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Comment on "Lundmark, A.M., and Corfu, F., 2008, Emplacement of a Silurian granitic dyke swarm during nappe translation in the Scandinavian Caledonides, Journal of Structural Geology 30, 918–928"

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Lundmark and Corfu (2008) are to be congratulated on their investigation into the granitic Årdal dyke complex intruded into the Upper Jotun Nappe during its emplacement in SW Norway. I was particularly interested that dyke elements with different orientations are both folded and boudinaged. These syn-magmatic strains are attributed to thrusting of the Upper Jotun Nappe at 427 ± 1 Ma, the minimum age for initiation of Caledonian thrusting of the crystalline crust of Baltica onto western Norway.

It strikes me that these authors could have used the contemporaneous shortening and extension of planar elements of the dykes for deeper strain analyses than they presented. I demonstrate this point here by using the approach developed in Talbot (1970) to discuss their 3D data published on equal area lower hemispheric projections and interpret strain ellipses for one of the outcrops they illustrate.

Talbot (1970) advocated constraining the shapes, orientations and intensities of strain ellipsoids at specified locations by identifying the angle subtended by the elliptical *polar surface of no elongation* (*polar snoe*) in the principal planes on lower hemispheric stereographic projections of 3D data (see Ramsay and Huber, 1983, p. 215), or the two lines *of no elongation* (*lnoe*) of strain ellipses in 2D outcrops. The *snoe* is the conical surface joining the intersection between the finite strain ellipsoid and its parent sphere passing though the common centres. The *polar snoe* is the elliptical boundary on a stereographic projection separating poles to planar marker elements extended in at least one direction from shortened marker elements. Observations of inhomogeneous strains on small scales allow the constraint of ellipsoids describing homogeneous strains on larger scales.

Distinguishing the orientation of extended from shortened elements constrains the *polar snoe* which, if it is elliptical, can be attributed to a homogeneous bulk strain. An elliptical *polar snoe* is symmetrical about the principal axes of the strain ellipsoid $X \geq Y \geq Z$, centred on *Z*, elongate in *ZX* (with *X* 90°from *Z*) and *Y* is the pole to *XZ*. The shape (e.g. *k*) and intensity (e.g. axial ratios) of the strain ellipsoid centred on a particular location can be calculated by using two of the three values of $\Psi zx°$, $\Psi zy°$ or $\Psi xy°$ (Fig. 1A) in formulae derived by Flinn (1962) or the nomogram in Fig. 1B.

Talbot (1970) introduced this method using suites of competent planar marker elements that record finite shortening as concentric folds and finite extension as pinches, boudinage or straight (uniformly extended) marker elements. Talbot and Sokoutis (1995) adapted the method to incompetent planar markers that develop internal foliations in all orientations, mullions (class 3 folds: Ramsay, 1967) after finite shortening and inverse pinches or straight planar elements after finite extension. Lundmark and Corfu (2008) report folds, boudins *and* internal foliations in the Årdal dykes which suggest that some may have deformed as incompetent layers (in surviving granulite facies mineralogies?) and others deformed as competent layers (after hydration of their country rocks?). I use here boudinaged and folded dyke elements that presumably deformed as competent markers.

One or other of the methods described in Talbot (1970) or Talbot and Sokoutis (1995) have been used to successfully analyse in 3D the histories of superposed homogenous strains on scales from outcrop to regional using quartz and neosomes veins, and both competent silicic and incompetent mafic or intermediate dykes in metamorphic rocks of a variety of ages in several regions in 3 continents (see Supplementary data: annotated reference list).

1. 3D data

Despite being counter-intuitive, it is usually easier and more efficient to constrain the *polar snoes* of strain ellipsoids from 3D data than it is to constrain strain ellipses from *lnoes* (Talbot and Sokoutis, 1995, p. 930). However, this turns out not to be so here because Lundmark and Corfu (2008) published only contours to

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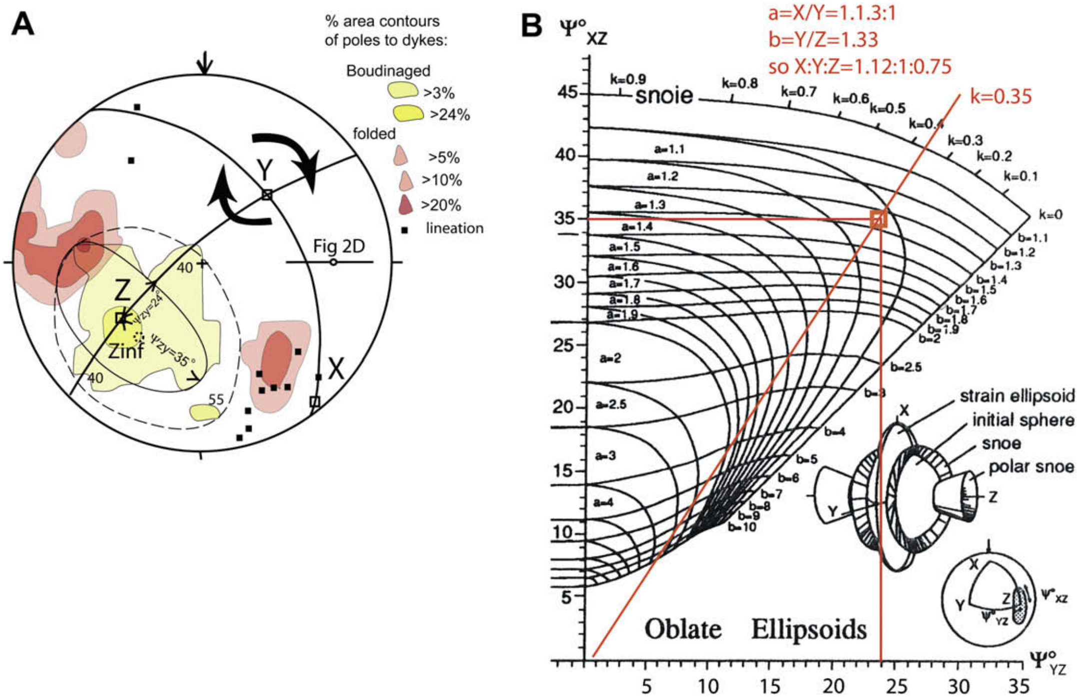

Fig. 1. A. Lower hemisphere equal area projection from Fig. 3E and F of Ludmark and Corfu (2008) with polar snoes (solid and dashed), and principle axes and planes of "best fit" strain ellipsoid added. Black arrows indicate sense of shear around Y. B. Nomogram relating half angles subtended by solid polar snoe to axial ratios of ellipsoid interpreted in A.

poles of deformed dyke elements in a rather large area of heterogeneous strain (rather than their poles in smaller domains of homogeneous strain).

Superposing the contours to boudinaged and folded veins (in figs. 3 G and H of Lundmark and Corfu, 2008) on the same stereographic projection (Fig. 1A here) reveals the symptoms of data having come from heterogeneously strained rocks. Thus the contour of >3% area concentration of poles to boudinaged dykes is too large and irregular to be the ellipse expected of a homogeneous strain; furthermore contours of poles to boudinaged and folded dyke elements overlap. Experience in other regions suggests strongly that plotting poles to planar elements of boudinaged and folded vein for smaller domains would soon find some that strained homogeneously. For these, elliptical *polar snoes* would constrain the orientation of strain ellipsoids for which the shape and axial ratios can be found from Ψzx° and Ψzy°. *Polar snoes* remain recognisable in deformed rocks of all metamorphic facies except the most intense mylonites because material lines (making up the markers) rotate faster than such immaterial lines as the *polar snoe* (Talbot, 1970).

I have added two (solid and dashed) poorly fitting *polar snoes* to the field of overall extension in Fig. 1A here. In Fig. 1B I have plotted the Ψzx° (=35°) and Ψzy° (=24°) for the smaller of the two (solid) on the nomogram published as fig. 4 in Talbot and Sokoutis (1995). The results indicate a minimum strain ellipsoid with $a = X/Y = 1.1.3{:}1$, $b = Y/Z = 1.33$ so that $X{:}Y{:}Z = 1.12{:}1{:}0.75$ with the orientations of the principal axes and planes labelled in Fig. 1A. The ellipsoid indicated is a triaxial oblate ellipsoid with a k value near 0.35.

Lundmark and Corfu (2008) make clear that some of the Årdal dykes were synkinematic. This means that poles to new undeformed dykes may have been intruded parallel to already deformed dykes. This can result in mixing of poles to extended and shortened dyke elements that can be expected to be randomly dispersed around the *polar snoes* of irrotational (pure) bulk strains but near the leading edges of elliptical *polar snoes* of rotational (spinning) bulk strains (see Talbot and Sokoutis, 1995, section A.1.5). The mixture of poles to boudinaged and folded planar elements in Fig. 1A therefore suggest that, as the Årdal dykes deformed, the bulk X and Z axes rotated clockwise (top-to-the-southeast) looking along the Y axis which plunges ~40° to the NE. Potentially, poles to folded boudins may be recognised near the trailing edge of *polar snoes* for this region in future.

The Z axis in Fig. 1A is within the >24% area concentration of poles to boudinaged veins (fig. 3H in Lundmark and Corfu, 2008), and poles to the foliation (Fig. 3F), ~10° NW of the contour of >24% area concentration of poles to both the planar elements of all dykes (fig. 3D), and of the 39 dykes >1 m (fig. 3E). It is also close to the maximum concentration of poles to the compositional layering in the country rock (fig. 3C). The lineations (fig. 3F) fall in a partial small circle with a radius of ~20° around the interpreted X axis. All these relationships are reasonably consistent with the strain ellipsoid constrained and Lundmark and Corfu's (2008) explanation.

The larger dashed elliptical *polar snoe* (Fig. 1A) is elongate along much the same ZX plane (and centred on a Zinf axis shown by a small dashed circle slightly SE of Z) and resembles the field of overall extension that might be expected for the infinitesimal strain ellipsoid indicated by the solid *snoe*. Such a relationship reinforces Lundmark and Corfu, 2008 argument that the Årdal dykes were intruded during a regional strain.

Adding poles to straight "undeformed" dykes would doubtless help as experience indicates that some are undeformed (and unfoliated) but others may be foliated after having elongated uniformly. Plotting poles rather than contours would clarify whether the *polar snoe* is constrained by poles to shortened dykes- or areas of no data (suggesting that the field of poles to extended dykes could stretch across the net as a result of constriction). The latter is unlikely as Lundmark and Corfu (2008) indicate in their fig. 3D that poles to planar dyke elements spread across the projection in what looks suspiciously like a great circle girdle.

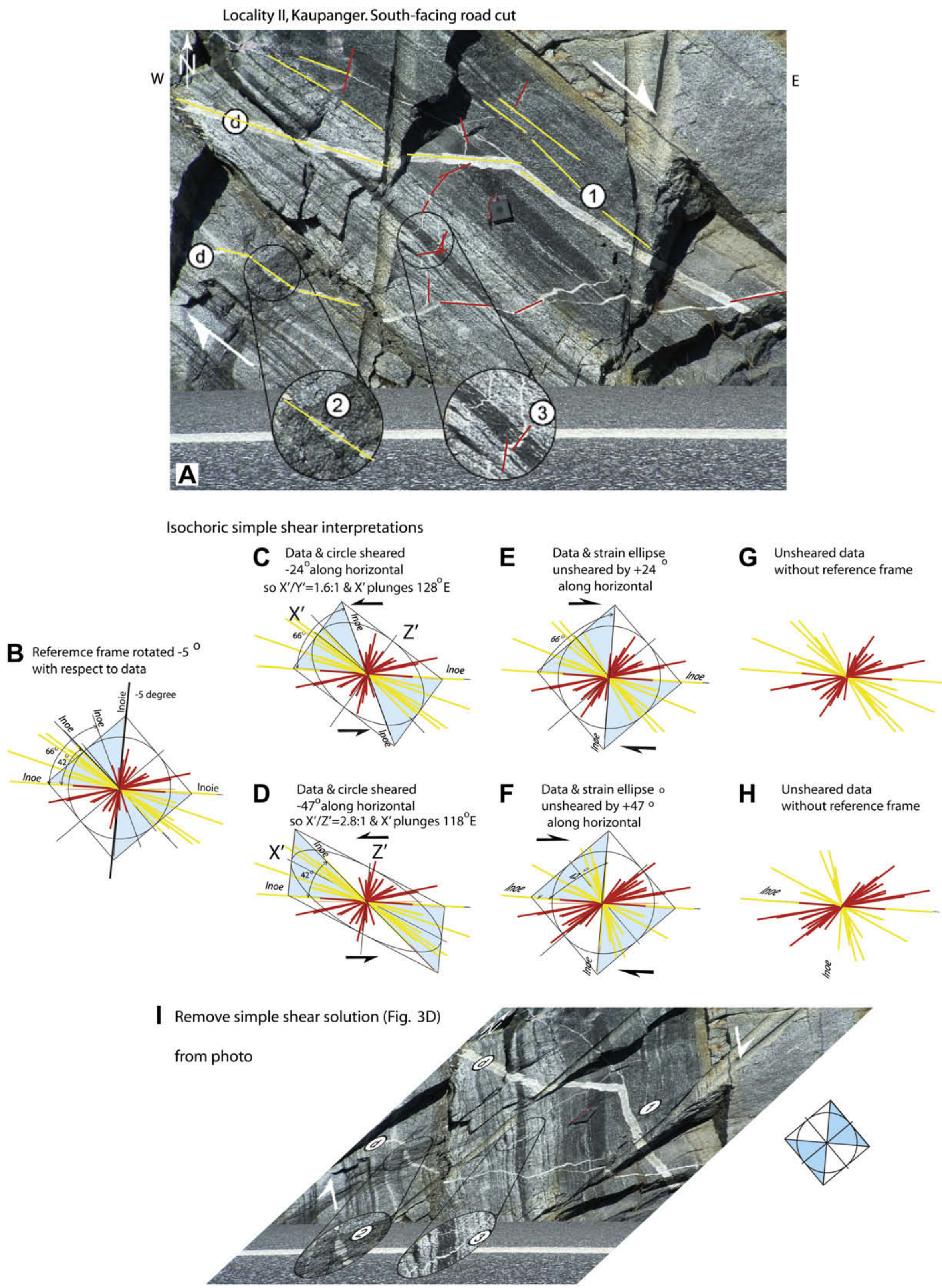

Fig. 2. Interpretation of strain ellipse using Fig. 5 of Ludmark and Corfu (2008). A: Fig. 5 with extended linear dyke elements (yellow) distinguished from shortened elements (red). B: Orientations of yellow and red bars from A transposed to pass through centre of reference frame of initial circle and square. Angles between maximum and minimum possible lnoes labelled. C: Initial circle and square in B sheared empirically to account for orientations of elongated and shortened elements and lnoes 65 degrees apart. D: Initial circle and square in B sheared to fit lnoes 42 degrees apart. E: Initial circle and square recovered by undoing shear illustrated in C. E: Yellow and red bars after removal of shear shown in C. F:Initial circle and square recovered by removing shear in D. G: yellow and red bars after removal of shear indicated in C. H: Yellow and red bars after removal of shear in D. I: Removal of shear shown in D from photo (plus "initial circle and square") (For interpretation of colour please refer to the web version of this article).

2. Analysis of 2D data from Kaupanger

Fig. 2A shows Årdal dykes (d) emplaced obliquely to the compositional layering of the metatroctolite in a south-facing road cut at Locality II, Kaupanger (copied from fig. 5 from Lundmark and Corfu, 2008). I have added 15 yellow bars along linear dyke elements that I assume have undergone finite extension and 19 red bars are along shortened elements. Of the 34 coloured bars, only two of different colours have the same orientation; all the remainder are self exclusive in orientation as expected of a homogeneous strain. All 34 bars have been translated to pass through the centre of a horizontal and vertical reference frame rotated $-5°$ in Fig. 2B where they constrain the orientations of the two *lnoes* at mutual angles of ($2\Psi°$) 42° and 66° that describe the maximum and minimum strains recorded by the dykes. The diagonals of the superposed square represent the two *lnoies* of the initial circle rotated so that one of the *lnoies* parallels one of the *snoes*.

In Fig. 2C and D I have empirically deformed the circle, square and *lnoies* centred on the reference frame in Fig. 2B to produce isochoric simple shear ellipses with *lnoes* parallel to the two sets labelled in Fig. 2B. Fig. 2C and D illustrate ellipses with labelled X'/Z' ratios of 3.6 and 5.6:1 and X' plunging 126° and 117°E as a result of isochoric simple angular shears of $-54°$ and $-63°$ respectively along a horizontal shear plane. The thick solid W-E vertical line labelled Fig. 2D in Fig. 1A represents the field of extension seen in Fig. 2D; notice that X' is close to the *XY* plane constrained using the 3D data. The orientation of this section through the extension field is confusing because the 2D data involve lines and the 3D data involve poles to planes.

Fig. 2E and F illustrates the results of reversing the strains indicated in Fig. 2C and D. Notice that both the X' axes interpreted from the folds and boudins in the Årdal dykes are close to the compositional layering of the country rocks. Fig. 2G and H remove the strains shown in Fig. 2E andF from the data (Fig. 2B) without the ellipse and square and Fig. 2I removes the larger of the two horizontal simple shears from the photograph (Fig. 2A).

Lundmark and Corfu (2008 p. 923) considered the section in Fig. 2A here to be typical of the locality and used the cumulative offsets of a dyke that crosses successive mafic layers across the ca. 4 m width of outcrop seen in that photograph to estimate the local minimum angular shear as 11°. This compares with a horizontal shear with $-54°$ in Fig. 2C here so that $X'/Y' = 3.6$ with X' plunging 126°E, parallel to the layering.

3. Discussion

The 2D interpretations shown in Fig. 2 assume that the outcrops are planar, that I have distinguished extended and shortened dyke elements correctly, and that the strains of the dyke elements used was essentially homogeneous and isochoric. In fact, as emphasised by Lundmark and Corfu, 2008, some dyke elements with similar orientations appear deformed to different degrees implying that some dykes were intruded synkinematically. Assuming that the strain ellipses shown in Fig. 2C and D are appropriate, there is no unique solution for their deformation path so the paths used to undeform the data are open to discussion.

Looking at Fig. 2 it is easy to accept Lundmark and Corfu's (2008) conclusions that the Årdal dyke swarm at Kaupanger was intruded oblique to the layering due to an external stress field and that shearing is ubiquitous. Their claim that "the deformation primarily reflects top-to-southeast heterogeneous simple shear parallel to the compositional layering of the country rock" is surprising for Fig. 2C and D indicate that shearing to rotate the longer principle axis parallel to the layering was horizontal with top-to-the-northwest. However, the extension field for the ellipses in Fig. 2C and D have awkward orientations relative to the principal planes in Fig. 1A which inverts the sense of shear visible in the profile with respect to the sense of shear on the 3D projection. The solid line on Fig. 1A represents the extension field bound by the great circle lnoes shown in Fig. 2D. Surprisingly, the top to the left shear of X' apparent in the profile of Fig. 2D is entirely consistent with the top to the SE shear abut Y obvious in 3D on Fig. 1A. This complication merely emphasises that it is easier to deal with 3D poles rather than 2D lines.

I hope that I have illustrated here the potential of constraining the *snoes* or *polar snoes* for strain ellipses or ellipsoids that measure the strains of rock domains that have deformed homogeneously. I suggest to Lundmark and Corfu that the application of this general approach would add considerable detail to their strain analysis. Finally, I ask them if any of foliated the Årdal dykes display the mullions that would indicate their deformation as incompetent layers, possibly while their country rocks were still granulitic.

Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.jsg.2008.11.003.

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