Quantifying and Correcting Errors Derived from Apparent Dip in the Construction of Dip-Domain Cross-Sections

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Abstract

This paper deals with the errors introduced in the construction of cross-sections due to the use of apparent dips and thicknesses when projecting data onto the plane of section. These errors are analyzed under the perspective of cross-sections constructed with the dip-domain method. A method to evaluate variations of unit thicknesses due to distortion during projection is presented, and modifications to the dip-domain method are proposed to account for them, including the use of apparent bisectors. Methodology is discussed for inclined section planes, and the equations to calculate apparent thickness on inclined sections are presented. An analytical definition of cylindrical folding is also derived.

1. Introduction

The construction of geological cross-sections implies the need to project data onto the plane of section, and to interpolate between these points of known information. The projection is generally performed according to a vector of structural significance, and yields a set of data (apparent dips and thicknesses) on the cross-section plane. Interpolation between these points can then be carried out by different methods (e.g. Suppe, 1985, Wojtal, 1988, Groshong, 1999). The concepts in this paper will be discussed under the perspective of cross-section construction with the dip-domain method, but are also applicable to other methods in most cases.

Natural deviation from ideal geometrical models, as well as simplifications made by the geologist during section construction can lead to the appearance of certain errors that are frequently overlooked and not accounted for. The most important of these aspects is the variation of apparent thickness of units throughout the cross-section, an inevitable result of the projection of field and well data onto the plane of section.

This paper provides the tools to evaluate the error associated to variations of apparent thickness on the plane of section, as well as the mathematical methods to account for these variations. Cases of both vertical and inclined sections are discussed, and the manner of calculating apparent thicknesses on inclined sections is defined.

2. Basic considerations

As has been mentioned, for the present analysis, the case of cross-sections constructed with the dip-domain method will be considered. The planar dip-domain method (Suppe, 1985, Wojtal, 1988, Groshong, 1999) is widely used in the construction of cross-sections through the brittle domain of the Earth's crust and is very easily applied either by hand, with the use of CAD software or with the use of specialized geological software. Furthermore, cross-sections constructed in this manner permit an easy length and area balance.

The basic assumptions to the dip-domain method are:

a) unit or bedding thickness is constant throughout the section. It is possible to apply the dip-domain method in cases where the thickness of units varies along the cross-section due to stratigraphic geometry or internal strain, with a slight modification, as described by Suppe (1985), Wojtal (1988), and Groshong (1999);

b) folds are **kinkoidal**, which means the limbs are planar dip-domains, the hinge zone is reduced to the actual hinge line or axis, and the axial surface is planar. Folds of complex geometry can be broken down into as many planar dip-domains as necessary, separated by as many axial planes; and

c) the axial plane bisects the angle formed by both limbs, and neatly distinguishes two domains of constant dip.

These conditions imply that on a cross-section, limbs of a fold are represented as straight lines, and the axial surface is the bisector of the angle formed by both lines. By this means, thickness is preserved from one dip-domain to the next.

One can also deduce from condition (b) that adjacent dip domains behave as a cylindrical fold (as described by Wilson, 1967), their hinge line –which is the intersection of both limbs– being the generatrix and fold axis. To effectively preserve thickness of layers throughout the section, fold axes must be perpendicular to the section plane, such that dip directions of all the dip-domains and axial planes are contained within the section plane.

For a more thorough treatment of the dip-domain method, the reader is referred to Suppe (1985), Wojtal (1988), and Groshong (1999).

TABLE 1

3. Apparent dips, thicknesses and bisectors

Geological structures will rarely adjust perfectly to a geometrical model, as these models are mere approximations to physical reality. When applying the dip-domain method, we are assuming we can break down structures into a finite amount of planar dip-domains. This operation means we are sacrificing precision for the sake of simplification, and therefore introducing a certain error in our interpretation. This error is sometimes small enough as to be negligible.

For the ideal application of the dip-domain method, we must be able to assume the conditions considered in Section 2. Furthermore, the proper use of this method requires for the plane of section to be perpendicular to all fold axes, such that thickness and angular relations between fold limbs and axial planes are effectively preserved on the plane of section.

If we consider a vertical section plane* perpendicular to all fold axes, then the dip direction of all the dip-domains is contained within the plane of section. The same happens with the dip direction of axial planes. We know the apparent dip (β') of these dip-domains and axial planes on the section will be equal to their real dip (β), according to the following equation (see Fig. 1):

$$\tan \beta' = \tan \beta \cdot \cos \theta \qquad (1)$$

and apparent thickness of the units on the section (*t*') will be equal to their real thickness (*t*) (equation from Coates, 1945, see Fig. 1):

$$t' = t \cdot (1 - \sin^2\beta \cdot \sin^2\theta)^{-1/2} \qquad (2)$$

as θ=0 for both cases, where θ is the horizontal angle formed by the dip direction of the dip-domains (α) and the strike of the cross-section (δ_S), and is defined as:

$$\theta = \alpha - \delta_S \qquad (3)$$

FIGURE 1

In a case such as this, the dip-domain method will prove perfectly valid, as unit thickness remains constant for all the dip-domains, and always equal to the real thickness. Apparent dips of layers will also be equal to their real dips, and bisecting axial planes will be represented on section as lines bisecting the angle formed by adjacent dip-domains.

However, these ideal conditions are rarely found. Most frequently we face cases where the plane of section is not perpendicular to all fold axes because:

a) fold axes are not parallel among themselves, i.e. the structure is not perfectly cylindrical;

* From now on, we will work with vertical section planes to make calculations and concepts easier to express. The case of inclined section planes is considered in a latter section.

b) the section is deliberately built so as not to be perpendicular to the axes.

Therefore, angle θ will not necessarily be $\theta = 0$, nor constant, for all dip-domains. This has two major consequences:

a) apparent dips of dip-domains will not be equal to real dips. The same will happen for axial planes, as their dip direction need not be contained in the section. Thus, axial planes projected onto the cross-section will *not necessarily bisect the angle* between adjacent dip-domains. The projection of axial planes onto the section are what we will call **apparent bisectors**;

b) dip-domains with different values of θ will have different apparent thickness. This change in apparent thickness is accounted for by the fact that apparent bisectors do not bisect the angle between dip-domains on the section, and therefore thickness varies across them.

4. Importance of apparent bisectors and thicknesses

The construction of a cross-section requires us to accept certain premises and simplify reality to a certain extent, as well as to rely on measurements and calculations performed to input the basic data onto the cross-section. The whole process implies the need to deal with errors, which in some cases may be negligible. The sources of error may be diverse and we will only discuss errors derived from the incorrect use of the dip-domain method in section construction. In case of units or beds of constant thickness, the correct application of the dip-domain method requires these units to maintain constant thickness throughout the cross-section. This will only occur when the plane of section is oriented perpendicular to all fold axes in an area. When this cannot be achieved we will have departures from the ideal geometry that will prevent thickness from being preserved between different dip-domains. Each dip-domain will present different geometrical relationships with the cross-section plane, yielding different apparent thicknesses when projected.

The resulting variations in apparent thickness from one dip-domain to another can often be overlooked as being too small to significantly alter a proper interpretation. However, such an assumption could sometimes lead to introduction of significant errors in a cross-section, and would require a more careful geometrical analysis.

The best way to estimate the possible error derived from this assumption is to observe the variations in apparent thickness between the different dip-domains in the section. We know that the relative difference in apparent thickness between two dip-domains can be defined as follows, according to Eq. (2):

$$t_1' / t_2' = (1 - \sin^2\beta_2 \cdot \sin^2\theta_2)^{1/2} / (1 - \sin^2\beta_1 \cdot \sin^2\theta_1)^{1/2} \qquad (4)$$

Ideally, this calculation should be performed for all possible combinations of dip domains along the section to find out what the maximum variation in apparent thickness will be.

For a general case in which we assume a perfectly cylindrical structure projected onto a vertical plane, we can calculate apparent thicknesses for beds belonging to that structure. The minimum apparent thickness for any family of beds will correspond to that which has a value of θ=0º. Maximum apparent thickness will be displayed by that bedding with a value of θ=90º[*]. For a certain cylindrical structure (defined by the orientation of its fold axis), we can find the orientation of the beds with values of θ=0º and 90º using Eq. 6 (see section 6), and considering δ=0 for a general case.

The results of calculating maximum variation thickness for different fold axis orientations are shown in Fig. 2. Given is the maximum variation in apparent thickness (expressed as

[*] This can be easily proven by taking the first derivative of Eq. 2 ($dt'/d\theta$). Relative maxima and minima will occur at values of $\theta = n*\pi/2$, where n is a whole number.

[maximum possible apparent thickness - true thickness]/true thickness) as a function of the orientation of the fold axis relative to the section plane (δ) and its plunge (β_0).

FIGURE 2

5. Evaluating errors and obtaining apparent bisectors

An aspect to bear in mind is what the maximum acceptable tolerance for apparent thickness variation is. This is a decision that will depend largely on:

a) the precision required and expected from the cross-section;

b) the degree of complexity one is wishing to tackle in calculations;

c) the precision of the original measurements (field data: dips, unit thicknesses);

d) the variability of dips within the dip domains defined; and

e) the variability of the original stratigraphic thicknesses.

If variations in apparent thickness are small enough (say, for example, under 5% or 10% maximum variation), then we may choose not to represent these variations when constructing our cross-section. In such a case, we can use the regular dip-domain method, and build our section with dip-domains separated by bisectors, assuming constant thickness.

However, when these variations are relevant enough to be represented on the cross-section, they should be depicted by separating dip-domains with apparent bisectors. This section deals with the different ways in which we can determine the angular relations between dip-domains and apparent bisectors on the plane of section.

5.1. From thickness variations

When apparent thickness is well known for the different dip-domains, and is known to vary across axial surfaces –either because of real thickness variations (due to stratigraphy or strain), or if apparent thickness of a unit changes along the section– we can determine the dip of the apparent bisector through the following equation (Groshong, 1999):

$$t_2' = t_1' \cdot \sin(\beta_2' - \beta_B') / \sin(\beta_B' - \beta_1') \qquad (5)$$

where t_1' and t_2' are the apparent thicknesses on both sides of the axial surface, β_1' and β_2' the corresponding dips, and β_B' the apparent dip of the axial surface or apparent bisector.

5.2. From real dip-domains

When we know the real dip of the dip-domains we want to separate with an apparent bisector, the geometrical problem posed is simple. All we need to do is calculate the orientation of the axial surface bisecting these dip-domains and then project it onto the section plane to find its apparent dip (Eq. 1).

There are two ways of obtaining the orientation of the axial surface. The most straightforward way consists in using a stereoplot as is described in most manuals of structural geology (e.g. Marshak and Mitra, 1988, Leyshon and Lisle, 1996).

The second possibility, more useful for larger amounts of data, is calculating the orientation numerically (method adapted from Groshong, 1999). This process implies a certain complexity as it requires converting regular dip direction – dip measurements into 3D vectorial coordinates. For a description of the process look into Appendix 1.

5.3. From apparent dips on the cross-section

One last way to calculate the apparent dip of the bisectors is from data already projected onto the section plane, through the assumption of a perfectly cylindrical folding. If we can make such an assumption (even if it is only for two adjacent planar dip-domains), we can consider our fold as a family of planes defined by the orientation of the fold axis (with plunge β_0, direction α_0). We can therefore define any plane in the cylindrical fold (with dip direction α_1, dip β_1, Fig. 3) as:

$$\cos(\alpha_1 - \alpha_0) = \tan(\beta_0) / \tan(\beta_1) \qquad (6)$$

FIGURE 3

From combining Eqs. (1) and (3) we get:

$$\tan \beta_1 = \tan \beta_1' / \cos(\alpha_1 - \delta_S) \qquad (7)$$

and solving Eq. (6) we find that:

$$\tan \beta_1 = \tan \beta_0 / \cos(\alpha_1 - \alpha_0) \qquad (8)$$

Knowing the values for α_0, β_0, and δ_S, for any dip-domain on the cross-section with a certain apparent dip (β_1') we can calculate the orientation of the real plane which corresponds to such an apparent dip.

Repeating this process we can obtain the real dips for the two dip-domains we mean to bisect, and can proceed to repeat the steps outlined in Section 5.2.

NOTE: The system of equations posed (Eqs. 7 and 8) cannot be solved either by substitution or by the more frequent iterative processes. One possible way around this problem is by substituting in for α_1, values in intervals of 0.5° or 1° until both equations yield the same result. This can be done either with a spreadsheet or with a simple BASIC program.

6. Non-vertical section planes

As has been mentioned, all previous calculations took into consideration a vertical cross-section plane. In case the section plane is not vertical, the equations applicable to calculate apparent dips and thicknesses vary considerably. However, the concepts mentioned in this paper are still the same.

To obtain the apparent dip of any plane (dip direction α, dip β) on an inclined section, one must apply the following equations (DePaor, 1988) instead of Eq. (1):

$$\tan \beta' = \sec \beta_S / L \qquad (9)$$

$$L = [(\sec \theta \cdot \tan \beta_S) / \tan \beta] - \tan \theta \qquad (10)$$

where β_S is the dip of the section plane, and θ is defined according to Eq. (3), where:

$$\delta_S = \alpha_S - 90^\circ \qquad (11)$$

As for the apparent thickness of units on inclined sections, the reader is referred to Appendix 2, where a new method to obtain apparent thickness on an inclined section is proposed. No general formula is presented, rather a sequence of steps that can easily be performed with a spreadsheet or a simple BASIC program.

However, for evaluation of errors, due to the complexity of calculations in the case of an inclined section, it is recommended to rotate the section plane to a vertical position, and all the data accordingly (this process can be done easily using structural geology software). Once this has been done, evaluation of errors due to variations of apparent thickness can be easily performed as for a vertical section plane (Section 4). Computation and projection of axial planes and apparent bisectors can then be done with the original orientation data (Section 5).

7. Illustrative example

To complete the discussion, an example is provided showing the application of apparent bisectors in the construction of cross-sections. A hypothetical case has been chosen, following the geometrical models of Suppe & Medwedeff (1990) for fault-propagation folding. In this case, a model considering a ramp dipping 30º to the right and horizontal flat has been constructed (Fig. 4a). The model considers 5 layers (A, B, C, D, and E; Fig. 4a) folded into 5 different dip-domains (I, II, III, IV, and IV; Fig. 4a), and contains projected surface dip data and dip data from two wells. Fig. 4a is a cross-section parallel to transport direction, i.e.

perpendicular to the fault-propagation fold axis, and therefore represents the real dips and thicknesses of the depicted units.

The structure is assumed to be laterally continuous, that is, the fault and fold geometry is preserved along strike (which is a direction perpendicular to the plane of section in Fig. 4a). With this assumption in mind, two cross-sections with strike at 45º to Fig. 4a have been constructed (Figs. 4b and 4c). The dip data and wells have been projected onto the new cross-section plane horizontally along strike (perpendicular to the section in Fig. 4a), and apparent dips have been calculated with Eq. 1 (with a value of θ=45º).

FIGURE 4a,b,c

The cross-section in Fig. 4b has been constructed considering the apparent dip of the bisecting planes. Therefore, thickness varies along the section up to 30% with respect to the real thickness of units. As can be observed, section in Fig. 4b is equivalent to that in Fig. 4a, applying a horizontal exaggeration factor of 1.414 (cosine of 45º).

The cross-section in Fig. 4c, on the other hand, has been constructed using the geometrical bisectors of the projected dip-domains (bisecting the angles formed by the apparent dips). It is impossible to generate a proper cross-section with such a geometrical construction, and what is shown is an attempt to adjust to the given data as best as possible. This section has been constructed assuming a fault-propagation fold geometry, to establish the overall distribution of axial surfaces. By placing the axial surfaces between dip-domains I and II and IV and V, the base of the ramp and the tip of the fault can be found, assuming the ramp to dip parallel to the backlimb of the fold. Subsequently, the position of the other axial surfaces can be found. However this produces the following errors:

a) dips that should be in domain III fall into dip-domains II and IV;

b) the tip of the fault reaches into unit B;

c) the crest of the anticline rises with respect to its original position (the well located on the crest has been projected at the same height as in Fig. 4a);

d) the well on the crest of the anticline cuts through the fault, when it originally didn't;

e) displacement along the fault (along transport direction) increases by 45% with respect to the displacement along the section in Fig. 4a;

The case which has been presented is intended for illustrative purposes, and as such, conditions have been exaggerated to accentuate errors in section construction. However, similar errors (although less spectacular) will also be observed constructing sections with lower obliquity to transport direction.

8. Conclusions

The errors that can arise from the use of the dip-domain method, with dip-domains separated by angle bisectors instead of apparent bisectors on the plane of section, can sometimes be negligible. However, it is important to evaluate the possible error involved (by means of the possible variation in apparent thicknesses) before engaging in the construction of the cross-section. The use of apparent bisectors will account for variations in thickness, of either stratigraphic or deformative origin, or due to distortions introduced by projection.

When working with inclined section planes, the considerations are the same. However, it is suggested that in these cases the section plane be rotated to a vertical position along with the data. Once error evaluation has been performed, all other steps can be performed with the original orientations.

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Appendix 1. Finding the bisecting planes for two planar dip-domains

For any two given planar dip-domains of known orientations (α_1, β_1 and α_2, β_2), we must firstly calculate the direction cosines for their poles (i.e. the cosine of the angles formed by the planes' poles and the *x*, *y* and *z* axes). They are defined as follows:

$$l = \sin\beta \cdot \sin\alpha \qquad (12.1)$$

$$m = \sin\beta \cdot \cos\alpha \qquad (12.2)$$

$$n = \cos\beta \qquad (12.3)$$

The vectors so obtained are of unitary length. Addition (or subtraction) of two vectors of equal length results in a vector that will bisect the angle they form. Thus, to find the pole of the plane bisecting the angle between the two dip-domains, all we need to do is add the two vectors obtained with Eqs. (12.1, 12.2, 12.3).

$$l_{B1} = (l_1 + l_2) / K_{B1} \qquad (13.1)$$

$$m_{B1} = (m_1 + m_2) / K_{B1} \qquad (13.2)$$

$$n_{B1} = (n_1 + n_2) / K_{B1} \qquad (13.3)$$

Where K_{B1} is the length of the bisecting plane's pole:

$$K_{B1} = (l_{B1}^2 + m_{B1}^2 + n_{B1}^2)^{1/2} \qquad (14)$$

To obtain the vector parallel to the maximum dip for the bisecting plane, all we need to do is first make sure the plane is "upright", i.e. the pole points upwards. Therefore, if $n_{B1}<0$ we need to reverse the signs on all the direction cosines (l_{B1}, m_{B1}, n_{B1}). Next we must find the dip of the bisecting plane (β_{B1}):

$$\beta_{B1} = \arccos(n_{B1}) \qquad (15)$$

The dip direction of the bisecting plane (α_{B1}) is:

$$\alpha_{B1}' = \arctan(l_{B1} / m_{B1}) \qquad (16)$$

which must be corrected according to the following table.

$\alpha_{B1} = 180 + \alpha_{B1}'$	if $m_{B1}<0$
$\alpha_{B1} = 360 + \alpha_{B1}'$	if $m_{B1}>0$ and $l_{B1}<0$
$\alpha_{B1} = \alpha_{B1}'$	if $m_{B1}>0$ and $l_{B1}>0$

However, there is a second possible bisecting plane, which will be perpendicular to this first plane. Of the two bisecting planes, one will bisect the acute angle formed by the dip-domains, while the other will bisect the obtuse angle. It is up to the geologist to decide which of the two is suitable in each case.

The operation to obtain the second bisecting plane is now the same as in the first case except that Eqs. (13.1, 13.2, 13.3) are replaced by subtractions:

$$l_{B2} = (l_1 - l_2) / K_{B2} \qquad (17.1)$$

$$m_{B2} = (m_1 - m_2) / K_{B2} \qquad (17.2)$$

$$n_{B2} = (n_1 - n_2) / K_{B2} \qquad (17.3)$$

And we repeat all the following steps until we obtain the orientation of the second bisector (α_{B2} and β_{B2}).

For a more complete description of the mathematical basis of the process, the reader is referred to Chaps. 2 and 4 of Groshong (1999).

Appendix 2. Apparent thickness on inclined section planes

This section describes two possible methods to obtain the apparent thickness of a unit with known orientation, on an inclined section plane. The first consists in rotating the section plane and the unit so the section is in a vertical position. Having thus preserved the angular relation between both, the apparent thickness can be estimated with Eq. (2).

However, an analytical solution is also possible, and preferrable, as it requires simpler calculations. It is as follows. First we must generate a vertical plane containing the line of maximum dip of the bedding (we will call this vertical plane π). We project onto it the cross-section plane and calculate its apparent dip (Eqs. 1 and 3):

$$\tan \beta_S' = \tan \beta_S \cdot \cos(\alpha_S - \alpha_1) \qquad (18)$$

On plane π we generate a segment perpendicular to the bedding with the length of the real thickness of the unit (t). We project this segment onto a line with the apparent dip of the plane of section (Fig. 5a). The length of the projected segment (t_π) is defined:

$$t_\pi = t / \sin(\beta_S' - \beta_1) \qquad (19)$$

FIGURE 5a,b

We now work on the plane of section (Fig. 5b). We calculate the apparent dip of segment t_π (which is the same as the apparent dip of plane π, β_π') on the plane of section. For this we combine Eqs. (3, 9, 10 and 11) to find the apparent dip (β') of a plane on an inclined section:

$$\tan \beta' = \sec \beta_S / L \qquad (20)$$

$$L = [(\sec(\alpha - \delta_S) \cdot \tan \beta_S) / \tan \beta] - \tan(\alpha - \delta_S) \qquad (21)$$

$$\delta_S = \alpha_S - 90º \qquad (22)$$

where β_S is the dip of the section, δ_S its strike (defined by Eq. 22), and β is the dip of the plane we are projecting and α its dip direction (Eqs. 20 and 21 after DePaor, 1988).

For plane π, these equations simplify to:

$$\tan\beta_\pi' = - \sec\beta_S / \tan(\delta_1 - \delta_S) \qquad (23)$$

as $\beta_\pi = 90°$, and $\alpha_\pi = \delta_1$.

The apparent dip of the layer on the plane of section can be found using the same equations (Eqs. 20 and 21):

$$\tan\beta_1' = \sec\beta_S / [(\sec(\alpha_1 - \delta_S) \cdot \tan\beta_S) / \tan\beta_1 - \tan(\alpha_1 - \delta_S)] \qquad (24)$$

The thickness of the unit perpendicular to the apparent dip of the layer on the plane of section (apparent thickness) can then be defined (Fig. 3b):

$$t' = t_\pi \cdot \sin(\beta_\pi' - \beta_1') \qquad (25)$$

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Table 1. Notation used in text:

Variables:

α	azimuth of dip direction/plunge
β	angle of dip/plunge
β'	angle of apparent dip on section plane
δ	strike
θ	horizontal angle between a line and the strike direction of section plane
t	thickness of layer
t'	apparent thickness of layer on section plane

Subindices:

$_0$	corresponding to fold axis
$_{1,\ 2}$	corresponding to dip-domains/bedding
$_{B,\ B1,\ B2}$	corresponding to bisecting planes (axial planes)
$_S$	corresponding to section plane
$_\pi$	corresponding to plane π (Appendix 2)

no subindex indicates a general case (any subindex is applicable)

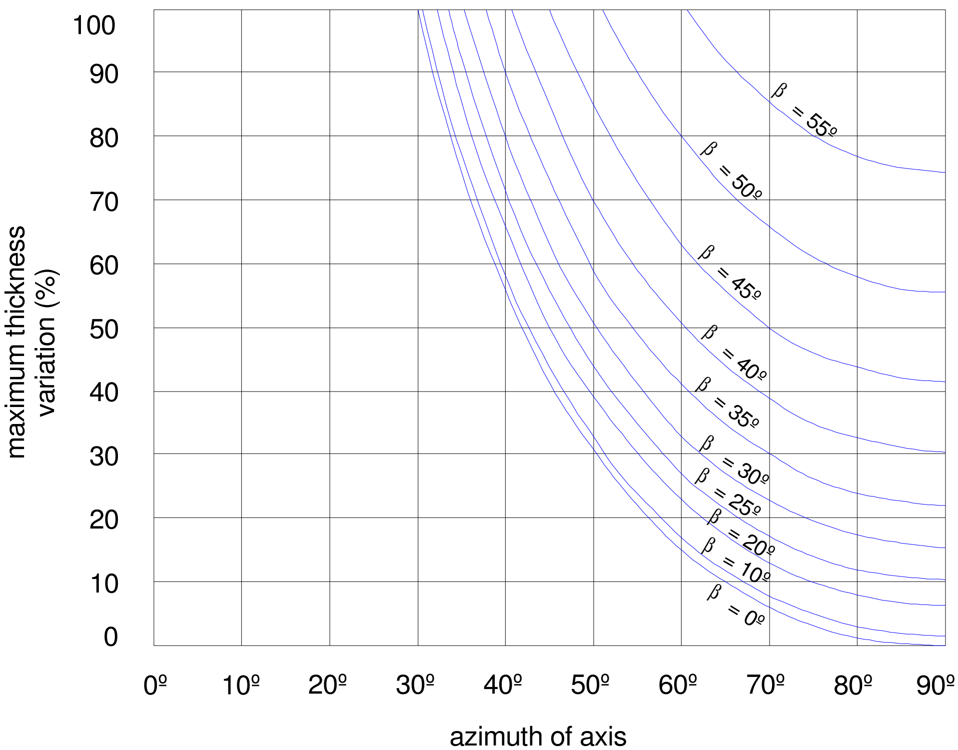

Figure 1. Maximum possible variation in apparent thickness throughout a N-S plane of section in function of orientation of fold axes. The structure has been interpreted as cylindrical, and the corresponding family of planes has been constructed for each axis orientation (Eq. 6). The apparent thickness for each possible plane in the family of planes has been calculated, and the maximum and minimum values have been compared ([maximum thickness – minimum thickness]/minimum thickness). Note that this graph includes axis plunges up to 60º (not depicted as the corresponding curve appears only in the right uppermost corner), and plunges over 60º will always present maximum possible variations in thickness beyond 100%. For axis azimuths 90º<α<180º, the graph is symmetrical across the y-axis.

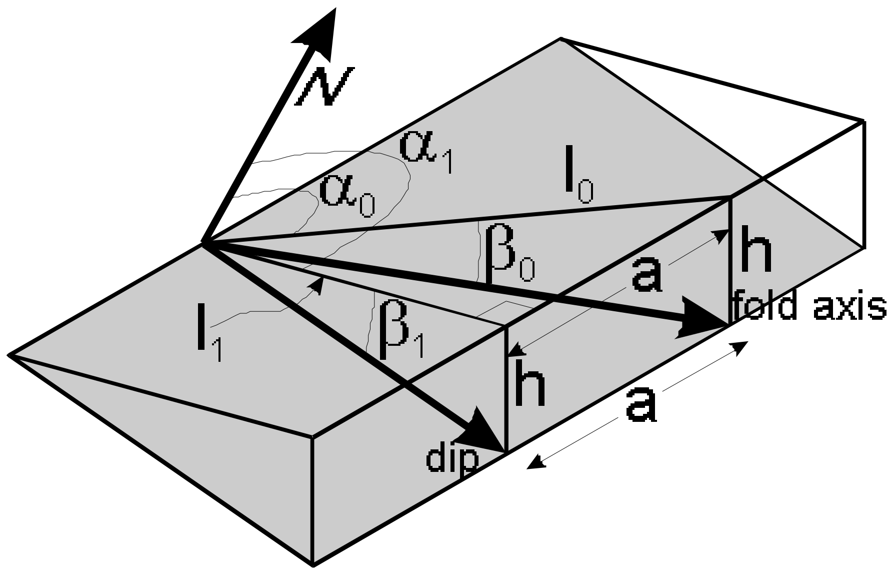

Figure 2. Construction used to derive Eq. (6). In gray is a plane belonging to a cylindrical fold. The fold axis and dip vector of the plane are depicted. We know $h = l_0 \cdot \tan(\beta_0) = l_1 \cdot \tan(\beta_1)$; and $l_1 = l_0 \cdot \cos(\alpha_1 - \alpha_0)$.

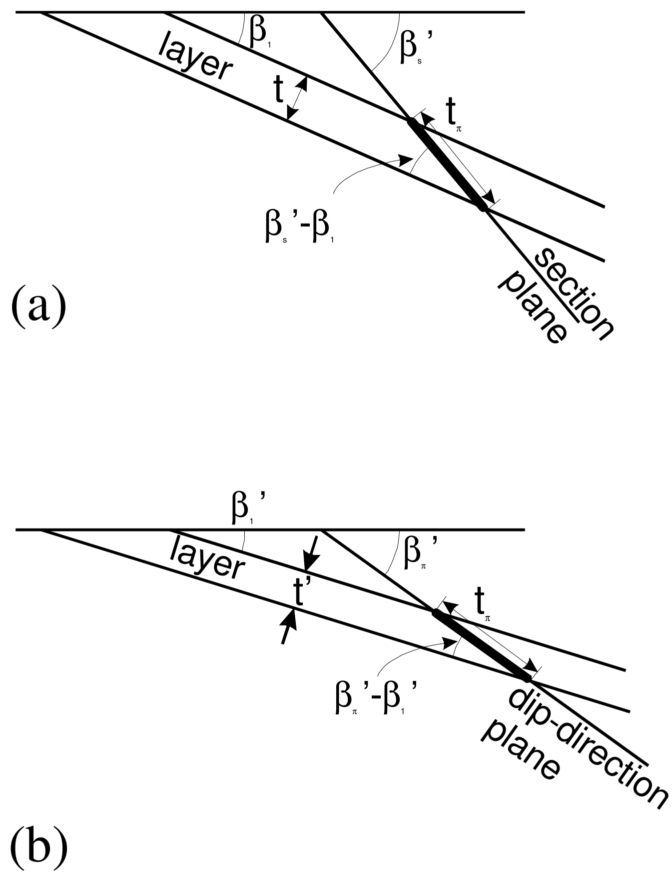

Figure 3. (a) construction used to derive Eq. (19). This corresponds to a view of plane π onto which the section plane and the bedding have been projected (b) construction used to derive Eq. (25). This corresponds to a view of the plane of section onto which the bedding and plane π have been projected.