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# A rapid method for strain estimation from flattened parallel folds

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**Abstract**

Superimposition of homogeneous strain on parallel folds is a potential mechanism for development of flattened parallel folds. Estimation of flattening strain by existing graphical approaches requires a large number of angular and/or linear measurements. We propose a new computer-based approach, which rapidly destrains a flattened parallel fold into a parallel fold with help of any of the commonly available graphic software. This method is based on the principle that the magnitude of flattening directly relates to change in the inherent orthogonality that exists between a tangent and an isogon, at any given angle of the limb dip, on the profile of a parallel fold.

Using six examples of flattened parallel folds, we show that the results of our destraining method are consistent with those yielded by other existing methods. Besides estimating the flattening strain rapidly and involving a relatively low amount of error, our method also restores the pre-flattening fold shape without any additional geometrical or numerical operation.


*Keywords:* Flattening; Parallel fold; Flattened parallel fold; Oblique-flattening; Fold analysis; Destraining

## 1. Introduction

Structural geologists have long recognized the significance of geometric analysis of folds because it provides important clues to the mechanism of folding (Ramsay, 1967, pp. 386–411; Hudleston, 1973a; Bastida et al., 2003), besides defining the precise shapes of the fold hinge zones that commonly host petroleum reservoirs and saddle-reef ore bodies. Buckling of a relatively competent layer, enclosed in an incompetent medium, produces class 1B, or parallel folds (Biot, 1961; Ramberg, 1963; Ramsay, 1967, pp. 372–377; Ghosh, 1993, pp. 252–264). These folds are characterized by a unique orthogonal relationship between the tangent and the isogon at any given angle of the limb dip. Flattening, caused by the superimposition of a homogeneous strain on a class 1B fold, results in thickening of the hinge zone, thinning of the limbs and modification of the fold shape into class 1C geometry. The extent of geometrical modification due to flattening is directly related to the magnitude of the superimposed homogeneous strain.

Several graphical methods are available for the determination of magnitude of flattening. Ramsay (1962, 1967, p. 413) uses the relationship between the limb dip angle $\alpha$, and the normalized orthogonal thickness, $t'_{\alpha}$, for estimation of flattening in class 1C folds. Hudleston (1973a) proposes a graphical method, which is based on the relationship between the limb dip angle $\alpha$ and, an angle $\phi$ between the isogon and the normal-to-the-tangent. Lisle (1992) suggests a polar plot between the inverse thickness, $1/t$, and the limb dip angle $\alpha$, which yields the required strain ellipse. Srivastava (2003) gives a somewhat similar solution, but his method is applicable only to truly concentric folds. None of these existing methods restores the pre-flattening shape of class 1C folds without the application of an additional step that destrains the fold shape either by geometrical or numerical technique.

In this paper, we propose an alternative method for estimation of the flattening strain in class 1C folds. This method, based on destraining by simple computer application, gives the flattening strain and restores the pre-flattening shape of the fold in the same operation. We test the efficacy and the validity of this new method on six examples of natural and numerically simulated folds, and

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compare our results with those obtained by other common methods.

## 2. Destraining method

We assume that the fold to be analyzed develops as a class 1B fold and it assumes class 1C geometry due to superimposition of a post-buckling homogeneous strain ($X \geq Y \geq Z$), albeit a class 1C fold can also develop due to simultaneous buckling and flattening (Hudleston, 1973b).

Our method makes use of two geometrical properties of folds. First, in the class 1B folds, all the isogons are perpendicular to their respective tangents. Second, flattening introduces an angular shear, due to which the orthogonality between the isogons and their corresponding tangents is changed, except at the limb dip, where the isogon and the tangent parallel the principal axes of the strain ellipse. The angle, $\delta$, between the tangent and the isogon at any point in a class 1C fold is a function of the magnitude of flattening, or axial ratio, of the strain ellipse on profile plane. The proposed method destrains a class 1C fold into a class 1B fold by restoring the orthogonal relationship between isogons and their respective tangents. The ratio, arc length/half wavelength, measured on the restored fold shape, gives buckling strain $R_B$, provided the area remains constant during folding. If the initial layer-parallel-shortening is insignificant, then the estimate of bulk strain, $R_{Total}$, can be made by multiplying the strains due to buckling and flattening, i.e. $R_{Total} = R_B R_F$.

### 2.1. Application

The destraining of class 1C fold, based on the principle of restoring orthogonal relationship between isogons and their respective tangents, is best applied using any common graphic software, e.g. CorelDRAW, Corel Photo-Paint, Adobe Illustrator or Smartdraw. The two limbs of any given fold can be analyzed together, or separately, depending upon the presence, or the lack, of perfect mirror image symmetry across the axial trace. We first consider a simple situation where the $X$–$Z$ plane is profile plane and the $X$-axis parallels axial trace on profile plane of class 1C fold. These simplifying assumptions are realistic because many natural examples of the class 1C folds show a parallelism between axial trace and cleavage trace on profile plane. These class 1C folds, characterized by the orthogonal relationship between the isogon and the tangent at hinge points, can be destrained as follows:

(i) Import the digital or scanned image of profile section of the given fold into a graphic software, say CorelDRAW. Rotate the fold until its axial trace becomes vertical.

(ii) Draw two or three isogons and their respective tangents at convenient angles of the limb dip (Fig. 1a). In principle, only one pair of tangent and isogon at an angle of the limb dip, $90 > \alpha > 0$, is necessary. Also, draw a reference circle near the fold (Fig. 1a).

(iii) Group all objects, namely, the given fold, the tangent lines, the isogons and the circle. Select the grouped objects using the pick tool. This operation displays a set of eight handles, numbered *1–8* in Fig. 1a.

(iv) Drag the handle-*4* horizontally across the axial trace until all the isogons become perpendicular to their respective tangents. The shape of the given fold now restores back to class 1B geometry and the circle, drawn in step-(ii) (Fig. 1a), transforms into the reciprocal strain ellipse of axial ratio $R_F = \sqrt{(\lambda_z/\lambda_x)}$, where $\lambda_z$ and $\lambda_x$ are the principal quadratic elongations (Fig. 1b).

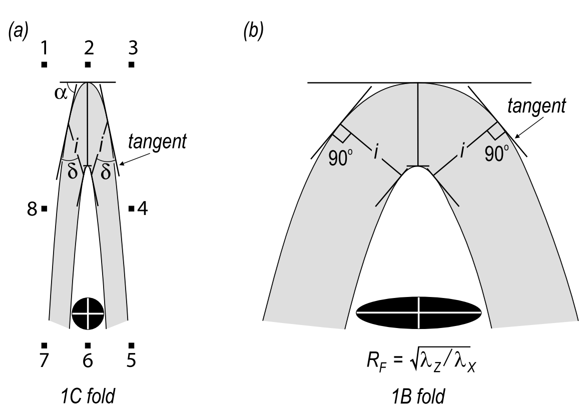


Fig. 1. Destraining methodology. (a) Image of a class 1C fold, and a reference circle. $\delta$—angle between isogon ($i$) and tangent at any given angle of the limb dip ($\alpha$). Selection of these objects displays a set of eight handles as the squares, *1–8*. (b) Destraining is achieved by pulling the handle-*4* towards the right until the orthogonal relationship between isogons and their respective tangents is restored. The reference circle in (a) transforms into the reciprocal strain ellipse of axial ratio $R_F$ in (b). $\lambda_z$ and $\lambda_x$—principal quadratic elongations.

Alternatively, the destraining can also be achieved by dragging any one of the handles numbered *2*, *6* or *8* in Fig. 1a.

We now consider the situation of oblique-flattening, where a class 1B fold assumes class 1C geometry due to flattening in such a manner that neither of the principal directions of strain parallels axial trace on profile plane (Hudleston, 1973a; Srivastava and Srivastava, 1988). In such class 1C folds, the isogons and the tangents at the hinge points neither display an orthogonal relationship nor parallel the principal directions of strain. Of the two orthogonal pairs of the isogons and the tangents, which may occur at limbs of the obliquely-flattened parallel folds ($I$–$T$ and $I'$–$T'$ in Fig. 2a), the identification of any one pair is sufficient for knowing the principal directions of strain. The procedure for the estimation of flattening strain and the restoration of