NIANDU: a MATLAB® program to model folds related to double-edge propagating faults.

Authors: Pablo D. García & Hodei Uzkeda

Please contact H. Uzkeda if interested on getting the source code or with comments, enhancements and suggestions for changes (hodei@geol.uniovi.es)

Installation procedure

We suggest creating a directory called "C:\NIANDU" and unzip the contents of NIANDU.zip file on it.

Enter Matlab program and add this directory to the matlab path:

>>addpath C:\NIANDU

Execute the main program from the command line:

>>NIANDU % (with capital letters)

After that follow the on-screen instructions and enjoy modelling folds.

Working with NIANDU

When you start NIANDU a window with three possibilities will appear (Fig. 1).

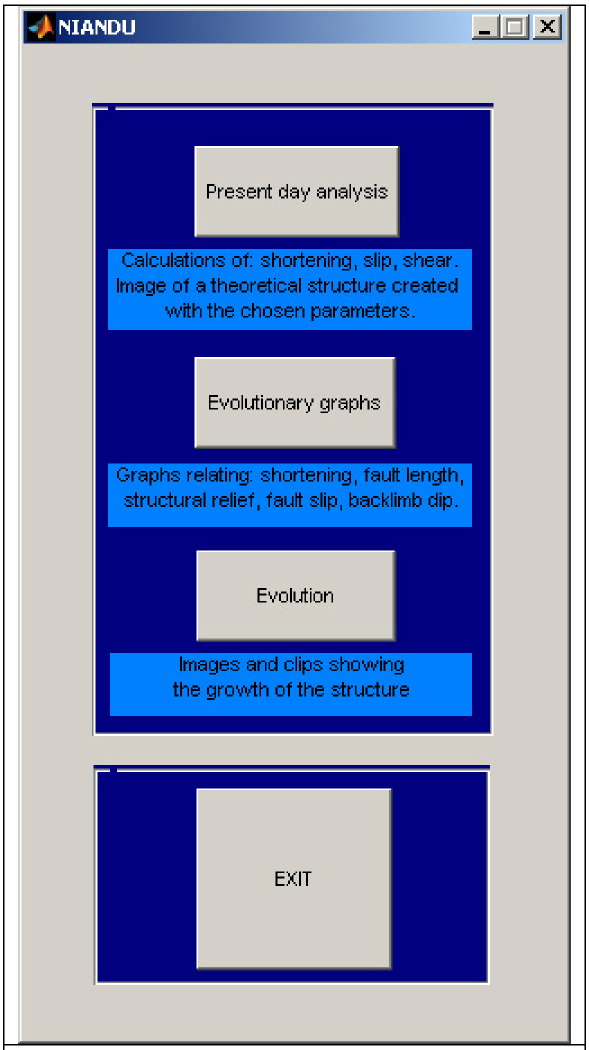

Fig. 1. Main menu.

Present day analysis:
This option allows:
-Obtaining graphs of shortening, fault slip and structural relief bed-by-bed, and a .xls file with their values.
-Plotting an image of a theoretical structure built with the chosen input parameters.

Evolutionary graphs:
By choosing this option graphs relating parameters such as fault length, shortening, fault slip, structural relief, backlimb dip, etc. and showing the growth of the structure via different modes are obtained.

Evolution:
The third option allows creating pictures and a clip of the structure evolution by one of the different basic modes proposed.

(It is recommended, but not necessary, to use the three options in a row as here presented)

Present day analysis

When clicking the "Present day analysis" button a new window will open asking whether new input parameters are needed. If it is the first time you run NIANDU during the present session, you will need to click "Yes", if that is not true and you want to use the same parameters introduced for a previous analysis (for example, to obtain a clip with "Evolution") you can click "No" and NIANDU will use the parameters kept in the workspace.

Considering that you want to use new parameters, or need to introduce them for the first time you will be requested to input four data:

-Backlimb length: e.

-Back axial trace dip: γ.

-Fault dip: θ.

-Forelimb dip: ψ.

These are the angles and length measured in the field and can take the value you want honouring the following expression for the fault dip:

$$(180 - 2\gamma) \leq \theta \leq \frac{180 - \psi}{2}.$$

If you are not sure about your fault dip you can click "HELP" (Fig. 2) and check, with the forelimb and back axial trace dips, the limits for the fault dip.

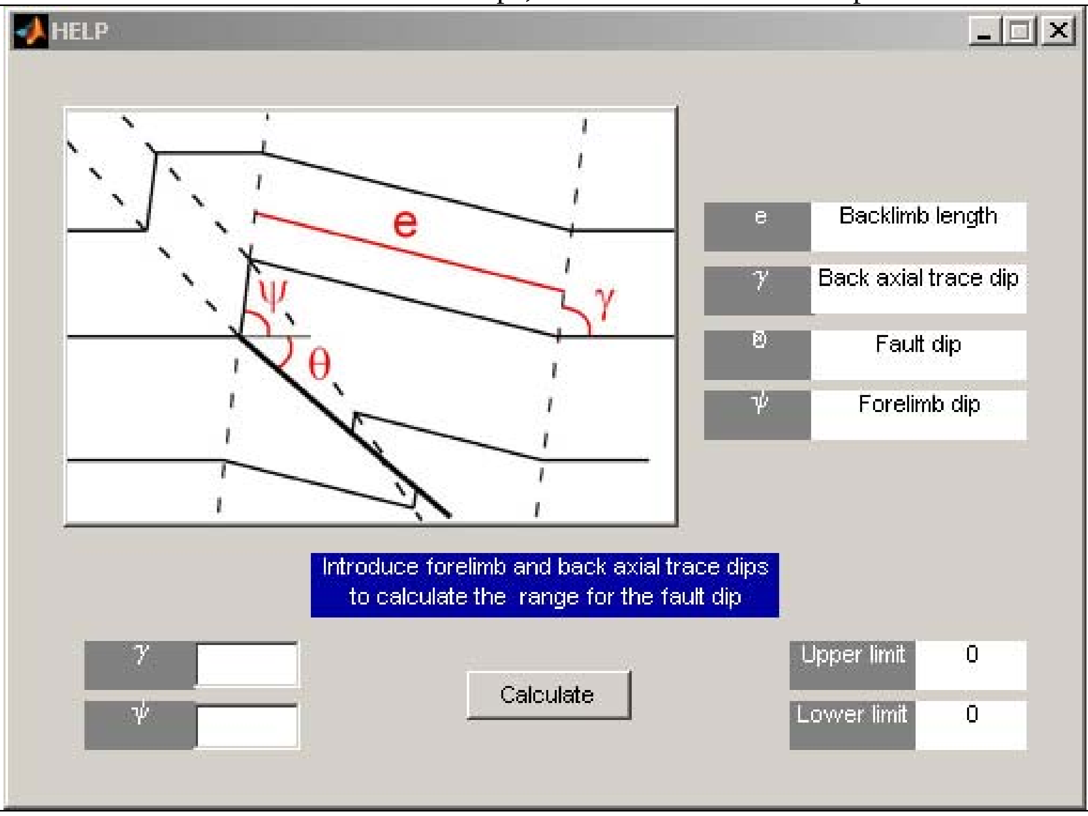

Fig. 2. Help for input parameters.

Once you have introduced the desired parameters a new window will open in which you will be solicited to write the structure width. The value for this data should be in the same units employed to the backlimb length (m, km, cm, etc.). There is also a help window available at this step (Fig. 3) (by clicking "HELP") together with a suggested value that depends on the backlimb length chosen. The next step is to define the four limits for the graphic representation: Top, Bottom (negative if you want to plot under the fault nucleation point, that works as reference level), Right and Left (negative) (Fig. 3). There are no restrictions for their values but the horizontal limits should be, in absolute value, notably greater than half the width to view the whole structure. With the vertical limits the only consideration to take into account are the beds to be represented, if the selected values are not big enough some beds could not be plotted or could appear cut.

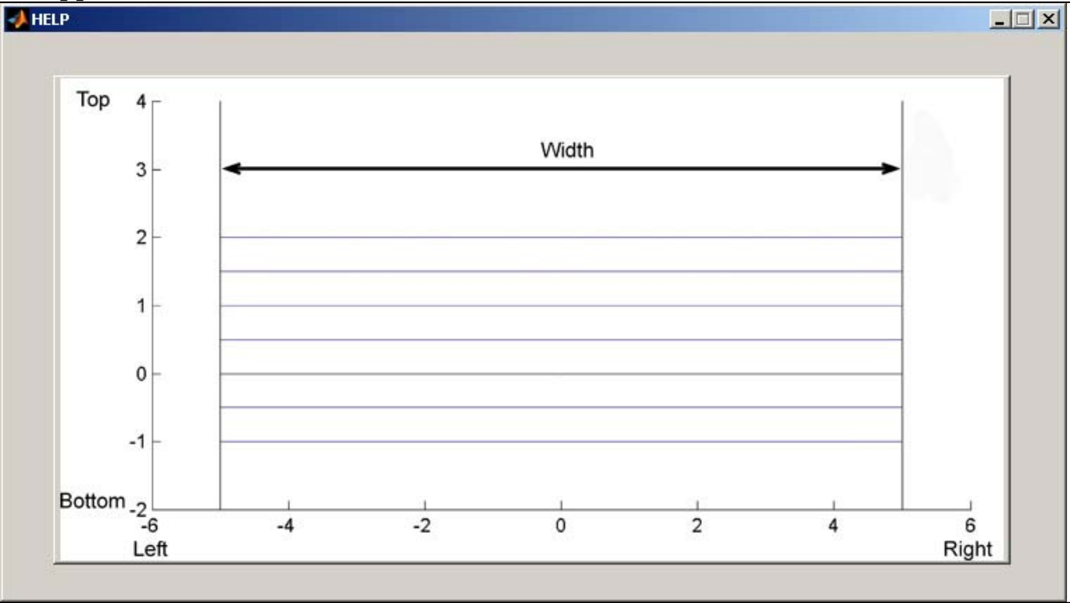

Fig. 3. Help for structure width and graphic limits.

Now is time to introduce as much horizons as required to simulate the natural structure (Fig. 4). First you input the **height** of the beds above the reference horizon, which is located at the fault nucleation point, what coincides with the fault midpoint. It is important to remark that the values are the stratigraphic height above that level, not the thickness of the beds, if you have any problem click "Help" and an image showing the parameters to introduce will open (Fig. 5).

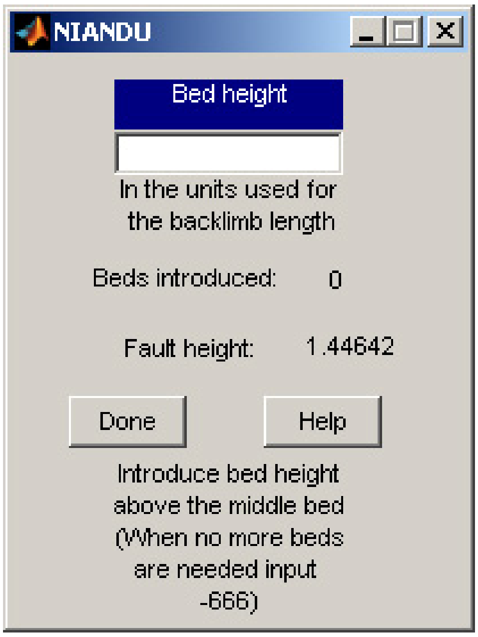

Fig. 4. Window to input the bed height.

To introduce a bed, write its height within the white box and click "Done". The "Beds introduced: 0" will change to 1. If more beds are needed you just have to repeat the procedure. The fault height is shown as reference to you to know if the bed will be cut or not by the fault at the final evolutionary stage of the structure. The fault height is helpful to introduce the bed heights, for instance, if you do not know the height above the reference level, middle bed, but know that your bed is 0.5 m below the fault tip you should enter the fault height minus 0.5 as the bed height.

When finished input "-666" (without the "") and click "Done". Another window like the shown in Fig. 4 will appear to input the beds under the reference level. The procedure is the same, it is important to remember that the heights **below** the reference level must be written as **absolute values**.

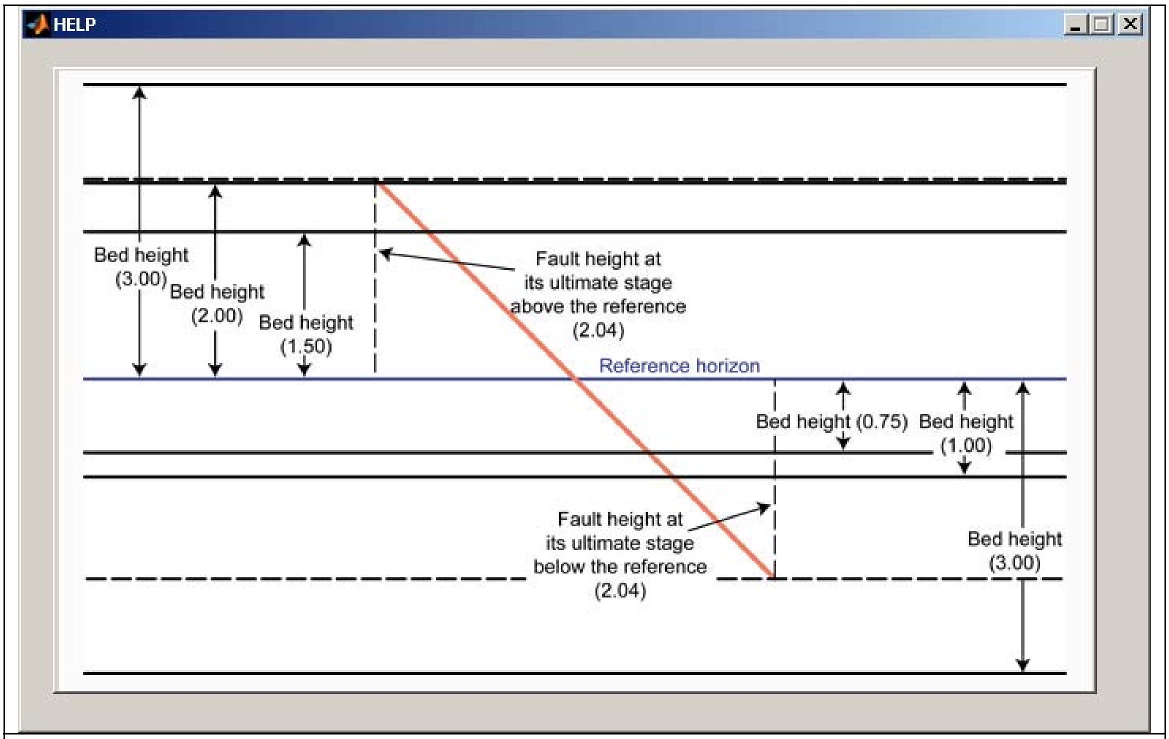

Fig. 5. Help image for the bed heights.

When all the beds are introduced the program will create an image of the resulting structure built with the chosen parameters. This picture is saved as .jpg and .ai in the current directory with the name Before_thickening. The structure depicted there is without thickening in the forelimb (if thickening is not required just follow the instructions below and discard the results).

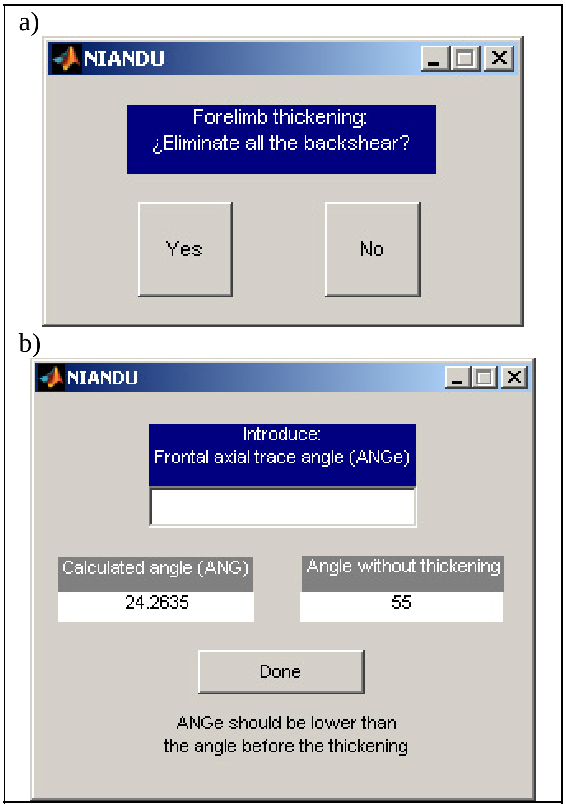

Fig. 6. Forelimb thickening.

The next step is to introduce forelimb thickening by rotating the frontal axial trace (Fig. 6a). The angle for this axial trace can be chosen manually (by clicking "No") or can be used the one calculated by NIANDU that eliminates completely the backshear of the beds not cut by the fault (clicking "Yes"). If you select the manual input another window will appear showing the calculated angle (ANG) and the frontal axial dip with no thickness change as references (Fig. 6b). The closer the value introduced is to the calculated one the lesser shear will remain and the greater the thickening will be. The capacity of choosing the frontal axial trace dip permits a better geometrical fitting of the natural structure. By changing it you can control the shape of the theoretical forelimb and try to make it as similar as possible to the example analyzed.

That was the last step of the "Present day analysis", the first window of NIANDU will appear together with another one in which are shown the results of the theoretical structure built (shortening, maximum fault slip, structural relief, and shear, negative shear implies backshear). In addition to this information graphs of shortening (before and after the thickening, in the second case there will be a certain component of length loss, LPS), fault slip and structural relief versus stratigraphic height and an image of the structure with the thickened forelimb are plotted and saved as .jpg and .ai within the current directory. Also a .xls file called "Bed_by_bed_results" is created containing the bed by bed values (sorted by stratigraphic height) of: horizon height above (+) or below (-) the horizon at the fault nucleation point (column 1); structural relief (column 2); shortening before thickening (column 3); total shortening after thickening (column 4); curvimetric shortening after thickening (column 5); LPS after thickening (column 6); fault slip (column 7).

Evolutionary graphs

This second part of NIANDU is to elaborate graphs showing how some parameters (shortening, backlimb length, backlimb dip, fault length, fault slip, etc.) vary as the structure grows. Up to eleven graphs are generated and saved as .jpg and .ai in the current directory.

When you enter this second module of NIANDU you will be asked if new input parameters are required, if you want to continue with the same parameters entered before for, for example, "Present day analysis" click "No". But, if this is the first time you run the program during the session or need other different click "Yes" and follow the instructions previously presented in the chapter "Present day analysis".

Then you can choose the growth mode between the three end-member possibilities (hinge migration, rotation or migration + rotation) or work with all of them at the same time. In the resulting graphs the backlimb hinge migration is the red function; backlimb rotation is pink; migration with critic angle + rotation is green; and migration with angle different to the critic + rotation is blue. Some graphs work only with backlimb rotation. The critic angle (back axial trace provoking that, with the chosen forelimb and fault dips, the core axial trace affects the horizon initially situated at the fault nucleation point) is calculated when all the modes or the rotation alone is chosen.

Evolution

Here you can obtain pictures of how your theoretical structure could have grown following one of the three basic growth modes developed for this kind of structures. NIANDU saves the images as .jpg sequentially numbered and creates a short clip (20 seconds) in avi format with them.

The procedure is analogue to that explained for the "Present day analysis", you have to enter the fault dip, back axial trace dip, forelimb dip, backlimb length, structure width, bed heights and graph limits, or use the previously input by clicking "No", when asked if new values are needed. After typing in these parameters you must chose the growth mode: hinge migration (Fig. 7), rotation (Fig. 8) or migration + rotation (Fig. 9); and the number step for each of the stages. The red number refers to the backlimb length, and the blue one is the back axial trace dip.

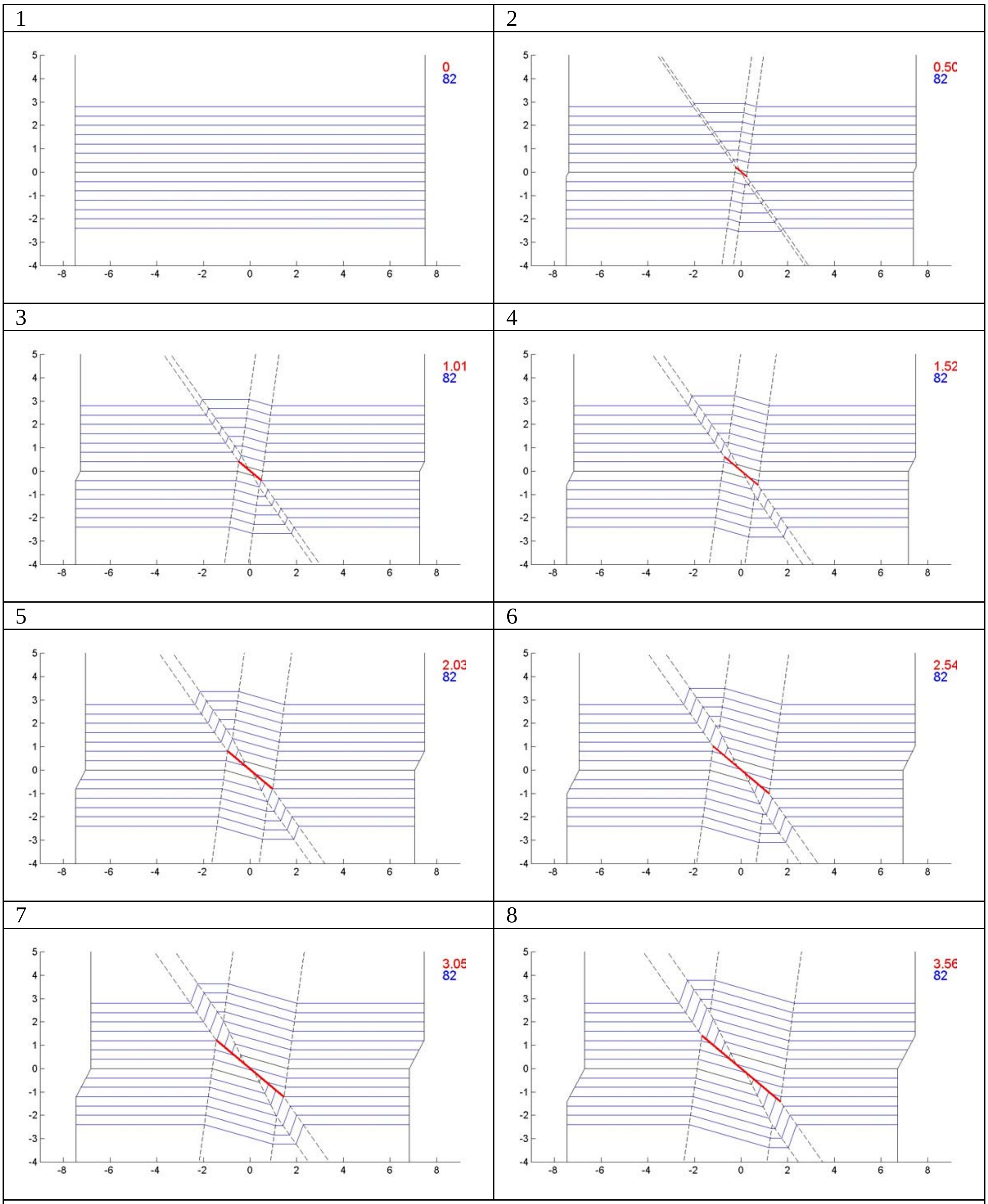

Fig. 7. Evolution by hinge migration.

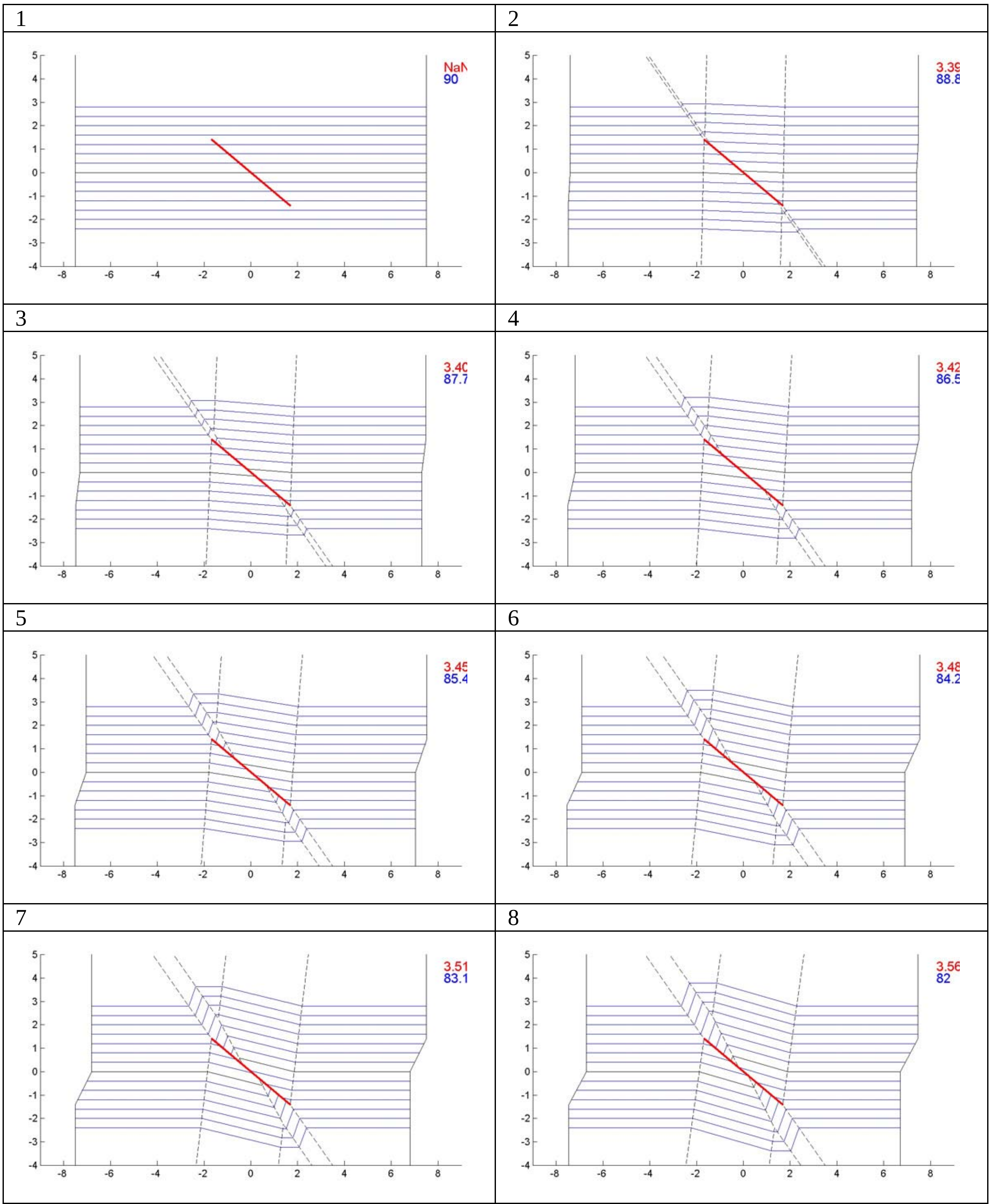

Fig. 8. Evolution by backlimb rotation.

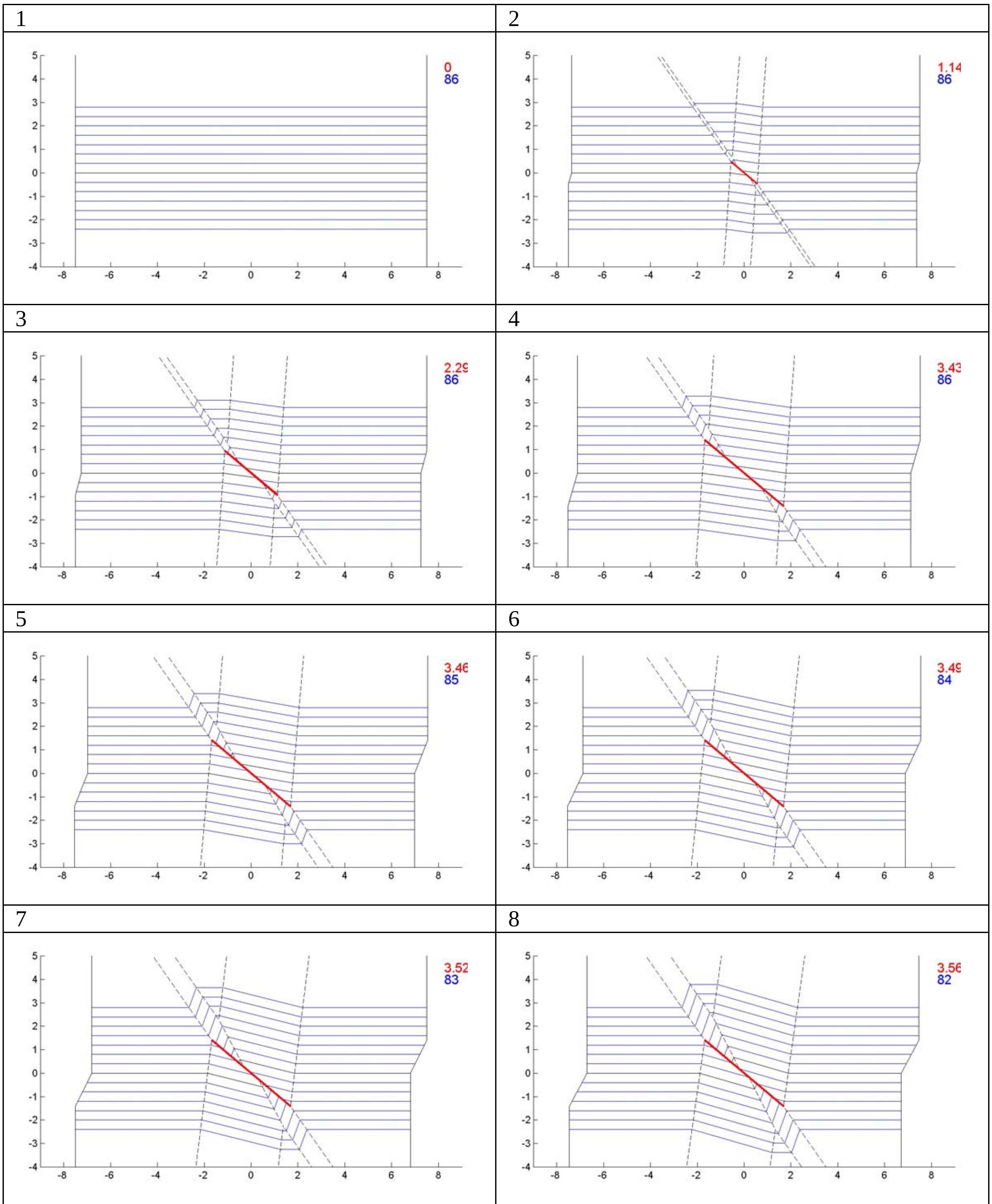

Fig. 9. Evolution by migration (1-4) + rotation (5-8).

There is a last stage common for all the modes in which the forelimb thickening is introduced (Fig. 10), the number of steps to achieve the final configuration is selected as in the previous ones.

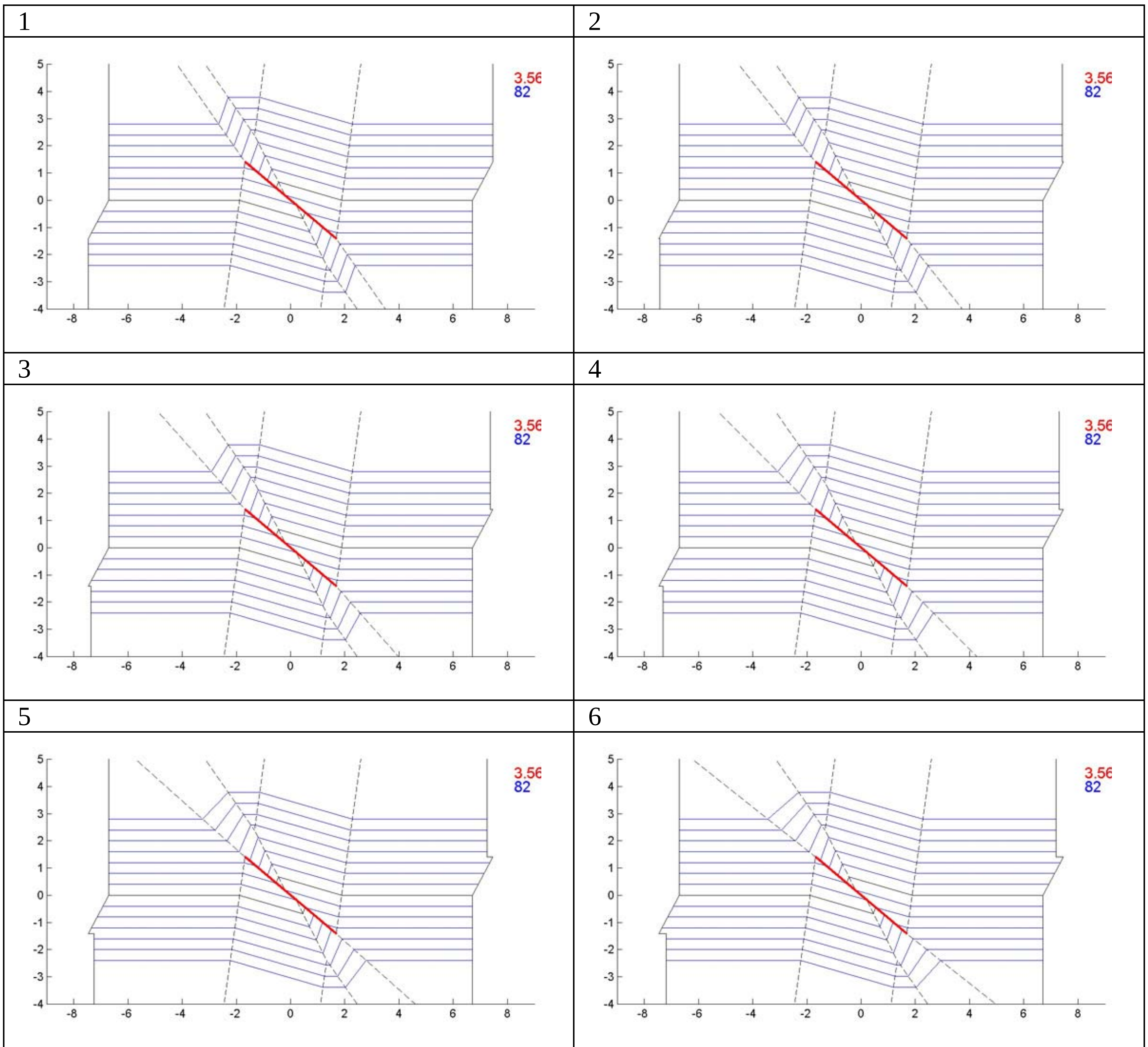

Fig. 10. Forelimb thickening.

Appendix: model formulation

Now the equations in which the model is based are presented with accompanying figures showing the most important angles and lengths involved. To make all the calculations we start from the knowledge of: γ (back axial trace dip), ψ (forelimb dip), θ (fault dip) and e (backlimb length).

With the back axial trace (γ) the acquisition of the backlimb dip (δ) is immediate:

$$\delta = 180 - 2\gamma \qquad \text{(A.1).}$$

By knowing the backlimb length (e) is possible to calculate the width H (fold width for the bed situated at the fault tip), length necessary to determine the fault length:

$$H = e\left(\frac{\sin(180 - \psi - \delta)}{\sin\psi}\right) \qquad \text{(A.2).}$$

With this length and the fault and back axial trace dips the fault length (P) can be calculated using the following expression:

$$P = H\left(\frac{\sin\gamma}{\sin(180 - \gamma - \theta)}\right) \qquad \text{(A.3).}$$

Now we move on to obtain the value of t' (separation between the horizon at the fault tip and the one at the nucleation point measured following the back axial trace):

$$t' = \frac{H}{2}\left(\frac{\sin\theta}{\sin(180 - \gamma - \theta)}\right) \qquad \text{(A.4).}$$

The stratigraphic separation between those two horizons is:

$$t = t' \cdot \sin\gamma \qquad \text{(A.5).}$$

β is the angle between the fault plane and the backlimb:

$$\beta = \theta - \delta = \theta + 2\gamma - 180 \qquad \text{(A.6).}$$

To calculate Y (being 2·Y the original length of the bed situated at the fault nucleation point between the back axial trace) two angles (θ and γ) and a length (P) are required (Fig. A.1). This length is compulsory to calculate the shortening undergone by that horizon:

$$Y = \frac{P}{2}\left(\frac{\sin(180 - \gamma - \theta)}{\sin\gamma}\right) \qquad \text{(A.7).}$$

To achieve this same goal, mid bed shortening calculation, some lengths are required (X, Z2, Z1) (Fig. A.1):

X is calculated through the equation:

$$X = Y\sin\delta \qquad \text{(A.8).}$$

To obtain Z2, the values of Y and d must be known:

$$Z2 = Y\cos\delta \qquad \text{(A.9).}$$

Z1 is calculated via the expression:

$$Z1 = X\cot\beta \qquad \text{(A.10).}$$

The total length (Z) of the backlimb, if not affected by the core axial trace, would be:

$$Z = Z1 + Z2 \qquad \text{(A.11).}$$

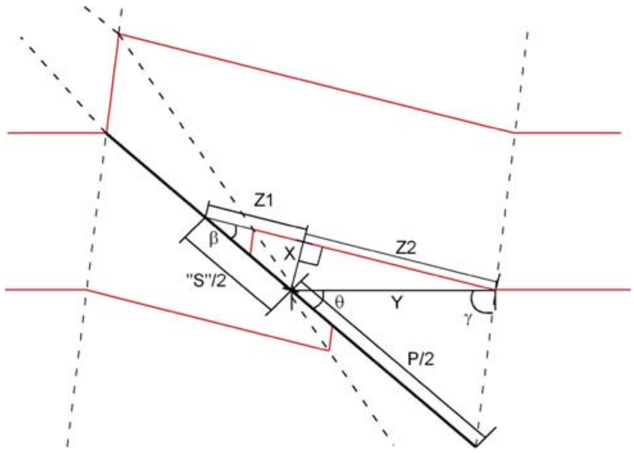

Fig. A.1. Figure showing the lengths X, Z2, Z1, Y and “S”/2 and the angle β.

The fault slip “S” (Fig. A.1), slip of the mid bed if not affected by the core axial trace, can be obtained using the expression:

$$\frac{"S"}{2} = X \csc \beta \qquad \text{(A.12).}$$

The forelimb length for those beds not affected by the fault can be computed with the equation (Fig. A.2):

$$d = 2Y\left(\frac{\sin(\delta)}{\sin(180-\psi-\delta)}\right) \qquad \text{(A.13).}$$

Knowing Y and t’ is possible to calculate J’, that is equal to half the fault length (A.2):

$$J' = \sqrt{Y^2 + t'^2 - 2Yt'\cos\gamma} = \frac{P}{2} \qquad \text{(A.14),}$$

what allows calculating the value of J (A.2):

$$J = \sqrt{J'^2 + d^2 - 2J'd\cos(\psi+\theta)} \qquad \text{(A.15).}$$

The angle between J and the fault plane is σ (Fig. A.2):

$$\sigma = \arcsin\left(\frac{d\sin(\psi+\theta)}{J}\right) \qquad \text{(A.16).}$$

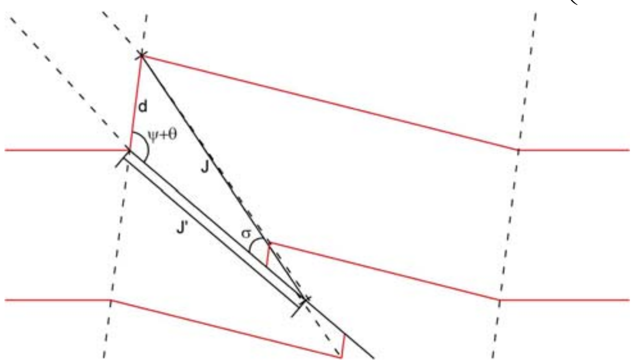

Fig. A.2. Figure showing the lengths d, J and J’ and the angle σ.

The angle formed by X and Y (ρ) responds to the expression (Fig. A.2):

$$\rho = 90 - \delta \qquad \text{(A.17).}$$

Analogously the value of ε is obtained (Fig. A.3):

$$\varepsilon = 180 - \rho - \theta - \sigma \qquad \text{(A.18),}$$

what permits to calculate the angle k, between the segment J and the backlimb:

$$\kappa = 90 - \varepsilon \qquad \text{(A.19).}$$

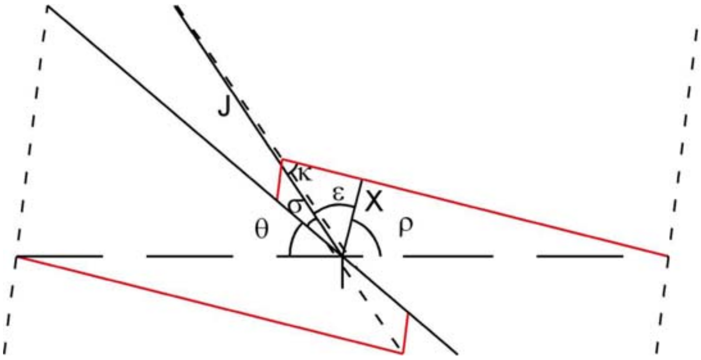

Fig. A.3. Figure showing the angles ρ, ε and κ.

The computation of W, length of the J segment between the fault plane and the prolongation of the backlimb, (Fig. A.4) can be done with the expression:

$$W = X \csc\kappa \qquad \text{(A.20).}$$

Knowing W, J and P, it is feasible to calculate S* (Fig. A.4):

$$S^* = \frac{P \cdot W}{J} \qquad \text{(A.21).}$$

Using the value of W (got with A.20) and of s (got with A.16) we obtain M* (Fig. A.4):

$$M^* = W\left(\frac{\sin\sigma}{\sin(\psi+\theta)}\right) \qquad \text{(A.22).}$$

To calculate N* it is necessary to use the next formula:

$$N^* = X \tan\varepsilon \qquad \text{(A.23).}$$

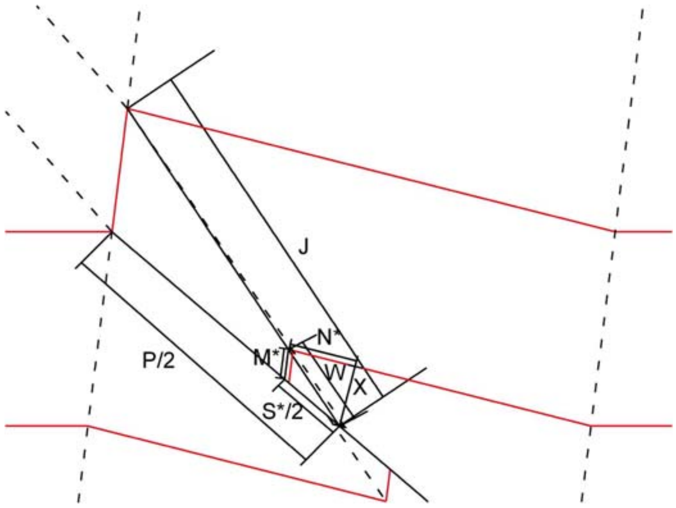

Fig. A.4. Figure showing the lengths S*, M* and N* and the angles ρ, ε and κ.

The value of a, length that the backlimb of the middle bed prolongs to its intersection with J, can be achieved through the equation (Fig. A.5):

$$a = (J - W)\left(\frac{\sin\left(\kappa - \left(\frac{180-\psi-\delta}{2}\right)\right)}{\sin\left(\frac{180-\psi-\delta}{2}\right)}\right) \qquad \text{(A.24).}$$

To calculate λ, angle between the segment J and the forelimb, two dips are required, ψ and θ (Fig. A.5):

$$\lambda = 180 - \psi - \theta \qquad \text{(A.25).}$$

The length X*, portion of the segment J bounded by the forelimb of the middle bed and the prolongation of its backlimb, is obtained with the following equation (Fig. A.5):

$$X* = a\left(\frac{\sin(180-\beta-\lambda)}{\sin\lambda}\right) \quad \text{(A.26).}$$

Once a and X* are known it is time to calculate the remaining edge of the triangle, c, using the expression (Fig. A.5):

$$c = a\left(\frac{\sin\beta}{\sin\lambda}\right) \quad \text{(A.27).}$$

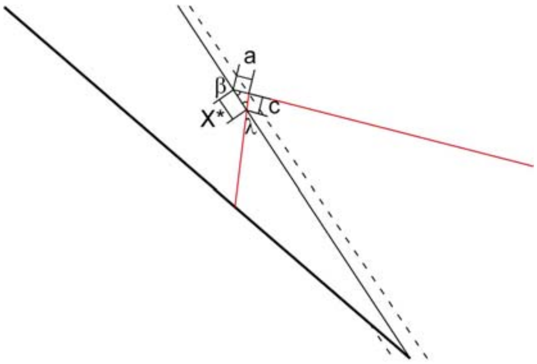

Fig. A.5. Figure showing the lengths a, X* and c and the angle λ.

The fault slip, S, when the horizon initially at the fault nucleation point is affected by the core axial trace can be determined following the expression:

$$S = S*-2X* \quad \text{(A.28).}$$

Subtracting the length a to N* permit the calculation of N:

$$N = N*-a \quad \text{(A.29).}$$

M is the sum of M* plus c:

$$M = M*+c \quad \text{(A.30).}$$

The shortening (Sh) undergone by the bed originally at the fault nucleation point, if affected by the core axial trace, can be calculated with the equation:

$$Sh = 2(Z2+N+M-Y) \quad \text{(A.31).}$$

In the case that this horizon was not folded by the core axial trace the shortening would be "Sh":

$$"Sh" = 2(Z-Y) \quad \text{(A.32).}$$

The difference between half the fault length and half the fault slip of the horizon originally at the nucleation point if it is not affected by the core axial trace ("S") is equal to "u" (Fig. A.6):

$$"u" = \frac{P}{2} - \frac{"S"}{2} \quad \text{(A.33).}$$

The angle between the core axial trace and the fault plane is v and is calculated with the equation (Fig. A.6):

$$\mu = 180 - \theta - \frac{\psi}{2} - \gamma \quad \text{(A.34).}$$

To obtain u (Fig. A.6), length measured along the fault plane from the upper tip to the intersection point of the fault and the core axial trace in the hanging wall, the expression shown below should be used:

$$u = d\left(\frac{\sin\left(\frac{180-\psi-\delta}{2}\right)}{\sin\mu}\right) \quad \text{(A.35).}$$

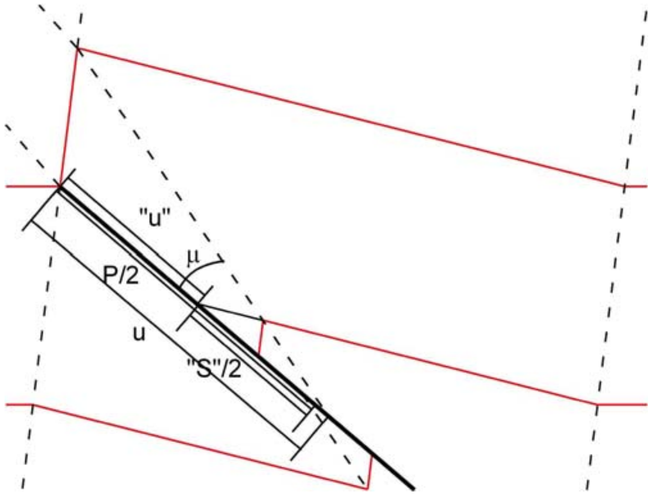

Fig. A.6. Figure showing the lengths u and "u" and the angle μ.

The value of γ that, with fixed θ and ψ, makes u equal to "u" is the critic angle. Values of γ lower than the critic one make that the core axial trace affects the horizon at the fault nucleation point.

The folded length of the bed at the fault tip between the back axial trace and the frontal axial trace (l) can be obtained via the following equation:

$$l = e + d \qquad \text{(A.34).}$$

The structural relief of the horizons above the upper fault tip is r and can be computed using the expression:

$$r = e \cdot \sin \delta \qquad \text{(A.35).}$$

The shear existing between the horizon originally at the fault nucleation point and the horizon at the fault tip (φ) (Fig. A.7), when the mid bed is affected by the core axial trace, can be computed with the expression:

$$\varphi = \arctan\left(\frac{l - 2(Z2 + N + M)}{t}\right) \qquad \text{(A.36).}$$

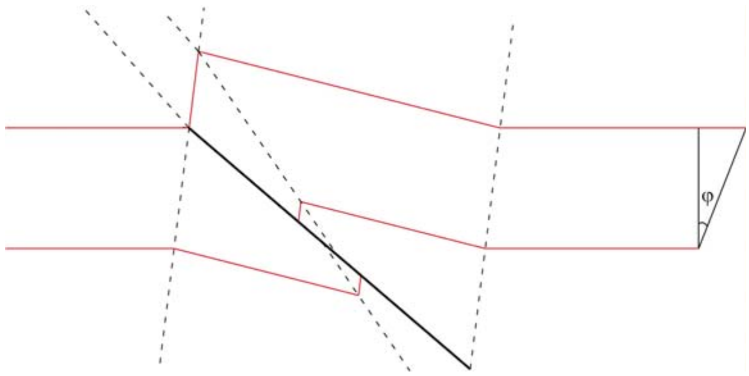

Fig. A.7 Figure showing the shear angle.

If the core axial trace did not affect the horizon at the fault nucleation point the angle of shear would be "φ", whose value can be obtained solving the equation:

$$"\varphi" = \arctan\left(\frac{l - 2Z}{t}\right) \qquad \text{(A.37).}$$

To eliminate the backshear the faults not cut by the fault have, we introduce a forelimb thickening (Fig. A.8). This thickening is controlled by the rotation of the frontal axial trace:

$$A^* = A \qquad \text{(A.38).}$$

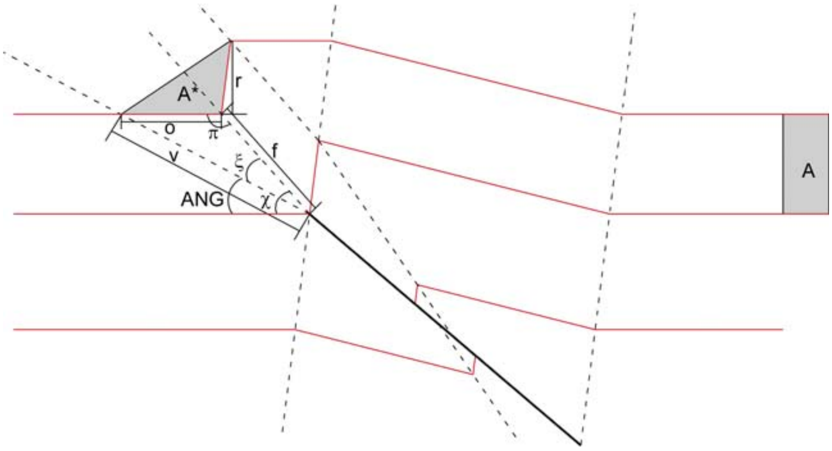

Fig. A.8. Figure showing the area introduced in the forelimb to compensate the backshear, as well as the angles and lengths implied in the process.

The excess of area is calculated with the formula:

$$A = h \cdot t \cdot \tan \varphi \qquad \text{(A.39)},$$

being *h* an arbitrary height.

Knowing the area and the height of the triangle the base length, o, is computed (Fig. A.8):

$$o = \frac{2A}{r} \qquad \text{(A.40)}.$$

The dip of the frontal axial trace (χ) before the thickening is (Fig. A.8):

$$\chi = \frac{180 - \psi}{2} \qquad \text{(A.41)}.$$

The length f can be determined through the equation (Fig. A.8):

$$f = h \csc \chi \qquad \text{(A.42)}.$$

Then the angle π (Fig. A.8), supplementary of χ, is computed:

$$\pi = 180 - \chi \qquad \text{(A.43)}.$$

To calculate the length v (Fig. A.8) is required to employ the equation:

$$v = \sqrt{o^2 + f^2 - 2 \cdot o \cdot f \cdot \cos \pi} \qquad \text{(A.44)}.$$

To find out the dip of the frontal axial trace that eliminates the whole backshear is necessary to know the angle ξ, angle between the sought axial trace and the axial trace without thickening (Fig. A.8):

$$\xi = \arcsin\left(\frac{o \sin \pi}{v}\right) \qquad \text{(A.45)}.$$

Finally we can calculate the value of ANG (Fig. A.8):

$$ANG = \chi - \xi \qquad \text{(A.46)}.$$

If the core axial trace did not affect the horizon initially at the fault nucleation point, in A.39 "φ" should be used instead of φ.