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NOTES ON THE DETERMINATION OF SHORTENING BY FLEXURE FOLDING MODIFIED BY FLATTENING

By

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(With six text figures.)

ABSTRACT

A simple visual field method of determining the amount of flattening of a flattened flexure fold is described. The method allows estimation of the pre-flattening thicknesses and dips of the deformed beds, so that original thicknesses of sequences and the total shortening of the layers by folding may be calculated.

INTRODUCTION

Van Hise (1894) recognised two fundamental groups of folds—the flexure (also known as parallel or concentric) type and the similar folds. The geometrical characters of the two groups differ markedly. With flexure folds the thicknesses of the beds measured at right angles to the bedding surfaces remain constant throughout the fold, whereas with similar folds the thicknesses of the beds measured parallel to the axial surface to the fold are constant but thicknesses measured perpendicular to bedding are variable (fig. 1).

In general, it appears that folds usually encountered in the field are of a flexure type modified by flattening, which when extensive results in folds that superficially resemble those of similar type (de Sitter, 1958; Ramsay, 1962). Only flattened flexure folds are considered in these notes.

Flattened flexure folds are usually readily distinguished especially where variations in the thickness of some layers are significantly less than adjacent ones. Again, acutely pinched lower boundaries of beds are characteristic of this type of fold (fig. 2). Where doubt exists as to whether the examined fold is of the type considered here, marked variations in thicknesses of beds measured parallel to the axial plane of the fold are diagnostic (see Ramsay, 1962).

In the following geometrical analysis it is assumed that layers were initially of uniform thickness. Deformation is divided into two distinct types—flattening and pure flexure folding—for geometrical analysis only. In the actual fold development parts may be undergoing flexure folding whilst other parts are being flattened (Williams, 1965).

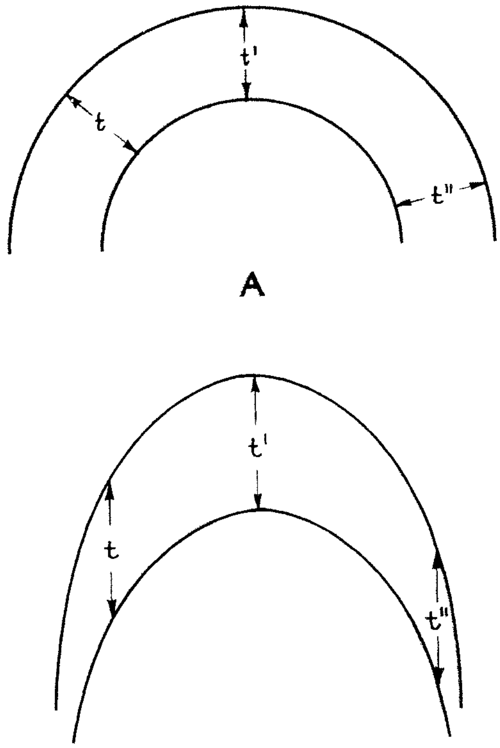

FIG. I

A. Profile of flexure fold illustrating uniform thickness of layer normal to bedding. t = t' = t''.

B. Profile of similar fold with uniform thickness of layer measured parallel to axial surface. t = t' = t''.

ESTIMATION OF FLATTENING

Ramsay (1962, p. 314-15) has presented a graphical method whereby the percentage of flattening of a flexure fold may be determined. The method involves the comparison of thicknesses measured perpendicular to bedding of a competent horizon of known dips with the thickness of that bed at the fold hinge. However, where difficulties are encountered in measuring with sufficient accuracy thicknesses of competent horizons, due perhaps to well developed sole markings or tectonically frayed boundaries, Ramsay's graphical method is unsatisfactory. Furthermore, with folds exhibiting differential flattening Ramsay's method is uncertain, for this phenomenon may be attributed to inaccurate field measurements.

In order to determine the shortening of strata by folding an estimation of the amount of flattening in a fold is of use only if the form of the profile of the pre-flattened fold is known. Therefore, in using Ramsay's method it is necessary to reconstruct the original fold profile by trial and error before any further calculations can be made.

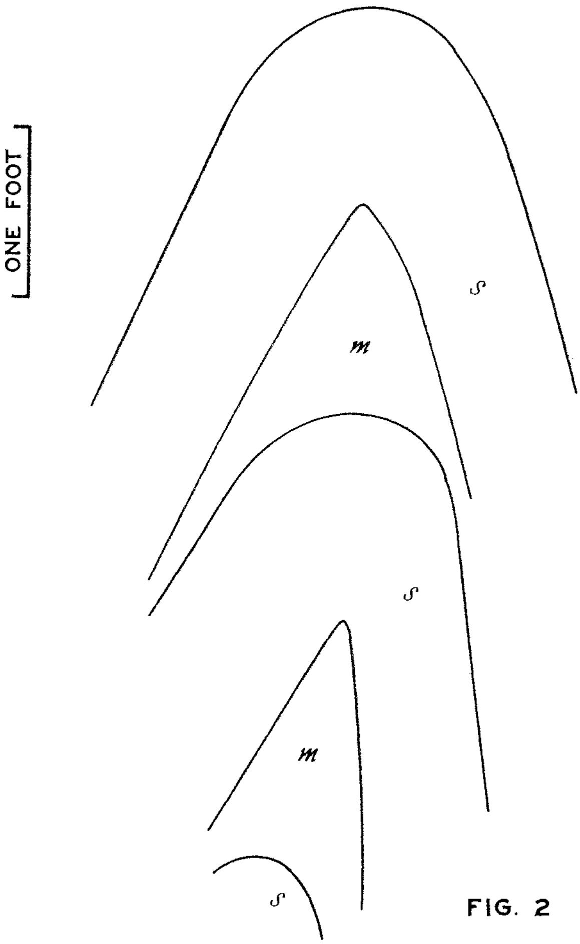

FIG. 2

Profile of flattened flexure fold of sandstone (*S*) and interbedded mudstone (*M*). Location near Tullochgorum on the South Esk Highway, North-East Tasmania. Field orientation: fold axes plunge 28° in direction 145°, axial surface dips approximately 56° in direction 205°.

Note marked difference in competence of sandstone and mudstone, and acute pinch at lower boundaries of sandstone.

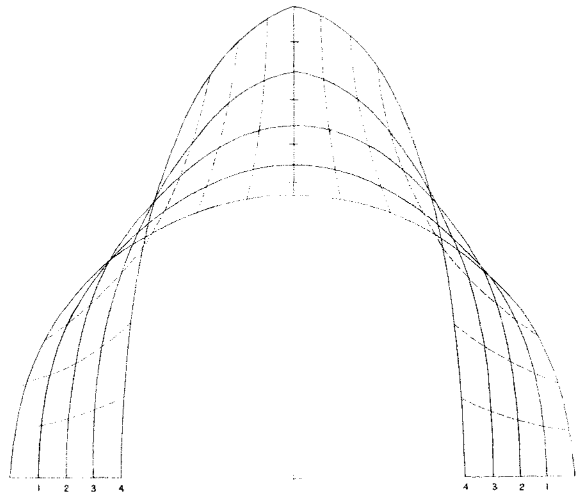

FIG. 3

Semi-circular area flattened by 10, 20, 30 and 40 per cent. Corresponding points on the curves are indicated by broken line. See text for further explanation.

In the writer's experience pre-flattened fold profiles correspond to arcs of circles, and this appears to be the experience of many others in that it is the underlying assumption of the treatment given to flexure folds in text-books (e.g., de Sitter, 1964) and in Ramsay's paper. Nevertheless, it is considered necessary that in any method used in the calculation of shortening by folding, pre-flattened fold profiles which do not correspond to arcs of circles are immediately recognised, for in such cases the calculation of shortening is unique for each fold and they are therefore not considered in this paper.

During routine mapping activities it appears advisable to use methods for determining flattening in folds which do not depend on numerous accurate measurements of the thicknesses of layers, find no difficulties with differential flattening and give an immediate indication as to whether the pre-flattened fold profile is of an arc of a circle. With these points in mind simple graphs, based directly on the theoretical consideration of de Sitter (1958), have been constructed for visual comparison with the folds encountered.

Figure 3 shows an area bounded by a semi-circle flattened by 10, 20, 30 and 40 per cent. Corresponding points on the curves are indicated by a broken line. The figure, with a semi-circle of three inches radius, is engraved on a perspex sheet of 1/12th inch thickness. This sheet is used in the field by holding, preferably mounted on a light tripod, at a suitable distance between eye and outcrop perpendicular to the direction of the fold axis. The distance between eye and perspex sheet is varied until the fold profile fits the set of engraved curves. Quicker results are obtained when the method is used with folds in layers showing acute pinches at a boundary surface so that the approximate centres of folding during the flexural deformation are known. By comparing the fold profile with the set of engraved curves on which corresponding points have been superimposed the pre-flattened dips of the sectors of the fold can be readily determined. Figure 4A illustrates the use of this method.

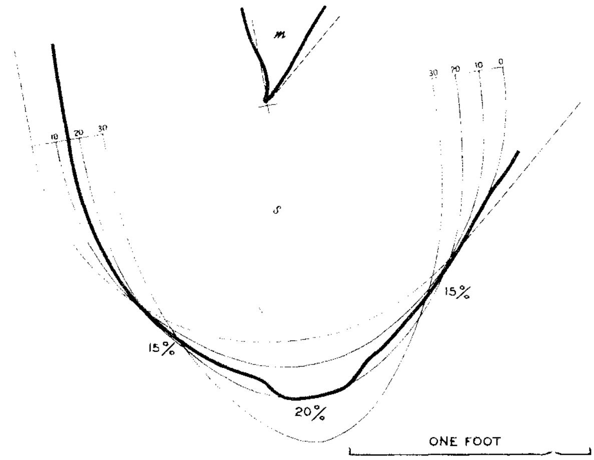

FIG. 4A

A. Profile (thick line) of syncline in sandstone (*S*) with amounts of flattening determined by superimposed graph (thin line) shown on outer arc. Broken line indicates unflattened fold profile. Location near Tullochgorum, on South Esk Highway, North-East Tasmania. Field orientation: fold axis plunge 14° in direction 125°, axial surface dips approximately 61° in direction 200°.

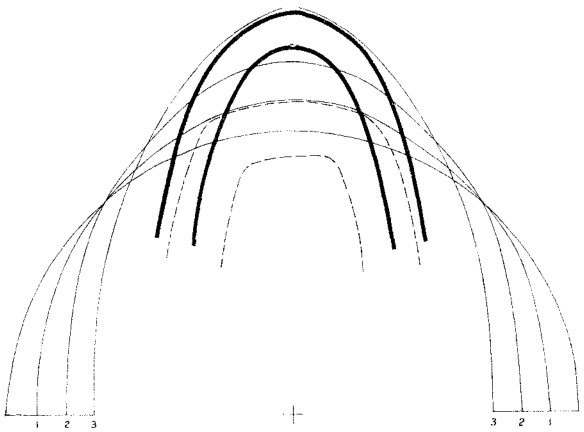

FIG. 4B

B. Misfit folds (thick and broken lines) indicating pre-flattened fold forms are not of arcs of a circle.

Misfitting fold profiles (fig. 4B) and differences in the percentage flattening determined by comparing both upper and lower surfaces of a bed with the curves inscribed on a perspex sheet, indicate that the pre-flattening fold profiles are not of a circular arc. *It must be emphasised that pre-flattened fold forms which are not of an arc of a circle are readily recognised by using the method described.*

Having determined the percentage of flattening of a fold of a pre-flattened profile of an arc of a circle, it remains to determine the amount of shortening by pure flexure folding.

ESTIMATION OF SHORTENING BY FLEXURE FOLDING

For simplicity let the angle of the arc of uniform curvature be the same in both anticline and adjacent syncline, and let the limbs be straight. Then in fig. 5, where the radius of curvature of the hinges is greater or equal to the thickness of the competent unit folded, it is evident that the percentage shortening is—

$$\frac{l\left(1-\cos\alpha\right)+\left(r_1+r_2\right)\left(\frac{\pi\alpha}{180}-\sin\alpha\right)}{l+\frac{\pi\alpha}{180}\left(r_1+r_2\right)}\,.\,100 \quad \ldots\ldots\ldots(1)$$

where l is the length of the fold limb, α half the angle of uniform curvature, r_1 the radius of curvature of the synclinal arc and r_2 the radius of curvature of the anticlinal arc.

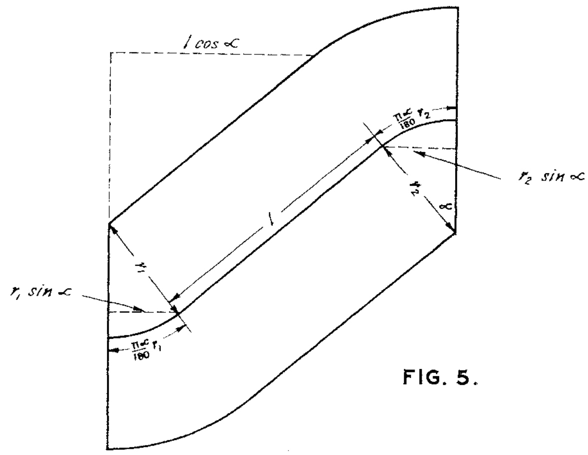

FIG. 5.

Geometry of profile of flexure fold of competent unit where α is half angle of uniform curvature, r_1 radius of curvature of synclinal arc, r_2 radius of anticlinal arc, and l length of fold limb.

In the special case of simple flexure folding, where arcs are of constant curvature (fig. 6) and l is zero, the percentage shortening is—

$$\left(1-\frac{180\sin\alpha}{\pi\alpha}\right).\,100 \quad \ldots\ldots\ldots(2)$$

In simple flexure folding, shortening is constant for each value of α, and when centres are colinear is approximately 36.6% (fig. 6B), which is the amount often incorrectly quoted for the maximum amount of shortening by flexure folding (see Ramsay, 1962, p. 313), for in the more general cases it is evident by inspection of equation (1) that considerably more shortening can occur.

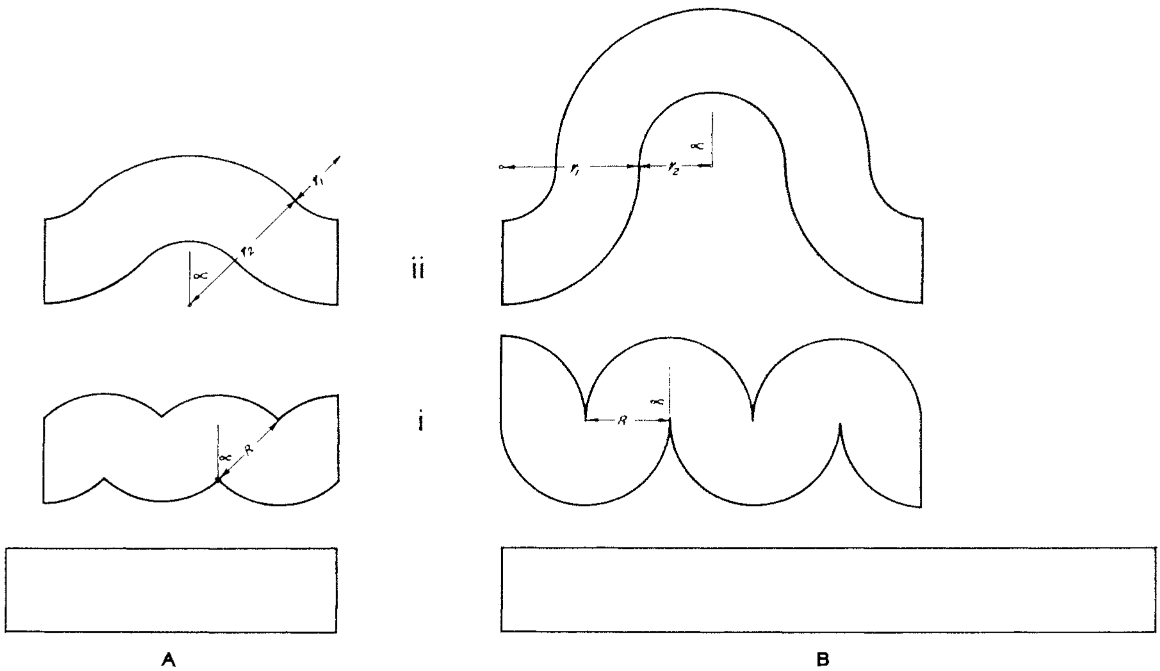

FIG. 6

Geometry of profiles of simple flexure folds of competent units for varying values of α, half angle of uniform curvature, and R, distance between centres of curvature. Shortening in A is 10% and B 36.6%.
(i) R = thickness of layer.
(ii) $R >$ thickness of layer.
Note $R = r_1 + r_2$, where r_1 is radius of curvature of synclinal arc, and r_2 radius of anticlinal arc.

ESTIMATION OF TOTAL SHORTENING

If the shortening by pure flexure folding is X% and by flattening Y%, then the total shortening is—

$$\left(X + Y - \frac{XY}{100}\right) \% \qquad (3)$$

With accordian or concertina folds of long straight limbs it is essential to study the hinges in order to determine the amount of flattening (see Williams, 1965). However, the folds may be neglected in the final calculations of shortening. Using the visual comparison method both the flattening percentage and the pre-flattened dip of the limbs can be determined (fig. 4A), and the total shortening is given by—

$$\left[1 - \left(1 - \frac{X}{100}\right) \cos \alpha\right] . \, l \, . \, 100\% \qquad (4)$$

where X is the percentage flattening, α the dip of the pre-flattened limb and l the length.

CONCLUSIONS

Usually folds encountered in the field are of a flattened flexure type which when unflattened have profiles of arcs of circles. The visual graphical method described above is constructed to analyse these folds, but it is designed so as to allow immediate recognition of a fold with a pre-flattened profile of curves not of arcs of circles in the event of one being encountered.

A comparison of fold profiles in the field with a set of curves representing various percentages of flattening of a semi-circular area inscribed on a perspex sheet, allows a calculation to be made of not only the original thicknesses of the deformed layers but also the horizontal extent of the beds before folding. Determinations such as these will give true variations in stratigraphic thicknesses from one locality to another and greatly help in building up a picture of the amounts of structural deformation in regions.

ACKNOWLEDGMENTS

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