Appendix DR1. Kinematic Model

Here we detail the analytical equations used to compute the displacements due to fault-bend folding of initially flat lying layers (Figure B). We consider a finite-width hinge zone with a curved fault geometry. Within the hinge zone the fault is approximated by an arc of circle with radius $R_c$ and opening angle $\beta$. The hinge zone connects a horizontal decollement and a ramp which are both approximated by linear segments. We assume that flexural slip (bed parallel shear) occurs only within the hinge zone so that outside this zone the hanging wall is translated along the thrust fault as a rigid block. The dip angle of the hinge zone has to bisect the angle between the decollement and the ramp so that beds thickness is preserved during folding (Suppe, 1983).

In the equations below the origin of the x-coordinate is taken at the entry axial surface and the axis is oriented positively from the piggyback basin toward the fold. The depth axis is positive downward. Let’s consider a particle initially deposited at point $X_0$, $Z_0$ (Figure B). So the center of curvature of the bed of interest within the hinge zone lies at $(0, Z_0-R_c)$. The new coordinates $X$, $Z$, after an increment of slip $S$ on the horizontal decollement, can be calculated using the 12 equations below. The geometry of the fold is then obtained by assigning a cumulative shortening to any bed lying any given depth. Note that the axis origin is different for beds lying at different depths to account for the dip angle of the hinge zone.

- A particle deposited before the hinge zone at a distance larger than $S$ from the entry axial surface (particles 1 and 2 on Figure B) is translated horizontally by $S$:

$$X = X_0 + S; \quad (1)$$

$$Z = Z_0. \quad (2)$$

No tilt is induced in this case.

- A particle deposited before the hinge zone but at a distance smaller than $S$ from the entry axial surface (particles 3 on Figure B) enters the hinge zone. If the particle does not exit the hinge zone we get:

$$X = R_c \sin\left(\frac{S + X_0}{R_c}\right); \quad (3)$$

$$Z = Z_0 - R_c \left[1 - \cos\left(\frac{S + X_0}{R_c}\right)\right]. \quad (4)$$

In that case the bed segment to which the particle belongs is tilted by an amount, $\theta$, smaller than $\beta$, which can be easily computed from equations (3) and (4).
- Lets again consider a particle deposited before the hinge zone at a distance smaller than \( S \) from the entry axial surface (particles 3 on Figure B). If the particle is now assumed to exit the hinge zone we get:

\[
X = R_x \sin \beta + (S + X_a + R_x \beta \cos \beta) \quad (5)
\]

\[
Z = Z_o - R_x (1 - \cos \beta) - (S + X_a - R_x \beta \sin \beta) \quad (6)
\]

In that case the bed is tilted by \( \beta \).

- In the case of a particle deposited within the hinge zone and which remains within the hinge zone (particles 4 and 5 in Figure B) we get:

\[
X = R_x \sin\tan^{-1} \left( \frac{X_a}{R_x} + \frac{S}{R_x} \right) \quad (7)
\]

\[
Z = Z_o - R_x [1 - \cos\tan^{-1} \left( \frac{X_a}{R_x} + \frac{S}{R_x} \right)] \quad (8)
\]

In that case the bed segment to which the particle belongs is tilted by an amount, \( \theta \), smaller than \( \beta \), which can be easily computed from equations (7) and (8).

- In the case of a particle deposited within the axial zone but that exits the hinge zone (particle 6 on Figure B) we get:

\[
X = R_x \sin \beta + (S - R_x \cdot \beta - R_x \cdot \tan^{-1} \left( \frac{X_a}{R_x} \right) \cos \beta) \quad (9)
\]

\[
Z = Z_o - R_x (1 - \cos \beta) + (S - R_x \cdot \beta - R_x \cdot \tan^{-1} \left( \frac{X_a}{R_x} \right) \sin \beta) \quad (10)
\]

In that case the bed segment to which the particle belongs is tilted by an amount, \( \theta \), smaller than \( \beta \), which can be easily computed from equations (9) and (10).

- A particle deposited after the hinge zone (particles 7, 8 and 9 on Figure B) is translated parallel to the ramp leading to:

\[
X = X_a + S \cos \beta \quad (11)
\]

\[
Z = Z_o - S \sin \beta \quad (12)
\]

No tilt is induced in this case.
Appendix DR2. Uncertainty on shortening and ages

We detail here how the uncertainties on dip angles measurements are estimated and can be converted into uncertainties on the estimate of shortening.

Our structural measurements of pre-growth strata, which are assumed to parallel the ramp, form a pool of 50 measurements. The mean value is 55.0° and the standard deviation is 5°. We therefore estimate to 5° the 1-σ uncertainty on each individual dip angle measurement.

This uncertainty accounts for measurement errors and the natural roughness of bedding surfaces. We then use the Chi-square criterion to estimate the resulting uncertainty on the shortening at the 67% (1-σ) confidence level, $\Delta S$.

Each age is assigned a confidence interval corresponding to the chron defined by the magnetostratigraphic data points bracketing the stratigraphic location of the point of interest. Providing that the interpretation of the magnetostratigraphic section is correct these uncertainties would represent the range of possible values at the 100% confidence level. The possibility of an error in the correlation between the observed magnetostratigraphic sequence and the reference scale is not taken into account. This is probably a reasonable assumption given the dense sampling rate of the magnetostratigraphic section except may be for the most recent growth strata (younger than about 2.5Ma). Also, the uncertainties on the age assigned to the reference magnetostratigraphic scale, which are estimated to typically less than a few 10kyr for the Miocene to present period (Lourens et al., 2004), are neglected.

Finally, this uncertainty also ignores the uncertainties on the model itself, i.e. regarding the geometry of the model and the flexural-slip assumption. This is because these uncertainties are quite difficult to assess although they might be significant. For example, we haven’t taken into account any direct constraints on sub-surface seismic velocities. The model therefore assumes a constant seismic velocity. The consistency with the dip angles measured at the surface and those observed on the depth-converted seismic profiles show that it is probably a reasonable first-order assumption, but departure from this first order approximation could be a significant source of errors that is not explicitly taken into account in our analysis.

Appendix DR3. Statistical analysis of shortening rate

Average shortening rates are calculated by adjusting the shortening-time estimates by a straight line or several segments of straight lines (Figure 3). We use a general least-squares procedure that allows to take into account the uncertainties on shortening estimates as well as
on ages (Tarantola, 2005). We assume normally distributed errors on shortening estimates. To relax the hypothesis that the probability distribution of an age is uniform within a chron to which it belongs and should be null outside this chron, we also assumed normally distributed errors on ages. We define a confidence interval to each age that is centred on the estimated age encompassing the whole chron within which this age falls and assign it a 95% confidence level (2-σ). We implemented a general least squares inversion in which either both the shortening rate and the intercept are inverted for, \( S = R \cdot t + S_0 \), (in that case our implementation is equivalent to the algorithm of (York et al., 2004)), or only the shortening rate is inverted while the intercept is forced to be zero, \( S = R \cdot t \), to meet the requirement that the cumulative shortening over the period of time with negligible duration is zero.

The model with a constant shortening rate yields a reasonably good fit corresponding to a reduced Chi-square
\[
\chi^2 = \frac{1}{2N-1} \sum_{i=1}^{N} \left( \frac{S_{\text{ob}}^i - S_{\text{mod}}^i}{\Delta S_i} \right)^2 + \left( \frac{t_{\text{ob}}^i - t_{\text{mod}}^i}{\Delta t_i} \right)^2 = 1.8 \quad (\text{where indices ‘mod’ and ‘ob’ refer respectively to the observations and to the model prediction and where } \Delta t_i \text{ is the uncertainty on age at the 67% confidence level). The model in which two periods with different shortening rates are considered depends on three parameters. It yields a better reduced Chi-square
\[
\chi^2 = \frac{1}{2N-3} \sum_{i=1}^{N} \left( \frac{S_{\text{ob}}^i - S_{\text{mod}}^i}{\Delta S_i} \right)^2 + \left( \frac{t_{\text{ob}}^i - t_{\text{mod}}^i}{\Delta t_i} \right)^2 = 0.7 . \quad (\text{From the F-test, based on the Chi-square values obtained from these two models, we estimate that the probability that the two periods have the same rate is less than 1%.)

Figure 3 shows the comparison between the data and the two models. Errors bars on shortening values show uncertainties at the 2-σ confidence level derived from assuming a \( \sim 5^\circ \) uncertainty on dip angle measurements. This uncertainty accounts both measurements errors and the variability of initial dip angle of the growth strata. Errors bars on time correspond to the limit of magnetic reference chron Lourens et al. (2004).

Appendix DR4. Effect of compaction
The implemented fold model used in this study neglects the fact that compaction could be a source of bed tilting. Actually, if we consider a bed overlain by growth strata compaction could be a source of tilt. The thickness of the growth strata must indeed vary laterally so that some lateral variations of compaction should be induced leading to some tilt of the bed that is not related to the fold growth. This effect can be estimated approximately. Let’s consider two points deposited at the same time at close by horizontal distances \( x \) and \( x + \Delta x \), respectively,
within the piggy-back basin. These two points will have travelled different distances beneath
the piggy-back and are therefore overlain by a different thickness of sediment \( \Delta h = \frac{R_{sed}}{R_{sh}} \Delta x \).

Let’s now assume a standard compaction law in which porosity decays as a exponential function of depth, \( p(z) = \alpha \exp(-\beta z) \). The tilt \( \Delta \theta \) due to the difference of compaction at abscissa \( x \) and \( x+\Delta x \) is then:

\[
\Delta \theta = \frac{R_{sed}}{R_{sh}} \cdot \alpha \cdot (1 - \alpha) \cdot \exp(-\beta z). \tag{13}
\]

where \( R_{sed} \) is the sedimentation rate, \( R_{sh} \) the shortening rate. We have estimated these tilts using \( \alpha = 0.68245 \) and \( \beta = 1/918 \) taken from Metivier et al. (1999). The correction is maximum for the youngest growth strata considered in this study, which were deposited at a depth of about 800m from surface, about \( \sim 1.3 \) Ma ago. It amounts to \( \sim 4^\circ \). It decreases rapidly to less than 1° for strata older than \( \sim 3.5 \) Ma, a value negligible in view of the uncertainty on dip angle measurements. We have then revised the estimated shortening values taking into account these corrections. It only affects the 0-4Ma period and the revised shortening rate is then revised to 1.16+/-0.03 mm/yr, which is insignificantly different from the 1.14+/-0.02 mm/yr rate estimated without correcting for compaction. We thus conclude that this correction is not necessary in the present study.

References


Figure DR2

Exit axial surface

Rc

Entry axial surface

Deformed marker

Initial marker

Trajectories

Fig. B