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Detecting cleavage-transected folds using cleavage–bedding intersections

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Abstract—Cleavage-transected folds, those with a non-axial planar cleavage, often have a cleavage–bedding intersection (cbi) that does not parallel the fold axis. The variation in attitude of the cbi around a fold is shown to be a sensitive indicator of even small amounts of axial transection in folds. The change in cbi plunge across a fold hinge is a particularly useful criterion for field recognition of transection in folds on a scale larger than the available outcrop.

The patterns of cbi are first investigated theoretically for cylindrical folds showing only axial transection, that is with no apparent transection in the profile plane. More complicated folds involving cleavage fanning and refraction are then considered. The use of cbi variation is especially sensitive for tight folds and for those having divergent cleavage fans. The technique is valid only where cleavage faces sympathetically with the fold-facing direction throughout the fold.

CLEAVAGE-TRANSECTED FOLDS

FOLDS with an associated cleavage which does not parallel their axial planes, even allowing for some fanning and refraction, have now been documented from a number of areas (e.g. Borradaile 1978, Gray 1981, Murphy 1985, Woodcock *et al.* 1988, Johnson 1991 and references therein), and it seems that they may be a widespread feature of many orogenic belts. However the angular transection involved is usually small (<20°) and many transected folds have gone unrecognized using standard structural techniques. In particular the confidence limits on estimates of fold axes, axial planes and cleavages may be greater than the transection angles, particularly for folds on a scale larger than the available outcrop.

This paper describes a sensitive method of detecting transection, implicit in some previous treatments (e.g. Moseley 1972, p. 579, Powell 1974, p. 1059, Stringer & Treagus 1980, fig. 10, Cameron 1981, p. 61) but detailed here. The method uses the attitudes of cleavage–bedding intersection (cbi) in folds. It can be used rapidly in the field to assess transection qualitatively, or indirectly to determine the magnitude and variation of transection.

A transected fold was originally defined (Powell 1974) as one in which cleavage cuts across the axial surface from one limb to the other. Fold transection can be most simply described in terms of two components. These are the d and Δ components of Borradaile (1978), termed, respectively, profile transection and axial transection by Johnson (1991). Profile transection is where the cleavage trace on the profile plane is not parallel to the trace of the axial plane. Common reasons for this are the fanning of a cleavage around a folded layer and the refraction of cleavage from one layer to the next, but more marked profile transection is possible. If a cylindroidal fold is purely profile-transected, its cbi remains parallel to its fold axis. By contrast axial transection is where the cleavage does not contain the fold axis. Such a fold will have a cbi which does not parallel its fold axis (e.g. Fig. 1), whether or not it shows any degree of profile transection. Axially-transected folds form the main subject of this paper.

The concept of structural facing is particularly important in describing transected folds. Throughout this paper the usage of the term facing follows that of Shackleton (1958) for folds and for cleavage. A fold faces in that direction within the axial plane and perpendicular to the fold hinge in which younger beds are encountered. Facing within a cleavage is the direction, perpendicular to the intersection of cleavage and bedding, in which younger beds are encountered. Most folds face generally upwards rather than downwards, reflecting the original upward-younging of sedimentary sequences, but transection may occur irrespective of fold-facing directions.

This paper is mainly concerned with the geometry of transected folds, not their interpretation. In particular the recognition that a cleavage transects a fold does not in itself imply that cleavage either wholly post-dates folding (e.g. Duncan 1985) or is synchronous with it (e.g. Soper 1986). However any method which helps to quantify transection angles gives a basis for distinction between these two possibilities. In the first case, transection angles would be expected to vary markedly with swings in fold orientation, whereas synchronous folding and cleavage formation should produce more subtle variation in transection angles. In the examples used in this paper, from the Welsh Caledonides, folds and cleavage formed in the same deformational event.

RECOGNITION OF AXIALLY-TRANSECTED FOLDS

Direct observation

Axial transection of folds by cleavage is directly detectable in the field if folds are small enough to be visible

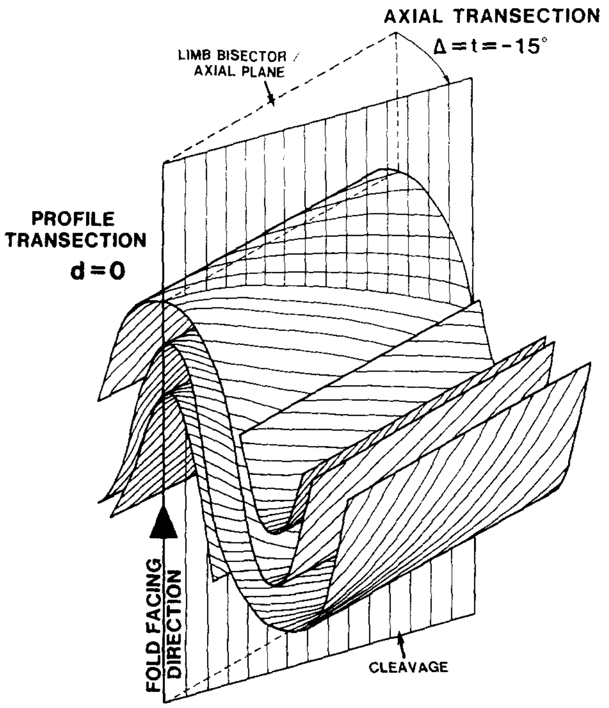

Fig. 1. Upright, horizontal, upward-facing fold, transected by a non-fanning cleavage. Profile transection is zero ($d = 0$); axial transection is clockwise ($\Delta = -15°$). Note the opposed plunge of cbi across each hinge.

on an outcrop scale. An obliquity between cleavage traces and fold hinges is visible when folds are viewed down their facing direction, that is within their axial plane and normal to the fold axis. If folds are macroscopic then recognition relies on the following methods.

Mapping of surface traces of fold axial planes and cleavage

For upright horizontal folds, any mapped obliquity between the traces of axial planes and cleavage on flat ground will indicate axial transection. However, if folds plunge or have inclined axial surfaces or if topographic relief is pronounced, apparent axial transection may arise and even an apparently anomalous sense of axial transection (e.g. clockwise rather than anticlockwise; Johnson 1991). It is not usually practical to construct axial surface traces with enough accuracy to detect small amounts of hinge transection. Cleavage vergence and facing cannot be used to detect fold axial traces accurately in such folds (Bell 1981). Problems are exacerbated if folds are asymmetrical or if outcrop is of limited extent.

Stereographic analysis of structural data

Axial transection can in theory be detected by estimating mean cleavage and fold axis attitudes from measured orientation data, using stereographic plots or statistical computation. The fold axis is estimated as the pole to the π-circle of bedding poles. The axial plane cannot be found by stereographic techniques from bedding data alone and therefore any profile transection component may go undetected. The limb-bisector plane can be used as an alternative reference surface (Johnson 1991), though it may have no physical significance.

In practice folds and cleavage are usually irregular enough to give marked dispersion of orientation data, and to give confidence intervals on the fold axis and cleavage estimates of the same order as the transection angle. Any one transection determination may therefore be inconclusive. One statistical solution to this problem is to check the consistency of transection sense between a number of adjacent areas (Woodcock 1990).

Cleavage–bedding intersection geometry

The simple, rapid and sensitive method described here for the detection of axially transective cleavage uses the degree and direction of cbi plunge relative to the fold axis. Axially-transected folds have cbi in variable directions, none of which are parallel to the fold axis (Fig. 1). Synformal folds usually have intersection lineations with a component of plunge towards their hinges whilst those of antiforms plunge away from their hinges. The cbi trends on opposing fold limbs indicate the sense of axial transection. For instance, a N-trending clockwise-transected upright antiform will have a NE-plunging cbi on E-dipping limbs and a SW-plunging cbi on W-dipping limbs (Fig. 1).

In areas of sub-horizontal folds this reversal of plunge direction across each fold hinge gives a direct indication of the presence and sense of axial transection (Fig. 2). This criterion can be used qualitatively in the field on any scale where limited exposure prevents its direct observation. If the folds are plunging, the cbi may plunge alternatively less than and more than the fold plunge on adjacent limbs, rather than necessarily showing opposed plunges.

In this paper a quantitative investigation of the variation in cbi attitude is undertaken in order to find the range of transected fold geometries which can be detected using the cbi method. The cbi plunge is dependent on the attitudes of the fold axis and bedding, which are known, and on the magnitudes of axial and profile transection, which are unknown. Prerequisites for use of this method are that: (i) only one cleavage affects the rocks; (ii) cbi is clearly developed and measurable; (iii) there are no localized deflections of cleavage near to lithological interfaces which would alter the expected plunge of the cbi; (iv) no conical folds are present on any scale; (v) any fold non-cylindricity which occurs is of a minor nature and is symmetrically developed with respect to fold limbs; and (vi) cleavage apparently 'faces with the fold' in the fold profile. Several of these conditions are detailed later.

GEOMETRY OF SIMPLE AXIAL TRANSECTION

Theoretical relationships

The variation of cbi is quantified first for cylindrical folds with zero profile transection. The geometry is

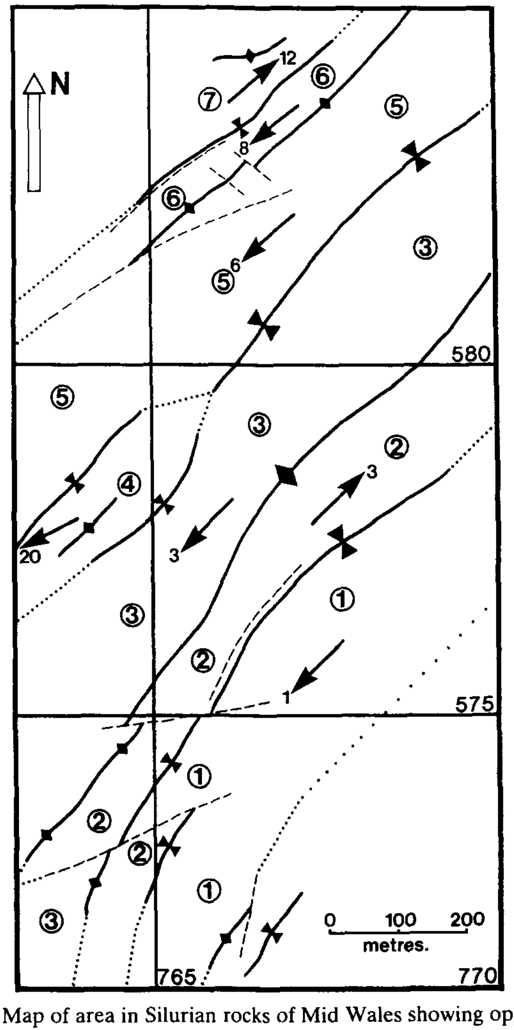

Fig. 2. Map of area in Silurian rocks of Mid Wales showing opposing cbi plunge across most fold hinges, indicating clockwise transection. Arrows are mean cbi for each fold limb. Folds plunge gently SW. Location, given by National Grid ticks, is within the area detailed by Woodstock (1990).

conveniently described for upright folds with horizontal hinges cut by a vertical planar cleavage (Fig. 3). However, this geometry remains invariant within the fold axis/axial plane reference frame for other fold orientations. The trigonometry of the structure in Fig. 3 shows that plunge of the cbi (ψ) is related to the bedding dip (α) and axial transection angle (Δ) by:

$$\tan\psi = \tan\alpha\cdot\sin\Delta. \tag{1}$$

This relationship is essentially the same as that relating true and apparent dips. It is shown graphically in Fig. 4. For the low axial transection angles ($\Delta < 20°$) common in natural folds, the plunge of the cbi increases modestly at low bedding dips and rapidly at high bedding dips.

Angular folds will have two discrete clusters of cbi with opposing senses on the two limbs (Fig. 3). In more rounded folds (Fig. 1) there is a spread of plunges between the two extremes. In either case a measurable parameter is the cbi plunge separation (2ψ), the maximum angle of lineation divergence between limbs of a transected fold. It is this angular separation across the hinge zone of a fold which most clearly demonstrates transection in the field. For all but gentle folds the cbi plunge separation (2ψ) is greater than the transection angle (Δ), effectively amplifying weak transection to discernible levels. Even where the value of the plunge separation is less than the transection angle (the stippled field of Fig. 4) its value is directly measurable in the field, which the transection angle rarely is. The variation in cbi across folds therefore provides a powerful practical method of determining transection.

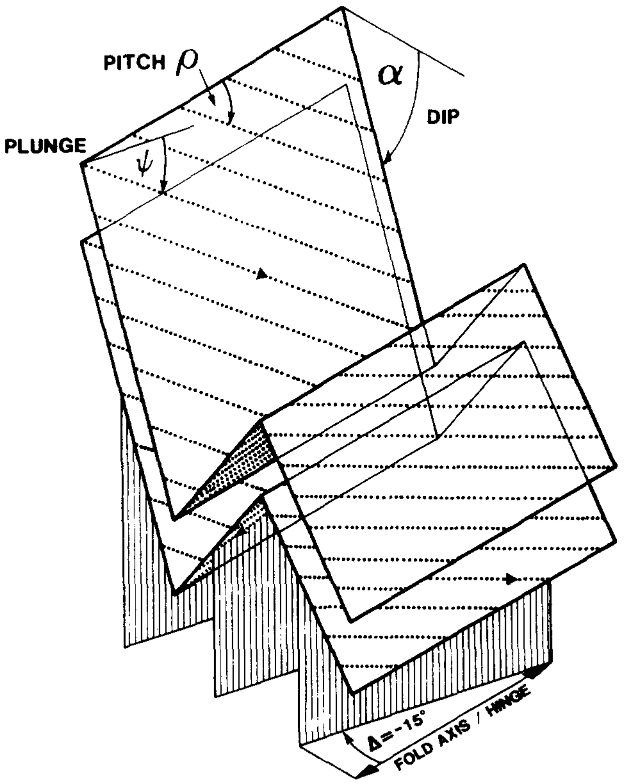

Fig. 3. Angular, symmetric fold with vertical axial plane and horizontal axis, cut by a coplanar, non-fanning cleavage. Profile transection (d) is zero. Axial transection is clockwise, here measured by Δ, the smallest angle between the fold axis and the cleavage. α = bedding dip, ψ = plunge of cbi, ρ = pitch of cbi in the bedding.

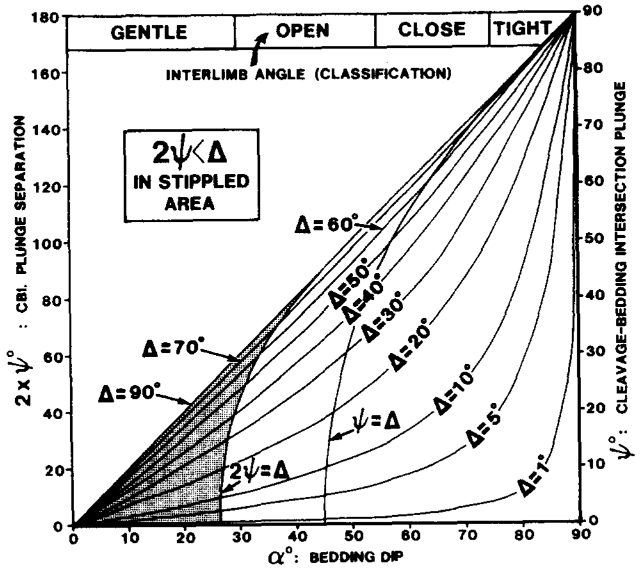

Fig. 4. Graph showing variation of cbi plunge (ψ) with bedding dip (α) on one limb of an upright horizontal fold, plotted for various axial transection angles Δ. The upper left shows calibration of the same plot for the angular separation (2ψ) of cbi plunge between two limbs of a symmetric fold of given interlimb angle. Stippled field is where cbi plunge separation is less than the transection angle.

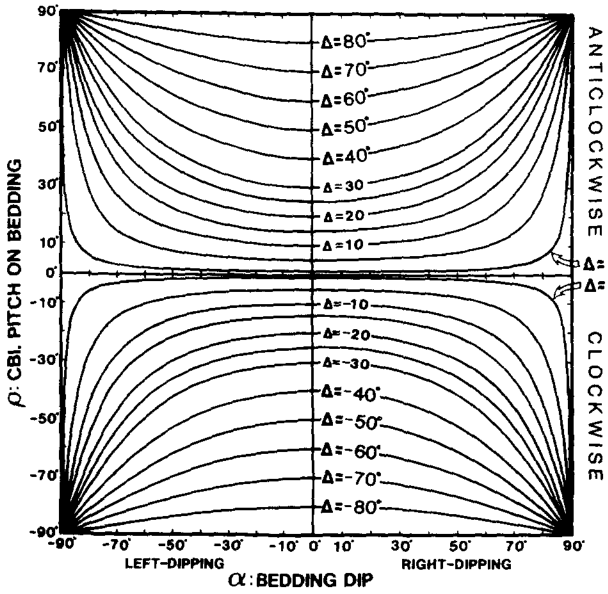

Fig. 5. Plot of bedding dip against the pitch of cbi on bedding for various axial transection angles Δ, for an upright horizontal fold.

The sensitivity of the cbi plunge separation to transection is strongly dependent on fold tightness, with tight folds showing a large separation even at low values of Δ (Fig. 4). Most observed cleavage-transected folds have Δ values of less than 20° (e.g. Borradaile 1978, Gray 1981, Soper *et al.* 1987, Woodcock *et al.* 1988), the range in which the sensitivity of plunge separation to tightness is most pronounced. In practice then, axial transection is most easily detected in tighter folds.

The geometrical relationships in Fig. 4 can be applied to asymmetric folds in which profile transection is, or is assumed to be, zero. In a reference frame with the fold axis horizontal and axial plane vertical, the plunge separation will be the sum of two unequal cbi plunges on the two unequally dipping limbs. The greater sensitivity of cbi plunge on the steep limb in this reference frame means, in practice, that axial transection will be most easily detected from the cbi on the limb closest in attitude to the axial plane. Tighter folds are again the more sensitive indicators of transection.

The plot of bed dip vs cbi plunge produces a restricted graph-fill (Fig. 4) because cbi plunges cannot exceed bed-dip values. A convenient alternative is to plot the pitch of cbi on bedding against bed dip for various Δ (Fig. 5). The cbi pitch is best measured directly in the field, because of the potentially large error in converting plunge readings to pitch, especially on low dipping bedding (Woodcock 1976). Alternatively the measured plunge can be plotted directly onto a graph which converts cbi plunge ψ to pitch ρ if bedding α is known. The graph (Fig. 6) is based on the relationship:

$$\sin \rho = \sin \psi / \sin \alpha. \qquad (2)$$

A practical example

The pitch vs dip plot can be used to estimate the magnitude and sense of the axial transection angle Δ. An example using field data is illustrated in Fig. 7(a). The example is of folds at outcrop scale in order that axial planes could be directly observed and the method verified.

The raw data are paired measurements of bedding and cbi attitudes. Also required are estimates of the fold axis, either from local fold hinges or from the π-pole to dispersed bedding, and the axial plane. All bedding and cbi data are then rotated stereographically so that the fold axis is horizontal and the axial plane vertical. The dip of bedding and the pitch of the cbi within it are then abstracted and plotted on the pitch vs dip plot.

If the folds are not transected, the data will group about the zero pitch line. In the example (Fig. 7a) the data clearly fall mainly in the clockwise-transected half of the plot. Most points fall in the range of Δ from −10° to −25°, though there is considerable dispersion.

A common problem is that the attitude of the axial plane may not be accurately known. An alternative reference surface is the limb-bisector plane (Johnson 1991) which can be derived stereographically knowing bedding attitudes at the fold inflexion points or on planar fold limbs. This plane has no genetic significance in a fold, but provides a consistent datum to allow comparison of transection angles between folds. An uncertainty in axial plane attitude affects the assumption that profile transection is zero. This is just one component of a range of complications in profile plane geometries including cleavage refraction and fanning.

GEOMETRY INVOLVING FANNING AND REFRACTING CLEAVAGES

Theoretical relationships

The two-dimensional fanning concept (Ramsay 1967, p. 405) can be extended into the third dimension by considering transective cleavage geometries (Johnson 1991). Four main geometric types are based on the

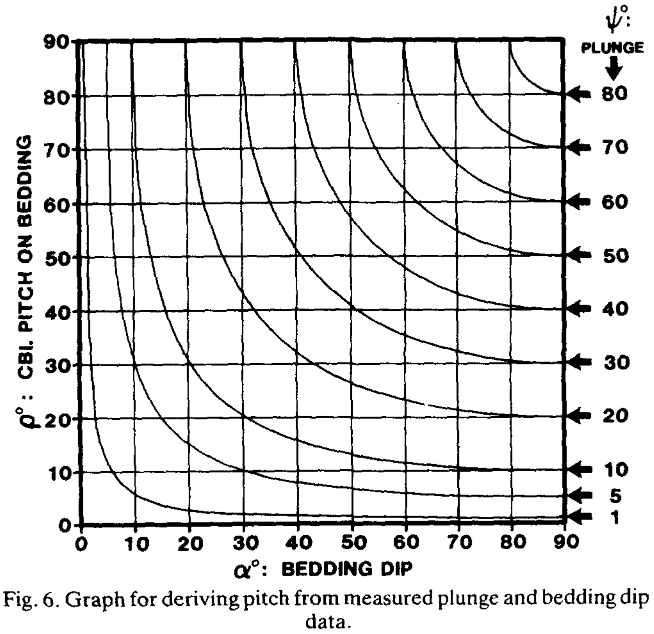

Fig. 6. Graph for deriving pitch from measured plunge and bedding dip data.

senses of profile transection (equivalent to convergent- or divergent-fanning) and of axial transection. Generally, cleaved multilayer folds have fanning and refracting foliations. Senses (and therefore signs) of both types of transection may change across fold axial surfaces.

Fanning and cbi attitude

A block diagram of bedding–cleavage relations in a transected fold (Fig. 8) shows that varying profile transection produces varying cbi attitude. Cleavage planes in this diagram all have equal *t*, the axial transection measured in the 'hinge-tangential plane' perpendicular to the axial plane. Some cleavages (d and e) fan convergently, that is adjacent cleavage planes converge when traced towards the fold core. Other cleavages (f and c) are divergent or (a and b) do not fan. A divergent-fanning cleavage (cleavage f) will have higher cbi plunge and pitch than a non-profile-transective cleavage (a). Conversely convergent-fanning cleavages (b and d) will have relatively lower cbi plunges and pitches.

This geometry leads to practical strategies for detecting small amounts of axial transection. The cbi is a more sensitive indicator of axial transection in a fold with a divergent cleavage fan than it is in a fold with a convergent fan. Similarly, axial transection is best detected in beds with refraction of cleavage into a more divergent geometry. In a fold with pervasive profile transection ("transected fold core" of Powell 1974), beds which most nearly parallel the cleavage will show the most sensitive cbi variation. By this careful selection of sites for cbi observation the presence and sense of even very weak transection can be detected. This method takes no account of the theoretical variations in Δ with cleavage fanning or refraction.

A quantitative adjustment for the effect of fanning can be made on the plot of bed dip vs cbi pitch (Fig. 5). Each point is shifted parallel to the dip axis by *d*, the amount of profile transection. The sense of shift depends on

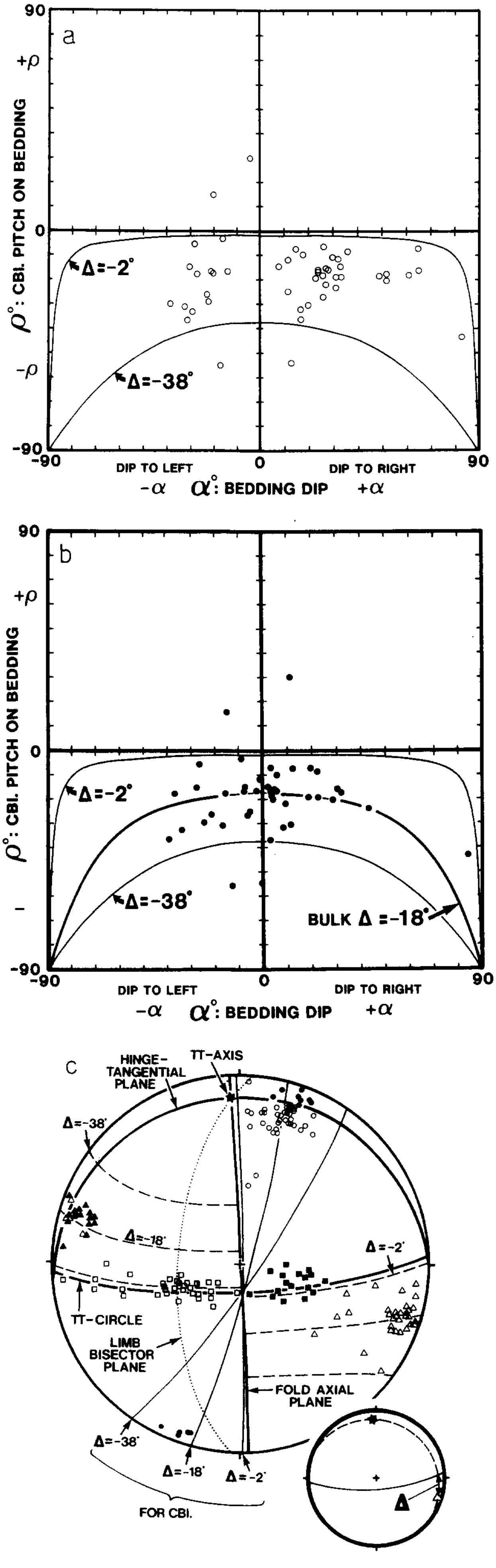

Fig. 7. Bed dip vs cbi pitch plots for six open asymmetric upward-facing anticline–syncline pairs with wavelengths up to 3 m in Wenlock siltstone at the 'Boot and Slipper' quarry, near Llanbister, Mid Wales (SO 132717). In (a) field measurements have been rotated so that fold axes are horizontal and axial planes vertical. In (b) points have also been shifted parallel to the dip axis to compensate for fanning (mainly convergent) of the cleavage. See text for explanation. (c) Equal-area projection of unrotated data from the 'Boot and Slipper' locality. Squares are bedding poles, triangles are cleavage poles and circles represent cleavage–bedding intersections. Filled symbols represent readings from the W-dipping limbs of folds, those half-filled come from the fold hinge zones and unfilled symbols are from the E-dipping limbs. The limb-separated cbi plunge mainly on different sides of the hinge-tangential plane and are clockwise oblique to the axial- and limb-bisector planes. Lines (solid great circles) of equal axial transection angle for non-fanning variously plunging cbi are shown. Cleavage poles lie mainly off the π-circle in a clockwise sense indicating clockwise axial transection of the folds. The limb-separated data show that the cleavage fans convergently. Lines (dashed small circles) of equal axial transection for cleavage poles show that the mean transection angle (Δ) is −18°. The inset equal-area projection shows the measurement of Δ between the mean cleavage pole and π-circle in the plane containing the π-axis and mean cleavage pole.

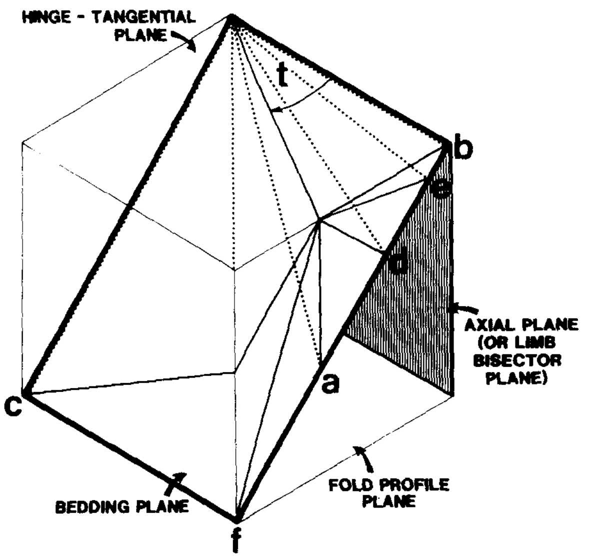

Fig. 8. Various cleavage planes (a–e) intersecting a bedding plane in an upright horizontal upward-facing fold. The bedding plane strikes parallel to the fold axis. Cleavages shown all have equal clockwise hinge-tangential plane transection, t, but variable profile transection d and axial transection Δ. Excepting cleavage b, all cleavages shown face upwards. Profile transection $d = 0°$ for cleavage a and 90° for cleavage b. Cleavage c has a trace parallel to bedding in the fold profile plane and an intersection down dip on the bedding (pitch = 90°).

whether the cleavage fans divergently (overestimating Δ) or convergently (underestimating Δ).

A practical example

The data plotted on Fig. 7(a) are adjusted in Fig. 7(b) according to the method above. The fanning in this example is almost entirely convergent, resulting in an underestimate of Δ, so that points shift mainly towards the centre of the plot, effectively reducing the dip to the value appropriate to a cleavage with zero profile transection. A best-fit Δ line can now be estimated more reliably. Alternatively, a bulk Δ value may be derived from stereographic construction after confirmation that poles to bedding define a non-random girdle and poles to cleavage a non-random cluster at the 99% level of confidence. This method is further explained by Johnson (1991) and shown stereographically on Fig. 7(c). The bulk Δ value (−18°) derived from stereographic analysis is plotted as a line on Fig. 7(b). The dispersion of the data points on Figs. 7(a) & (b) is partly due to the relatively large change in cbi pitch caused by slight deviations in bedding from the cylindrical model. This is to be expected when more than one fold pair has been sampled.

Facing constraints

Cleavages which are apparently upward-facing in the profile plane and truly upward-facing in three dimensions give rise to cbi which is offset from the fold axis in a direction sympathetic with the sense of axial transection (Fig. 8; cleavages a, d, e, f). This includes all non-fanning–refracting axially-transective cleavages (e.g. Fig. 8; cleavage a). However, refracting or fanning cleavages which are apparently downward-facing in the profile plane have cbi offset from the fold axis in a direction antipathetic to the sense of fold axial transection. The limiting case of neutral-facing is shown by cleavage c (Fig. 8). The techniques discussed in this paper are not valid for folds which show opposite apparent cleavage-facing directions on opposite limbs in the profile plane. This is an important limitation in theory. In practice, however, anomalous facing only arises with higher values of transection than are common in folds and cleavage formed in the same deformational event. Anomalous facing relationships are more common where cleavage is superimposed on folds formed during an earlier event.

Non-cylindrical folds

Axially-transected cylindroidal folds (Roberts 1982) may be detected by the same techniques described for cylindrical folds but detection limits will necessarily be raised because of the increased variability of bedding and therefore cbi. Indeed some of the scatter of data in Fig. 7 may be due, in part, to non-cylindricity. However, non-cylindroidal folds are not likely because all bedding poles lie on a girdle with a 99% level of confidence. The technique cannot be directly applied to non-cylindroidal or conical folds.

CONCLUSIONS

(1) The presence of axial transection of a cylindroidal fold by cleavage can be detected by the change in attitude of cbi across the fold hinge.

(2) The sense of axial transection can be deduced from the sense of angular offset of the cbi relative to the fold hinge, provided that the apparent facing directions of cleavage on the profile plane are consistent throughout the fold.

(3) The attitude of cbi is particularly sensitive to small amounts of axial fold transection: (a) in tight folds; (b) on fold limbs sub-parallel to the cleavage; (c) in divergent cleavage fans; and (d) in beds with cleavage refracted to a more divergent geometry.

(4) The sensitivity of cbi attitude to small variations in axial transection angle is most pronounced in the range of the majority of naturally occurring axially-transected folds.

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