

## Thickness Measurements and Thickness Maps

### 4.1

#### Thickness of Plane Beds

Thickness has multiple definitions, the choice of which depends on the purpose and the data available (Fig. 4.1). The true stratigraphic thickness (TST) is always the distance between the top and base of a unit measured perpendicular to the top. In a completely exposed outcrop, bed thickness can be measured directly across the bed. In a well that is perpendicular to bedding, the measured thickness in the well (MD) is the true stratigraphic thickness. Commonly, however, thicknesses must be determined from oblique traverses across beds or from wells that are not perpendicular to the bed boundaries. The measured thickness in a vertical well (or along a vertical traverse) is the true vertical thickness (TVT). The measured thickness in any other direction is here termed a slant thickness. A “thickness” measurement that is easily derived from well data is the TVD or true vertical depth thickness, and is the difference in elevation between the top and base of a unit in a well log. This “thickness” is more related to the orientation of the well, however, and for a horizontal traverse or a horizontal well, the TVD is zero. In the following sections the true stratigraphic thickness is found first and then other thickness determined from it, as needed.

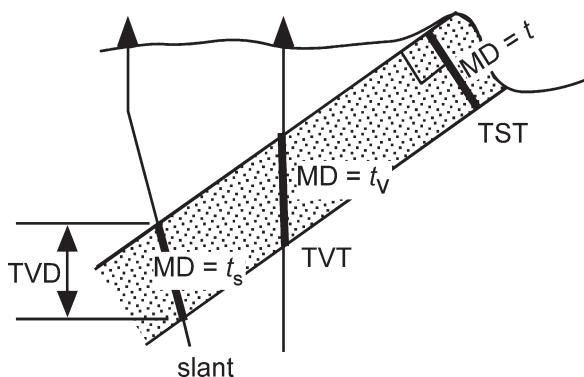
#### 4.1.1

##### Universal Thickness Equation

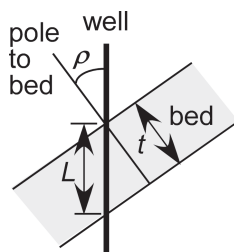
The stratigraphic thickness can be determined from a single equation (Hobson 1942; Charlesworth and Kilby 1981) based on the angle between the direction of the thick-

Fig. 4.1.

Vertical cross section in the dip direction showing measures of thickness: MD: measured distance on well log or traverse;  $t$ : true stratigraphic thickness = TST;  $t_v$ : true vertical thickness = TVT;  $t_s$ : slant thickness; TVD: true vertical depth thickness = difference in  $z$  coordinates between top and base of unit. (Standard well-log terminology from Robert L. Brown of Shell Oil Co.)



**Fig. 4.2.**  
Data needed to determine  
thickness of a unit from the  
universal-thickness equation  
(Eq. 4.1)



ness measurement and the pole to bedding (Fig. 4.2). The method is convenient for data from a well or a map. It is here called the *universal* thickness equation because it always works, regardless of the direction of the measurement or the dip of the bed. The advantage of this method is that the thickness is given by a single, simple equation, eliminating most potential sources of error. The disadvantage for hand calculation is the need to determine an angle in three dimensions, although this is easily done with a stereogram or spreadsheet. The apparent thickness is measured along the direction  $L$ . In the plane defined by the line of measurement and the pole to bedding

$$t = L \cos \rho \quad , \quad (4.1)$$

where  $t$  = the true stratigraphic thickness and  $L$  is the straight-line length between the top and base of the unit (MD), measured along a well or between two points on a map. The angle  $\rho$  = the angle between  $L$  and the pole to the bed. If the acute angle is used in the equation, the thickness is positive. If the obtuse angle is used the thickness will be correct in magnitude but negative in sign; taking the absolute value gives the correct result for either possibility. If  $L$  is vertical, then the angle  $\rho = \delta$ , the dip of the bed. If the true thickness is known, then the vertical thickness can be found by rewriting Eq. 4.1 as

$$t_v = t / \cos \delta \quad , \quad (4.2)$$

where  $t_v$  = vertical thickness,  $t$  = true thickness, and  $\delta$  = true dip.

If  $L$  is not vertical, its inclination must be determined. For a well, a directional survey will give the azimuth of the deviation direction and the amount of the deviation; the latter which may be reported as the kickout angle, the angle up from the vertical. Alternatively, the deviation of a well may be given as the  $xyz$  coordinates of points along the well bore. The angle  $\rho$  can be found graphically or analytically, as described in the following two sections.

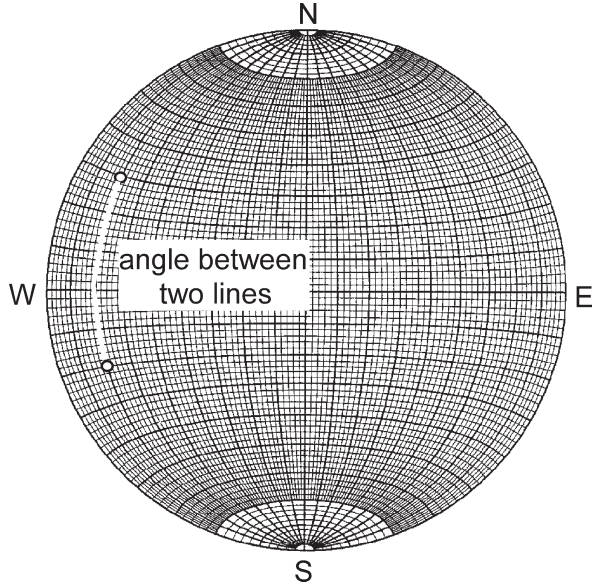
#### 4.1.1.1

##### Angle between Two Lines, Stereogram

To find the angle  $\rho$  with an equal-area stereogram, on an overlay, plot the point representing the pole to bedding by marking the trend of the dip on the overlay, rotating the overlay to bring this mark to the east-west axis, and counting inward from the outer circle (the zero-dip circle) the amount of the dip plus  $90^\circ$ , and mark the point. Return

**Fig. 4.3.**

Equal-area stereogram showing the angle between two lines. Angle  $\rho$  is the great circle distance between the points giving the pole to bedding and the orientation of the apparent thickness measurement. Lower-hemisphere projection



the overlay to its original position. Plot the line of measurement (or well bore) by similarly marking the trend of the measurement on the outer circle, bringing the mark to the east-west axis and measuring the dip inward from the outer circle if given as a plunge, or outward from the center of the graph if given as a hade or kickout angle. Rotate the overlay until the two points fall on the same great circle (Fig. 4.3). The angle  $\rho$  is measured along the great circle between the two points.

As an example of the thickness calculation based on the universal thickness equation, find the true thickness of a bed that is  $L = 10$  m thick in a well. The well hades  $10^\circ$  to  $310^\circ$  and the bed dip vector is  $20, 015$ . Plot the bed on the stereogram and find its pole. Then plot the well and measure the angle between the two lines ( $\rho = 27^\circ$ ). Equation 4.1 gives  $t = 8.9$  m.

#### 4.1.1.2

##### Angle between Two Lines, Analytical

Method 1. Using bed dip vector and well dip vector

To find the angle between the bed pole and the well, both given as bearing and plunge, substitute well dip vector (Eq. 12.3) and the bed pole from the dip vector (Eq. 12.13) into the equation for the angle between two vectors (Eq. 12.25) to obtain

$$\rho = \cos^{-1} \rho = -\cos \delta_w \sin \theta_w \sin \delta_b \sin \theta_b - \cos \delta_w \cos \theta_w \sin \delta_b \cos \theta_b + \sin \delta_w \cos \delta_b, \quad (4.3)$$

where  $\rho$  = angle between bed pole and fault dip vector,  $\delta_w$  = dip of well,  $\theta_w$  = azimuth of well dip,  $\delta_b$  = dip of bed,  $\theta_b$  = azimuth of bed dip.

Method 2. Using bed dip vector and points on top and base of unit

If the locations of the unit boundaries are given by their  $xyz$  coordinates, and the orientation of bedding by its azimuth and dip, the angle  $\rho$  required in Eq. 4.1 may be found by substituting Eq. 12.9 into Eq. 12.25:

$$\rho = \cos^{-1} \{ [(x_1 - x_2) / L] \sin \theta_b \sin \delta_b + [(y_1 - y_2) / L] \cos \theta_b \sin \delta_b + [(z_2 - z_1) / L] \cos \delta_b \} , \quad (4.4)$$

where  $\theta_b$  and  $\delta_b$  =, respectively, the azimuth and dip of the bed dip vector, and  $L$ , the apparent length, is

$$L = [(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2]^{1/2} . \quad (4.5)$$

Method 3. Using bed dip vector and line on map

If the line of the thickness measurement is defined by its map length,  $h$ , change in elevation,  $v$ , and orientation given by the azimuth,  $\theta$ , to the lower end of the line, then the angle  $\rho$  required in Eq. 4.1 may be found by substituting Eq. 12.7 into Eq. 12.25:

$$\rho = \cos^{-1} \{ \cos \delta_b \sin [\arctan (v / h)] - \sin \delta_b \cos [\arctan (v / h)] (\cos \theta_b \cos \theta + \sin \theta_b \sin \theta) \} , \quad (4.6)$$

where  $\theta_b$  and  $\delta_b$  =, respectively, the azimuth and dip of the bed dip vector, and  $L$ , the apparent length, is

$$L = (v^2 + h^2)^{1/2} , \quad (4.7)$$

where  $v$  = vertical distance between end points and  $h$  = the horizontal distance between end points. The angle in Eq. 4.6 must be acute and must be changed to  $180 - \rho$  if it is obtuse.

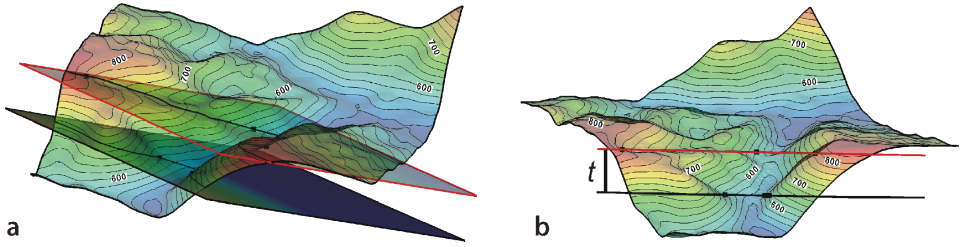
#### 4.1.2

##### Thickness between Structure Contours

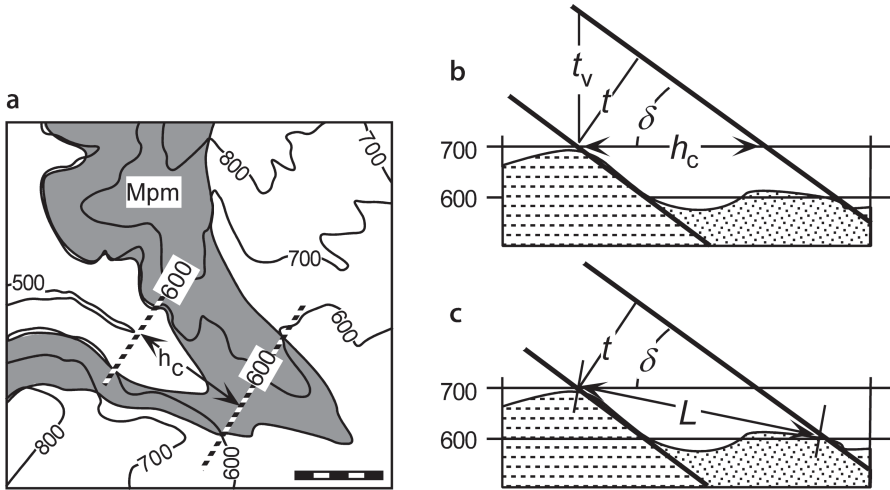
The thickness determined between structure contours is straightforward to compute and generally shows much less variability than that determined between individual points on an outcrop map. This approach provides a more reliable value in situations where the attitudes and contact locations are uncertain on a map. Determining the best-fit structure contours uses a large amount of data simultaneously to improve the attitude of bedding and the contact locations. This method requires a structure contour at the top and base of the bed (Figs. 4.4, 4.5a). The width of the unit is always measured in the dip direction, perpendicular to the structure contours. If contours at the same elevation can be constructed on the top and base of the unit, from the geometry of Fig. 4.5b, the thickness of the unit is

$$t = h_c \sin \delta , \quad (4.8)$$

where  $h_c$  = horizontal distance between contours at equal elevations on the top and base of the unit,  $t$  = true thickness, and  $\delta$  = true dip. If the contours on the top and



**Fig. 4.4.** Oblique views of planar unit boundaries cutting a topographic surface. Map view is in Fig. 4.5a. **a** Upper and lower bed surfaces, view toward north. **b** View to northeast parallel to bedding showing thickness,  $t$



**Fig. 4.5.** Thickness measured between structure contours. **a** Structure contours at 600-ft elevation on the top and base of a formation;  $h_c$  is perpendicular to structure contours (3-D views in Fig. 4.4). **b** Measurement along a constant elevation on a vertical cross section in the dip direction. **c** Measurement between points of different elevations on a vertical cross section in the dip direction. For explanation of *symbols*, see text

base of the unit are at different elevations (Fig. 4.5c), then the line on the map that connects the upper and lower contours has the length  $L$ , and the thickness can be calculated from Eq. 4.1. Equation 4.1 gives the same result as Eq. 4.8 for the special case where  $L$  is horizontal.

The vertical thickness can readily be computed by taking the difference in elevation between structure contour maps on the top and base of the unit at a given  $xy$  point (Fig. 4.5b). Then the true thickness is calculated from Eq. 4.2, rewritten as

$$t = t_v \cos \delta, \quad (4.9)$$

where  $t$  = true stratigraphic thickness,  $t_v$  = vertical thickness and  $\delta$  = dip.

As an example, in Fig. 4.5a, the 600-ft contour has been located on both the top and base of the Mpm, and so the simplest means of thickness determination is with Eq. 4.8. The value of  $h_c$  measured from the map is 1 387 ft, and the dip,  $\delta$ , is  $04^\circ$ , giving a thickness of 97 ft.

### 4.1.3

#### Map-Angle Thickness Equations

The calculation of the thickness of a unit based entirely on map distances and directions results in two equations, depending on whether the topographic slope is in the same direction as the dip of the unit or the opposite direction to it. For the bed dip and topographic slope in the same direction, the equation (derived at the end of this chapter as Eqs. 4.18 and 4.21) is

$$t = |h \cos \alpha \sin \delta - v \cos \delta|, \quad (4.10)$$

where the notation  $|\dots|$  = the positive value of the expression between the bars. For a bed dip and topographic slope that are in opposite directions:

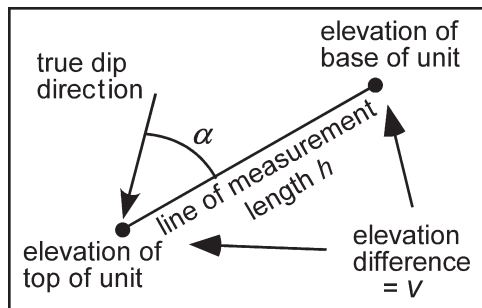
$$t = h \cos \alpha \sin \delta + v \cos \delta, \quad (4.11)$$

where  $h$  (Fig. 4.6) = the horizontal distance along a line between the upper and lower contacts on the map,  $\alpha$  = the angle between the measurement line and the dip direction,  $\delta$  = the true dip of the unit, and  $v$  = the elevation difference between the end points of the measurement line. If the measurement is in the dip direction,  $\alpha = 0$  and  $\cos \alpha = 1$ ; if the base and top of the unit are both at the same elevation,  $v = 0$ .

As an example, determine the thickness of the Pride Mountain Formation (Mpm) indicated by its outcrop width on the map of Fig. 4.7. Along line a on the map, the horizontal width of the outcrop is  $h = 1\,250$  ft, the vertical drop from highest to lowest contact is  $v = 100$  ft, the attitude of bedding is  $\delta = 07^\circ$  (the average of the  $06$  and  $08^\circ$  dips mapped) at an azimuth  $\theta = 135^\circ$ , and the angle between the dip direction and the measurement line is  $\alpha = 85^\circ$ . The bed and topography slope in the same direction (strike of bedding =  $225^\circ$  and the thickness traverse is along azimuth  $220^\circ$ ), making Eq. 4.10 appropriate. The resulting thickness is 86 ft.

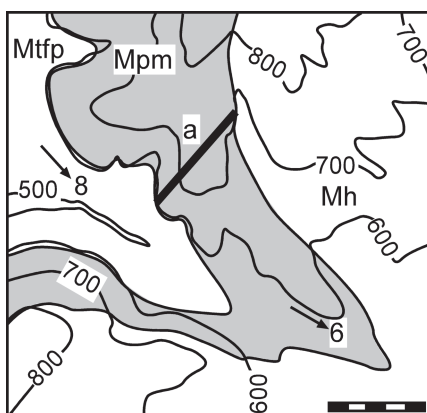
Fig. 4.6.

Map data needed to determine the thickness of a unit from outcrop observations using the map-angle thickness Eqs. 4.10 and 4.11



**Fig. 4.7.**

Line of a thickness measurement (*a*) on a geologic map on a topographic base



#### 4.1.4

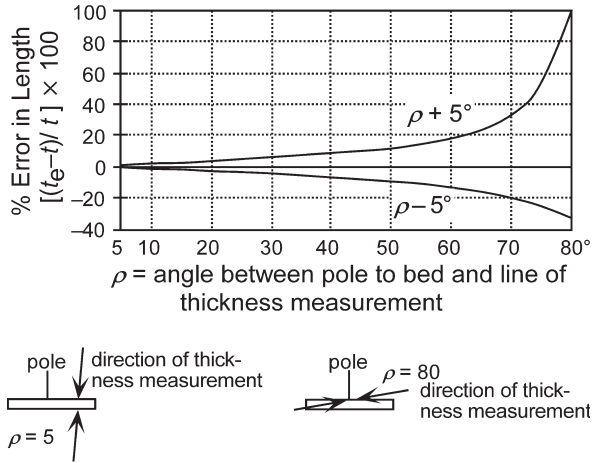
##### Effect of Measurement and Mapping Errors

In the determination of thickness from measurements on a map, there are three sources of error, the length and the direction measurements, the dip measurement, and the contact locations. Errors in length will result from the finite widths of the contact lines at the scale of the map. The minimum possible length error is approximately equal to the thickness of the geologic contacts as drawn on the map. For example, the geologic contacts in Fig. 4.7 are about 20 ft wide. Thus a thickness error of about  $\pm 20$  ft is about the best that could be done on this map. Small errors in contact locations may lead to large errors in the calculated thickness, depending on the measurement direction. Uncertainties in the dip amount and dip direction of a degree or two are to be expected. The effects of error in the dip range from very small if the thickness measurement is at a high angle to the bed boundary, to very large if the measurement is at a low angle to the boundary.

The effect of errors in bedding attitude and measurement direction on a thickness determination can be estimated using Eq. 4.1 which places the variables in their simplest form. The true thickness ( $t$ ) is directly proportional to the apparent thickness ( $L$ ) and so the erroneous thickness ( $t_e$ ) is directly proportional to the error in the length of the apparent thickness measurement. The error measure ( $t_e$ ) is normalized in Fig. 4.8 to remove the effect of the length scale. The true thickness in Eq. 4.1 is proportional to the cosine of the angle between the pole to the bed and the line of the thickness measurement ( $\rho$ ), leading to a non-linear dependence of the error on the size of the angle (Fig. 4.8). The angle error could be in the orientation of the bed, in the orientation of the apparent thickness, or a combination of both. A combined error in  $\rho$  of  $\pm 5^\circ$  from the correct value seems like the upper limit for careful field or well measurements. An angle of  $\rho = 0^\circ$  means that the thickness measurement is perpendicular to bedding; this is the most accurate measurement direction. An angle of  $\rho = 90^\circ$  means that the measurement direction is parallel to bedding, an impossibility. The sensitivity of a thickness measurement to error in the angle goes up rapidly as  $\rho$  increases (Fig. 4.8). The thickness error exceeds  $\pm 10\%$  at an angle of  $40^\circ$  and is about 100% at  $80^\circ \pm 5^\circ$  and

**Fig. 4.8.**

Effect of attitude and angle measurement errors on thickness calculation. Normalized error in thickness measurement, in percent as a function of the angle  $\rho$  (Eq. 4.1) for angle errors of  $\rho = \pm 5^\circ$ .  $t$  True thickness of bed;  $t_e$  erroneous thickness given the angle error;  $\rho$  angle between the pole to the bed and direction along which thickness is measured

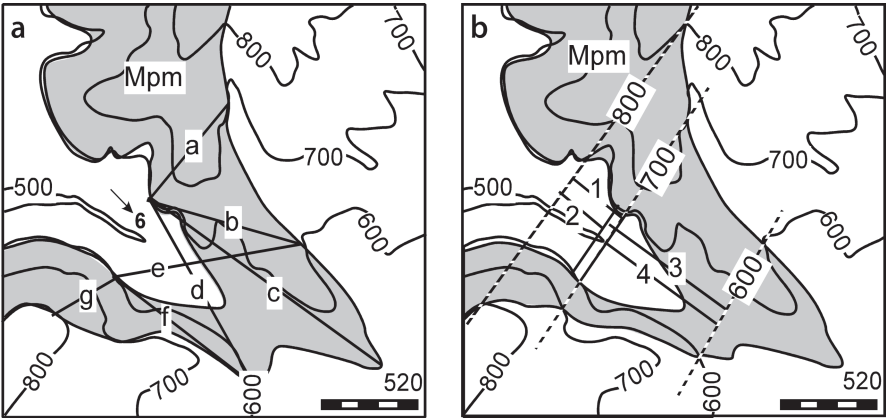


-35% at  $80 - 5^\circ$ . This means that thickness measurements made at a low angle to the plane of the bed may produce very large errors, with a strong bias toward overestimation. At angles between the measurement direction and bedding of  $10^\circ$  or less ( $\rho = 80^\circ$  or greater), very large thickness errors will occur with very small orientation errors and thickness determinations made from maps should be considered suspect.

From Fig. 4.8, a bed having a true thickness of 100 m measured at an angle of  $10^\circ$  to bedding ( $\rho = 80^\circ$ ) for which the angle is overestimated by  $5^\circ$  (giving  $\rho = 85^\circ$ ) will yield a thickness of nearly 200 m. The same measurement with a  $5^\circ$  underestimate in the angle will give a thickness of 65 m. The average thickness for these two measurements is 132.5 m, still an overestimate. Thickness measurements made nearly perpendicular to bedding ( $\rho = 0^\circ$ ) are rather insensitive to errors in the angle. At  $\rho = 20^\circ$  the error is about  $\pm 3\%$ ; a 100 m thick bed would be measured as being between 97 and 103 m thick.

Thickness calculations between two points on a map are very sensitive to the accuracy of the contact locations and the attitude of bedding, as illustrated by the data obtained from Fig. 4.9a. The thickness of the Mpm from the seven locations a-g (Table 4.1) ranges from 84 to 230 ft, as calculated from Eq. 4.1. This is an unreasonably large variation in thickness at what is nearly a single location at the scale of the map. What is the probability that the thickness variation is due to small measurement errors? The bedding azimuth of 4, 125 represents the value determined from the structure-contour map (Fig. 4.9b). The difference in dip from  $04^\circ$  on the structure contour map to  $06^\circ$  from the field measurement is responsible for a large variation in the calculated thickness. For example, at point c, the thickness along a single line is 127 ft for a  $04^\circ$  dip compared to 230 ft for a  $06^\circ$  dip (Table 4.1). However, the substantial difference in calculated thickness along lines a and g is not the result of uncertainty in the dip, but must be attributed to the uncertainty both in the location of the lower contact and in the exact dip direction. Changing the azimuth of the dip from  $135$  to  $127$  at location a increases the thickness from 84 to 108 ft at a bed dip of  $08^\circ$ ; at location g the same change reduces the thickness from 173 to 159 ft. If we say that the thickness of





**Fig. 4.9.** Alternative thickness measurements. **a** Point-to-point measurement lines *a*–*g*. **b** Measurements *1*–*4* between structure contours

**Table 4.1.** Thickness data in map area of Fig. 4.9. All thicknesses calculated with Eq. 4.1

Location	Bed		Azimuth of apparent <i>t</i>	<i>h</i> (ft)	<i>v</i> (ft)	$\alpha$ (deg)	Calculated <i>t</i> (ft)
	Dip	Azimuth					
a	7	135	220	1 242	100	85	86
	8	135	220	1 242	100	85	84
b	7	125	105	1 658	0	20	190
	4	125	105	1 658	0	20	109
c	6	125	126	2 960	80	1	230
	4	125	126	2 960	80	1	127
d	6	125	150	2 104	0	25	199
	4	125	150	2 104	0	25	133
e	7	125	080	1 030	0	45	174
	4	125	080	1 030	0	45	99
f	7	125	127	1 770	0	2	216
	4	125	127	1 770	0	2	123
g	7	135	059	741	200	76	177
	8	135	059	741	200	76	173
1 SE	8	127	127	631	200	0	110
2 NW	8	127	127	564	200	0	120
3 SE	4	124	124	1 503	0	0	105
4 NW	4	124	124	1 387	0	0	97

the Mpm is the average of the values at locations *a*–*g* obtained using the observed dips, then the thickness is 181 ft with a range from 84 to 230 ft, a poorly constrained result. The thicknesses determined at locations 1–4 (Fig. 4.9b) between the structure contours on the top and base of the unit average 108 ft thick and range from 97 to 120 ft

(Table 4.1) or  $108 \pm 12$  ft based on the whole range of values. The SE lengths (Table 4.1) are measured to a southeasterly position on the base of the Mpm, at the 600-ft contour, which lies directly beneath the 700-ft contour on the top of the unit; the NW measurements are from the more northwesterly position of the lower contact. Changing the location of the structure contour of the base has only a small effect on the thickness. The average thickness determined from the structure-contour-based measurements falls within the range of the point-to-point measurements, but is much smaller than the average of the point-to-point measurements, as expected from the behavior of the thickness equation (Fig. 4.8). Thickness measurements between two points (Eqs. 4.10 and 4.11, or 4.1) exhibit a non-linear sensitivity to error at low angles between the dip vector and the measurement orientation, leading to a high probability of an artificially high average from multiple measurements. Smoothing of the attitude errors by structure contouring leads to a better average thickness.

Where the thickness is known accurately from a complete exposure or from well-defined contacts in a borehole, the structure contours or bedding attitudes might be adjusted to conform to the thicknesses. The thickness measured between structure contours is the best approach at the map scale where there is uncertainty in the data.

## 4.2 Thickness of Folded Beds

In a folded bed, the dips of the upper and lower contact are not the same and the previous thickness equations are inappropriate. The fold is likely to approach either the planar dip domain or the circular arc form. Equations for both forms are given in the next two sections. For both methods it is assumed that the thickness is constant between the measurement points and that the line of the thickness measurement and the bedding poles are all in the plane normal to the fold axis. The latter condition is satisfied if the directions of both dips and the measurement direction are the same. If the geometry is more complex than this, then a cross section perpendicular to the fold axis should be constructed to find the thickness and projection may be required, as discussed in Chap. 6.

### 4.2.1 Circular-Arc Fold

The thickness of a bed that is folded into a circular arc (Fig. 4.10) can be found if the dip direction of the bed and the well or traverse line are coplanar. In this situation the bedding poles intersect at a point. Let  $\rho_1$  be the smaller angle between the well and the pole to bedding, thus always associated with the longer radius,  $r_1$ . The thickness,  $t$ , is

$$t = r_1 - r_2 \quad . \quad (4.12)$$

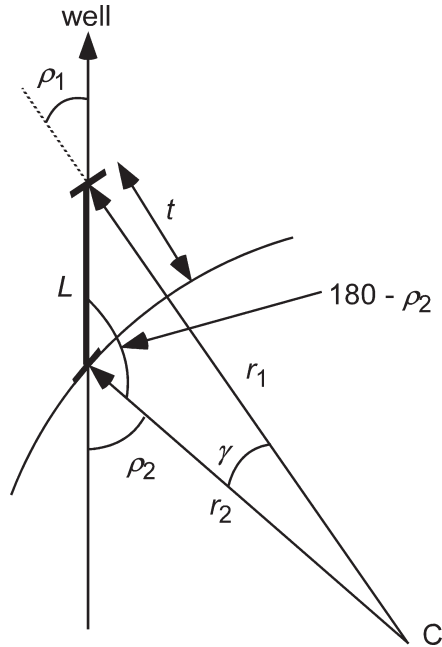
From the law of sines:

$$r_2 = (L \sin \rho_1) / \sin \gamma \quad , \quad (4.13)$$

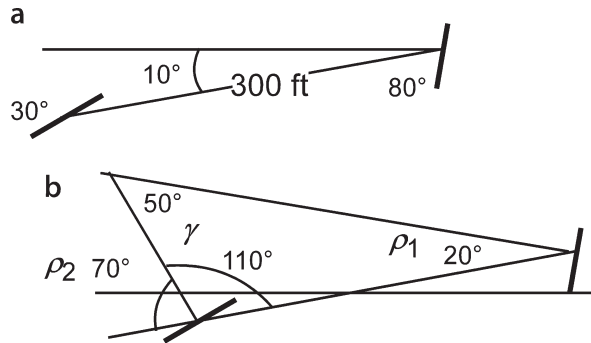
$$r_1 = (L \sin (180 - \rho_2)) / \sin \gamma \quad , \quad (4.14)$$

**Fig. 4.10.**

Thickness of a bed folded into a circular arc. The dip of the bed and the well are co-planar.  $C$  is the center of curvature where the poles to bedding intersect

**Fig. 4.11.**

Example of thickness determination of a circularly folded bed. **a** Field data: bedding dips are shown by heavy lines, distance between exposures of upper and lower contacts is 300 ft on a line that plunges 10°. **b** Angles required for the thickness calculation



where  $\rho_2$  and  $r_2$  =, respectively, the angle between the bed pole and the well and the radius associated with the larger angle, and  $\gamma = \rho_2 - \rho_1$ . Substitute Eqs. 4.13 and 4.14 into 4.12 and replace  $\sin(180 - \rho_2)$  with  $\sin \rho_2$  to obtain the thickness:

$$t = (L / \sin \gamma) (\sin \rho_2 - \sin \rho_1) \quad (4.15)$$

A typical data set is shown in Fig. 4.11a. The cross section is in the dip direction. The angles between the line of measurement and the poles to bedding are determined as well as the acute angle between the poles (Fig. 4.11b). From Eq. 4.15, the true thickness of the bed is 234 ft.

## 4.2.2

## Dip-Domain Fold

The dip-domain method can be used to find or place bounds on the thickness of a unit that changes dip from its upper to lower contact (Fig. 4.12). For constant bedding thickness, the axial surface bisects the angle of the bend. The total thickness of the bed along the measurement direction,  $t$ , is the sum of the thickness in each domain, found from Eq. 4.1 as

$$t = L_1 \cos \rho_1 + (L - L_1) \cos \rho_2, \quad (4.16)$$

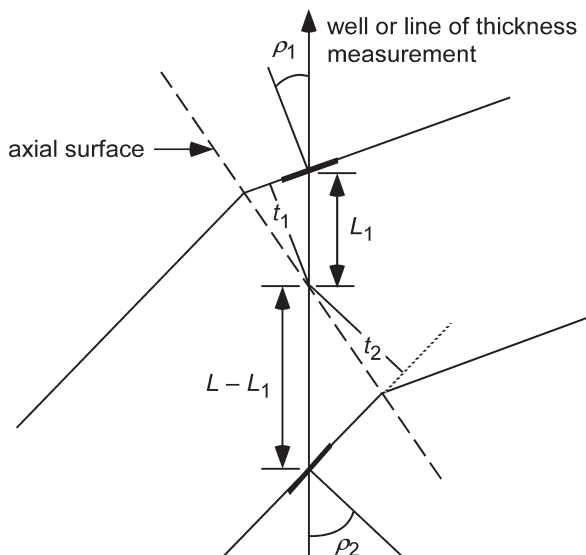
where  $\rho_1$  = the angle between the well and the pole to the upper bedding plane,  $\rho_2$  = the angle between the well and the pole to bedding of the lower bedding plane, and  $L_1$  = the apparent thickness of the upper domain. If the position of the dip change can be located, for example with a dipmeter, then it is possible to specify  $L_1$  and find the true thickness. If the location of the axial surface is unknown, the range of possible thicknesses is between the values given by setting  $L_1 = 0$  and  $L_1 = L$  in Eq. 4.16. The circular-arc thickness (Eq. 4.15) is usually half-way between the extremes that are possible for dip-domain folding.

## 4.3

## Thickness Maps

Thickness maps are valuable for both structural and stratigraphic interpretation purposes. Because multiple measures of thicknesses can be mapped, care is required in the interpretation. The calculated thickness is related to the dip and so uncertainties

**Fig. 4.12.**  
Thickness of a dip-domain  
bed that changes dip in the  
measured interval, in a cross  
section normal to the fold axis



or errors in the dip may appear as thickness anomalies. An isopach map is a map of the true thickness of the unit ( $t$ , Fig. 4.1) measured normal to the unit boundaries (Bates and Jackson 1987). An isocore map is defined as a map of the vertical thickness of a unit ( $t_v$ ; Fig. 4.1; Bates and Jackson 1987). The drilled thickness in a deviated well ( $t_s$ , Fig. 4.1) will usually differ from either the true thickness or the vertical thickness. It is not possible to correct the thickness in a deviated well to the vertical thickness or to the true thickness without knowing the dip of the bed. The thickness differences resulting from the different measurement directions are not large for nearly horizontal beds cut by nearly vertical wells, but increase significantly as the relationships departs from this condition. The effects of stratigraphic and dip variations on thickness maps are considered here. The effect of faults on isopach maps are discussed in Sect. 8.5.

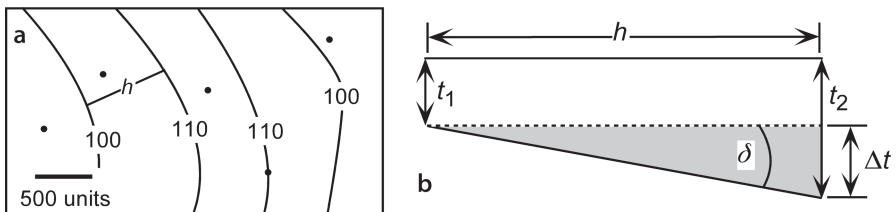
#### 4.3.1 Isopach Maps

An isopach map is used to show thickness trends from measurements at isolated points (Fig. 4.13a). An isopach map can be interpreted as a paleotopographic map if the upper surface of the unit was close to horizontal at the end of deposition. If the paleotopography was controlled by structure, then it can be considered to be a paleostructure map. The thickness variations represent the structure at the base of the unit as it was at the end of deposition of the unit. The trend of increased thickness down the center of the map in Fig. 4.13a could imply a filled paleovalley.

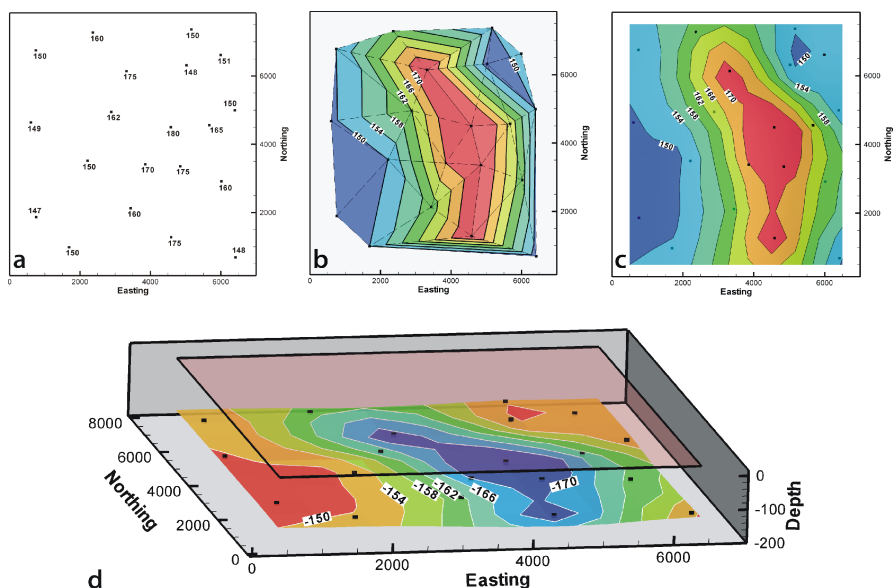
The slope of the base of the paleovalley can be determined from the thickness difference and the spacing between the contours according to the geometry of Fig. 4.13b:

$$\delta = \arctan(\Delta t / h) \quad , \quad (4.17)$$

where  $\delta$  = the slope,  $\Delta t$  = the difference in thickness between two contours, and  $h$  = the horizontal (map) distance between the contours, measured perpendicular to the contours. For the map in Fig. 4.13a, the slope implied for the western side of the paleovalley is about  $0.5^\circ$  ( $\Delta t = 10$ ,  $h \approx 900$ ). Stratigraphic thickness variations could be caused by growing structures. The dip calculated from an isopach map using Eq. 4.17 could represent the structural dip that developed during deposition. According to this interpretation, Fig. 4.13a could represent a depositional syncline.



**Fig. 4.13.** Paleoslope from thickness change. **a** Isopach map. Dots are measurement points;  $h$  is the location of a cross section. **b** Cross section perpendicular to the trend of the thickness contours, interpreted as if the upper surface of the unit were horizontal



**Fig. 4.14.** Interpretation of a thickness map. **a** Thickness data. **b** Triangulation contouring. **c** Kriged map on a  $10 \times 10$  grid. **d** Paleostructural interpretation produced by making the thicknesses negative on the kriged map. The plane of zero elevation is shown above the map and would represent the upper surface of the unit at the end of deposition

As an example, an isopach map is constructed from the data in Fig. 4.14a. For the purpose of discussion, the points are contoured by both triangulation (Fig. 4.14b) and kriging (Fig. 4.14c). The paleogeographic implications of the map should be considered before either map is accepted. The triangulated map suggests a stream channel whereas the kriged map suggests an isolated depocenter. Both computer contouring methods close the contours within the map area. Re-examination of the data reveals that if the unit represents a channel, it could be extended off the map to both the north and south and still be consistent with all the control points. Accepting the depocenter interpretation, it can be visualized in 3-D as a paleostructure map by reversing the sign on the contours so that the thickest part plots as the deepest (Fig. 4.14d).

Thickness trends on isopach maps could alternatively represent unrecognized faults that are too small to be identified directly. A normal fault will cause a thinning of the isopachs and a reverse fault will cause a thickening. Section 8.5 discusses faults on isopach maps. Figure 4.14 could represent a reverse fault that is too small to repeat the top and base of the unit.

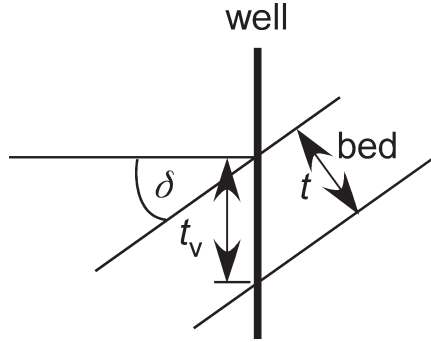
### 4.3.2

#### Isocore Maps

Isocore maps are particularly valuable for determining the volume of a unit present in the area of interest. The area enclosed by each isocore contour is multiplied by the

**Fig. 4.15.**

Dip of bed related to vertical apparent thickness,  $t_v$ : vertical thickness;  $t$ : true thickness,  $\delta$ : dip of bed



contour interval and then summed to obtain the volume. This is only an approximation because it assumes that the volume consists of a stack of vertical-sided regions. The smaller the contour interval, the better the estimate.

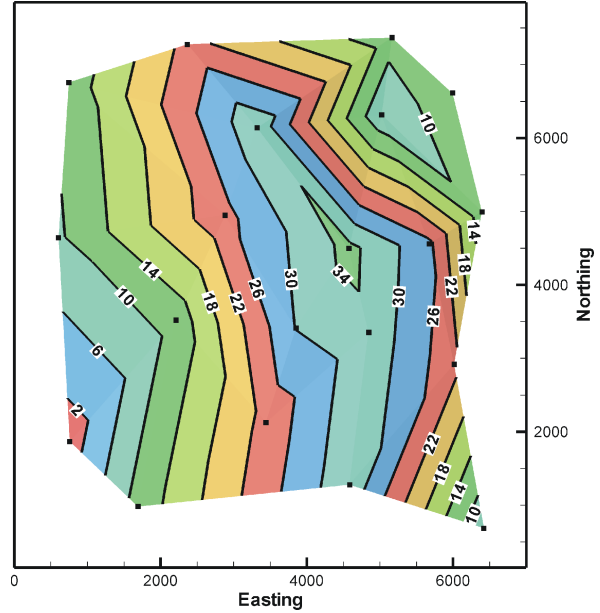
Apparent thickness variations in vertical wells can provide a very sensitive tool for structural analysis if bed thickness is known (Fig. 4.15). True dip is not known in a well unless the interval of interest has been cored or a dipmeter log is available. If the true thickness is known, the dip can be determined by solving Eq. 4.1 to obtain

$$\delta = \arccos(t/t_v) \quad (4.18)$$

If a unit has a true thickness of 100 m, a dip of  $10^\circ$  gives an exaggerated thickness of 102 m,  $20^\circ$  gives 106 m,  $30^\circ$  gives 115 m,  $40^\circ$  gives 131 m,  $50^\circ$  gives 156 m. The importance of this effect will depend on the level of detail being interpreted, but will become significant for nearly any purpose at dips over  $20$ – $30^\circ$ . For example, a measured thickness of 103 ft for a unit having a true thickness of 100 ft may be stratigraphically insignificant, yet implies a dip of  $14^\circ$  which is steeper than the dip producing the closure in many oil fields. If the unit mapped in Fig. 4.13a actually has a constant thickness of 100 units, then the dips in the center of the map where the isocore thickness is 110 units must be  $25^\circ$ . Alternatively, the unit could be horizontal and the wells in which the thicknesses were observed could deviate  $25^\circ$  from the vertical.

As an example of the importance of dip on the variation of apparent thickness, the thickness map in Fig. 4.14a is reinterpreted as representing isocore thicknesses of a folded unit of constant stratigraphic thickness. The thickness variations are converted into dips with Eq. 4.18, assuming a stratigraphic thickness of 150 units, and the values triangulated (Fig. 4.16). What was previously interpreted as a thickness trend is now seen as a dip trend with dips up to  $34^\circ$ . This could represent a significantly folded unit with the steepest dips representing the inflection point on the limb between syncline and anticline. A structure contour map of the unit should be constructed and examined for correspondence between the trends. Note that thicknesses smaller than the assumed constant value yield spurious values when processed with Eq. 4.18. The northeast and southwest corners of the map in Fig. 4.16 would be better interpreted as regions of zero dip because the thicknesses are close to and slightly less than the assumed regional constant value.

**Fig. 4.16.**  
Dip map of data from Fig. 4.14a interpreted as isocore thicknesses measured in a folded, constant-thickness unit. True stratigraphic thickness is 150, dips in degrees



#### 4.4 Derivation: Map-Angle Thickness Equations

The traditional method for determining thickness based on data from a geologic map on a topographic base results in two equations, depending on the relative dip of topography and bedding. The following derivations are after Dennison (1968). If the ground slope and the dip are in the same general direction, Fig. 4.17 shows that  $t = ah$  = the true thickness,  $bc = fe = v$  = the vertical elevation change,  $ac = h$  = the horizontal distance from the upper to the lower contact, angle  $cae = \alpha$  = the angle between the measurement direction and the true dip, and angle  $aej = feg = \delta$  = the true dip. The thickness is

$$t = aj - hj = aj - eg \quad , \quad (4.19)$$

where

$$eg = v \cos \delta \quad , \quad (4.20a)$$

$$aj = ea \sin \delta \quad , \quad (4.20b)$$

$$ea = h \cos \alpha \quad . \quad (4.20c)$$

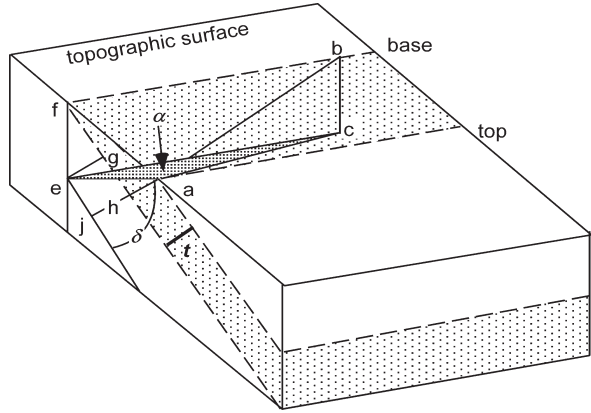
Substitute Eqs. 4.20 into 4.19 to obtain

$$t = |h \cos \alpha \sin \delta - v \cos \delta| \quad . \quad (4.21)$$

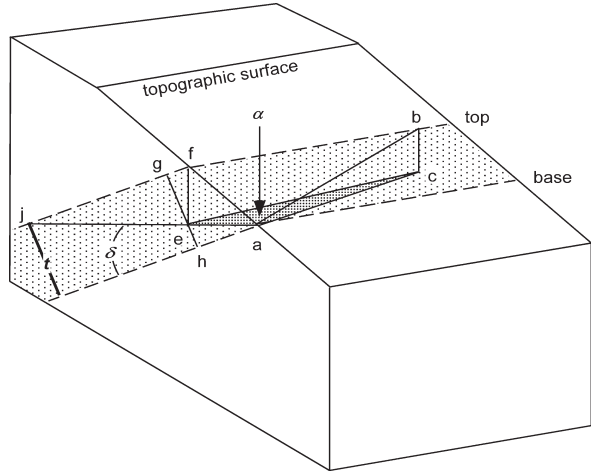


**Fig. 4.17.**

Thickness parameters for a bed and topographic surface dipping in the same general direction

**Fig. 4.18.**

Thickness parameters for a bed and topographic surface dipping in opposite general directions



If the dip of bedding is less than the dip of the topography, the second term in Eq. 4.21 (D2.24) is larger than the first, giving the correct, but negative, thickness. Taking the absolute value corrects this problem.

The thickness of a unit which dips opposite to the slope of topography (Fig. 4.18) is

$$t = eg + eh \quad , \quad (4.22)$$

where

$$eh = ea \sin \delta \quad . \quad (4.23)$$

Substituting Eqs. 4.20a, 4.20c, and 4.23 into 4.22:

$$t = h \cos \alpha \sin \delta + v \cos \delta \quad . \quad (4.24)$$

## 4.5 Exercises

### 4.5.1

#### Interpretation of Thickness in a Well

Based on the data in Table 2.2, what is the isocore thickness of the Smackover? What is the true thickness of the Smackover given its attitude of 12, 056 from the dipmeter log and the orientation of the well from Exercise 2.9.1? Discuss the significance of the difference between the isopach and isocore thickness.

### 4.5.2

#### Thickness

Given a bed with dip vector 10, 290, and a measured thickness of 75 m in a vertical well, use the universal-thickness equation to determine its true thickness.

### 4.5.3

#### Thickness from Map

Use the map of the Blount Springs area (Fig. 2.27) to answer the following questions. What is the thickness of the Mpm between the structure contours using the map-angle equations and the pole-thickness equation? Are the results the same? If they are different, discuss which answer is better. What is the difference between the true thickness and the vertical thickness of the Mpm? What is the thickness of the Mpm in its northeastern outcrop belt, assuming that the dip is  $28^\circ$  at its northwestern contact and the value determined above occurs at its southeastern contact? Use the concentric fold model and the dip-domain model. Discuss the effect of changing the location of the axial surface on the thickness computed with the dip-domain model. Measure the thickness of the Mpm at 5–10 locations evenly distributed across the map. Measure thicknesses between structure contours where possible. Construct an isopach map from your thickness measurements. Is the unit constant in thickness? What would be the apparent thickness of the Mpm in a north-south, vertical-sided roadcut through the northwestern limb of the anticline?

### 4.5.4

#### Isopach Map

Make an isopach map of the sandstone thicknesses on the map of Fig. 4.19. The thickest measurements form a trend that could be a channel or the limb of a monocline. If the thickness anomaly is due to a dip change, what is the amount? If the thickness anomaly is due to paleotopography, what is the maximum topographic slope?

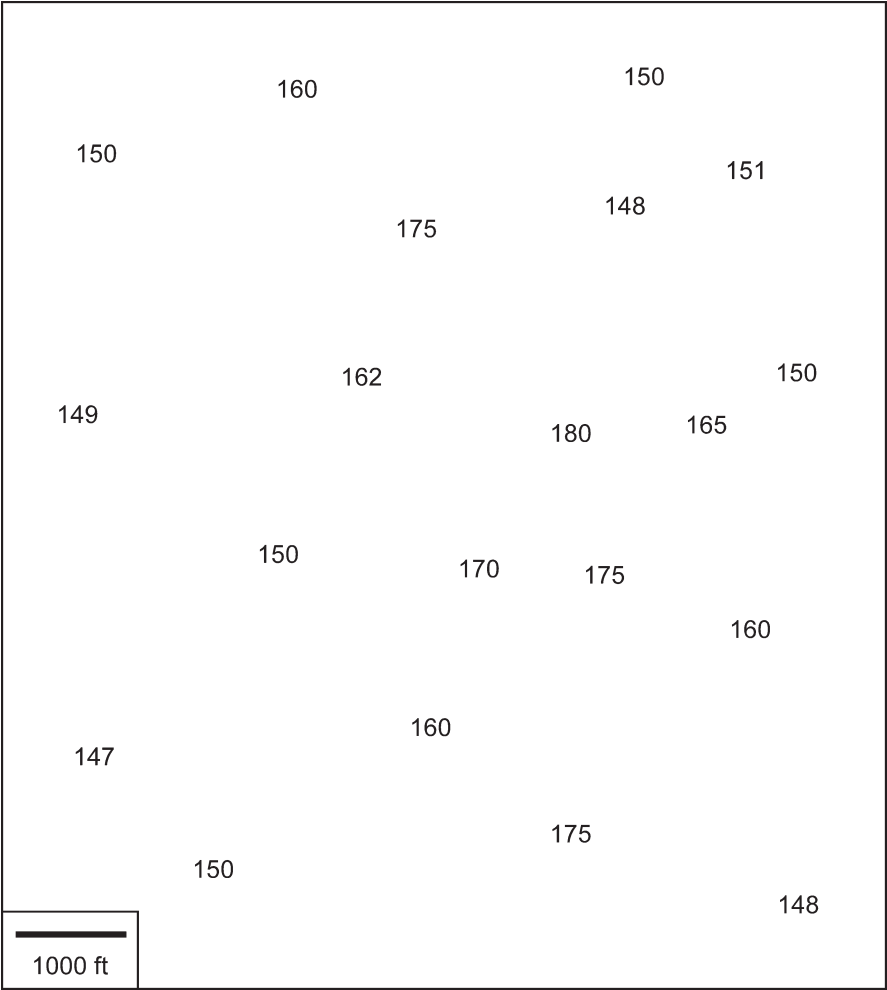


Fig. 4.19. Map of thicknesses (in feet) in the John S sandstone

