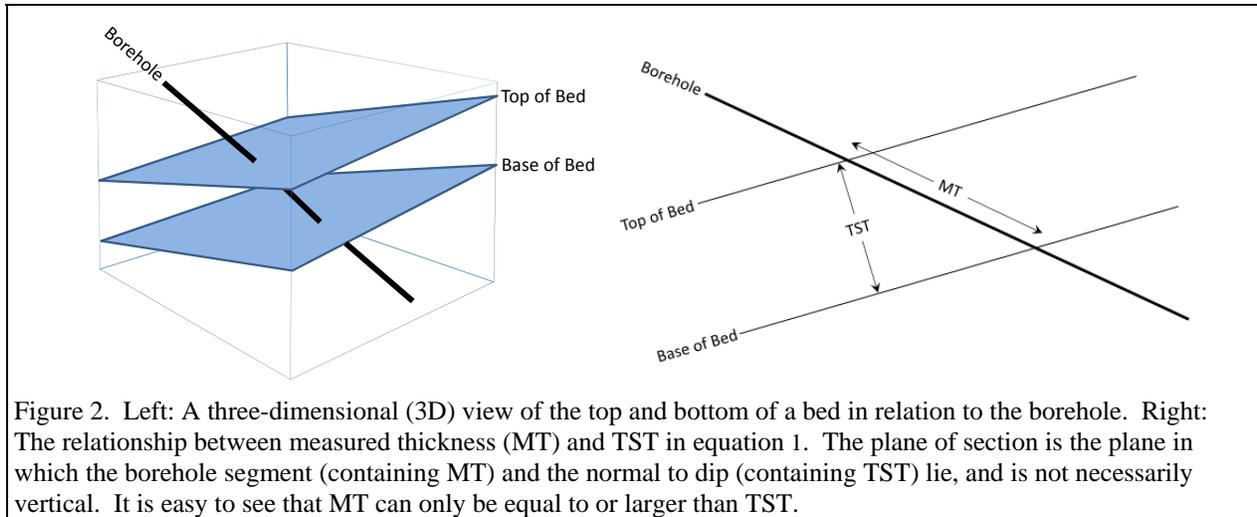
Figure 1. A forward model of a synthetic fold illustrating various features common in horizontal wells. The green horizon A is an artificially generated surface representing a concentric fold, and the dips have been calculated from where the borehole intersects the surface. The thicknesses on the model log (upper) have been stretched and inverted relative to the pilot log (lower). The template (or pilot) log is shown in true relative scale. The red coloring on the inverted part of the log denotes that the borehole is traveling up section, or from older beds to younger; this is an example of mirroring or reflection.

True Stratigraphic Thickness (TST)

Figure 2 shows the relationship between the borehole and bedding in the calculation of TST. Any thickness measured in a borehole is an apparent thickness unless the borehole is exactly perpendicular to dip. To calculate the true bed thickness, the dip of the bed and the borehole deviation must first be known. In most applications we need to know thickness over many beds which may or may not be parallel, so the term "true stratigraphic thickness" has been used to describe the total thickness of a given interval as opposed to a "true bed thickness" for a single bed. Several equations have been derived to calculate TST, but perhaps the most common is the Setchell equation (Tearpock and Bischke, 1991):

$$TST = MT \left(\cos\psi - \sin\psi \cos(\theta_d - \theta_b) \tan\varphi \right) \cos\varphi \, , \qquad (1)$$

where MT = measured thickness, TST = true stratigraphic thickness, ϕ = dip, θ_d = the dip azimuth, ψ = borehole inclination, and θ_b = borehole azimuth. Although most of the published relationships will calculate a correct thickness, not all will produce the correct sign, which is important in geosteering because a positive sign denotes that the bit is traveling stratigraphically down section (top to bottom), while a negative sign denotes that the bit is traveling up section. A more detailed discussion on TST calculation may be found in Berg (2011).

Figure 2. Left: A three-dimensional (3D) view of the top and bottom of a bed in relation to the borehole. Right: The relationship between measured thickness (MT) and TST in equation 1. The plane of section is the plane in which the borehole segment (containing MT) and the normal to dip (containing TST) lie, and is not necessarily vertical. It is easy to see that MT can only be equal to or larger than TST.

TST logs and forward modeling

Figure 3 shows the relationship between TST and MT regarding logs. The trace next to TST represents the template log while the trace next to MT represents the modeled log. It is evident that a log that has been converted from MT to TST (using equation 1) should automatically be squeezed down. This log should have the same intervals as in a pilot well, assuming that the pilot was drilled vertical to bedding. Conversely, if we were to forward model the pilot log into the drilling well, we should end up with a log trace with the same intervals as the drilling well. It is clear that geosteering by simple stretching and squeezing one log to match the other is identical in concept to using TST. The term "true stratigraphic position" or TSP is commonly used describe the result of the log manipulations by themselves. Dips can be calculated on the basis of TSP, but those dips are apparent dips unless the section is oriented on the dip azimuth.

A corollary to the idea that most measured thicknesses in a borehole are apparent thicknesses is the idea that most measured thicknesses are greater than the TST. This fact is important to remember when comparing logs, because it means that to compare thicknesses in a horizontal well to those in a pilot well, the log in the horizontal well (the correlation log) will always be squeezed down to compare to the pilot log. Conversely, the pilot log will always be stretched to model the correlation log. The only case where the apparent thicknesses will be true thicknesses in a horizontal well is where the beds are vertical. Likewise, the only case where apparent thicknesses will be true thicknesses in a vertical well is where the beds are horizontal. This is why vertical pilot wells are frequently used for "type" stratigraphic logs.

Figure 3. The idealized relationship between TST (template log) and MT (modeled log). This has the same configuration as in the right-hand plot in Figure 2. A log that is in TST will be stretched to fit onto MT. Likewise a log that is MT will be squeezed to fit into TST. Now imagine if the bit was traveling up section (from base to top). In this case, measured depth would be increasing while TST is decreasing. In this case, a log would need to be reversed to compare with the other, in addition to being stretched or squeezed. The Setchell equation (1) will always give a negative number when drilling up section and a positive number when drilling down section.

Method

Pilot vs. template

The term "template" here is used to describe a TST log used for forward modeling. A pilot well is normally assumed to be in TST, but that is not always the case (Figure 4). If the dips are higher than 5˚, the logs should be converted into TST before using as a TST template. The dips do not necessarily have to be from the borehole (they can be from seismic or subsurface maps), but they should be accurate to within 5˚.

Cross section display types

In borehole deviation surveys, there are two related variables that are used in creating cross sections in horizontal wells: departure and displacement. Departure is the distance of a point along a cross section starting with the surface location and ending with the bottomhole location. Displacement (sometimes called "vertical section") is the cumulative distance of each successive point over the previous one. A third section type is the vector section, which is superior to the other two sections in places where there are high angle dips and a vertical or high angle borehole.

    Vertical sections

Perhaps the most common display type for horizontal-well cross sections is the vertical section. Vertical sections use departure for the x-axis. They are basically cross sections of the well from the surface location to the bottomhole location. One disadvantage of vertical sections is that if the borehole strays laterally from the plane of section and there is cross dip, then points will appear out of place relative to the actual vertical location of the horizon in the vertical plane. Another, related, disadvantage is that apparent dips may not appear to match those of their respective horizons plotted on the vertical plane.
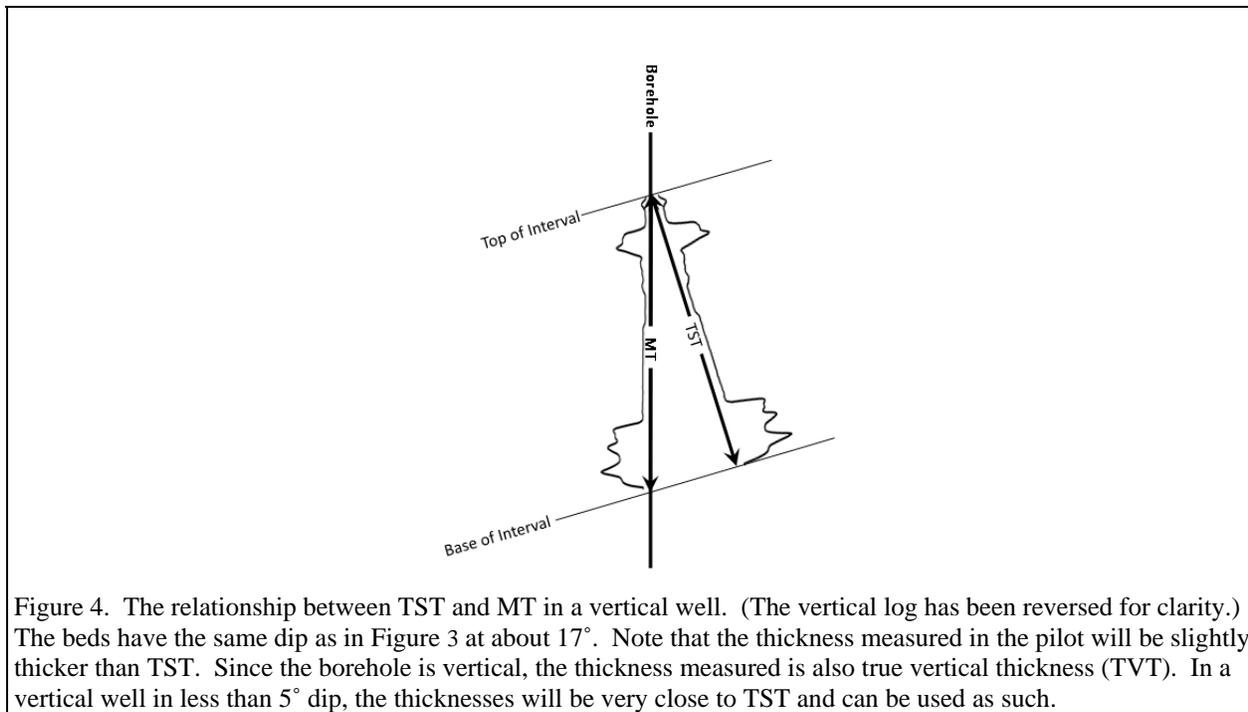
Figure 4. The relationship between TST and MT in a vertical well. (The vertical log has been reversed for clarity.) The beds have the same dip as in Figure 3 at about 17˚. Note that the thickness measured in the pilot will be slightly thicker than TST. Since the borehole is vertical, the thickness measured is also true vertical thickness (TVT). In a vertical well in less than 5˚ dip, the thicknesses will be very close to TST and can be used as such.

Displacement sections

Displacement sections (usually called "curtain" sections) are becoming more popular as a display method. As the name implies, they use displacement for the x-axis. Displacement sections can be visualized as being a cross section cut directly down the path of the borehole. They have the advantage that points on the section will not appear offset vertically (with respect to other objects, such as 3D seismic horizons) because of dip out of the plane of section. In a drilling well, a displacement section has an additional advantage over a vertical section because the completed portion of the section will never change, whereas in a vertical section, each new point added as the well is drilled may change the azimuth of the cross section, thus changing the appearance of the plot with respect to earlier plots. This happens when the well path does not form a straight line in map view. Displacement sections have an additional advantage when the borehole has large azimuth changes, because no overplotting can occur, whereas in vertical sections, overplotting can happen, especially near the turn.

Both vertical sections and displacement sections plot horizons directly above and below the borehole based on known stratigraphic thicknesses. This method of plotting horizons is fairly accurate in areas with low dips, but in higher dip areas, mismatches between dips and thicknesses result. These sections can only be used in horizontal wells because distortions will result in wells that are simply high angle, and in vertical wells they are totally unusable because the entire section will plot on a single, vertical line. Although vertical sections and displacement sections are adequate in most situations, they fall short in high-angle dips and/or when the borehole has not yet reached horizontal. This is where vector sections are needed.

Vector sections

Vector sections (Figure 5) are not true cross sections, but are 3D objects that are created from vectors starting at the borehole, each of whose direction is the normal to structural dip and whose length is equal to the stratigraphic distance of a point to a horizon. They can be thought of as a type of displacement section, but since they will not normally lie in one plane of section, they are projected onto a vertical plane in 2D displays. Vector sections will

normally use some kind of averaging to create the vectors; otherwise a small amount of scatter between individual dips will be amplified to create an accordion effect. Even better is to interpret the structural dip and use those dips to create the vectors. A limitation of vector sections is that a vector section can only cover one structural domain. Vector sections aid especially in the visualization of structure in steep dip and non-horizontal deviation (Figure 6).
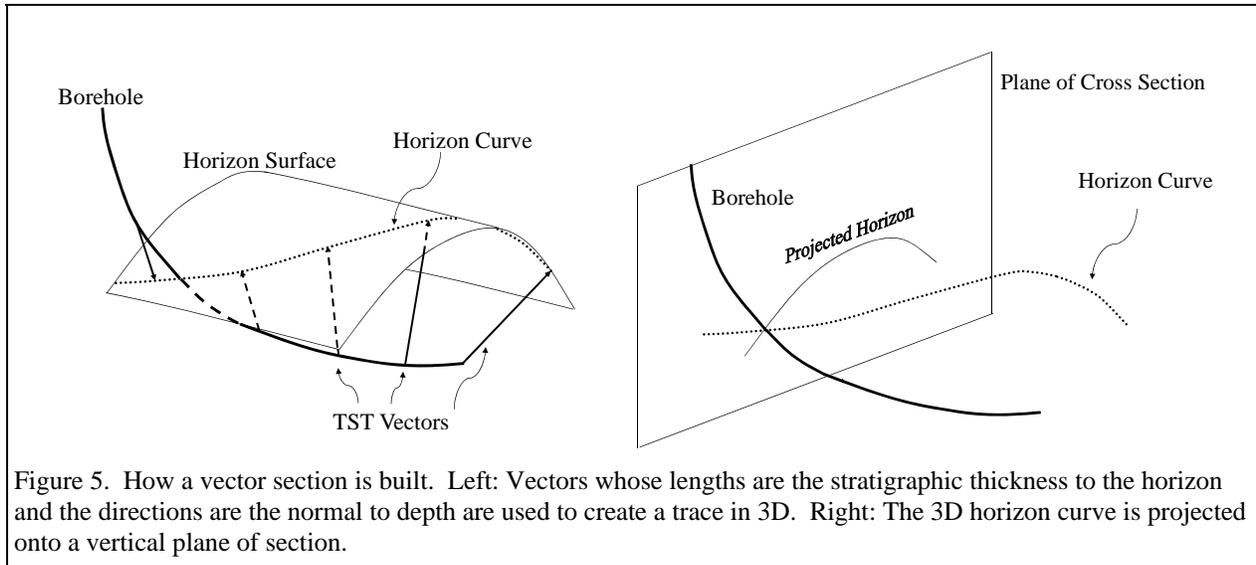
Figure 5. How a vector section is built. Left: Vectors whose lengths are the stratigraphic thickness to the horizon and the directions are the normal to depth are used to create a trace in 3D. Right: The 3D horizon curve is projected onto a vertical plane of section.
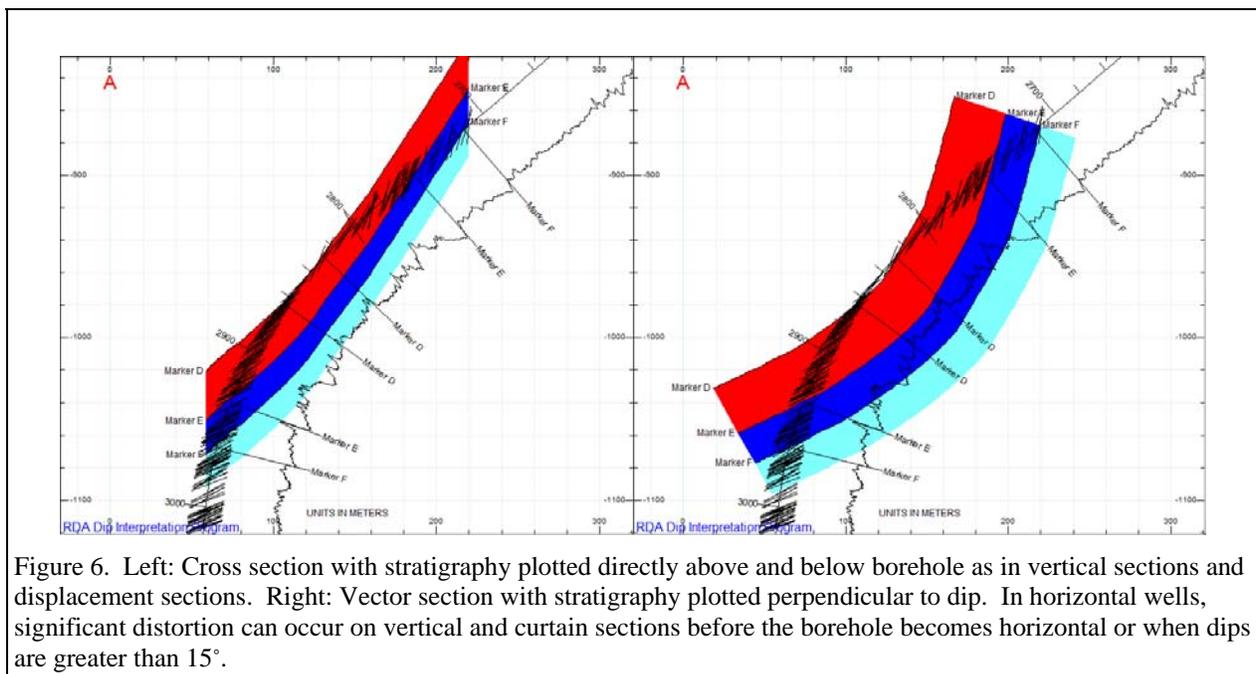
Figure 6. Left: Cross section with stratigraphy plotted directly above and below borehole as in vertical sections and displacement sections. Right: Vector section with stratigraphy plotted perpendicular to dip. In horizontal wells, significant distortion can occur on vertical and curtain sections before the borehole becomes horizontal or when dips are greater than 15°.

Calculating the forward model

The purpose of the forward model is to elucidate structure by taking the trace of the template will into the domain of the horizontal well. This is done by putting in dips and faults in the horizontal well so that the modeled trace from the template will match the trace in the horizontal well.

Calculating the log trace

To calculate the modeled template log, the well is first put into true stratigraphic thickness by applying equation 1 successively down the hole and adding each new value to a cumulative list of TST. The lists of deviation and dip must first be resampled so that there is a dip for every deviation and vice versa. The resampling should be done by 3D angular interpolation rather than interpolating the angles and azimuths separately or interpolating the vector cosines. Angular interpolations may be performed by methods such as Euler-pole rotation (Cox and Hart, 1986) or minimum curvature (Taylor and Mason, 1972).

Linear interpolation of TST over long intervals will create error because TST (equation 1) is nonlinear. To maintain accuracy when large angular differences are involved, it is necessary to further subdivide the deviation and dip lists into smaller angular increments, once again using angular interpolation, before calculating the TST list.

If the template is a vertical pilot in low dips, the depths can be used directly in the calculation process. Otherwise, the log should be converted into TST in a manner similar to the correlation log.

Next, a top common to both the correlation log and the template log is used to "hang" the template onto the well. The difference in TST between the top in the template and the same top in the TST list is then subtracted from all of the points on the TST list.

Finally, points in the template log are interpolated onto points with the same value on the TST log. A difficult part of programming the forward model is to write a fast interpolation routine that will sense a reverse in direction of the TST in the well and change direction accordingly on the template. A good way to test such a routine is to first write a brute force routine that simply searches the entire template for each point. Such routines are very slow, however and should only be used for testing.

Using angular interpolation implicitly assumes that folds are concentric in nature. This is why figures 1 and 7 used the concentric model. This can most easily explained in the deviation calculations, since the calculations explicitly define circular arcs, but it is also true of the dip calculations, which use basically the same mathematics. This fact will not create problems in modeling, however, because to match other structural styles, the modeler simply adds more dips to better define the structure.

Faults

Faults are handled by adding or subtracting to the TST in the well according to the repeated or missing section (Figure 7). It must be noted at this point that repeated or missing section in a horizontal well does not mean the same thing in a vertical well. Since the borehole is traveling horizontally, the issue of reverse or normal faulting is usually unknown. However, repeated or missing section is related to whether the bit is traveling up or down section, as well as the direction of throw (Figure 8).
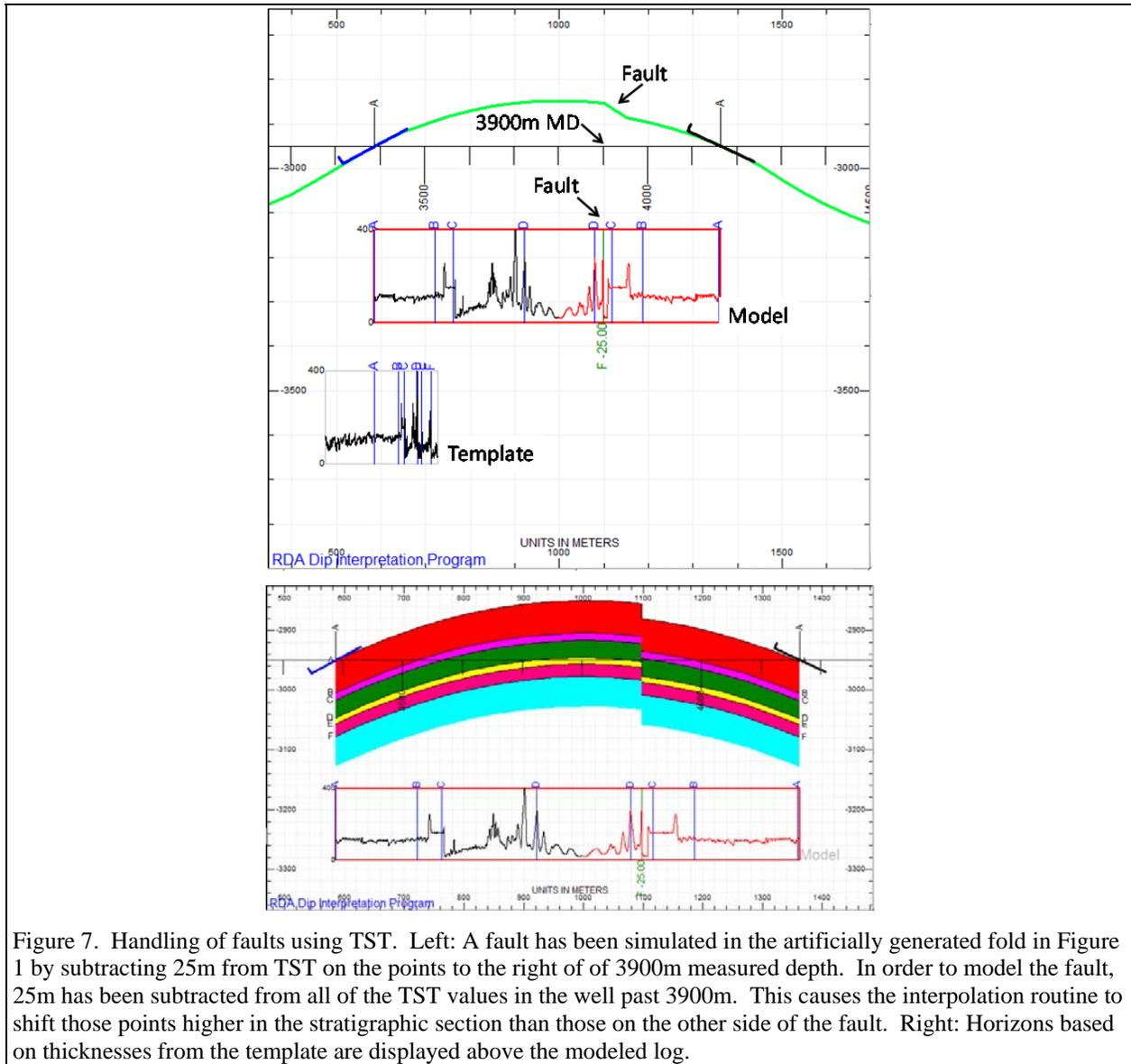
Figure 7. Handling of faults using TST. Left: A fault has been simulated in the artificially generated fold in Figure 1 by subtracting 25m from TST on the points to the right of of 3900m measured depth. In order to model the fault, 25m has been subtracted from all of the TST values in the well past 3900m. This causes the interpolation routine to shift those points higher in the stratigraphic section than those on the other side of the fault. Right: Horizons based on thicknesses from the template are displayed above the modeled log.

Figure 8. Left: Borehole traveling left to right from the upthrown to the downthrown side of a fault. Right: Borehole traveling left to right from the downthrown to the upthrown side. The two upper cases both have repeated section and the two lower cases have missing section, even though their respective faults have opposite throw. Whether or not section is repeated or missing depends on whether the bit is traveling up section or down section as well as the sense of throw. When interactively modeling faults, it is often easier to do trial and error on the sign rather than puzzling it out in advance. (The fault in Figure 7 is the lower left case.)

Discussion

Effective sample rate and log character

A common criticism of MWD gamma ray logs is that they appear "jittery" or "chattery" when compressed down to compare to pilot logs. Most of the time the jittery appearance is caused by the different effective sample rates of the two logs (Figure 9).   Some shales seem to have a jittery appearance which cannot completely be explained by sample rate differences. These may be caused by local lateral inhomogeneity, and therefore would not reflect a deficiency of the logging tools. (In fact, because of the longer measurement time of MWD tools, the gamma ray might actually be more accurate than wireline gamma ray logs.) Since the data in the correlation log are valid, important features may be missed (or dismissed) when the correlation log is compressed down to match the template log.

Figure 10 is an example of a possible missed clue in a well in the Haynesville Formation in Louisiana. The correlation log is so compressed when being compared to the template that it is easy to miss a possible reflection of an event on the larger scale correlation log.

Figure 9. Top Left: The correlation log in the horizontal well showing sample points. Middle Left: The modeled template log showing the original sample points. Bottom Left: The correlation log with points averaged to a sample rate comparable to the template log. The differences in appearance of the modeled template to the correlation log are due partly to the difference in sample rates and partly to relative depth of investigation. To the right of the three plots are the same traces compressed to a more typical display scale. This illustrates how compression would make the correlation log appear "jittery" when compared to the template. Units are in meters.

Figure 10. An example of how compressing the correlation log down to the template scale has the potential to miss valuable information. At the top is a digitized gamma ray curve from a horizontal Haynesville well in Louisiana that has crossed a large fault at about 3550ft (vertical section), and has probably gone into lower Haynesville (Buckner). Top right is exactly the same log interval shown at approximately the same scale as was used to compare to the template. Note the two peaks at 3900ft and 4010ft that have been reduced to two vertical lines. At bottom left, the interval from 3857-4082ft. has been isolated. At bottom right, the interval from 3857-3942ft has been reversed and stretched to 4082ft, showing that it is likely that the log character is a mirror image caused, perhaps, by a rollover. The apparent dip at this point in the interpretation was calculated at 2-3° where it should have been close to 0°, so the geosteerer probably did not notice the feature. This example was digitized from a vertical section plot by HSI (2008). (No logs of this interval were released to the state, so the interpretation is not certain.)

Stratigraphy as a guide

Structural modeling assumes that stratigraphic intervals are constant. In other words, when modeling, choose intervals for modeling that will remain fairly constant, and also bear in mind where the rapidly changing stratigraphy might be located when modeling. As with any modeling technique, it must be remembered that there can be more than one solution to any one problem, so it is advisable to base models on as much geologic evidence as possible, and to not unconditionally accept the first model that fits the data as the correct one.

Other applications of structural dip modeling

Under the broader category of structural dip modeling, TST forward modeling is useful in integrating existing dip data into a structural framework (Figure 11) and it is also useful in well planning. TST forward modeling can also be used in vertical wells with high angle dip (Figure 12).
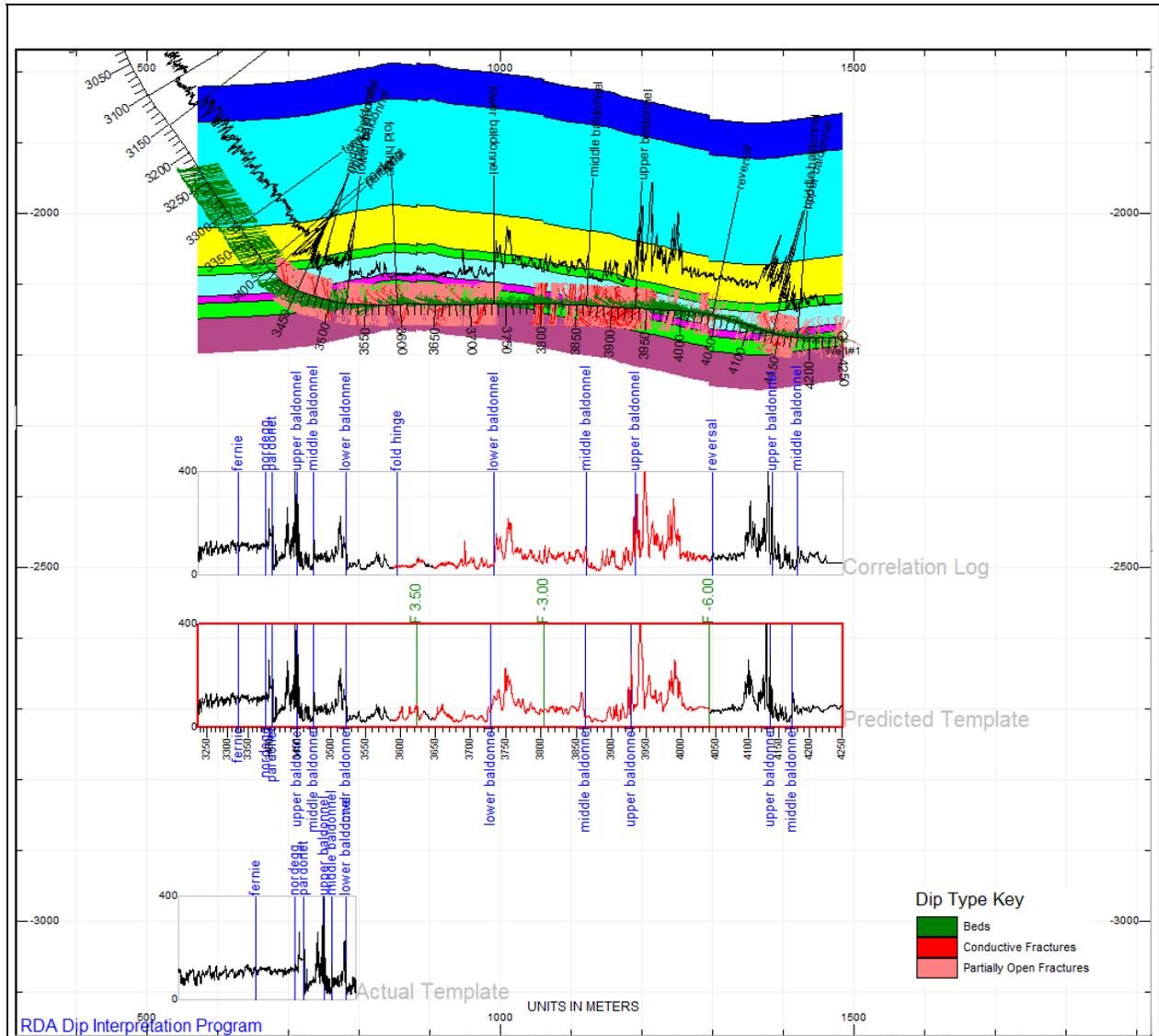
Figure 11. A horizontal well in northeastern British Columbia, Canada showing how imager-derived dips can be used to model structure. The template log, in this case, has been generated by converting the correlation log down to 3600m into TST. That self-template is then used to forward model the rest of the well. The presence of faults in the self-template log can complicate the interpretation, so it is necessary to check if the intervals look correct. In this particular case, there may be a small fault with repeated section at 3570m.

Figure 12. Application of structural forward modeling in a vertical well. In this case the only data used to do the interpretation were the template log, the correlation log, the deviation survey, and the tops from the respective logs. The display type here is a vector section because curtain and vertical sections would be useless. In vertical wells it is especially easy for the interpretations to be reversed, that is, the dips pointing the opposite direction. It is therefore important to integrate as much of the surrounding geology as possible into an interpretation. The dips were derived by adding or changing dip values until the log trace in the modeled log matched the log in the well.

Examples

The predictive power of TST

In addition to forward modeling the log trace, TST can predict changes in apparent dip as the borehole direction changes. Figure 13 is an example showing how the use of TST can provide a prediction of apparent dip, as well as stratigraphic position, in a well where the borehole azimuth is changing. In this example, TSP might correctly predict the changes in dip up until the 90 turn, but would essentially try to keep on with the same apparent dip. On

the other hand, TST forward modeling has correctly predicted that the apparent dip should flatten out and reverse slightly. In other words, TST provides an educated guess while TSP can only extrapolate the current trend.

Figure 13. A synthetic example showing how a single dip enables calculated TST to accurately predict changes in apparent dip. In this displacement or "curtain" section, a single dip has been input at 2400m measured depth. As the well azimuth changes from NE to SE, the apparent dips on the section change to reflect the relationship of the section to structural dip. It is important to stress here that a single dip has been used to create the cross section.

Curtain sections vs vertical sections

Figure 14 is an example of why curtain sections are better for display of horizontal well data. As previously mentioned, when a horizontal well deviates away from the plane of a vertical section, curtain sections show better relative positioning as well as better apparent dip when compared to vertical sections.

Figure 14. Same example as in Figure 13 showing a curtain section (top) and vertical section form (bottom). On each section, a line is drawn representing how the formation dip would be displayed in cross section. (Refer to Figure 13 for the reference map.) This figure shows the benefit of curtain sections relative to vertical sections. This is equivalent to how a gridded surface such as a 3D seismic horizon would be plotted in cross section. (The formation dip in this case represents the Kc horizon.) In the curtain section the gridded horizon follows the cross section tops exactly, while in the vertical section, the vertical position as well as the apparent dips are different. The differences may not seem large here because of the small scale and no vertical exaggeration, but they are significant when they are displayed close-up with high vertical exaggeration. Also note that the vertical section on the right side is highly compressed horizontally because the borehole azimuth is nearly perpendicular to the plane of section.

Conclusion

TST forward modeling is a powerful tool for geosteering. The modeling is performed by adding and/or changing dips until the log trace on the modeled template matches that of the horizontal well. Using the full 3D nature of dip, structural modeling can better anticipate what is ahead of the bit than can TSP.

Using TST for geosteering horizontal wells is part of the general category of structural dip modeling. The modeling can be applied to vertical wells in steep dip and the same principles can be used to determine placement and throw of faults when dip data are already present.

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