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Vergence: an evaluation

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Abstract—Fold asymmetry is an independent concept distinct from facing. Fold vergence is a direction relating to the sense of asymmetry of folds. The complementary concept of cleavage vergence is defined allowing asymmetry to be used to locate major fold traces where no minor folds exist. Cleavage vergence is a valuable tool in complex structural terrains. Both concepts can be used singly or in combination to identify refolding. Vergence can define structural way-up where sedimentological or stratigraphic way-up cannot be recognised.

INTRODUCTION

THE TERM vergence has been used extensively by geologists for over 50 years since its introduction by Stille (1924, 1930), but there have been differences of opinion over its precise meaning (see e.g. the discussion to Roberts 1974, p. 123). Stille used the word "vergenz" to describe both the directional sense of overturning of minor folds and the up-dip direction on planar fabrics. These two meanings were linked by a genetic implication of 'direction of overthrusting' in a kinematic sense. Implications of movement like this are undesirable in a term which describes only geometrical relationships, consequently use of the term has fallen into disarray. No international agreement on the use of vergence exists, and various authors have defined the term in distinctly different ways; the direction up the dip of the axial surface of a fold (Whitten 1966, Fleuty 1964), as an indicator of 'thrust direction' (de Sitter 1964) and the direction of overturning or of inclination of a fold (Gary *et al.* 1972). Asymmetric folds have been said to have 'dextral or clockwise' or 'sinistral or anticlockwise vergence' (Hobbs *et al.* 1976, Fleuty 1964) and 'right-handed, left-handed or neutral shear sense' (Billings 1972). Ramsay (1967, p. 351) notes that the symmetry of folds may be recorded on a map by one of three symbols; *M* (symmetric), *S* or *Z* (asymmetric).

Particularly, there is disagreement as to whether vergence should refer to the up-dip or down-dip direction on an axial surface (see e.g. Gary *et al.* 1972). The original meaning was clear (up-dip) and in this discussion it is proposed that the term vergence be standardised in accord with the spirit of its original usage.

Unfortunately, Gary *et al.* (1972, p. 775) continued their definition of vergence as "the direction in which a ... structure ... is facing." This American usage of vergence is contrary to the British usage of facing and it is important to make a distinction between the two. Shackleton (1957) has defined fold facing as the direction, normal to the fold axis and along the axial plane, towards younger beds. In Fig. 1, fold (a) faces upwards and fold (b) faces downwards. However both folds have the same sense of asymmetry. Thus the concept of fold facing is entirely independent of fold vergence as defined below. Shackleton (1957) extended his definition of facing to facing on cleavage. The direction within an axial-plane cleavage in which younger beds are met defines both fold facing and facing on cleavage. The latter is similarly distinct from cleavage vergence (see below). Facing and vergence are therefore independent concepts, both of use to the geologist.

Originally, vergence was introduced as a direction relating to fold asymmetry and this paper attempts to clarify the concepts of vergence of both folds and cleavage so that the term has maximum value for all field geologists.

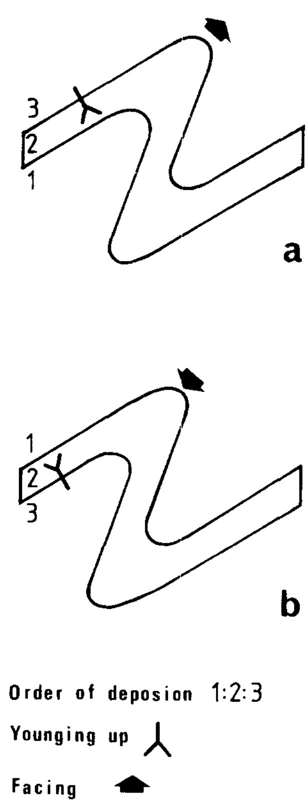

Fig. 1. Distinctions between fold asymmetry and facing. Both folds have the same sense of asymmetry, but (a) faces upwards whilst (b) faces downwards.

FOLD VERGENCE

Geometrically, asymmetric folds can be considered to have short limbs which have been rotated from a position now preserved by the longer limbs. Vergence of asymmetric folds has been defined (Roberts 1974, p. 123) as "the horizontal direction, within the plane of the fold profile, towards which the upper component of ... rotation is directed" (Fig. 2). The use of an azimuth to define vergence is both clear and unique. This definition has the advantage over descriptions of fold asymmetry as '*S*'- or '*Z*'-shaped, or 'sinistral or dextral', in that the vergence is independent of fold plunge variations. In Fig. 3(a), the minor folds A and B both verge northwards but when viewed down-plunge, fold A has '*S*' or sinistral asymmetry and fold B has '*Z*' or dextral asymmetry. Clearly the most useful definition permits minor folds with the same geometric relationship to any major structure to be classified together, irrespective of their plunge direction.

Minor folds in hinge regions (Fig. 3b, folds D and F) are symmetric (i.e. they have '*M*'- or '*W*'-shaped symmetry) and show neutral vergence. If the plane of the fold profile is horizontal (vertical fold plunge), then no unique direction of vergence exists since the upper component of rotation cannot be recognised. Asymmetric folds may then be said to show either sinistral or dextral vergence (Figs. 3c & d respectively).

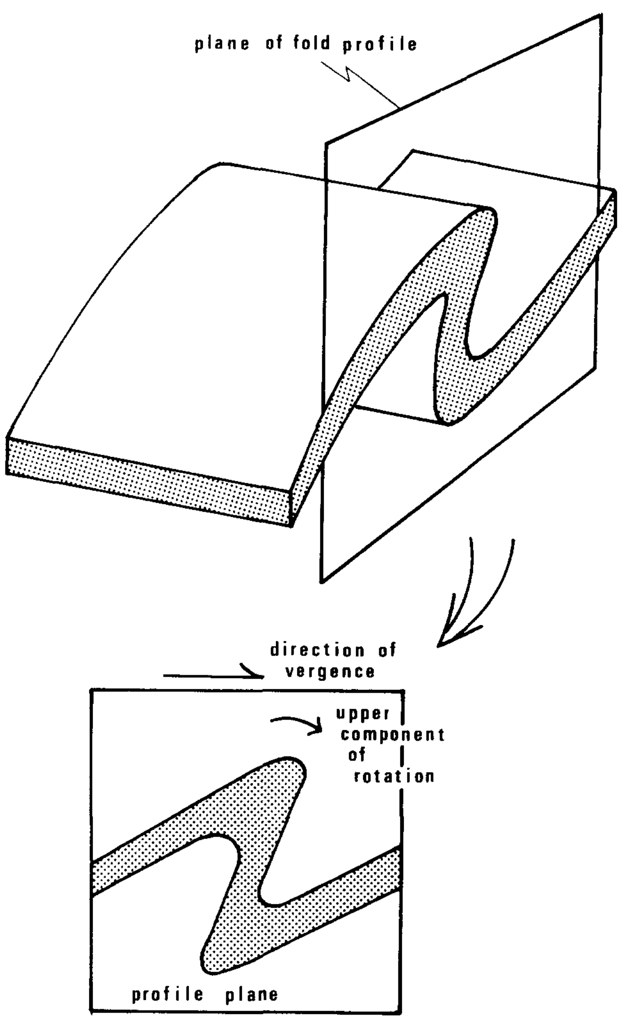

Fig. 2. Definition of fold vergence (for discussion see text).

The principal use of minor fold vergence is to locate major fold axes. In simple geometries minor folds change vergence across major fold traces. From Fig. 3(b) the sequence of folds C, (northward vergence), D (neutral), E (southward vergence), F (neutral) and G (northward vergence) indicates that the axial traces of a major fold pair have been crossed.

In areas of refolding, minor fold vergence changes are useful in locating major folds of their own generation (e.g. Ramsay 1967, p. 535). In Fig. 4(a), minor folds (F_1 in age) do not change their vergence across F_2 axial traces but do change their vergence across F_1 traces, and therefore locate them. Similarly, F_2 minor folds (central part of Fig. 4a) change their vergence across F_2 axial traces but not across F_1 traces. Note that this applies strictly to only minor F_2 folds of the first cleavage; minor F_2 folds of bedding may show anomalies (for example in F_1 crests). In this geometry (Fig. 4a), F_1 folds (major and minor) change their facing across F_2 traces. In the absence of F_2 minor folds F_1 facing changes alone may be used to define F_2 axial traces.

A more complex pattern is shown in Fig. 4(b). Here both F_1 and F_2 minor folds change their vergence across F_2 traces. F_1 folds verge north on the upper F_2 limb, west in the F_2 crest and south on the lower F_2 limb. F_2 folds verge east above the axial surface and west below it. Generally, refolded folds in which early fold axes pitch steeply relative to late fold axes (frequently type 1 interference patterns, Ramsay 1967) show these atypical vergence relationships. Significantly, F_1 folds do not change their facing around F_2 axial traces. This rather special geometry highlights the fact that vergence changes alone do not supply sufficient information to locate fold axes consistently; both vergence and facing must be taken into account.

CLEAVAGE VERGENCE

Roberts (1974, p. 123) also noted that vergence "can be extended to describe bedding–cleavage relationships where bedding is not folded" but did not provide a definition of this implied cleavage vergence. Such a concept is also useful in cleavage–cleavage relationships where bedding is not visible and facing on cleavage cannot be determined.

Any definition of cleavage vergence should parallel that of fold vergence and should highlight the distinction between geometric cleavage–cleavage (or cleavage–bedding) relationships and facing on cleavage. Cleavage vergence may be defined as the horizontal direction, within the plane normal to the fabric intersection lineation, towards which a younger fabric needs to be rotated so that it becomes parallel to the older fabric. In all cases the younger fabric should be rotated through the acute not the obtuse angle (see Fig. 5). The following method of construction may be used.

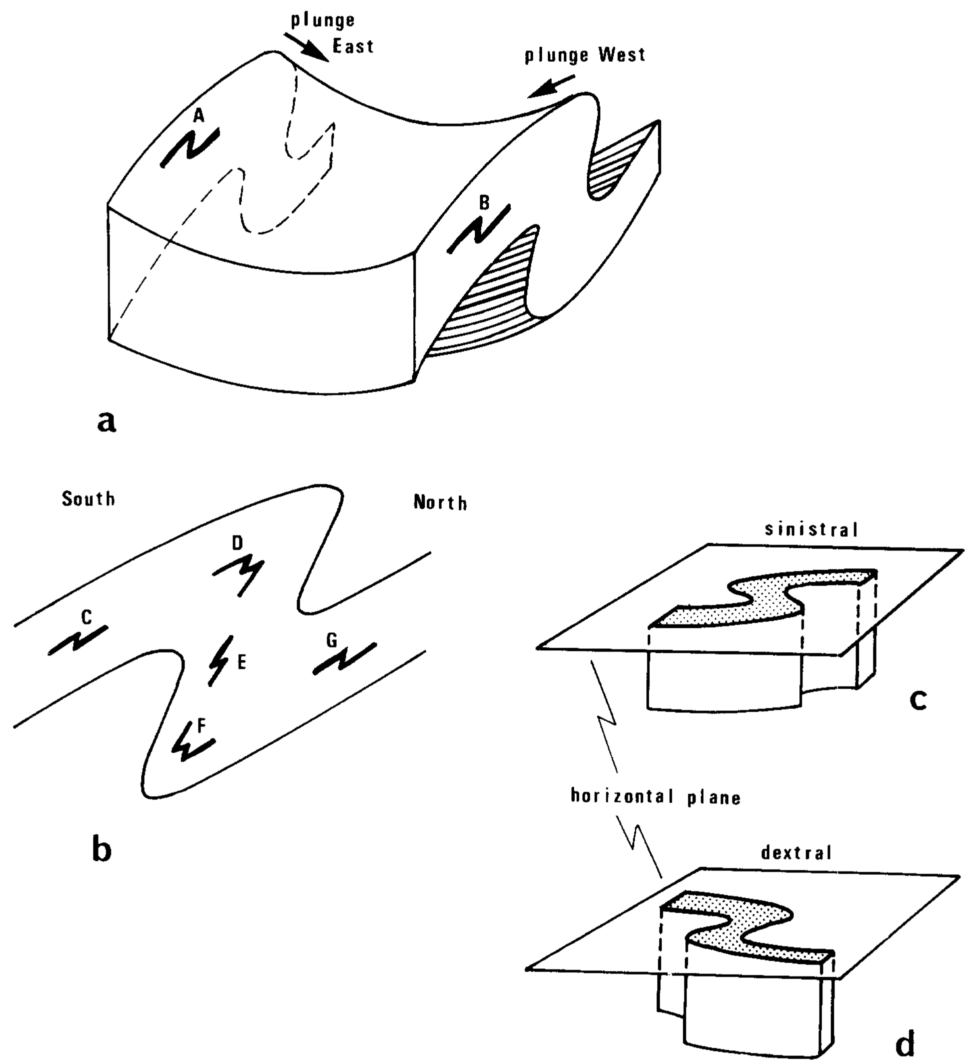

Fig. 3. (a) Plunge reversals lead to reversals of sense of asymmetry, but not of vergence (see text for details). (b) Minor fold vergence used to locate major fold axes. (c) & (d) Folds that plunge vertically have either sinistral (c) or dextral (d) vergence.

(i) Define the plane normal to the intersection lineation of two fabrics.
(ii) In that plane, project the normal to the earlier fabric upwards in space.
(iii) The direction towards which that normal would have to be rotated to lie parallel to the later fabric defines the direction of vergence of the later fabric.

The earlier fabric may commonly be bedding, but where the vergence of a second or later cleavage is being considered, this must be related to the immediately preceding fabric. Like fold vergence, cleavage vergence indicates the direction in which an antiform may be expected to be encountered. The construction is shown diagrammatically in Figs. 5(a) & (b). Three special cases are worth discussing.

(i) Where the normal lies parallel to the later fabric (in fold hinges), the cleavage vergence is neutral (Fig. 5c).
(ii) Where the normal lies at right angles to the later fabric, the fabrics are coplanar and cleavage vergence is not defined [Fig. 5(d)]. Such a composite fabric may be extremely difficult to recognise in the field. In this circumstance complex interference of two generations of minor folds may also occur; commonly information from one complex outcrop must be supplemented with data from adjacent outcrops where vergence is clearer.
(iii) Where the earlier fabric is vertical, it will be impossible to project a unique normal upwards in space (Figs. 5e & f). Here the later fabric may be said to have either sinistral (Fig. 5e) or dextral (Fig. 5f) vergence (cf. vergence of vertically plunging folds).

This definition of cleavage vergence is independent of facing of bedding on cleavage (Fig. 6). Although the direction of projection of the normal upwards in space will coincide with the direction of younging in right-way-up beds (Fig. 6a), this will not be the situation on inverted limbs (Fig. 6b). If the direction of younging had been used to define the normal, similar bedding, cleavage geometries (Figs. 6a & b) would have had an opposite sense of cleavage vergence, impairing the use of this form of vergence as a tool for the geologist.

The corollary to vergence-constant facing changes in refolded folds (Fig. 4a) exists in the concept of facing-on-cleavage changes. In Fig. 7, the cleavage S_2 has been superimposed across F_1. Within that plane, changes in facing, indicated by reversals of younging of beds, locate early F_1 fold traces. Younging reversals can be identified

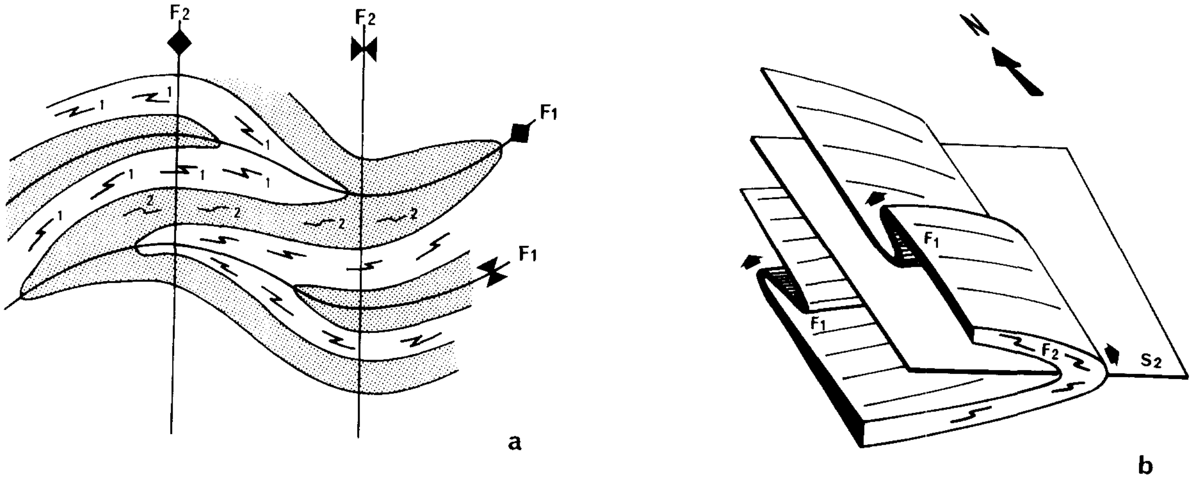

Fig. 4. Refolded fold geometries. (a) Coaxial refolding. Minor F_1 folds do not change their vergence across F_2 axes, but do change their facing direction. (b) Orthogonal refolding. Both F_1 and F_2 minor folds change vergence, but not facing direction, across F_2 fold axes. (Arrows indicate facing direction.)

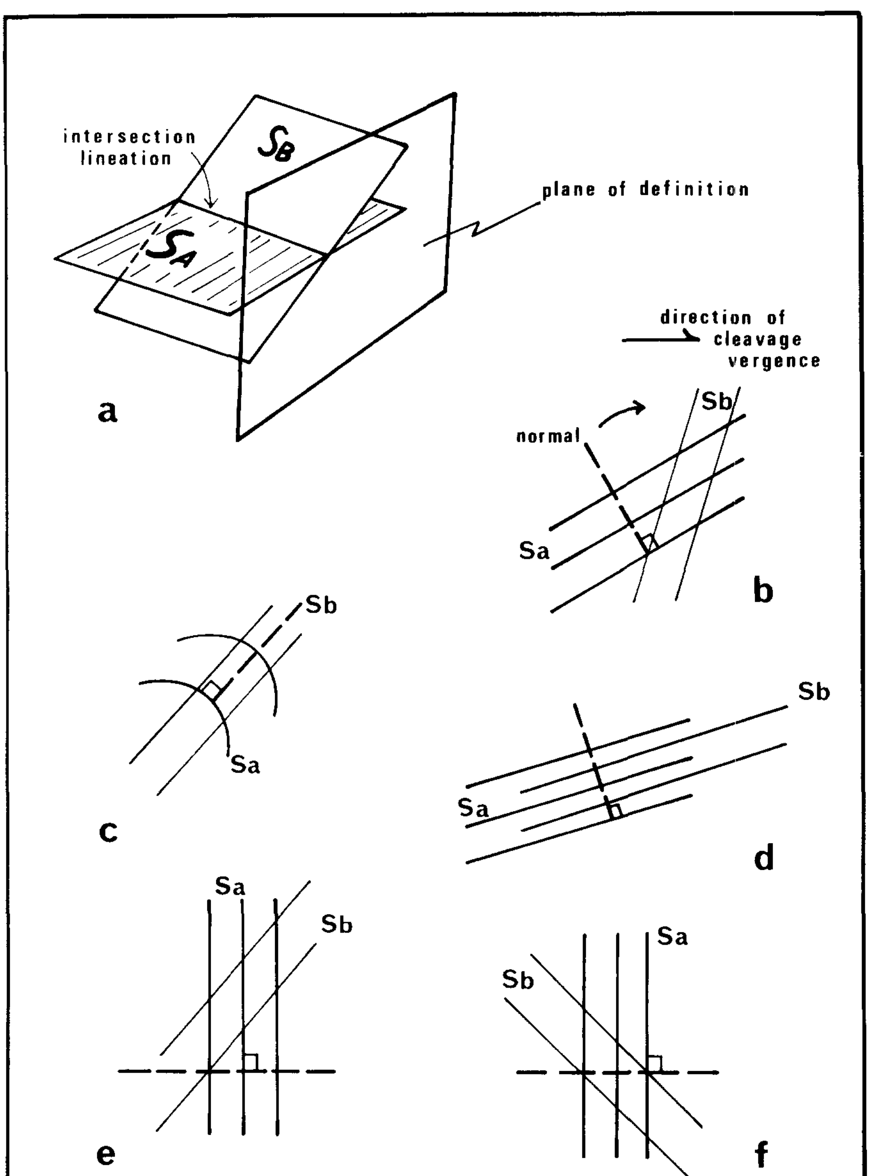

Fig. 5. Calculating cleavage vergence (for details see text). (a) Plane of definition of cleavage. (b) Construction of normal to older fabric. (c) Neutral cleavage vergence. (d) Coplanar fabrics. (e) Sinistral cleavage vergence. (f) Dextral cleavage vergence.

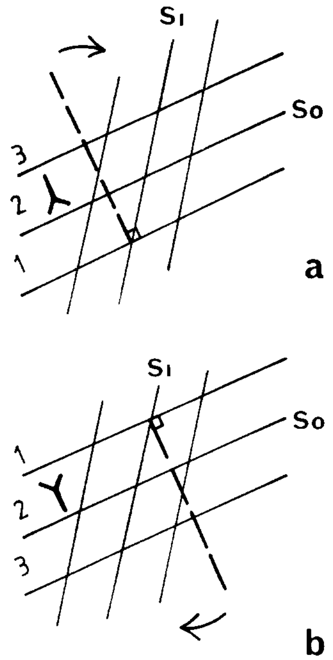

Fig. 6. Younging direction does not define cleavage vergence adequately. (a) Northward cleavage vergence. (b) Apparent southward cleavage vergence caused by the incorrect projection of the normal to bedding.

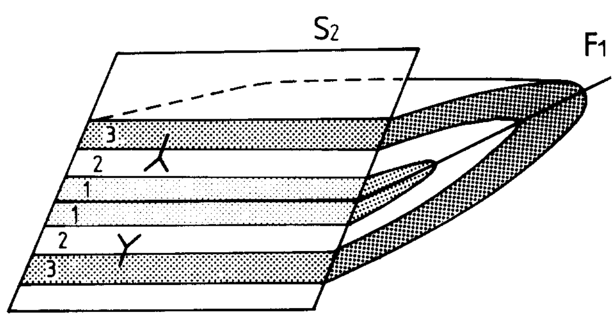

Fig. 7. Locating early fold traces by changes of facing direction on cleavage. Younging symbols as in Fig. 1.

on way-up evidence or repetition of stratigraphy. In the special case depicted in Fig. 4(b) neither generation of folds show facing changes on the superimposed cleavage.

This use relates only to cleavages which are axial planar to superimposed folds. Cleavages which are genetically related to folds but which are not axial planar (transected folds, Powell 1974, Borradaile 1978) can show facing on cleavage changes similar to those seen in superimposed axial–planar cleavages. The tighter the transected fold, the more pronounced is the facing-change effect. So, in general, whilst facing changes on an aial–planar cleavage locate early fold traces, not all early folds can be located this way. The method can be unreliable in the case of non-axial planar cleavages, but transected fold axes can be located by facing changes on the transecting cleavage. Geometrically, transected folds are a special case of superimposed cleavage. Where a transecting cleavage trace is markedly oblique to a fold axial trace in the plane of the fold profile (Borradaile 1978, fig. 1b) the loci of cleavage vergence changes occur where the transecting cleavage is at right angles or parallel to bedding, not at

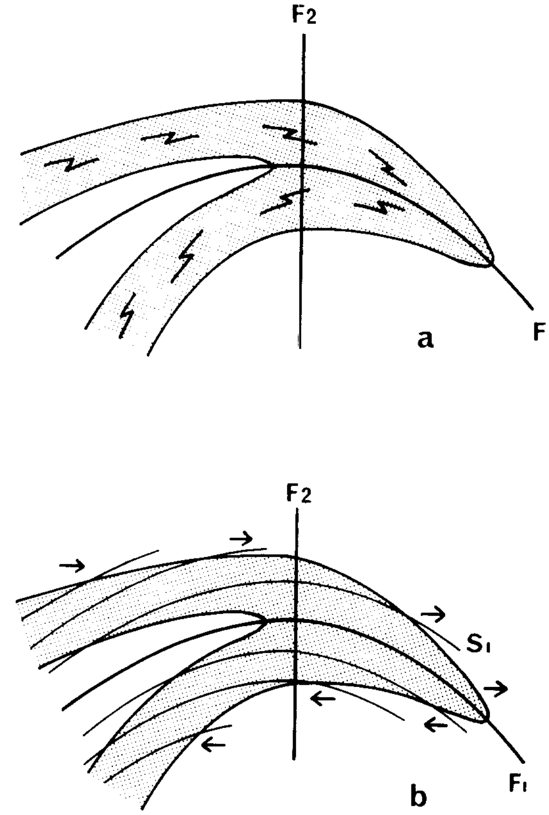

Fig. 8. Supplementing fold vergence data (a) with cleavage vergence data (b). Arrows indicate the direction of vergence. Note that F_1 vergence changes only across F_1 axes, not F_2 axes.

fold traces. In this special situation, cleavage vergence cannot be used to define fold traces.

CONCLUSIONS

Cleavage vergence as defined above is geometrically analogous to fold vergence and the two may be used singly or in combination to recognise refolding. More specifically, reversals of cleavage vergence may be used to recognise earlier folds, supplementing data from fold vergence, or to locate earlier structures where no minor folds exist (Fig. 8). Both types of vergence imply concepts distinct from fold facing or facing of bedding on cleavage. In some geometries both facing and vergence need to be defined to unravel complex structural histories. In all situations, systematic recording of vergence and facing (where known) greatly simplifies the task of the geologist mapping in areas of complex deformation. Taken together, these two complementary concepts may be used to identify structural way-up in beds where no stratigraphic or sedimentological way-up criteria can be recognised. If for example minor structures of known vergence and facing are located in one area, reversals of vergence of cogenetic structures in an adjacent area imply a change in younging of the beds. Clearly this has important implications for depositional sequences in areas which have suffered complex structural histories, although it must be noted that structural way-up is a relative, not an absolute term (Borradaile 1978).

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