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Measurement of fold axes in drill core

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Abstract

Measuring the orientation of fold axes is a routine component of field-based structural analysis. Determining the real-space orientations of small-scale folds in drill cores, however, remains a time consuming and often cumbersome task unless the fold axis lies on an exposed plane. We present a method for accurately determining the orientation of fold axes that do not lie on exposed planes in drill core, provided the core is oriented or can be reoriented using the assumed orientation of one of the fabrics within it. Two angles that uniquely specify the orientation of the fold axis with respect to the core are measured. One is the angle between the fold axis and the core axis. The other, measured in a plane perpendicular to core axis, couples the orientation of the fold axis to either a core orientation mark or another fabric of known orientation. The real-space orientation of the fold axis can either be calculated from the two measured angles and the plunge and azimuth of the drill hole or determined using a simple stereonet construction. Measurements are made with respect to the two points of intersection between the fold axis and the outer surface of the core. While this means the technique is best suited for use with a whole core, it has the advantage that fold axes need not lie on exposed planes in the core.

Keywords: Drill core; Structural measurements; Fold axis

1. Introduction

A variety of methods have been developed for determining the orientations of structures in axially-oriented drill cores (e.g. Zimmer, 1963; Laing, 1977; Johnston, 1985; Hinman, 1993; Scott and Berry, 2004). The measurement of small-scale fold axes that do not lie on exposed planes, however, remains a time-consuming and often cumbersome task. Determining the orientation of fold axes is an important component of conventional structural analysis, and is routinely carried out by field geologists. Therefore, a simple and accurate method for determining the real-space attitude of small-scale folds in drill cores is highly advantageous.

We present a technique that allows quick and accurate measurement of fold axes without the aid of a core orientation cradle. It is applicable to cores whose orientation is constrained either by a spear mark (or similar technique), or by a reference fabric of known orientation (e.g. cleavage with regionally consistent orientation). Measurements are made using a transparent template that allows simultaneous measurement of two angles that uniquely couple the orientation of the fold axis to either the core orientation mark or the reference fabric. Fold axes are not required to pass through the central axis of the core, nor do they need to be exposed on planar surfaces such as bedding or cleavage. As the orientation of fold axes are determined from their angular relationships to core orientation elements, rather than with a compass and clinometer, subsequent modification of the chosen reference fabric or drill hole survey data does not necessitate re-measurement of the folds. A simple stereonet construction can be used to determine the real-space orientations of a fold axes from the two measured angles in the core and the orientation of the drill hole. Alternately a free copy of a *Microsoft Excel*™-based computer program that calculates the real-space fold axis orientation from these parameters can be down-loaded from our website: http://www.codes.utas.edu.au/5_NewsAndMedia/Research.htm.

2. Measurement of fold axes in drill core

The orientation of any linear feature in drill core can be defined by its angular relationships with the drill core axis,

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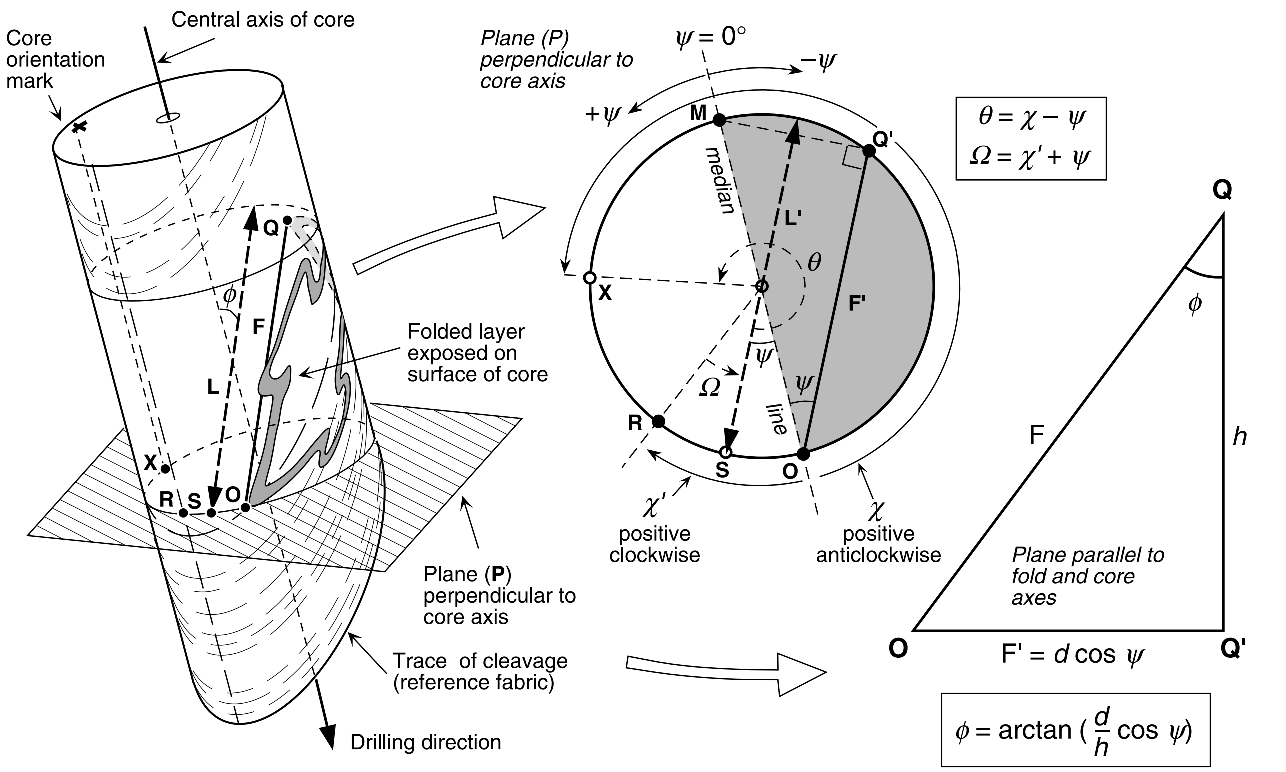


Fig. 1. Measurement conventions and geometric construction used to determine the orientation of a fold axis (F) from its two points of intersection with the outer surface of a drill core with diameter, *d*. The up- (Q) and down-hole (O) ends of F are separated by the distance, *h*, measured parallel to the core axis. F and Q project to F′ and Q′, respectively, in a plane P, perpendicular to the core axis and passing through O. L is a line parallel to the fold axis that passes through the central axis of the core, and projects to L′ in P. The real-space orientation of the fold axis is determined by coupling L to either a bottom-of-core mark (X) or the down-hole end (R) of the ellipse formed by the intersection of a reference fabric (of known orientation) and the core. See text for further discussion.

and a reference feature that specifies the real-space orientation of the drill core. Where a linear feature lies on an exposed plane in core, and the core can be correctly oriented, the orientation of the linear feature is readily determined by standard techniques (Zimmer, 1963; Laing, 1977). Here we are specifically concerned with the measurement of fold axes that do not lie on exposed planes in the core. Our method involves coupling the fold axis to an imaginary line, parallel to the fold axis but passing through the central axis of the core, and in turn coupling this line to a core orientation mark or known reference fabric.

Where both ends of a fold axis are visible on the outer surface of the core, the angle ϕ between the fold axis and the core axis is given by:

$$\phi = \arctan((d/h)\cos\psi) \quad (1)$$

where h is the distance, measured parallel to the core axis, between the up- and down-hole ends of the fold axis and d is the diameter of the core (Fig. 1). ψ is the acute angle between the projection of the fold axis onto a plane at right-angles to the core axis and the *median line* (a line perpendicular to the core axis passing through both the central axis of the core and the down-hole end of the fold axis; OM in Fig. 1). We define ψ as positive (0° to +90°) for fold axes that project left (anticlockwise) of the median line, and negative (0° to −90°) for those that project to the right (clockwise), looking down-hole. If $\psi = 0°$, the fold axis passes directly through the centre of the core. The sign of ψ has no bearing on the value of ϕ, but is important for specifying the *core orientation angles* (θ and Ω) that couple the fold axis to either a bottom-of-core line or reference fabric (typically a cleavage), allowing the real-space orientation of the fold axis to be determined (Fig. 1).

Parallel fold axes in the same piece of core must all have the same core orientation angle (i.e. same value of either θ or Ω). Therefore the core orientation angle is not specified with respect to the fold axis itself, but to an imaginary line—parallel to the fold axis but passing through the centre of the core. In the construction shown in Fig. 1, the down-hole end of a fold axis (F) intersects the outer surface of the core at O in the plane P, where P is perpendicular to the core axis. The down-hole end of the imaginary line, parallel to the fold axis and passing through the central axis of the core, intersects P at S. S is offset from O by the acute angle ψ (subtended at the centre of the core by the arc O and S). Whether S is clockwise (as in the example in Fig. 1) or anticlockwise of O, depends on the sign of ψ, as defined above.

Thus for oriented core, the imaginary line parallel to the fold axis and passing through the central axis of the core is coupled to the bottom-of-core line by the angle, θ:

$$\theta = \chi - \psi \quad (2)$$

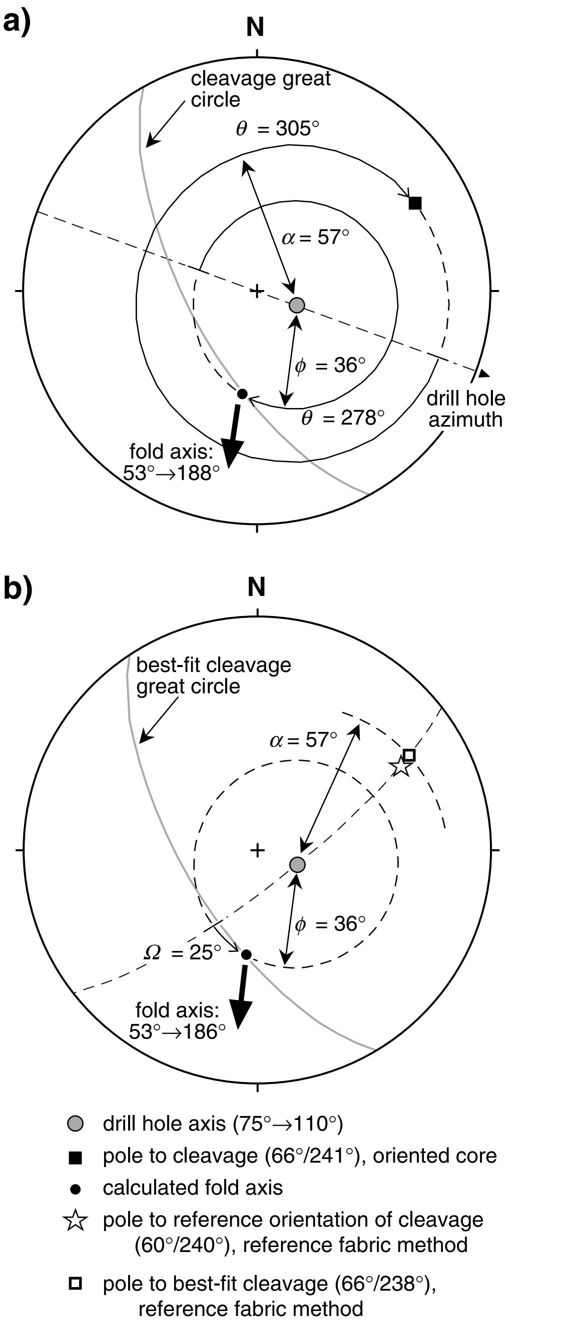


Fig. 2. Equal area stereonet constructions to determine the real-space orientation of the fold axis, F, depicted in Fig. 1. The drill hole plunges at 75° → 110°. Measurements of d (= 4.5 cm), h (= 5.5 cm), ψ (= −26°) and either χ (= 252°, oriented core) or χ' (= 51°, reference fabric method) yield (using Eqs. (1)–(3)) the angles ϕ (= 36°), and θ (= 278°, oriented core) or Ω (= 25°, reference fabric method) for the fold axis. For the axial plane cleavage, the core orientation angle θ, between the down-hole end of the elliptical trace of the cleavage and the bottom-of core mark is 305°. The pole to the cleavage makes an angle α (= 57°) with the core axis. (a) Oriented core. Small circles with radii of 36° and 57° about the drill hole axis indicate possible orientations of fold axis and the pole to the axial planar cleavage in the core, respectively. θ angles for the fold axis and cleavage fix the correct orientation of these fabric elements in the manner shown. Note that to determine the orientation of a fold axis in an oriented core it is not necessary to determine the orientation of any associated cleavage. This has been done here simply to show that the orientation determined for the fold axis does lie within the plane of the cleavage. (b) Reference fabric method. The most likely orientation of the core is based on the assumed orientation of the cleavage. The best-fit orientation of the cleavage (closest to its reference orientation) is determined by the intersection of (i) the small circle of possible cleavage pole orientations and (ii) the great circle linking the reference pole and drill hole axis (see Scott and Berry, 2004). The orientation of the fold axis is determined from the measured angles ϕ and Ω in the manner shown. The small discrepancy between orientations determined for the fold axis in parts (a) and (b) arises because the reference orientation (60°/240°) used for the cleavage in part (b) differs slightly from the correct orientation of the cleavage in core (66°/241°). In this example the reference fabric is an axial planar cleavage; however, the method does not require the reference fabric to have any specific geometric relationship to the fold axis.

where χ is the angle measured anticlockwise looking down-hole in the plane perpendicular to the core axis, between the down-hole end of the fold axis and the bottom-of-core line (Fig. 1). The real-space orientation of the fold axis can either be calculated from the plunge and azimuth of the core and the angles θ and ϕ (see Zimmer, 1963; Laing, 1977) or determined using a simple stereonet construction (Fig. 2a).

Alternately, if the core is reoriented using the assumed orientation of a reference fabric, the angle, Ω, between the down-hole ends of the elliptical trace of the reference fabric on the surface of the core (R, in Fig. 1) and the imaginary line parallel to the fold axis (S, in Fig. 1) is given by:

$$\Omega = \chi' - \psi \qquad (3)$$

where χ' is the angle between the down-hole ends of the fold axis and the elliptical trace of the reference fabric, measured clockwise looking down-hole (Fig. 2). The real-space orientation of the fold axis is determined from the assumed orientation of the reference plane, the plunge and azimuth of the drill hole and the measured angles ϕ and Ω (Figs. 1 and 2b). Different sign conventions for measuring χ and χ' (Fig. 1) reflect the angular conventions adopted for θ and Ω. Although not discussed here, these conventions have specific practical advantages for measuring structures in core.

3. Measurement template and example

From Eq. (1), the distance h (measured parallel to the core axis) between the two ends of a fold axis inclined at an angle, ϕ, to the axis of core with diameter, d, is simply a function of ψ. Thus for specific values of d and ϕ, a series of curves can be constructed, describing the change in h as a function of ψ. A series of such curves, for different values of ϕ, but constant d, forms the basis of the measuring template depicted in Fig. 3. To measure the orientation of a fold axis, the template is first photocopied onto transparent film at a scale appropriate to the diameter of core used. The template is then wrapped around the core, with the plus sign (+) at $\psi = 90°$, $\phi = 90°$ positioned over the down-hole end of the fold axis (Fig. 4a). With the template in position, the

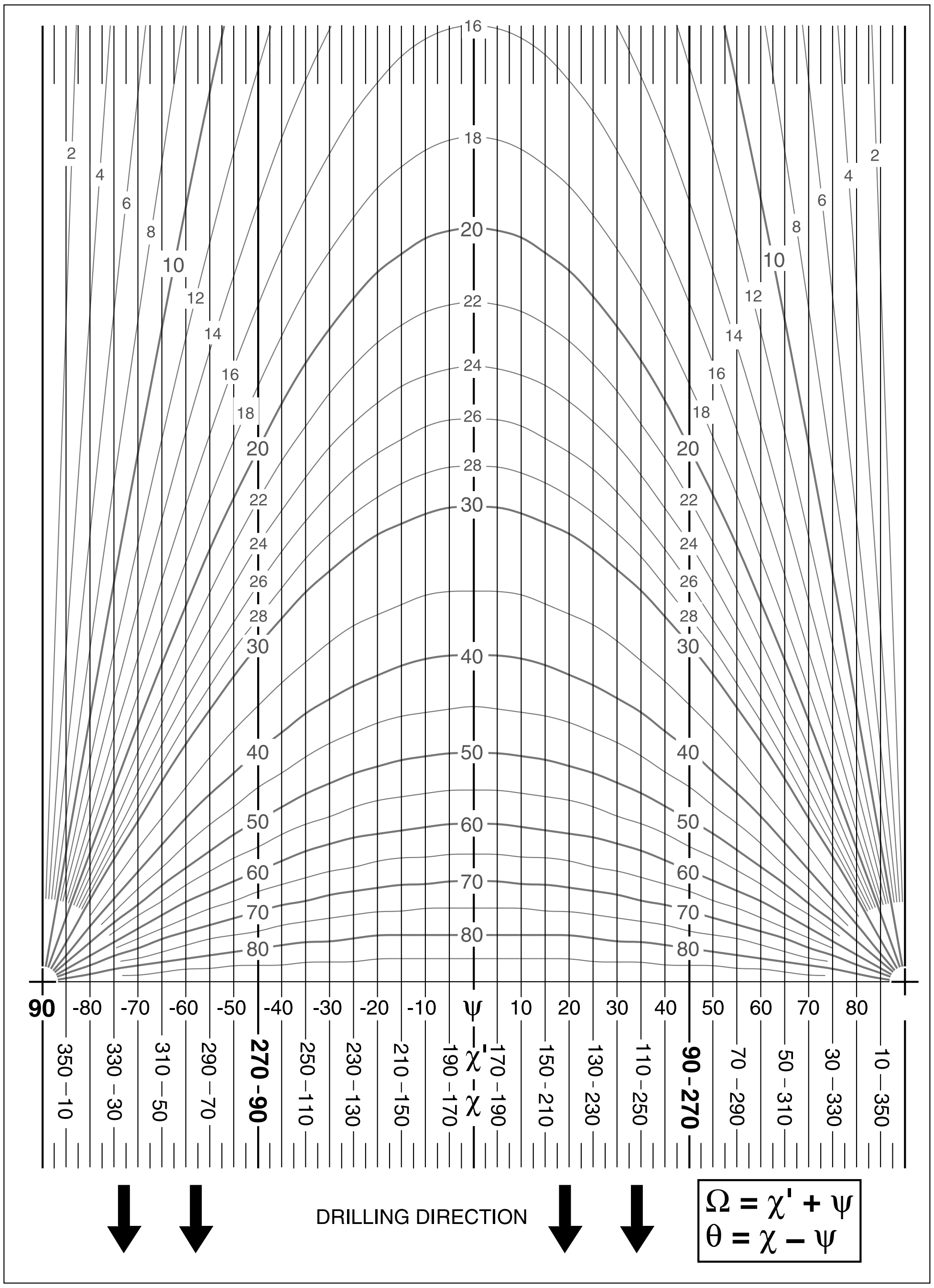
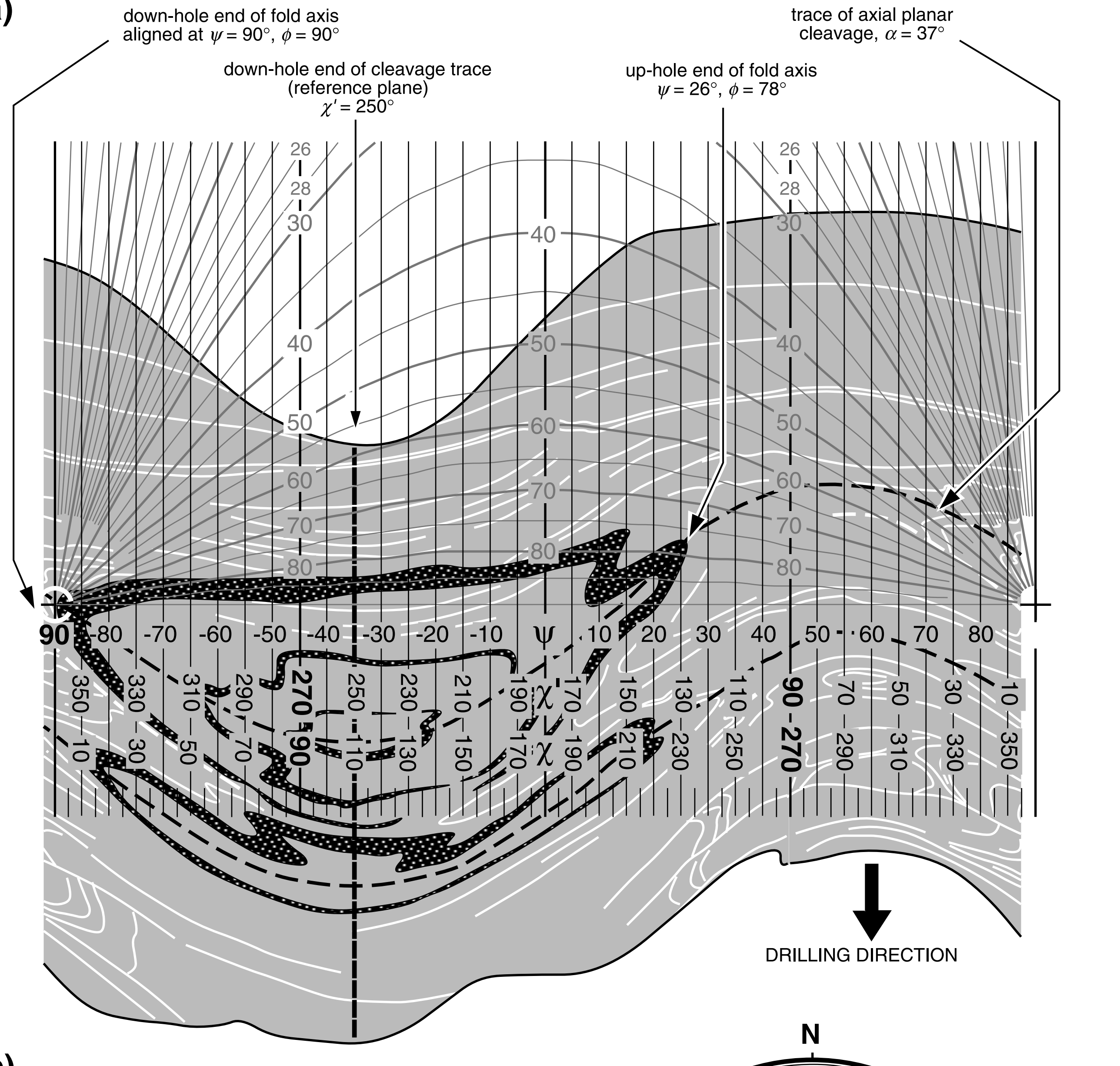


Fig. 3. Template for measuring the angles ψ, ϕ, χ and χ' in core. Parabolic curves trace the position of the up-hole end of the fold axis as a function of ψ, for specific values of ϕ and core diameter, d.

Fig. 4. (a) Unrolled measuring template (Fig. 3) shown superimposed over a series of small-scale folds, traced from the cylindrical surface of a drill core (sample location: DH69, 82.3 m, Chambishi Mine, Zambian Copperbelt). See text for explanation. (b) Angular measurements for five different folds (A–E) in the piece of core illustrated in (a) are used to derive the real-space orientations of their axes using the reference fabric method. The template illustrated in (a) is positioned to measure Fold A. For clarity only construction lines for Fold A are shown on the stereonet. The core was re-oriented using a representative orientation of cleavage from surface exposures at the Chambishi Mine (62°/189°, pole denoted by star). The drill hole orientation is 80° → 356°. For comparison, the orientations of four fold axes measured at the surface are also shown.

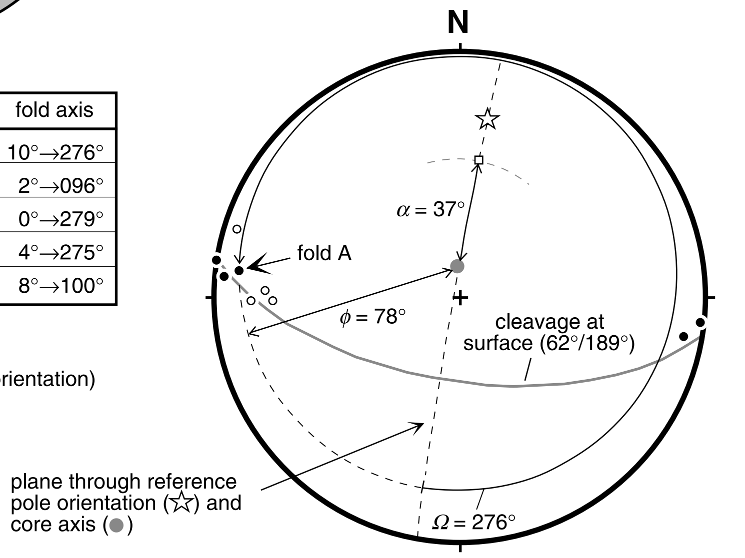
a)



b)

Fold	ϕ	ψ	χ'	Ω	fold axis
A	78°	+26°	250°	276°	10°→276°
B	90°	–27°	301°	274°	2°→096°
C	88°	–63°	335°	272°	0°→279°
D	85°	+16°	258°	274°	4°→275°
E	85°	+52°	37°	89°	8°→100°

- ● drill hole axis
- ☆ pole to cleavage at surface (reference orientation)
- □ best-fit pole to cleavage in core
- • calculated fold axis (core)
- ○ measured fold axis (surface)



up-hole end of the fold axis is located, and the corresponding ψ and ϕ angles read directly from the template (e.g. $\psi = 26°$ and $\phi = 78°$ in Fig. 4a). In the example illustrated, the core is to be reoriented using surface constraints on the orientation of the axial plane cleavage. Without moving the template (with respect to the core), the angle χ' ($= 250°$) corresponding to the position of the down-hole end of the cleavage trace is read from the appropriate protractor scale (Fig. 4a). From Eq. (3), the angle, Ω, coupling the cleavage to a line parallel to the fold axis passing through the centre of the core is $250 + 26° = 276°$. Angular measurements for five-fold axes from the illustrated piece of core are tabulated in Fig. 4b, along with their real-space orientations determined using the stereonet construction method illustrated in Fig. 2b. Comparison of structural data from surface and core indicates the axial planar cleavage is more gently dipping at depth, but the orientation of fold axes is potentially similar (Fig. 4b).

4. Conclusions

The method described herein enables the real-space attitudes of fold axes in axially-oriented drill cores to be simply and accurately determined, provided the correct orientation of the core is specified by either a core orientation mark or a reference fabric of known orientation. Folding in rocks is commonly accompanied by the development of a consistently oriented axial plane cleavage. Thus even in unmarked axially-oriented drill cores, a suitable reference fabric will often be present, enabling the real-space orientations of fold axes to be determined. As measurements are made with respect to the two points of intersection between a fold axis and the outer surface of the core, the method is best suited to use with a whole core. It has the advantage, however, that fold axes need not lie on the exposed planes in the core.

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