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Interpretation of refolding and asymmetric folds using vergence concepts in drillcore

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Abstract—Current vergence concepts are difficult to apply in the intepretation of folds and foliation in drillcore when only the orientation of the drill hole is known (axially oriented core). This problem can be overcome by defining polar vergence, a parameter similar to vergence, but perpendicular to the axial plane, specified in terms of plunge, azimuth and sense in outcrop; or in the case of drill core, in terms of angles to the long core axis, and sense.

Rotation of drillcore about its long axis can, like refolding, cause polar vergence changes. This occurs when (1) the cleavage or axial surface of the minor folds is at a smaller angle to the long core axis than the angle of fan and (2) the pole to the fold axis within the axial plane (d_1) is at a larger angle to the long core axis than the plunge of the drill hole. These conditions (1 and 2) may be tested either by rotating the core by hand or stereographically. When cleavage–bedding relationships are used, a third case of polar vergence change by rotation of core occurs when the bedding is at a greater angle to the long axis of the core than the plunge of the drill hole. For asymmetic folds, if neither conditions 1 and 2 hold, and for cleavage polar vergence, if none of the three conditions holds, then polar vergence may be used unambiguously to locate fold closures in drill core.

INTRODUCTION

VERGENCE, as originally defined in German by Stille (1924) described the sense of overturning of folds. However, in the English literature vergence has evolved into a term used to describe the asymmetry of folds and cleavage relationships (e.g. Means 1966, Roberts 1974, Bell 1981, Weijermars 1982a). Roberts (1974) and Bell (1981) define the vergence of asymmetric folds as "... the horizontal direction, within the plane of the fold profile, towards which the upper component of rotation is directed". A similar definition has been suggested by Weijermars (1982a) for cleavage vergence: "... the horizontal direction, within the plane normal to the fabric intersection lineation, towards which the younger fabric needs to be rotated through the upper acute angle, so that it becomes parallel to the older fabric". These are particularly useful definitions when mapping surface outcrops. However, when dealing with subsurface data, usually derived from axially oriented core (core in which the plunge and azimuth of the hole are known, but the orientation of the core within the hole is unknown), in such core vergence direction cannot be defined as there is no azimuthal information available.

Bell (1981), in his evaluation of vergence, demonstrated the weakness in the definition of vergence on the basis of 'S'- and 'Z'-shaped folds (Fig. 1). However, he did not emphasise the problems encountered if one tried to apply the system to drillcore. The basis of the ambiguity lies in the fact that an 'S' fold, if rotated through 180° around an axis perpendicular to the fold plunge within the axial plane, becomes a 'Z' fold.

To treat the geometrical ambiguities which arise in axially oriented core, it is useful to define a new parameter, polar vergence. This is almost the same as vergence, but has the important distinction that it is a directional parameter in three dimensions, parallel to the pole to the axial surface of the fold. In other words, the polar vergence of a fold pair is defined as the direction, perpendicular to the axial plane, towards which the upper component of rotation is directed. By corollary, the polar vergence of a cleavage on an earlier foliation is the direction, perpendicular to the axial-plane cleavage, towards which that cleavage needs to be rotated through the upper acute angle, so that it coincides with the earlier foliation. As polar vergence is a directional parameter it should be defined at outcrop in terms of plunge, azimuth and sense, in the same manner as facing direction.

During recovery, diamond drillcore becomes rotated and broken. Thus, if drillcore, drilled perpendicular to a fold axis is recovered, the sense of polar vergence may be

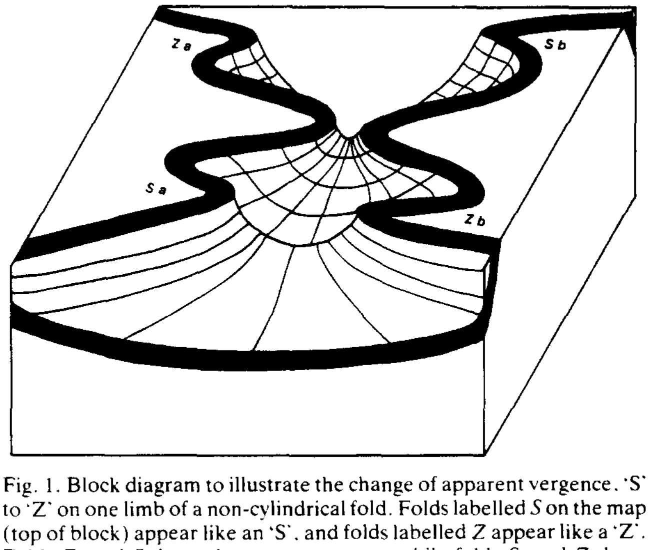

Fig. 1. Block diagram to illustrate the change of apparent vergence, 'S' to 'Z' on one limb of a non-cylindrical fold. Folds labelled *S* on the map (top of block) appear like an 'S', and folds labelled *Z* appear like a 'Z'. Folds Z_a and S_b have the same vergence, while folds S_a and Z_b have opposite vergence from Z_b and S_b.

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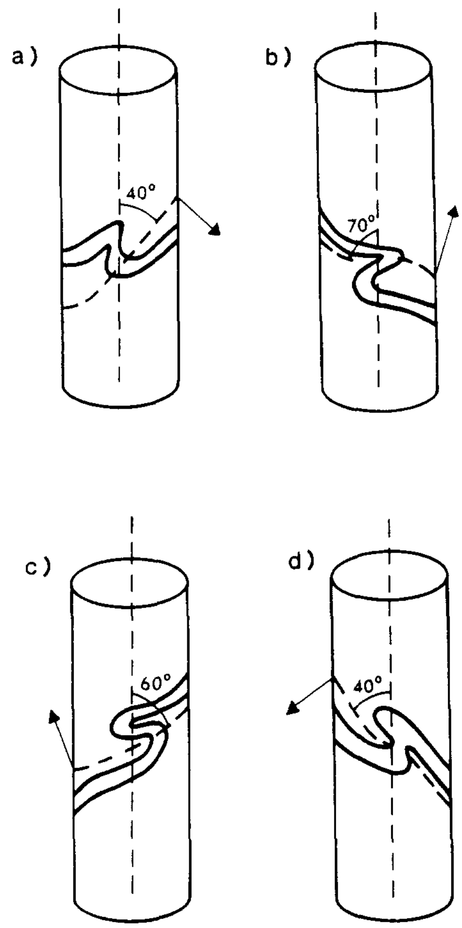

Fig. 2. Sketch diagram of drill core showing: (a) 'Z' fold polar vergence down at 40°; (b) 'Z' fold polar vergence up at 70°; (c) 'S' fold polar vergence up at 60° and (d) 'S' fold polar vergence down at 40°. The fold axis is perpendicular to the long axis of the core. If the core in (a) is rotated through 180° about its long axis it would appear as in (d). Arrows indicate polar vergence direction.

deduced only by using the upper component of rotation of the fold pair which, in core problems, should be given in terms of an angular relationship with the core axis, allied with sense (that is either up or down the core). Figures 2(a) and (d) are identical except rotated through 180° relative to each other around the long-core axis.

In the past, there have been attempts to overcome this problem. Two methods exist which partially overcome the difficulty. First, if some known feature can be oriented, then there is no ambiguity and vergence may be used as in outcrop. A second, more general approach has been described by Laing (1977) who effectively used vergence as the component of rotation up or down the drill hole rather than the horizonal component, but his analysis depends on either knowing some surface information, a three-hole technique described below, or else it is limited to curving holes penetrating subhorizontal folds which trend perpendicular to the drill hole dip direction. His technique is also limited to cases where the core axis is at a high angle to the fold axis.

This paper approaches the problem of fold asymmetry and axially oriented drill core, using the three-dimensional parameter, polar vergence. The technique is completely general and may be employed even in the absence of any surface information and where the core is oblique to the fold axes. To define fully the orientation of folds in a region where there is an absence of surface information, one needs to locate the same fold closure in at least three holes.

First, the case of the geometry of refolded polar vergence boundaries in outcrop is examined in a manner similar to the vergence-boundary techniques of Means (1966) and Weijermars (1982b). The geometrical cases in which polar vergence boundaries occur are established. Then, using the geometrical similarity of cones of distribution of linear features by both flexural-slip folding and folds in axially oriented core, the concept of polar vergence boundaries is used to establish where major fold closures may be located by the asymmetries of minor fold pairs in drillcore. Unfortunately, polar vergence has a geometrical ambiguity in outcrop, in both vertically plunging and recumbent terrains, and an analogous ambiguity occurs in drill core where the axial surface is parallel to the drill hole. The geometrical properties of vergence and polar vergence are summarized in Table 1.

INTERPRETATION OF POLAR VERGENCE AND VERGENCE IN REFOLDED TERRAINS

Weijermars (1982b) suggested the terms atypical and typical vergence boundaries (AVB and TVB) for axial traces across which minor folds and cleavages that are older and coeval, respectively, change vergence (Figs. 3a & b). A major fold hinge across which later minor structures change vergence is referred to here as a nontypical vergence boundary (NVB, Fig. 3c). Typical, atypical and nontypical polar vergence boundaries (TPBs, APBs and NPBs) exist which have the same age relationships to major structures as the vergence boundaries of Weijermars (1982b). However, in contrast to the AVBs of Weijermars (1982b), atypical polar vergence boundaries (APBs) are defined here as occurring only where the polar vergence direction changes as in a TPB. Figure 3(d) illustrates a refold which is not isoclinal resulting in an AVB, but not an APB (i.e. the vergence has changed but the polar vergence has not changed through 180°, as in a TPB.

Rotation of drillcore is geometrically analogous to flexural-slip folding (i.e. linear element distributions form double cones), and hence pseudo-polar vergence boundaries (PPBs) similar to APBs can occur in core. Because typical boundaries are just axial surfaces they are referred to as such below, while nontypical boundaries, because they are not relevant to drillcore problems, are not discussed further.

ANALYSIS OF ATYPICAL POLAR VERGENCE BOUNDARIES

Thiessen & Means' (1980) lucid review provides an excellent basis for the description of refolding and hence

Table 1. Summary of the advantages and disadvantages of polar vergence and vergence

	In outcrop or fully oriented core Use: To locate axial traces Outcrop	In axially oriented core Use: To locate axial traces Drill core
Vergence	*Ambiguities:* In vertically plunging folds it is necessary to use sinistral or dextral vergence. *Advantages:* Can be used in all situations with any fold pairs of any orientation.	*Ambiguities:* Useless in all situations unless the core is fully oriented. *Advantages:* If the core is fully oriented, it is extremely useful in constructing sub-surface plans.
Polar vergence	*Ambiguities:* In vertically plunging folds it is necessary to use sinistral or dextral polar vergence. In areas of recumbent folding, polarity is ambiguous. In a region where the vergence is, for example, due east, the polarity might be expressed as plunging 30° toward 270°, up. This can lead to confusion in areas of upward-polarity vectors. *Advantages:* Is useful in kinematics and poles to great-circle girdles to give fold plunges of later-phase folds.	*Advantages:* Can be used provided the drill hole orientation is known and if: (1) the angle between the axial surface of the fold pair and the core axis, plus the angle of fan of parasitic folds (or axial-plane cleavage) is less than the plunge of the drill hole; (2) the folds cannot be rotated through a reclined position and (3) the angle between the core axis and the axial surface is greater than the angle of fan of the parasitic structures about the major structure.

their labelling scheme is adopted: f_1 is the F_1 fold axis; d_1 is perpendicular to f_1 in the axial surface, S_1, and c_1 is the pole to S_1 (Fig. 4). In the simplest instance, for an initially upright F_1 fold, refolding about a horizontal F_2 (parallel to c_1), causes the fold axis to pass through the vertical and an APB results. This is illustrated in Figs. 5(a) and (b). In Fig. 5(a), an initially upright F_1 is refolded but it never becomes reclined, whereas in Fig. 5(b), an initially upright F_1 has been refolded and locally (at the APB) is reclined.

The geometrical reasons behind the statements outlined in Table 1 may be better understood if refolding is considered as a series of rotations about f_1, c_1 and d_1 axes (Figs. 6 and 7). This is one of the fundamental concepts in the following discussion: that is, any rotation about a fold axis may be resolved into a series of rotations about three orthogonal axes (f_1, d_1 and c_1). They are geometrical transformations and the presence or absence of flattening has no effect on the results.

Any arbitrary fold pair when folded may change its plunge direction: (a) through a steep plunge, and (b) through the horizontal, by rotation about d_1 (Figs. 6 and 7a) and/or c_1 (Fig. 7b). Likewise, its shape or asymmetry may change by rotation about its d_1 or c_1 axes. No vergence change results from rotation about f_1 (Fig. 7c). The four geometrical possibilities which may result from any arbitrary refolding event (shown as A, B, C, D in Fig. 8) may be rationalized in terms of this analysis. Only the component of rotation of the fold plunge about c_1 that pitches down dip in S_2, where S_2 is the axial surface of the second fold (case B, Fig. 8) or parallels d_1 (case C, Fig. 8), results in APBs. Cases A and D (Fig. 8), respectively represent examples where the component of rotation about c_1 results in f_1 change through the horizontal (Fig. 7b), and where F_1 remains constant in S_2 (i.e. coaxial refolding, Fig. 8c). The component of rotation about F_1 does not result in an APB (or AVB) and the component of rotation about c_1 only results in an APB (or AVB) if the fold pitches at 90° in S_1: that is, if it becomes reclined.

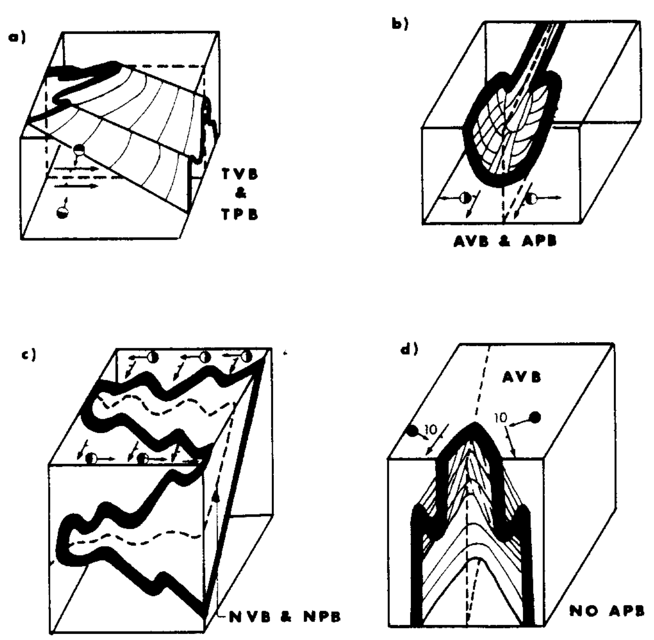

Fig. 3. Examples of polar vergence boundaries. (a) Typical vergence and polar vergence boundary (TVB & TPB). (b) Atypical vergence and polar vergence boundary (AVB & APB). (c) Non-typical vergence and polar vergence boundary (NVB & NPB). (d) An AVB (as defined by Weijermars 1982b) without an APB because there is not a 180° reversal of polar vergence. Solid arrowheads indicate fold plunge and ticks indicate vergence direction (horizontal component of polar vergence). Solid disc is downward polar vergence, open disc is upward polar vergence and half-shaded disc is horizontal polar vergence, arrowhead indicating direction.

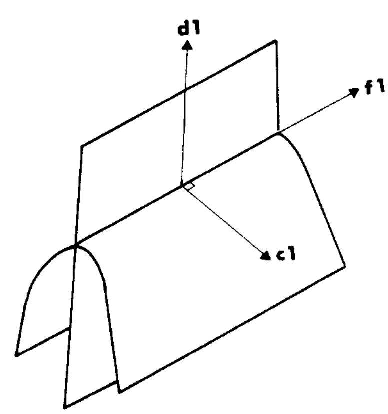

Fig. 4. Sketch of an F_1 fold to illustrate the location of the f_1, c_1, and d_1 axes.

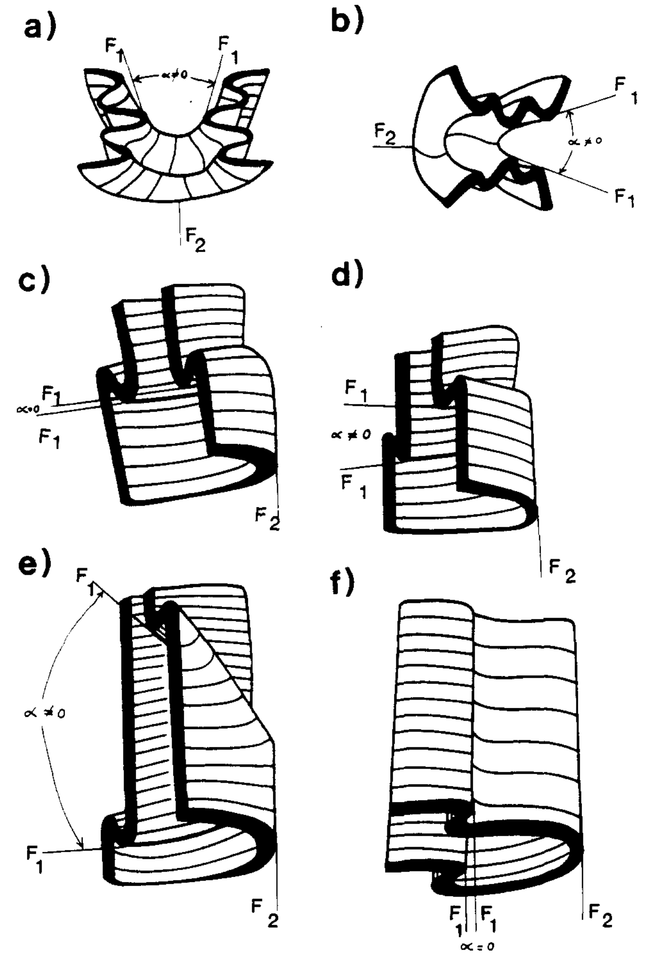

Fig. 5. Sketches of refolds of F_1 folds. (a) and (b) illustrate the point that the same interference pattern does (b) or does not (a), produce an APB, depending on whether the F_1 fold projection into ther S_2 plane pitches vertically as in (b). Therefore, polar vergence boundaries are not independent of the orientation with respect to the horizontal plane. (c)–(f) illustrate that unless F_1 is coaxial with F_2, recumbent F_1 isoclines passing through the reclined position produce atypical polar vergence boundaries (APB). For additional details see the text.

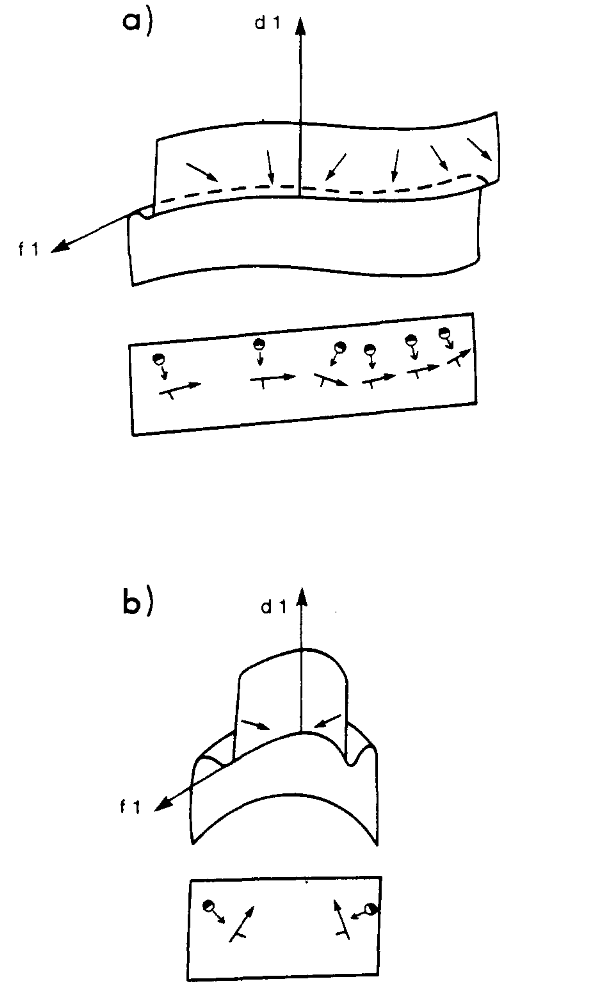

Fig. 6. Illustrations to show the effect of refolding about the d_1 axis. Although the azimuthal component of polar vergence varies even with gentle folding, with tight folding the polar vergence still fans the wrong way to create a polar vergence change that could be confused with a typical vergence boundary. Symbols as in Fig. 3. The planes below the folds are map views.

Figure 9(a), for example, which can be resolved into rotation around c_1 through the reclined position, plus a 180° rotation about d_1, results in no APB. Figure 9(b), which is geometrically the same as Fig. 9(a), but with F_2 vertical, can be resolved into a 180° rotation about d_1, plus rotation about c_1 through the normal fold position, resulting in an APB. The order of rotations does not matter.

In summary, refolding can be considered to be the product of some combinations of rotations about f_1, c_1 and d_1. If rotation about c_1 results in F_1 passing through the reclined position (which is the same as d_1 passing through the horizontal, e.g. Fig. 5a), or rotation about d_1 through 180° occurs, an APB results (Fig. 9b). If both occur, no APB results (Fig. 9a). With isoclinal F_2 folding, these conditions reduce to the case where the F_1 fold axes may be projected into S_2 to pitch at 90°, or form a pole to S_2.

This leads us to a general geometrical statement for isoclinally refolded folds: APBs occur if the projection of F_1 into S_2 pitches at 90° in S_2 or F_1 forms a pole to S_2 (Fig. 9b). This statement covers all geometrical possibilities: rotations about f_1, c_1 or d_1, and combinations of rotations around them.

The discussion above applies equally to vergence boundaries. The AVB, however, because it is the product of just azimuthal changes of vergence, can result from tight or close folding (e.g. Figs. 5c & d produce an AVB if F_2 is not isoclinal). Therefore, if the pitch of an F_1 fold projected into an S_2 surface passes through 90°, an AVB results.

Figures 5(c–e) are non-coaxial, refolded folds whereas Fig. 5(f) illustrates a coaxial refolded isocline. The first three cases produce AVBs and APBs while the last one does not. Figure 5(a) illustrates a more open F_2 refold which produces no APBs whereas the tight F_2 folds shown in Fig. 5(b) result in APBs. Furthermore, Figs. 5(a) and (b) are identical apart from their orientation with respect to the horizontal. Thus, isoclinal refolding is not an essential prerequisite for the formation of an APB: only for the formation of APBs by rotation about d_1 (e.g. Fig. 9b).

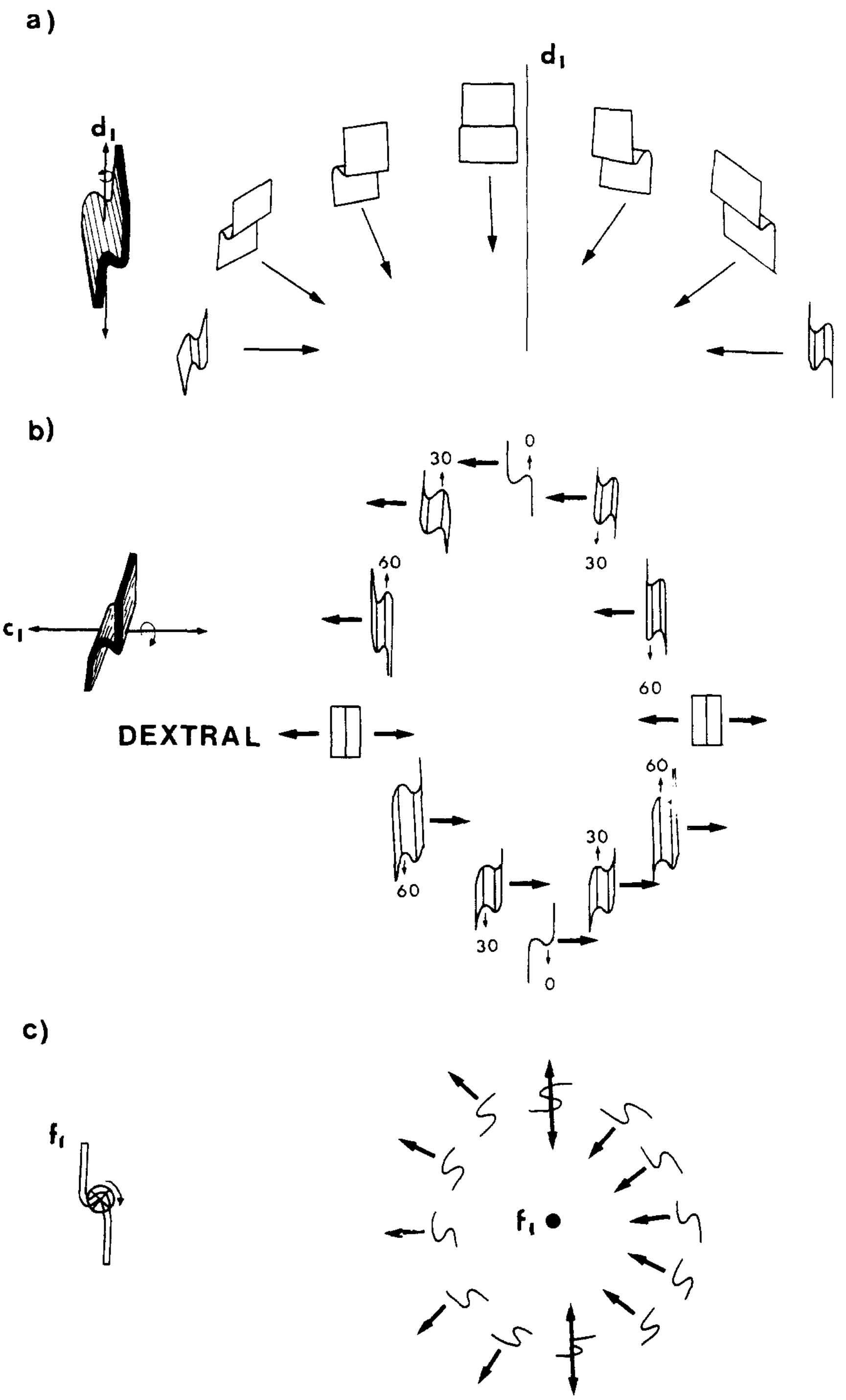

Fig. 7. Sketches to show the effects of components of rotation about the perpendicular to the fold axis in the axial plane, d_1, the pole to the axial surface, c_1, and the fold axis itself, F_1. (a) shows the effect of the component of rotation about the d_1 axis. Isoclinal folding involving rotation around d_1 through 180° therefore produces atypical polar vergence boundaries. (b) illustrates the changes of vergence resultant from the component of rotation about the c_1 axis. Sketches represent vertical projections of a folded surface. Note that when the plunge passes through the reclined position polar vergence changes through 180°. (c) illustrates that the component of rotation about the f_1 axis produces no change in the azimuthal sense of vergence.

IMPLICATIONS OF VERGENCE BOUNDARIES FOR STRUCTURAL ANALYSIS

In the previous section it was shown that if the horizontal projection of F_1 into S_2 pitches at 90° or projects as a point in isoclinal refolds, then an APB results. In this section the analysis of these conditions, using stereographic analysis is discussed.

For the horizontal projection of F_1 to pitch at 90° in S_2, F_1 must lie in the plane which contains the pole to S_2 and the dip direction of S_2 (see Figs. 10a & b). There may be cases where there is no APB (Fig. 10a) or APBs may occur (Fig. 10b). Note that F_1 becomes reclined (d_1 passes through the horizontal), but that it does not change its plunge direction, and thus there is no APB (Fig. 10a). The case where F_1 plots perpendicular to S_2

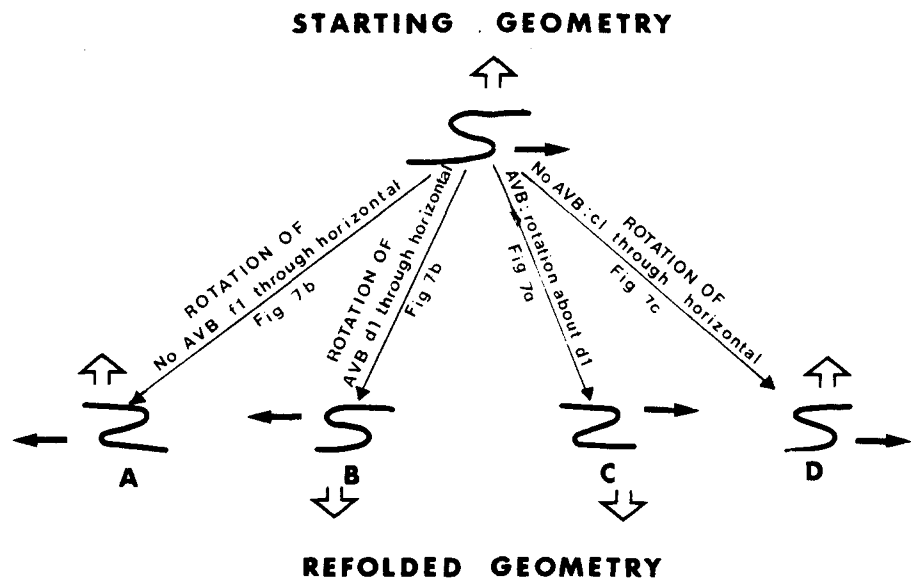

Fig. 8. 'Map' to show all the four possible polar vergence combinations starting from a single starting asymmetry during refolding. Rotation of d_1, the perpendicular to the fold axis in the axial plane, through the horizontal results in a 180° polar vergence reversal (i.e. the fold becoming reclined), (case B) while rotation about d_1 through 180° results in an APB. Open arrows indicate polar vergence and solid arrows show fold plunge.

(Fig. 10c) is a special limiting case, equivalent to that shown in Fig. 7(a), where F_2 is parallel to d_1. Figure 10(d) illustrates another case where no APB results, and here F_1 does not become reclined.

In summary, we can expect APBs to result from refolding if the following conditions are fulfilled. (1) If F_2 is parallel to d_1, that is F_2^1 is perpendicular to F_1 in S_1 and refolding is isoclinal, where F_2^1 is the second-phase fold defined by folded S_1. (2) If the F_1 fold plunges lie in the plane which contains the S_2 dip direction and the pole to S_2, provided that S_1 is folded: that is, F_2^1 is not parallel to the pole to S_1 (cf. Fig. 5a). (In the case where S_2 is horizontal we assume that the S_2 'dip direction' is perpendicular to F_1).

These geometries should all become apparent early in a structural analysis and hence provide the field geologist with a useful guide within which to constrain his interpretations. Stereoplots showing S_1, S_2 and the distribution of F_1 and L_1^0 can suggest and, in many cases, prove whether APBs are present.

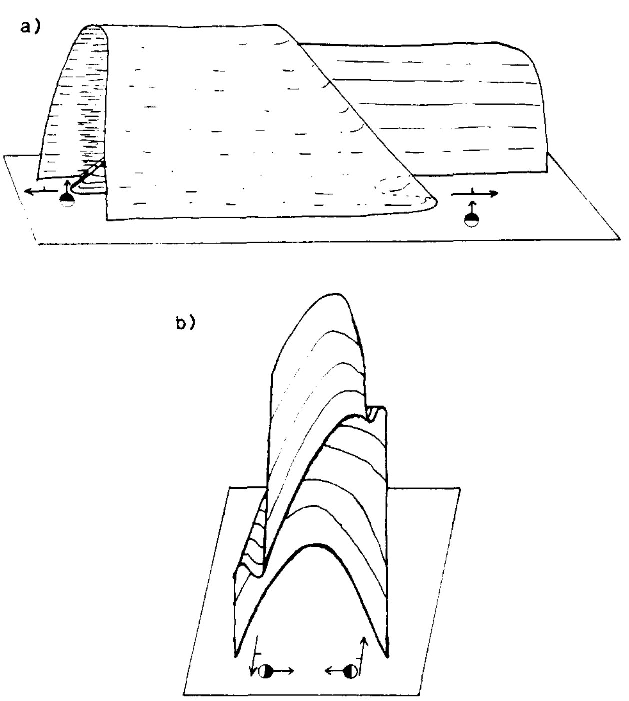

Fig. 9. (a) Two potential APB-producing rotations cancel each other's polar vergence reversal. The rotation from one limb to the other may be resolved into rotation about c_1 through the reclined position plus a 180° rotation about d_1. This creates two polar vergence reversals which cancel each other out. (b) The same geometry as illustrated in (a), but an APB results as there is a 180° rotation about d_1. The fold does not become reclined.

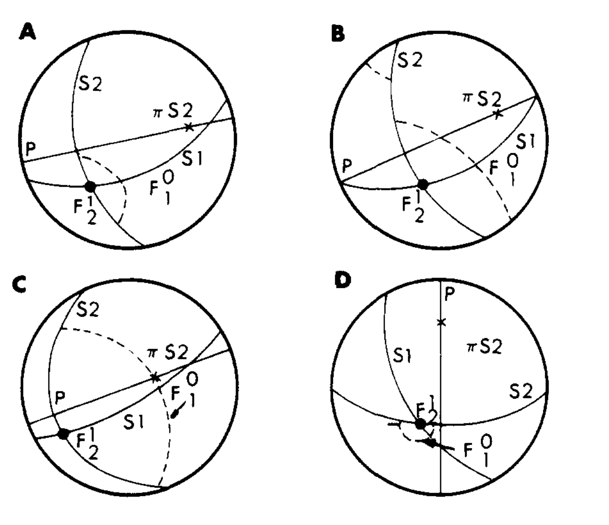

Fig. 10. Stereoplots to test for atypical polar vergence boundaries. (a) No AVB, the scatter of F_1 plunges does not project vertically into S_2. (b) An AVB occurs: the F_1^0 scatter intersects the pole to the plane containing S_2 and the S_2 dip direction. (c) Special case of an AVB: F_1 is locally perpendicular to S_2. (d) No AVB. If the F_1 girdle intersects the vertical plane (P) which encompasses the dip direction of S_2 and the pole to S_2, then F_1 will project into S_2 at a pitch of 90° or project as a point.

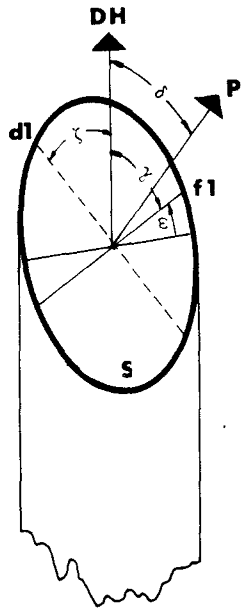

Fig. 11. Illustration of a foliation-intersection ellipse in core with the various parameters of Laing (1977). δ, angle between the long core-axis, DH, and the pole to the surface, P; γ, angle between the DH and the fold axis or intersection lineation; ϵ, angle measured anticlockwise looking down from the short axis, between the lineation and the short axis of the ellipse of intersection between the core surface and the axial surface. A further angle, ζ is the angle between the d_1 axis and DH. When this angle is less than β, the plunge of the drill hole, and the foliation is oblique to the core long and short axes, polar vergence may be used to locate macroscopic hinges. See text for discussion.

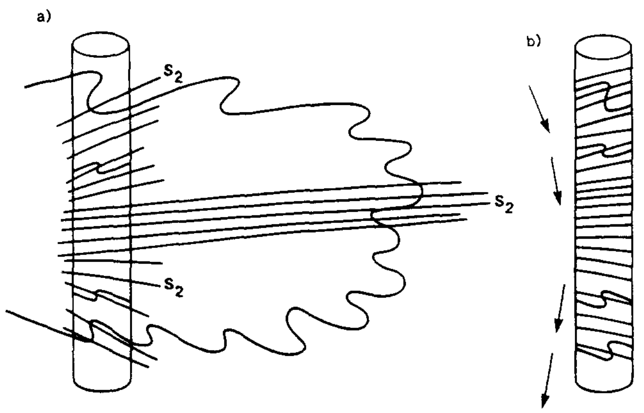

Fig. 12. Effect of drilling through a fanning fold at a high angle to the axial surface, with transposition in the hinge. Polar vergence indicated by arrows. (a) Fold in relation to the core. (b) The core. If the core is broken and the sections become rotated through 180° relative to each other, there is a constant polar vergence down-hole.

In flexural-flow folding, the angle between F_2^1 and F_1^0 remains constant. Therefore, if the $F_2^1 \wedge F_1^0$ angle plus the pitch of F_2^1 in S_2 is greater than 90°, then an APB results because the F_1^0 girdle intersects the plane which contains the pole to S_2 and the S_2 dip direction (Fig. 10b). In the more general case (i.e. where the poles of F_1^0 and L_1^0 do not form a small circle), so long as the $F_1^0 \wedge F_2^1$ angle in S_2 measured from the pitch of F_2, in the same angular sense, from the pitch of F_2^1 is greater than 90°, an APB results. Weijermars (1982b) includes AVBs where the F_1^0 and F_2 minor folds are non-congruent (e.g. his figs. 2e & f, and Fig. 6b, this paper), but these are not 180° changes of polar vergence and as they are not likely to cause confusion in field problems, they are not considered further here.

APPLICATION TO DRILLCORE

Application of polar vergence in drillcore

There are problems in applying the commonly accepted definitions of vergence to drill-hole data. Unless the core has been oriented using some downhole technique, when the techniques of Laing (1977), which depend on surface information, or deviating drillholes can be used; ambiguities remain.

When a fold axis (or an intersection lineation in a foliation), is measured it is necessary to measure the angle (δ) between the pole to the axial surface, the angle between the fold axis and the core, and the angle (ϵ) measured anticlockwise looking down from the short axis of the ellipse of intersection of the core surface and the axial surface. This is illustrated in Fig. 11. All the conventions are taken from Laing (1977) in the interests of conformity. To characterize fully an asymmetric fold pair one should record: (1) age of the structures, (2) interlimb angle measured in the profile plane, (3) angle between the axial surface or the pole of the axial surface and the long axis of core, (4) sense of polar vergence (up or down hole) and (5) pitch of fold plunge, or intersection lineation from the short axis of the ellipse of intersection on a surface. Where there is more than one foliation in the core, one must measure their relative dips as described in Laing (1977). It is important to look down the plunge when the fold is oblique to the core. Where the angle between the long core-axis and axial surface or foliation is large, polar vergence becomes unreliable as the core is discontinuous or broken (Fig. 12). Although a cursory inspection of Fig. 12(a) may suggest a polar vergence change, rotation of the lower half of the core through 180° disproves this (Fig. 12b). If the minor axial surfaces and the axial-surface cleavage fan around a closure, and no neutral parasitic folds are preserved in the hinge, then in non-oriented core, unless the angle between the pole to the cleavage and the core axis is greater than the angle of cleavage fan, vergence is unreliable. This angle of fan may be estimated by examining small-scale closures in unbroken sections of core and is normally less than 20°.

A further problem which can arise with the interpretation of core is that if the hole is not vertical, antiforms and synforms may become indistinguishable. This is because if the pole to the axial surface is close to parallel to the core axis an antiform may be rotated around its pole to appear as a synform.

Refolded folds and their geometrical similarity to axially oriented drillcore

Flexural-slip folding (Hobbs *et al.* 1976, pp. 183–200), which is equivalent to rotation about F_2^1, creates a

Table 2. Comparison of atypical polar vergence boundaries (APBs) with pseudo-polar vergence boundaries (PPBs)

APBs in areas of isoclinal refolding	PPBs in axially-oriented drillcore
Produced by rotation about F_2.	Produced by rotation about the long-core axis.
Occur where the F_1^0 girdle can be projected into S_2 to pitch at 90°, causing a 180° reversal of polarity.	Occur where the component of polarity parallel to the core reverses. This happens when the fold becomes reclined (i.e. d_1 intersects the horizontal).
Polar vergence is ambiguous in vertically plunging folded or recumbent terrains.	Polarity is ambiguous where the core is parallel to the fold axis and/or the axial plane.

conical distribution of linear elements resembling that of possible distributions of linear elements in axially oriented drillcore. Drill-hole problems in which the core is axially oriented are therefore directly analogous to refolding. Hence, in drillcore we may expect to find changes of polar vergence caused by rotation of the core around its long axis. The problem when dealing with drillcore is therefore, to discriminate between polar vergence changes caused by rotation of the core (these are APB analogues, referred to here as pseudo-polar vergence boundaries, PPBs) and those caused by fold hinges. In outcrop, there is an ambiguity in polar vergence in regions of recumbent folding. Likewise in drillcore, if the fold axial surface is parallel to the core axis, the polar vergence is ambiguous.

Pseudo-polar vergence boundaries in drillcore

In this section, the APB, caused by refolding, is compared and contrasted with the PPB, which is a boundary of apparent polar vergence reversal produced by rotation of drillcore (see Table 2). The drill hole is the axis of rotation, like F_2^1 (Fig. 10, cf. Fig. 12a) while the observed fold plunge at γ^0 to the drill hole (DH) is geometrically the same as the F_1^0 plunge distribution. However, because linear elements describe full double-cones in axially oriented core, unlike those being refolded, there is no axial surface. It is therefore necessary to resolve the rotations about the long core-axis into components about the f_1, d_1 and c_1 axes. In the simple situation of rotation about f_1 (coaxial refolding) one would normally not expect an APB (Fig. 7c). However, as the fold axis lies in the axial plane if the fold axis is at a low angle to the long core-axis, so is the axial plane. Because the plane which has the plunge of the core axis as dip direction is the frame of reference (i.e. a map analogue), this is geometrically analogous to recumbent folding in outcrop, and hence the polar vergence is ambiguous (Fig. 7c). If on rotation about d_1, the pole to the foliation passes through the plane to which the drill hole is pole, then the component of polar vergence should change along the core. However, the only way that the polar vergence (which is parallel to the pole to the foliation) can intersect that plane is where the core is parallel to the fold axial surface. Thus, the only problem remaining to be considered is that of the component of rotation about c_1 (Fig. 7b), of folds oblique to the core. If the core is rotated so that the fold passes through the reclined position, a PPB results. This may be tested visually by spinning axially oriented core by hand, or stereographically. The stereographic test is developed below.

Structural analysis of polar vergence in drillcore

As holes drilled perpendicular to the foliation are parallel to c_1 the folds may become reclined. Holes parallel to the foliation are also ambiguous. As it is a material line, d_1, like F_1, also describes a small-circle girdle. If d_1 intersects the horizontal, a PPB results and macroscopic fold hinges cannot be located in the core on the basis of polar vergence changes. A corollary of this result is that if d_1 is at a greater angle to the long core-axis than the plunge of the core a PPB results. Cases where c_1 is parallel to the long core-axis (Fig. 13c) and the drill hole parallel to the axial surface (Fig. 13d) are also apparent stereographically. Therefore, provided the fold axial surface is oblique to the core and its d_1 axis is at a smaller angle to the long core-axis than the plunge of the drill hole, polar vergence may be used unambiguously. Where the polar vergence of cleavage on a pre-existing foliation (bedding or an earlier cleavage) is

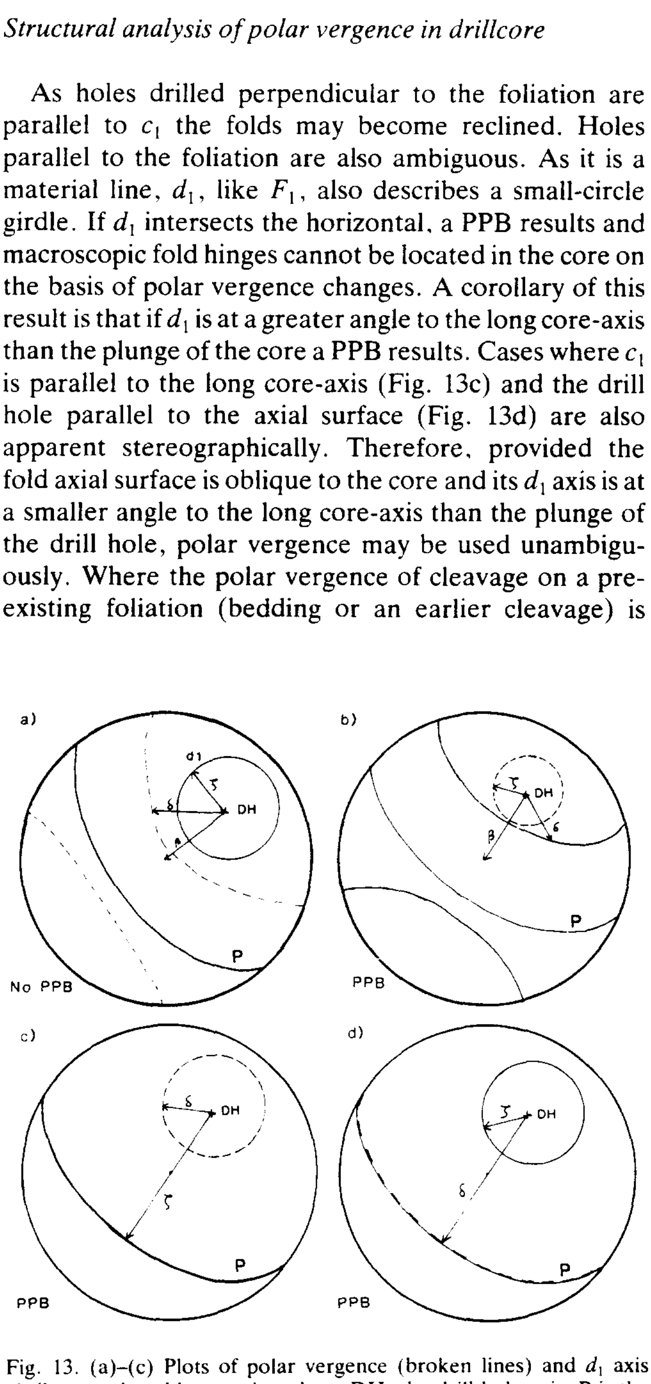

Fig. 13. (a)–(c) Plots of polar vergence (broken lines) and d_1 axis girdles, produced by rotation about DH, the drill-hole axis. P is the plane to which DH is pole. If the d_1 girdle intersects the horizontal plane a PPB results, i.e. if $\zeta > \beta$. (a) Example of no PPB; $\beta > \zeta$. (b) A PPB; $\zeta > \beta$. (c) Special case where c_1 is parallel to the long-core axis and d_1 forms a great-circle girdle so that a PPB results. (d) Alternative case of a PPB; the polar girdle intersects P.

used, in the absence of asymmetric folds, it is additionally necessary that the angle $90° - \delta$ (where δ is the angle between the pole to bedding and the long core-axis, Fig. 11), is less than β, the plunge of the drill hole.

DISCUSSION

In structural analysis it is usual to plot stereographs of poles to surfaces, fold plunges, and intersection and stretching lineations. Plots of poles to foliation are the same as plots of polar vergence, except that the latter, being directional, need to be plotted with a distinction between upward and downward polar vergence. Likewise, structural facing is a directional parameter parallel to the d_1 or a axis of the folds.

Polar vergence boundaries may be used in understanding minor structures in drill core. The method may be applied in the absence of any surface information except the orientation of the drill hole. It is independent of the interlimb angle of the folds as it depends on the axial plane and f_1/d_1 axes position, and not on polar girdles to pre-fold layering (cf. Laing 1977). The method does not require drill holes to deviate or drill holes of differing orientations. It does, however, assume congruence between major and minor structures, although allowance can be made for fanning of minor structures around the axial plane. In areas of transected folds or of parasitic folds plunging non-parallel to the major structures, complications arise. These are problems common to any structural analysis.

A worked example is illustrated in Fig. 14. Three holes, A, B, and C were drilled due south plunging 50, 50 and 40°, respectively to intersect a major anticlinal structure both oblique to the fold axis and axial plane in a region of no exposure. Polar vergence information recovered from cores from drill holes A and B indicated a closure at 38 m true depth in both holes. They revealed the strike of the axial plane was E–W, perpendicular to the drill hole azimuth. As the polar vergence was at 50° in both holes, it was immediately apparent that the axial plane dipped either vertically or gently south, with the fold axis plunging moderately to the east or gently southwest. Core from the third, more gently inclined hole, drilled in search of the proposed gently southwest plunging fold made an angle of 54° with the d_1 axis of the fold, and thus polar vergence could not be used. However, its smaller delta angle and neutral vergence at 26 m true depth indicated the axial surface was steeply dipping and the fold easterly plunging. Having deduced the orientation of the axial plane, lineation and fold axis (plunging 25° east), using polar vergence, this information was used to orient the core in hole C and hence the vergence confirmed the interpretation. Great care must be exercised in such interpretations however, because implicit in the interpretation presented above was the assumption that the major fold closure (typical polar vergence boundary) in each of the three drill holes is the same structure.

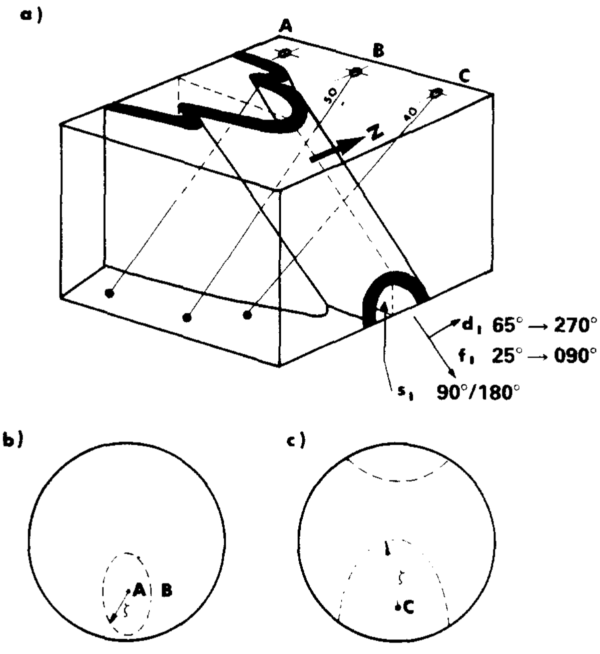

Fig. 14. (a) Block diagram of moderately plunging fold intersected by three drill holes. See Table 3 for sample measurements from holes. (b) Stereoplot of the possible distribution of d_1 about A and B, indicating no PPB, i.e. polar vergence may be used. (c) Possible distribution of d_1 about C; a PPB occurs and so vergence data cannot be used. See text for discussion.

In areas of multiple folding, where true APBs as well as PPBs may occur in the core, it is necessary, using superposition criteria, to identify the last phase of folding, and to identify closures of the last fold phase. Obviously, the technique must be used with care as non-planar folds, shear zones and faulting between drill holes can all lead to spurious results. Despite these shortcomings, the method has been applied successfully and is of enormous practical use.

CONCLUSIONS

(1) A new parameter of asymmetric fold pairs, polar vergence has been proposed. It is unambiguous unless the axial surfaces are horizontal and facing is unknown. Polar vergence should be recorded as an azimuth, plunge and sense, perpendicular to the axial surface. It possesses several advantages for interpreting subsurface information.

(2) Polar vergence boundaries may be divided into three categories: (a) atypical, reflecting hinges younger than the minor structures themselves, (b) typical, reflecting hinges the same age as the minor structures, and (c) nontypical, reflecting older structures than the minor structures defining them. Atypical polar vergence boundaries result from rotation of earlier folds, such that in isoclinal refolding the projection of the earlier axes in the later axial surface pitches vertically or is perpendicular to the later foliation, somewhere in the fold.

(3) There is a close geometrical analogy between refolded polar vergence and folds in axially oriented core.

Table 3. Sample measurements from drill holes

DH depth		Delta, δ, and polar vergence (Pole to axial surface and long core axis)		Gamma (γ) (Fold axis and long core axis)	Epsilon (ϵ) (Angle of fold axis from short axis of ellipse of intensification)	Epsilon-90° (Angle of d_1 axis from short axis of ellipse of intersection)
A	10	50	Down	70	155	25
	20	50	Down	70	155	25
	30	50	Up	70	155	25
	40	50	Down	70	155	25
	50	50	Neutral	70	155	25
	60	50	Up	70	155	25
	70	50	Up	70	155	25
	80	50	Down	70	155	25
	90	50	Up	70	155	25
	100	50	Up	70	155	25
The angle between d_1 and the long core axis, ζ (zeta) = 44°. 44° < β (beta), the plunge of the hole A = 50°, so polar vergence may be used unambiguously.						
B	10	50	Down	70	155	25
	20	50	Down	70	155	25
	30	50	Up	70	155	25
	40	50	Down	70	155	25
	50	50	Neutral	70	155	25
	60	50	Up	70	155	25
	70	50	Up	70	155	25
	80	50	Down	70	155	25
	90	50	Up	70	155	25
	100	50	Up	70	155	25
Beta and zeta as in hole A.						
C	10	40	—	74	155	25
	20	40	—	74	155	25
	30	40	—	74	155	25
	40	40	Neutral	74	155	25
	50	40	—	74	155	25
	60	40	—	74	155	25
	70	40	—	74	155	25
	80	40	—	74	155	25
	90	40	—	74	155	25
	100	40	—	74	155	25
The angle between d_1 and the long core axis, ζ (zeta) = 54° > β (beta) = 40°, the plunge of hole C, so that polar vergence cannot be used unambiguously.						

(4) Polar vergence information recovered from non-oriented drillcore can be used to deduce macroscopic structures if the fold plunge is at a high angle to the drill hole, provided: (a) the angle between the axial surface and the long axis of the core is smaller than the plunge of the drill hole less the fan of minor axial surfaces or cleavage about major structures, and (b) the core can not be rotated so that the minor structures become reclined. Another way of stating (b) is that the angle between the long core-axis and the perpendicular to the fold axis in the axial surface must be less than the plunge of the drill hole. When using cleavage–earlier foliation relationships, an additional requirement is that the angle $90° - \delta$ (δ is the angle between the pole to the earlier foliation and the long-core axis) is less than β, the plunge of the drill hole.

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