Determination of True Bed Thickness Using Folded Bed Model and Borehole Data

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Abstract

The true bed thickness \((t)\) is the actual thickness of a given formation perpendicular to the bedding plane. The value of \(t\) depends on the angle and the direction of the dip of the measured formation, as well as the drift angle and azimuth of the borehole. The traditional methods to calculate the parameter \(t\) consider only the case of monoclinal beds but not the case of a folded bed, which will cause deviations when the bed dip on the top is different from that on the bottom. To avoid these deviations, this paper shows an approach to calculate the values of \(t\) using a folded bed model. The deviations for the monoclinal bed model are positively related to the bed dip, the dip difference and the deviated angle of the wells. A case study from the Cantarell oil field complex in the southern Gulf of Mexico (offshore Campeche) is used to test the folded bed method. The results indicate that this model can yield more uniform spatial change of the values of \(t\), whereas the monoclinal bed model will overestimate the average value of \(t\). Compared to the folded bed model, the maximum relative deviation of \(t\) from the monoclinal bed model reaches 22.3% and the maximum absolute deviation of \(t\) reaches 34.5 m.

Calculation of the Value of \(t\) in the Case of Monoclinal Bed

First, the case of a monoclinal bed is reviewed here. Figure 1a shows the case of a vertical well crossing a monoclinal bed. If the well enters the top of the bed at A, and leaves the base of the bed at B, the depth difference between A and B is defined as \(h_d\). The true bed thickness of the bed \((t)\) can be expressed as:

\[
t = BC = h_d \cos \beta
\] ................................. (1)

Figure 1b shows the case of a well deviated at an angle \(\alpha\) from the vertical crossing a monoclinal bed. In this case, the vertical depth difference between A and B is \(h_d = AC\), which is not equal to the distance between A and B. The true bed thickness is \(t = BD\). The distance between A and B is \(h_d / \cos \alpha\). Assuming that both the bed azimuth and the well azimuth are the same, the values of \(t\) can be calculated from the following equation:

\[
t = BD = h_d \cos (\beta + \alpha) / \cos \alpha
\] ................................. (2)

If the dip direction on the top of the bed is not the same as the well azimuth, the value of \(\alpha\) needs to be corrected. The apparent deviation angle \((\alpha')\) in the dip direction of the bed can be calculated by:

\[\alpha' = \alpha - \beta \]
Calculation of the Values of $t$ for Folded Bed

As shown in Figure 1, it is assumed that the bed dip is the same at the point where the well enters the bed ($\beta_1$) as it is when the well leaves the bed ($\beta_2$). However, usually $\beta_2$ is not equal to $\beta_1$ in the case of flexed and folded beds, even if the well azimuth is the same as the bed dip direction. There are many types of folds in nature. Nevertheless, for most reservoirs with no severe plastic deformation or rheomorphic folding, a flexed or folded bed can be simply assumed to be a concentric parallel fold in a cross section. Under this assumption, for the folded bed model, the cases of a vertical well should be considered separately to calculate the values of $t$.

The case of a vertical well is shown in Figure 2a, in which $AB = h$. For the isosceles triangle OBD, the relationship $\angle ODB = 90^\circ - (\beta_2 - \beta_1)/2$ can be obtained. Then, it can be calculated that $\angle ADB = 90^\circ - (\beta_2 - \beta_1)/2$ and $\angle ABD = 90^\circ - (\beta_2 - \beta_1)/2$. For the triangle ADB, the true bed thickness can be estimated according to the Law of Sines:

$$t_1 = AD = AB \cos \frac{(\beta_2 + \beta_1)}{2} \cos \frac{\beta_2 - \beta_1}{2} = h \cos \frac{\beta_2 - \beta_1}{2}$$

(4)

Figure 2b illustrates the case of a deviated well with a deviation $\alpha$ from the vertical, crossing a fold in which the depth difference is $AE = h$. In this case, the bed azimuth and the well azimuth are assumed to be the same. For the isosceles triangle OBD, the relationship $\angle ODB = 90^\circ - (\beta_2 - \beta_1)/2$ can be obtained. Thus, it can be determined that $\angle ADB = 90^\circ + (\beta_2 - \beta_1)/2$ and $\angle ABD = 90^\circ - (\beta_2 + \beta_1)/2 + \alpha$. For the triangle ADB, according to the Law of Sines, the value of $t$ can be estimated by:

$$t_1 = AD = AB \cos \left(\frac{\alpha + \beta_2 + \beta_1}{2}\right) \cos \left(\frac{\beta_2 - \beta_1}{2}\right) = h \cos \left(\frac{\beta_2 - \beta_1}{2}\right)$$

(5)

The above calculation is based on the assumption that the bed dip direction and the well azimuth are the same. If the dip direction in the top of the bed has a certain intersection angle with the well azimuth, the apparent well deviation $\alpha'$ can be calculated from Equation (3).

Comparison of the Values of $t$ Estimated from the Monoclinal and Folded Bed Models

In order to understand the parameters that influence the values of $t$ between the two models, we define the absolute deviation ($D$) and the relative deviation ($\mu$) of the value of $t$ for the monoclinal bed model by the following equations. In the case of vertical wells, the absolute deviation is written as:

$$D_1 = t_1 - t = h\left[\cos \frac{\beta + \beta_1}{2} \cos \frac{\beta - \beta_1}{2}\right] \frac{\sin \gamma}{\sin \alpha}$$

(6)

whereas, the relative deviation is written as:

$$\mu_1 = D_1 / t$$

(7)

In the case of deviated wells, the absolute deviation can be calculated as:

$$D_2 = t_2 - t = h\left(\cos \frac{\beta + \beta_1}{2} \cos \frac{\beta - \beta_1}{2}\right) \frac{\sin \gamma}{\sin \alpha}$$

The horizontal lines indicate that the value of $\mu_1$ is related to the bed difference ($\beta_2 - \beta_1$), but not the depth difference ($h$).
Three parameters control the values of \(D\) and \(\mu\) including: the bedding dip \((\beta_i)\), the dip difference between the top and bottom of the bed and the deviated angle of wells. The following discusses in detail these three parameters, respectively.

1. The value of \(\beta_i\) is positively related to the relative deviation \(\mu\) for the monoclinal bed model (Figure 3a). This implies that a high bed dip for the monoclinal bed model will cause a large deviation of the value of \(D\). Therefore, it is better to use the folded model. As can be seen from Figures 3b and 3c, the depth difference \(h_j\) does not influence the relative deviation \(\mu\), although it affects the absolute deviation \(D_j\).

2. Figure 4 shows the values of \(D\) and \(\mu\) for the given values \(h_j\) and \(\beta_i\), which have a positive relationship with \(\beta_i - \beta_1\). When \(\beta_i > \beta_1\) or \((\beta_i - \beta_1) > 0\), the values of \(D\) and \(\mu\) are larger than zero, whereas when \(\beta_i < \beta_1\) or \((\beta_i - \beta_1) < 0\), the values of \(D\) and \(\mu\) are less than zero. Under the same condition, the values of \(D_2\) and \(\mu_2\) for vertical wells are smaller than those values \((D_j\) and \(\mu_j)\) for deviated wells. For example, given \(h_j = 200\) m, \(\beta_1 = 15^\circ\) and \(\beta_2 = 10^\circ\), therefore, \(D_j = 5.1\) m and \(D_2 = 8.2\) m (Figures 4a and 4c). As can be seen in Figure 4d, when \(0^\circ < (\beta_2 - \beta_1) < 10^\circ\) and \(0^\circ < \alpha < 30^\circ\) for the given value \(\beta_1 = 15^\circ\), the value of \(\mu_2\) is less than 10% (Figure 4d). The deviation angle of the well strongly influences the value of \(\mu_2\). When \(0^\circ < \alpha < 30^\circ\), the relationship between \(\mu_2\) and \((\beta_2 - \beta_1)\) is nearly linear; when \(\alpha > 30^\circ\), the relationship between \(\mu_2\) and \((\beta_2 - \beta_1)\) is evidently non-linear.

3. Both the absolute deviation \(D_j\) and relative deviation \(\mu_j\) are positively related to the deviated angle \(\alpha\) of wells (Figure 5). However, the influence on the values of \(D_j\) and \(\mu_j\) in the case of \(\alpha = 0^\circ\) is stronger than that in the case of \(\alpha < 0^\circ\), because the area of \(\mu_j < 10\%\) is much larger than that of \(\mu_j < -10\%\) (Figure 5b). Figure 5 shows that when \(\beta_1 = 15^\circ\), the point where \(D_j = 0\) and \(\mu_j = 0\), corresponds to that of \(\alpha = -15^\circ\) (Figures 5a and 5b). This indicates that when the well is perpendicular to the bed surface \((\alpha = \beta_1)\), there is no deviation between the two models.

### Application to the Cantarell Oil Field

The folded model was tested for the Cantarell Oil Field in the southern Gulf of Mexico (offshore Campeche). Previous studies have been published regarding the structural features of the Cantarell Oil Field. Recent interpretations of geophysical data suggested that Cantarell is a fold-thrust belt and duplex structure. The axis of the fold is about NW 300°. The fold is a SE-plunging normal fold and plunges to southeast. The stratigraphy in this oil field includes: Callovian salt, Oxfordian siliciclastics and evaporites, Kimmeridgian dolostones and terrigenous rocks, Tithonian silty and bituminous limestone, Cretaceous dolostone and dolomitized breccias in the Cretaceous/ Tertiary boundary and Lower Paleocene. The Tertiary system includes shale, sandstone and carbonate rocks. The Cretaceous/ Tertiary boundary dolomitized breccias (BKT) are selected to test the folded model. The attitudes of the top and bottom of this unit were obtained from structure contour maps. The stratigraphic depth data of the wells were obtained from PEMEX. One hundred and sixty-one deviated wells and 23 vertical wells were used to calculate the true bed thickness. The average dip of BKT is 17.3° at the top and 17.9° at the base (Table 1). The largest deviated angle of the deviated wells is 70.8°. The
average bed dip difference for the deviated wells is 29.7°. The average bed dip difference for the deviated wells is 32.3°. The largest value of \( \beta_d \) is 5.8°.

The following results were obtained by comparing the monoclinal bed model and the folded model:

1. The values of \( \beta_d \) for the folded bed model can be larger, equal to or less than those for the monoclinal bed model (Figure 6).

The average value of the true bed thickness for the folded bed model is less than that for the monoclinal bed model in both vertical and deviated wells (Tables 1 and 2). These results mean that, in general, the monoclinal bed model will overestimate the true bed thickness.

2. The average value of \( t_d = \left| t_1 - t_3 \right| \) for the deviated wells is not large (6 m), whereas the average relative value of \( t \) is only 2.4%. This small value is produced by two facts. One, is that the average value of \( \beta_d \) is small (5.8°).

3. The other is that most deviated angles of the wells are in the range of \(-10\% < \mu < 10\%\) when the average value of TV indicates the types of values, for which Max represents maximum value, Min represents minimum value and Av is average value. \( \lambda = 100 \frac{t_3 - t_1}{t_1} \). The significance of the other symbols is the same as that in the text and figures.

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**Table 1**: Parameters and results of the true bed thickness calculated for the BKT unit utilizing the inclined and folded models in the Cantarell Oil Field of the southern Gulf of Mexico (offshore Campeche). The original data is obtained from 161 deviated wells (Case A). Case B: deviated wells with \( \beta_2 - \beta_1 < 10^\circ \). Case C: deviated wells with \( \beta_2 - \beta_1 < 10^\circ \). TV indicates the types of values, for which Max represents maximum value, Min represents minimum value and Av is average value.

<table>
<thead>
<tr>
<th>Case</th>
<th>Number of Wells</th>
<th>TV</th>
<th>( \beta_1 ) (°)</th>
<th>( \beta_2 ) (°)</th>
<th>( \beta_d ) (°)</th>
<th>( t_2 ) (m)</th>
<th>( t_3 ) (m)</th>
<th>( t_4 ) (m)</th>
<th>( \lambda ) (%)</th>
<th>( \delta_l )</th>
<th>( \delta_e )</th>
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<td>A</td>
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<td>39.8</td>
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<td>363.7</td>
<td>512.6</td>
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<td>22.3</td>
<td>67.9</td>
<td>67.4</td>
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<td></td>
<td>M</td>
<td>6</td>
<td>5</td>
<td>0</td>
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<td>52.3</td>
<td>0</td>
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<td></td>
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<td>4.4</td>
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**Table 2**: Parameters and results of true bed thicknesses calculated for the BKT unit utilizing the monoclinal and folded models in the Cantarell Oil Field of the southern Gulf of Mexico (offshore Campeche). The original data was obtained from 23 vertical wells. \( \lambda = 100 \frac{t_3 - t_1}{t_1} \). The other symbols have the same significance as that in Table 1 and in the text and figures.

<table>
<thead>
<tr>
<th>Number of Wells</th>
<th>TV</th>
<th>( \beta_1 ) (°)</th>
<th>( \beta_2 ) (°)</th>
<th>( \beta_3 ) (°)</th>
<th>( t_1 ) (m)</th>
<th>( t_2 ) (m)</th>
<th>( t_3 ) (m)</th>
<th>( t_4 ) (m)</th>
<th>( \lambda ) (%)</th>
<th>( \delta_l )</th>
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<td>0</td>
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<td>0</td>
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<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Av</td>
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<td>9.6</td>
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<td>278.9</td>
<td>7.6</td>
<td>2.6</td>
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</table>
5. The average value of $\beta_d (\beta_d = |\beta_2 - \beta_1|)$ is 17.3° and the average value of $\alpha$ is 5.8° in the Cantarell Oil Field (Figures 7a and 7b).

4. The absolute value of the bed thickness difference between the two models ($t_d = |t_3 - t_1|$ or $|t_4 - t_2|$) is related to the dip difference ($\beta_d = |\beta_2 - \beta_1|$). For the deviated wells, when $\beta_d < 10°$, the average value of $t_d$ is 4.4 m. The average relative deviation of the value of $t$ is only 1.7%. When $\beta_d > 10°$ (10° - 29.7°), the average value of $t_d$ is 15.6 m. The average relative deviation of $t$ reaches 9.5% (Table 1). The maximum relative deviation is 22.3%.

5. The average value of $t_d$ for the deviated wells (6 m) is not larger than that for the vertical wells (7.6 m). The average relative deviation of the inclined bed model for the deviated wells (2.4% in Table 1) is also not larger than that for the vertical wells (2.4% in Table 2). These results indicate that the vertical wells do not cause the minimum deviations, which is consistent with the explanations in Figures 5a and 7b.

6. In all cases, the standard deviation of the true bed thickness for the folded bed model ($\delta$) is less than that for the monoclinal bed model ($\delta$) as seen in Tables 1 and 2. This result implies that the change of the bed thickness obtained from the folded bed model changes less than that from the monoclinal bed model. In other words, the folded model works better than the monoclinal model for this example.

7. In general, the form of contour lines in the isochores are similar between the monoclinal bed model and the folded model (Figures 8 and 9). However, there are some local differences in the isochores between the two models. For example, near point A, the area larger than the contour line 450 m for the monoclinal bed model is much larger than that for the folded bed model. Near point B, the contour line 250 m is closed in Figure 8, but it is not closed in Figure 9.

Conclusions

When the attitude of a bed is not the same at the point where a well enters as it is when the well leaves the bed, the folded bed model should be considered to calculate the values of $t$. In this case, the main factors that influence the values of $t$ are the bed dip ($\beta$), the dip difference between the top and base of the bed and the deviated angle of the well ($\alpha$). The folded bed model can yield fewer changed values of the true bed thickness. In general, the monoclinal bed model will overestimate the true bed thickness.

Acknowledgements

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FURTHER READING


SPECIFIC APPLICATION TO THE CANTARELL FIELD


Provenance—Original unsolicited manuscript, Determination of True Bed Thickness Using Folded Bed Model and Borehole Data (2005-10-20CS). Abstract submitted for review October 17, 2005; editorial comments sent to the author(s) May 23, 2007; revised manuscript received June 25, 2007; paper approved for pre-press June 25, 2007; final approval <Approved>.

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José Manuel Grajales Nishimura is working in a multidisciplinary team on the geological characterization of carbonate oil reservoirs at the Instituto Mexicano del Petróleo. He is responsible for diagenetic studies in order to characterize the origin and distribution of porosity in Cretaceous carbonate rocks in southern Mexico. He is currently working on sedimentology and stratigraphy of K-T boundary sedimentary sequences. He is a member of the GSA, as well as several Mexican technical associations such as the AMGP and SGM. His work has been published in 24 technical papers.

Gustavo Murillo-Muñetón earned an M.S. degree from the University of Southern California and a Ph.D. degree from Texas A&M University. He has worked for the Instituto Mexicano del Petróleo in Mexico City since 1984. His research areas include: sedimentology, stratigraphy and diagenesis; mainly of carbonate systems. He currently carries out research and applied projects on petroleum exploration and exploitation from diverse Mexican basins. Additionally, he has as a part-time teaching position at the Instituto Politécnico Nacional where he teaches in the Sección de Graduados of the Escuela Superior de Ingeniería y Arquitectura-Unidad Ticomán.

Jesús García Hernández is a petroleum geologist who has worked for PEMEX for the last 25 years. He received his degree in petroleum geology from the Instituto Tecnológico de Cd. Medero and an MBA degree from the Universidad Autónoma del Carmen-Tulane. He has extensive experience in prospect evaluation and production in the Cantarell Asset. Among his many publications, one article published in the AAPG Bulletin in 2005 won the Wallace E. Pratt Award. He is Asset Sub-Manager for the Cantarell Asset.

Angel F. Nieto-Samaniego received a Ph.D. in geology in 1995. He has twenty years of academic experience and is a researcher and professor of structural geology at the National University of Mexico (Universidad Nacional Autónoma de México, UNAM). In 1997-1998 he was President of the Mexican Geological Society. Currently, he is Editor of the Revista Mexicana de Ciencias Geológicas and the Boletín de la Sociedad Geológica Mexicana. Also, he is a member of the Editorial Advisory Board for the Journal of Structural Geology.