Journal of Structural Geology 27 (2005) 781–784

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Discussion on "Evidence for non-plane strain flattening along the Moine thrust, Loch Strath nan Aisinnin, North-West Scotland" by Mathew Strine and Steven F. Wojtal☆

G.I. Alsop[a,*], R.E. Holdsworth[b]

[a]Crustal Geodynamics Group, School of Geography & Geosciences, University of St. Andrews, St Andrews, Fife KY16 9AL, UK
[b]Reactivation Research Group, Dept. of Earth Sciences, University of Durham, Durham DH1 3LE, UK

Received 14 September 2004
Available online 5 March 2005

Based on an interpretation of field relationships and quartz CPO data, Strine and Wojtal (2004) propose that following WNW-directed thrusting across the Moine Thrust Zone in the Loch Strath nan Aisinnin area, there was a relatively late phase of NNW-directed shearing. This late-stage movement, which Strine and Wojtal tentatively suggest may relate to local warping of the thrust surface above a culmination, possibly involving gravitational collapse, has not been recorded previously in this classic geological area and merits further discussion. Strine and Wojtal base their interpretation on an analysis of recrystallized grains in quartzites below the Moine Thrust, together with the orientation of mesoscopic fold hinges and suggest a ~45° clockwise shift in the azimuth of the shearing direction from 286° to 331°. In this discussion we present new field data collected from the Loch Strath nan Aisinnin study area, which lends support to an alternative and more straightforward kinematic interpretation to that of Strine and Wojtal.

The dominant mineral extension lineation (Ln) is typically defined by quartz and consistently plunges gently towards the ESE in both the footwall quartzites and Moine psammites forming the hanging wall to the Moine Thrust (Fig. 1a). This mineral lineation is ubiquitously developed within the gently east-dipping mylonitic foliation (Sn) along the length of the Moine Thrust, and is regarded as paralleling the trend of tectonic movement. As noted by Strine and Wojtal, this mineral lineation (Ln) and the associated foliation (Sn) are commonly refolded by mesoscopic folds in both the footwall and hanging wall of the Moine Thrust. Within the Loch Strath nan Aisinnin area, Strine and Wojtal note that fold hinges typically plunge towards the SSE (mean 151°) oblique to Ln. Importantly, they suggest that these relatively late-stage folds have sheath-like geometries, with hinges interpreted as lying parallel to a late phase of (331°) NNW-directed movement along the thrust zone. However, our observations demonstrate that the great majority of these folds exhibit large interlimb angles (that may exceed 90°), which, coupled with a typical lack of widespread eye-shaped closures, suggests that most of the relatively late-stage folds in the Loch Strath nan Aisinnin area are *not* sheath folds. Detailed studies of sheath folds elsewhere within the Moine Supergroup indicates that fold hinges are rarely rotated into complete parallelism with the transport direction and that small angles of obliquity are commonly preserved (e.g. Alsop and Holdsworth, 1999, 2004a,b). Furthermore, the orientation of fold hinges may be highly variable, resulting in the classic stereographic fold hinge girdle patterns distributed over arcs of 180°. Such folds (and calculated sample means) are therefore of little value in defining tectonic transport without further careful analysis.

Strine and Wojtal confine their detailed analysis to the area immediately adjacent to Loch Strath nan Aisinnin on the southwestern side of a culmination that defines a recess in the mapped trace of the Moine Thrust (Fig. 1a). Minor variations in the mapped trace of the Moine Thrust immediately north of Loch Strath nan Aisinnin are controlled by local topography. Strine and Wojtal therefore sampled only the southern flank of the overall culmination in which they carefully record that fold hinges are typically SSE-plunging and therefore clockwise of the ESE-plunging

---

☆doi of original article: 10.1016/j.jsg.2004.02.011

* Corresponding author

E-mail addresses: gia@st-andrews.ac.uk (G.I. Alsop), R.E.Holdsworth@durham.ac.uk (R.E. Holdsworth).

doi:10.1016/j.jsg.2005.01.003

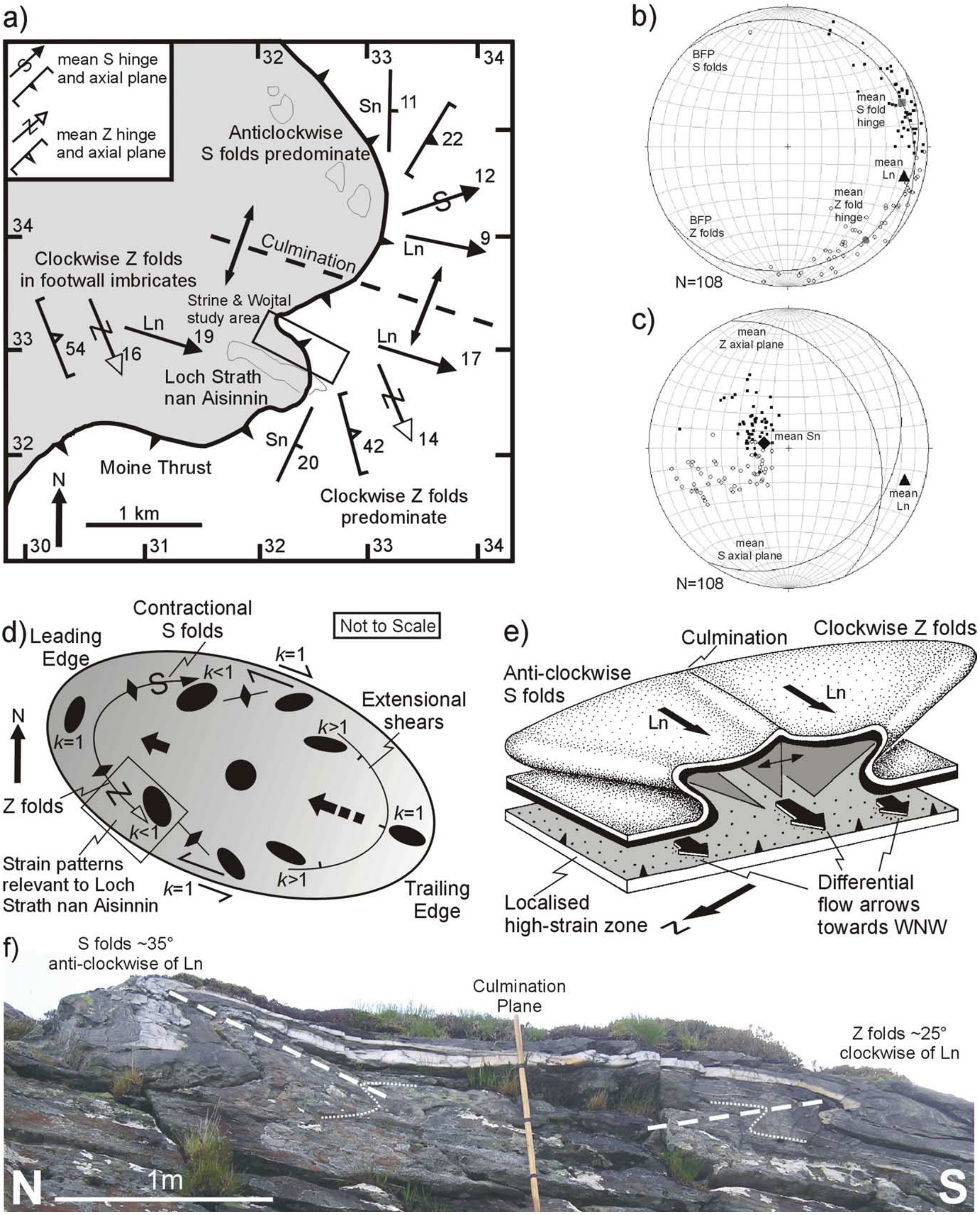

Fig. 1. (a) Simplified geological map of the Loch Strath nan Aisinnin area illustrating the trace of the Moine Thrust together with the dominant S and Z mean fold data from the northern and southern flanks of the WNW-trending culmination. Mean foliation (Sn) and lineation (Ln) data are also shown. The detailed case study area of Strine and Wojtal (2004) is indicated by the box. The reference grid refers to the UK National Grid with the map area falling within the NC prefix quadrangle (note that Strine and Wojtal display incorrect longitudes on their fig. 2). Equal area lower hemisphere stereographic projections of structural

Ln, which is refolded. Our observations concur with these relationships and we additionally note that these fold hinges typically display a Z-fold asymmetry when viewed down plunge (Fig. 1b). We have also collected data from the opposing northern flank of the mapped culmination in the Moine Thrust where fold hinges are typically NE-plunging and *anti-clockwise* of Ln, which they also refold (Fig. 1a). These folds typically display S-fold asymmetries (Fig. 1b). Thus, Z- and S-fold hinges are developed, respectively, clockwise and anti-clockwise relative to Ln on either side of the major culmination. Both Z- and S-fold hinges define stereographic girdle patterns over arcs of 90°, with the best-fit planes (BFP) to each girdle notably intersecting sub-parallel to the ESE-plunging Ln. We have also analysed the axial-planar orientations of S and Z folds and note that S-fold axial planes typically trend clockwise of foliation (Sn) strike, whilst Z-fold axial planes are anti-clockwise of Sn (Fig. 1c). On the stereographic projection, the intersection of mean S- and Z-axial planes is once again sub-parallel to the ESE-plunging Ln (Fig. 1c).

The observations and relationships noted above are identical to fold and fabric patterns described elsewhere in the Moine Thrust and overlying Moine thrust sheet (Holdsworth, 1990; Alsop and Holdsworth, 1993, 2002, 2004a; Alsop et al., 1996; Holdsworth et al., 2001). We interpret such patterns as reflecting flow perturbation folding in which variable flow along ductile high strain zones within mylonites generates differential shear (Fig. 1d–f; cf. Coward and Potts, 1983; Platt, 1983; Ridley, 1986). Interestingly, possible examples of such detachments are documented by Strine and Wojtal (2004) (e.g. their fig. 5c). Thus, in our model, sinistral differential shear is marked by Z-fold hinges clockwise of transport, and dextral differential shear is associated with anti-clockwise-trending S-fold hinges (Fig. 1d–f). The vergence of minor folds together with hinge-lineation obliquity reverses across the transport-parallel and foliation-normal culmination surface that bisects the flow cell (Fig. 1d and e). Such minor folds may *not* be interpreted as reflecting sheath folds since S and Z folds define distinct and consistent senses of obliquity about Ln that are typically lacking around the upper and lower limbs of major sheath folds (e.g. see Alsop and Holdsworth, 2004b). Importantly, these distinct reversals in minor fold vergence, coupled with the intersection of mean S- and Z-axial planes and best-fit planes to fold hinge girdles can be used to help define the direction of tectonic transport (Alsop and Holdsworth, 2002, 2004a). We therefore interpret these observations of 'later phase' folding as reflecting flow perturbations that are kinematically linked to continued WNW-directed thrusting.

The possible presence of flow perturbation structures also has very important implications for the interpretation of grain shape fabrics and strain presented by Strine and Wojtal. Coward and Potts (1983) have elegantly demonstrated that the development of differential shearing (their 'layer-normal shear', γ_2) on the flanks of flow perturbations can lead to very significant variations in both the shape and orientation of finite strain ellipsoids within thrust sheets without recourse to along-strike changes in length on a regional scale (Fig. 1d) (see also Coward and Kim, 1981). According to the analyses of Coward and Potts (1983) (e.g. see their figs. 18, 23 and 24 and accompanying text), the predominance of flattening strains recorded by Strine and Wojtal could be explained by a bulk flow-perturbation-related strain during regional WNW thrusting involving components of layer-parallel shortening, layer-parallel simple shear (γ_1) and layer-normal simple shear (γ_2). Our interpretation suggests that all the data presented by Strine and Wojtal (2004) lies on the southern flank of the flow perturbation where the Z-fold patterns are consistent with a component of sinistral differential (layer-normal) shear (Fig. 1d). This differential shear could easily lead to localised clockwise rotation of the finite stretching axes away from regional transport, i.e. from WNW to NNW, particularly if the layer-parallel shortening strains are modest (Fig. 1d) (Coward and Potts, 1983, fig. 18).

In conclusion, we suggest that the distinct and consistent fold and fabric relationships in the Loch Strath nan Aisinnin area reflect folding and localised complex strain patterns formed by flow perturbations during a single progressive deformation within WNW-directed high-strain zones. This

data collected from the study area are shown in (b) and (c). In both stereoplots Z folds ($N=55$) are shown with open circles whilst S folds ($N=53$) are shown with closed squares. In (b) Z- and S-fold hinges (with means given by grey symbols) are clockwise and anti-clockwise of the mean extension lineation (Ln), respectively. Both Z- and S-fold hinges define fold hinge girdles marked by best-fit planes (BFP) that intersect sub-parallel to mean (104°) Ln. (c) Poles to Z- and S-fold axial planes define distinct clusters on either side of the pole to the mean foliation (Sn). Note that the intersection of the great circles representing the mean S- and Z-axial planes is sub-parallel to the mean extension lineation (Ln). (d) Plan view of a schematic (not to scale) elliptical flow perturbation and associated strain patterns developed in the plane of a detachment. To aid comparison, the perturbation is aligned with the transport-parallel (WNW-trending) culmination shown in (a) above. The perturbation represents a relative increase in the local flow velocity with accelerating flow (marked by the broken arrow) associated with extensional shears at the trailing edge, and decelerating flow (solid arrow) marked by contractional folds at the leading edge. S folds and associated oblate strains ($K<1$) are developed anti-clockwise of transport, whilst Z folds and associated oblate strains (as observed at Loch Strath nan Aisinnin) are developed clockwise of transport. (e) Schematic 3D cartoon illustrating the flow perturbation fold model. Perturbations in WNW-directed ductile flow are developed on the underlying high strain zone with the larger arrow representing greater flow velocity. Variable flow results in differential dextral shear generating S folds trending anti-clockwise of Ln, whilst differential sinistral shear generates clockwise-trending Z folds. (f) Photograph looking ESE down the plunge of an upright mesoscopic culmination developed in mylonitised psammites of the Moine Nappe (NC 33381 32640). The gently east dipping foliation and sheared quartz veins are folded in to Z- and S-vergent minor folds (highlighted by dotted lines) developed clockwise and anti-clockwise of the (094°) lineation, respectively. The strike of the associated Z- and S- axial planes (highlighted by dashed lines) also display 50° clockwise and 65° anti-clockwise obliquity about the transport-parallel culmination plane (marked by the 1-m hiking stick). We interpret this (mesoscopic) outcrop in terms of the overall flow perturbation folding model illustrated in (e). Refer to text for further discussion.

model is wholly consistent with the quartz CPO data presented by Strine and Wojtal (2004), which indicate top-to-the-WNW thrusting. In our view, the field and microstructural data do not support the existence of the late-stage episode of NNW-directed shearing invoked by Strine and Wojtal. Our criticisms illustrate further the importance of taking mesoscopic fold data into consideration during microstructural studies of ductile shear zones (see also Carreras et al., 1977; Evans and White, 1984; Law, 1990).

References

Alsop, G.I., Holdsworth, R.E., 1993. The distribution, geometry and kinematic significance of Caledonian buckle folds in the western Moine Nappe, northwestern Scotland. Geological Magazine 130, 353–362.

Alsop, G.I., Holdsworth, R.E., 1999. Vergence and facing patterns in large-scale sheath folds. Journal of Structural Geology 21, 1335–1349.

Alsop, G.I., Holdsworth, R.E., 2002. The geometry and kinematics of flow perturbation folds. Tectonophysics 350, 99–125.

Alsop, G.I., Holdsworth, R.E., 2004a. Shear zone folds: records of flow perturbation or structural inheritance?, in: Alsop, G.I., Holdsworth, R.E., McCaffrey, K.J.W., Hand, M. (Eds.), Flow Processes in Faults and Shear Zones Special Publication of the Geological Society, London, 224, pp. 177–199.

Alsop, G.I., Holdsworth, R.E., 2004b. The geometry and topology of natural sheath folds: a new tool for structural analysis. Journal of Structural Geology 26, 1561–1589.

Alsop, G.I., Holdsworth, R.E., Strachan, R.A., 1996. Transport-parallel cross folds within a mid-crustal Caledonian thrust stack, northern Scotland. Journal of Structural Geology 18, 783–790.

Carreras, J., Estrada, A., White, S., 1977. The effects of folding on the c-axis fabrics of a quartz mylonite. Tectonophysics 39, 3–24.

Coward, M.P., Kim, J.H., 1981. Strain within thrust sheets, in: McClay, K.R., Price, N.J. (Eds.), Thrust and Nappe Tectonics Special Publication of the Geological Society, London, 9, pp. 275–292.

Coward, M.P., Potts, G.J., 1983. Complex strain patterns developed at the frontal and lateral tips to shear zones and thrust zones. Journal of Structural Geology 5, 383–399.

Evans, D.J., White, S.H., 1984. Microstructural and fabric studies from the rocks of the Moine Nappe, Eriboll, NW Scotland. Journal of Structural Geology 6, 369–389.

Holdsworth, R.E., 1990. Progressive deformation structures associated with ductile thrusts in the Moine Nappe, Sutherland, N. Scotland. Journal of Structural Geology 12, 443–452.

Holdsworth, R.E., Strachan, R.A., Alsop, G.I., 2001. Geology of the Tongue District. Memoirs of the British Geological Survey. Sheet 114E (Scotland), 76pp.

Law, R.D., 1990. Crystallographic fabrics: a selective review of their applications to research in structural geology, in: Knipe, R.J., Rutter, E.H. (Eds.), Deformation Mechanisms, Rheology and Tectonics Special Publication of the Geological Society, London, 54, pp. 335–352.

Platt, J.P., 1983. Progressive refolding in ductile shear zones. Journal of Structural Geology 5, 619–622.

Ridley, J., 1986. Parallel stretching lineations and fold axes oblique to displacement direction—a model and observations. Journal of Structural Geology 8, 647–654.

Strine, M., Wojtal, S.F., 2004. Evidence for non-plane strain flattening along the Moine thrust, Loch Strath nan Aisinnin, North-West Scotland. Journal of Structural Geology 26, 1755–1772.