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SHORT NOTE

The stereographic analysis of facing

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Abstract—Facing directions represent an accurate means by which tectonic structure and sedimentary way-up may be related. A simple method is presented for determining facing directions accurately, using a stereonet. Once determined, larger amounts of facing data can be quickly collated and analysed using similar techniques to those employed for other lineations. An example is given for some sheath fold structures in the Moine rocks of Sutherland, N. Scotland.

INTRODUCTION

THE use of sedimentary structures as indicators of primary younging in rocks that have suffered complex tectonism and metamorphism represented a significant advance in the field of structural geology. The direction of younging possesses a precise geometric relationship to most tectonic structures, and Shackleton's (1958) concept of facing is the most useful means of recording this association. Traditionally, it has been employed in areas which display folds and cleavage, but Lisle (1985) has expanded the use of facing to include faults.

Following Shackleton (1958) and Lisle (1985), three types of structural facing can be defined:

(i) *fold facing*—the direction, normal to the fold axis, along the fold axial plane, and towards the younger beds;

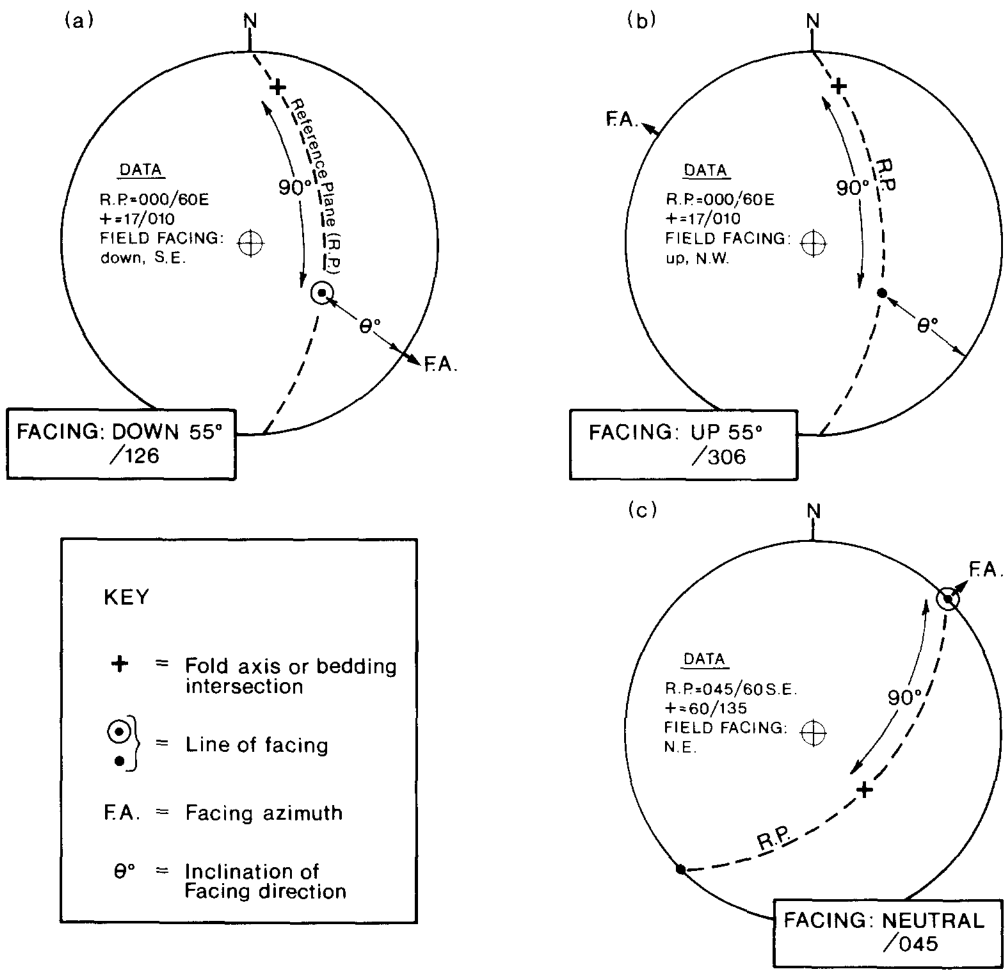

Fig. 1. Stereographic projections showing examples of how to determine (a) downward-, (b) upward- and (c) neutral-facing. In every case, the line of facing lies within the reference plane at 90° to the fold axis or bedding intersection. The appropriate line of facing intersection is selected on the basis of field data, and the azimuth and inclination (if any) of facing are 'read-off' in the normal way. Solid circle and circle with dot symbol denote upward- and downward-facing lines respectively. An arrow outside the primitive shows the facing azimuth.

(ii) *cleavage facing*—the direction, normal to the bedding plane intersection, along the cleavage plane, and towards the younger beds;

(iii) *fault facing*—the direction, normal to the bedding plane intersection, along the fault plane and towards the younger beds.

Like any linear feature, facing possesses an inclination and azimuth, but as it is a polar, rather than an axial lineation, a horizontal reference plane is used, and the terms upward-, downward- and neutral-facing, are employed to qualify the facing azimuth (Fig. 1). In folded terrains, facing is often used together with the geometric concept of vergence; these terms should not be confused (see Bell 1981).

Stereographic projection techniques are widely employed in the analysis and presentation of data from structural terrains of many types. Approximate facing directions, which are normally determined in the field, are frequently shown on structural maps and cross-sections but, as yet, no simple method has been described for determining or presenting such directions accurately. Such a technique is now briefly described.

FACING DETERMINATION USING A STEREONET

To avoid repetition in this description, cleavage, fault and axial planes are referred to collectively as the *reference plane*. The field measurements required are: the dip and strike of the reference plane, the plunge of the fold axis or of the intersection between the bedding and the reference plane, and the approximate direction of facing (e.g. upwards, downwards, east, north-west, etc.).

Plot the fold axis or bedding intersection on a stereonet, together with the reference plane (Fig. 1). The line containing the facing direction, here termed the *line of facing*, lies within the reference plane at 90° to the fold axis or bedding intersection (Fig. 1a). Hence, plot the point on the reference plane which lies at 90° to the fold axis–bedding intersection; this is the lower hemisphere intersection of the line of facing (Fig. 1). By referring to the approximate facing direction recorded in the field, it is obvious which 'end' of the line of facing is appropriate. Downward-facing directions are recorded by the lower hemisphere intersection, which can simply be 'read-off' as a plunge (Fig. 1a). Upward-facing directions are upper hemisphere intersections, which have an equal and opposite azimuth and inclination ($\theta°$) to that of the line of facing (Fig. 1b). Neutral facing directions have an azimuth, but no inclination, and it is easy to decide which intersection of the line of facing on the primitive is appropriate from field observations (Fig. 1c).

The simplicity of the construction means that facing directions can be determined in the field with considerable accuracy; a small stereonet and tracing paper are all that are required. The technique can be applied to a wide variety of geological problems where facing is an important factor; e.g. areas of refolding (Bell 1981), thrust and fault zones (Boyer & Elliott 1982, Lisle 1985), regions of facing 'oppositions', such as SW England (e.g. Sanderson & Dearman 1973), and regions where folds have curvilinear hinge, or sheath-like geometries (Dearman 1969, Holdsworth & Roberts 1984).

Once facing directions have been determined, the data can be analysed and presented in a similar manner to other lineation data. While facing is polar, the parallel lines of facing are axial and they can be manipulated on the stereonet if necessary. An example of facing data from some sheath fold structures in N. Scotland is now given.

FACING PATTERNS FROM SHEATH FOLD STRUCTURES IN MOINE ROCKS OF SUTHERLAND, N. SCOTLAND

In the region between the Moine and Naver Thrusts, Sutherland, N. Scotland (Fig. 2a), units of Lewisian basement have been interleaved with a cover sequence of Precambrian Moine metasediments during the Caledonian orogeny. Lewisian inliers presently occupy the cores of antiformal sheath folds, or lie along ductile

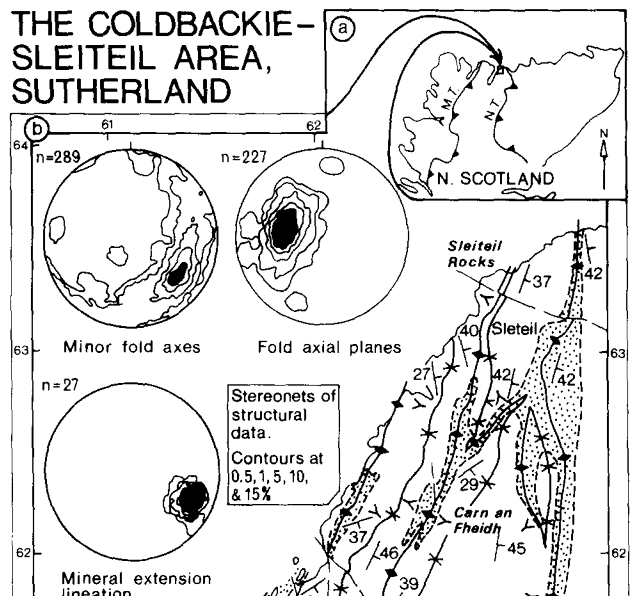

Fig. 2.(a) Map of northern Scotland showing the position of the Moine Thrust (M.T.) and Naver Thrust (N.T.); the location of (b) is also shown. (b) Simplified geological map of the Coldbackie–Sleiteil area, Sutherland, together with stereonets of structural data.

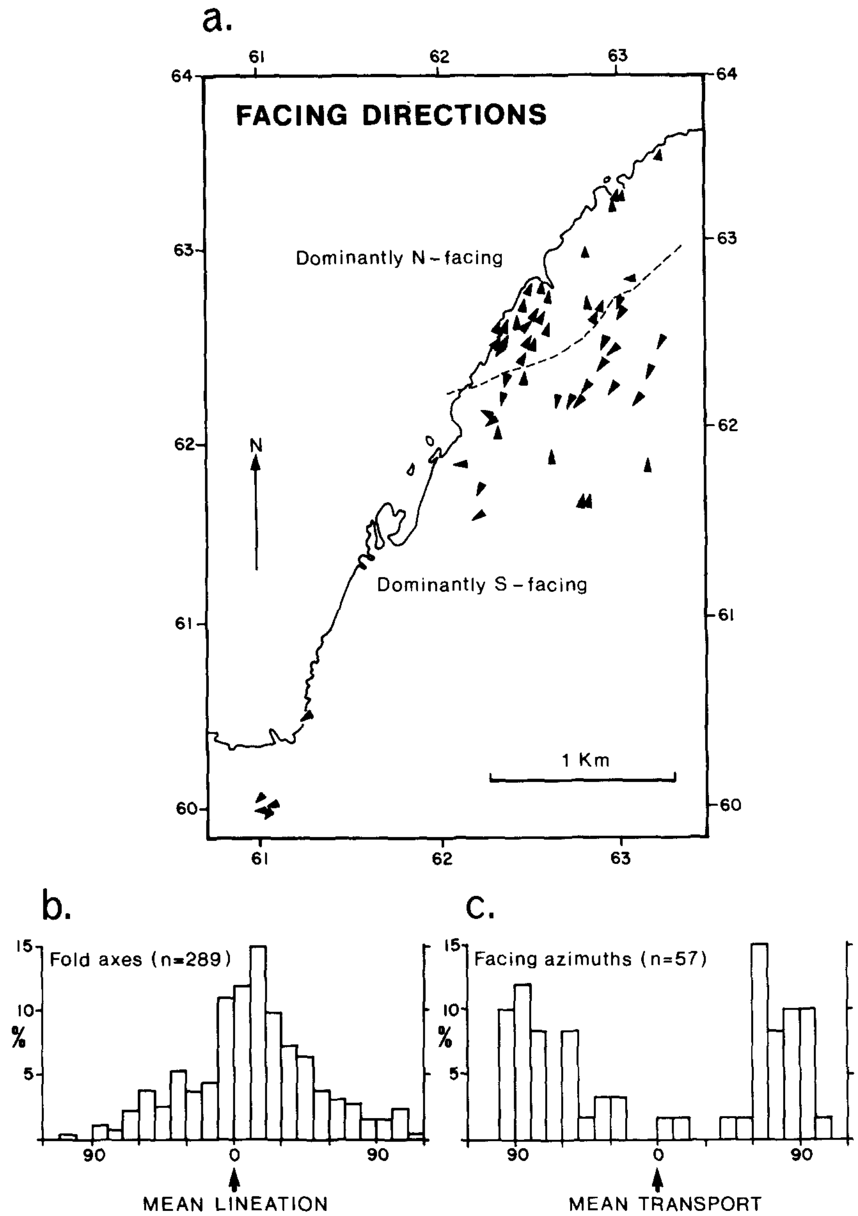

Fig. 3.(a) Map showing the calculated facing azimuths in the Coldbackie–Sleiteil area. (b) Frequency distribution histogram of minor fold plunge azimuths relative to the mean mineral lineation azimuth (114°). (c) Frequency distribution histogram of facing azimuths relative to the mean azimuth of tectonic transport (294°); note the strong bimodal pattern of facing.

thrusts (Barr *et al.* 1986, Holdsworth 1987, Strachan & Holdsworth 1988). An associated ESE–SE-plunging mineral extension lineation is thought to lie subparallel to the ductile thrust transport direction, which microscopic shear-sense indicators (mica fish, asymmetric pressure shadows, shear bands, etc.) suggest was towards the WNW–NW (Holdsworth 1987). Detailed structural analysis in the region suggests that the Caledonian folds formed initially as buckles overturned towards the WNW or NW, whose axes lay at high angles ($\approx$90°) to transport. Subsequent shearing associated with ductile thrusting, caused the rotation of fold axes towards the mineral extension direction (cf. Escher & Watterson 1974). As a result, the Caledonian folds frequently display sheath-fold geometries on all scales (Carreras *et al.* 1977). However, the deformation of the Moine rocks is heterogeneous on a small scale, with the result that sedimentary structures indicative of way-up are preserved locally in regions of lower strain. This permits a detailed analysis of facing patterns in areas where sheath fold structures and younging criteria are well exposed.

One of the best examples of sheath fold structures in N. Scotland occurs in the Coldbackie–Sleiteil area, on the NE coastal region of the Kyle of Tongue (Fig. 2b). Inliers of originally high-grade Lewisian basement cropout within the cores of tight to isoclinal, curvilinear antiforms, while the lower grade Moine rocks lie in the cores of adjacent synforms (Fig. 2b). Basement-cover contacts lack persistent zones of high strain and sedimentary structures in the psammites consistently young away from adjacent Lewisian material (Fig. 2b). Gritty horizons and conglomerate lenses (e.g. at NC 6298 6268) are common in the Moine rocks closest to the basement. Hence, the folded Moine–Lewisian boundary is interpreted as being an original unconformity, albeit one where moderate to intense tectonic strains have obliterated any obvious discordance. 'Eye-structures', which are typical of sheath folds (Cobbold & Quinquis 1980), are very common (e.g. at NC 6269 6292), and in some coastal sections (e.g. around NC 625 628) curvilinear fold patterns, bisected by a constantly ESE-plunging mineral lineation, are well exposed in three-dimensions. Along-strike changes in fold vergence and approximate facing direction recorded in the field are also indicative of a sheath-fold geometry (cf. Dearman 1969, Holdsworth & Roberts 1984). The stereonet data (Fig. 2b) display the classic sheath-fold pattern. Fold axes fall on a great circle corresponding to the mean axial plane, the plunge maxima lying near to the mean plunge of the mineral lineation. On a frequency distribution diagram (Fig. 3b), the azimuths of fold plunge show a strong unimodal distribution with respect to the mean lineation.

The facing data display the following features when plotted on a stereonet and map (Figs. 3a and 4):

(i) the lower hemisphere intersections of the lines of facing are distributed along a great circle which corresponds to the mean axial plane in the Coldbackie–Sleiteil area (Fig. 4);

(ii) the directions of facing display a strong bimodal distribution with respect to the mean mineral lineation and hence to the thrust transport direction (Figs. 3c and 4);

(iii) most folds face N–NNE or SSW–SW and show strong neutral components of facing. Small upward- or downward-facing components are attributed to gentle refolding by later, E–SE-plunging structures which occur in the area. All the slightly downward-facing data have N–NNE azimuths, suggesting that the later folding caused a small anticlockwise rotation about an axis parallel to the dip of the earlier fold axial planes;

(iv) where the folds face west, there is a strong upward-facing component;

(v) no downward- and easterly-facing structures are recorded.

The data are consistent with the Caledonian folds in the Coldbackie–Sleiteil area having a sheath-like geometry. The facing arrows on the map (Fig. 3a) show that N–NNE-facing structures are dominant in the N of the area, while SW–SSW-facing structures dominate in the south. The boundary region between these zones of different facing reveals the location of the major sheath fold culminations in the region, a feature also shown by the opposing closures of the Lewisian inliers along-strike (Fig. 2b).

The pattern of facing also demonstrates that the Moine succession was apparently right-way-up prior to the Caledonian folding. The arc of facing azimuths is broadly upward facing, and where the folds lie close to their original NNE–SSW-trending orientation, they always face upwards and to the west. It is therefore unlikely that earlier, pre-Caledonian folds are present in the area, a feature borne-out by a paucity of small-scale early folds. The data are consistent with the proposal that the Moine–Lewisian interface possessed a fairly undisrupted, planar form, immediately prior to Caledonian orogenesis, as suggested by Barr *et al.* (1986) and Strachan & Holdsworth (1988).

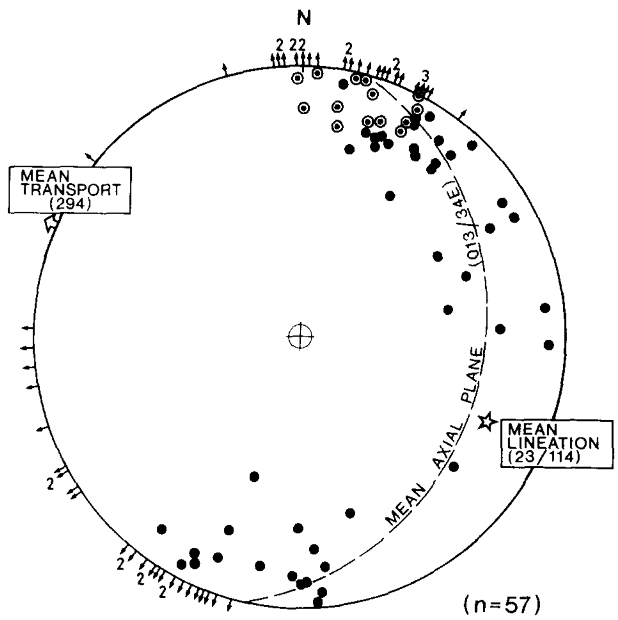

Fig. 4. Stereonet of facing data from the Coldbackie–Sleiteil area. Facing data shown as suggested in Fig. 1 (2 = two readings, etc.).

CONCLUSION

Facing represents a unique opportunity to incorporate a stratigraphic component into structural analyses in a wide variety of geological terrains. The only prerequisite is that the rocks must contain younging indicators. The quick method presented in this paper allows an accurate measurement of facing directions to be made on the stereonet, and its simplicity is an obvious advantage. Once calculated, the facing data can be represented and analysed in a far more rigorous fashion than was previously possible.

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