# Fold distortion: A new indicator of tectonic transport direction

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## ABSTRACT

In the Monte Reventino area of Calabria (southern Italy), minor fold axes provide directional markers on the limbs and in the hinges of major inclined folds formed of mechanically strong greenschist encased in weak serpentinite. These markers show that the opposite limbs of major folds have been rotated in opposite directions during Alpine-age emplacement of an overriding nappe. This fold distortion can be explained by tectonic transport roughly parallel to the axes of the major folds, and the sense of this movement can be determined from the pattern of rotated minor fold axes.

## INTRODUCTION

While studying an area of low-grade metamorphic rocks emplaced as Alpine-age nappe sheets in Calabria (the toe of the Italian boot), I have mapped a pile of peculiar distorted folds whose geometry makes it possible to determine the approximate direction of nappe transport. This study is the subject of an extensive forthcoming paper, but in the meantime, a brief description of this new technique for determining nappe transport direction may be useful to workers in other thrust belts.

## PATTERN OF DISTORTED MINOR FOLDS

Figures 1 and 2 show a geologic map and cross section of Monte Reventino (lat 39°02.4′N, long 16°18.6′E, 1,417-m elevation) where a kilometre-scale lens of deformed, metamorphosed ophiolite (serpentinite and banded greenschist) is caught along a major thrust contact between an upper nappe of pre-Mesozoic mica schist and a lower nappe of Cretaceous epimetamorphic phyllite and quartzite. In the ophiolite lens, the $S_1$ foliation of the greenschist is deformed into a pile of inclined, hundred-metre-scale major $F_2$ folds with axial surfaces dipping moderately to the southeast and axes plunging to the east. Parasitic minor $F_2$ folds are very abundant in the greenschist, and it is the pattern of alternating asymmetry of these minor folds that most clearly marks the limbs and hinges of the major folds. The greenschist fold pile is almost completely encased in sheared serpentinite, which occupies the cores of the major greenschist folds and forms the rest of the ophiolite lens.

The minor folds are classed as asymmetric "N-folds" (showing generally northward overturn and occurring on "N-limbs" of the major folds) or "S-folds" (generally southward overturn on major "S-limbs") or as symmetric "C-folds" (cascade folds in major fold hinges). In this characteristic pattern of parasitic folds (Ramsay, 1956; Ramberg, 1963, 1964), one expects the axes of the major folds and of all three types of minor folds to be statistically parallel. However, the fabric data of Table 1 show that this is definitely *not* the case in the Monte Reventino greenschist. The axes of minor folds show a striking trimodal distribution (Fig. 3), with N-folds plunging to the southeast, C-folds to the east, and S-folds to the northeast. The nonintersecting $\alpha_{95}$ circles show that the mean orientations of the three types of fold axes are significantly different at the 95% confidence level. Orientation data from twelve hinge and limb domains show that as one descends through the fold pile, passing through the oscillating sequence N-limb, hinge, S-limb, hinge, N-limb, . . . . , the trend of minor fold axes also oscillates: SE, E, NE, E, SE, . . . .

## INTERPRETATION

I have tried and discarded several inadequate explanations for this peculiar pattern of minor fold axes. Although the $F_2$ folds have been distorted and the rocks thus show polyphase deformation, the post-$F_2$ distortion is not folding, as the term is generally understood, and techniques for determining movement direction in areas of multiple folding (Ramsay, 1960) are not applicable. In addition, this is not the pattern discussed by Hansen (1971); in the present case the separation arc between the N- and S-folds is filled by the axes of symmetric folds, and whereas Hansen's pattern only applies to a single limb of a major fold, here the pattern does not appear unless one includes the hinge and both limbs.

Prior to final emplacement of the nappes, deformation of the greenschist produced a pile of recumbent major folds and their associated parasitic minor folds. All fold axes trended due east, axial surfaces were horizontal, and the mechanically strong greenschist was encased in a much weaker sheared serpentinite. Figure 4 illustrates a mechanism that seems to be capable of explaining the observed dispersion of minor fold axes.

Subsequently, during final nappe emplacement, the ophiolitic lens was caught along a major thrust surface as the overriding nappe moved either approximately to the east or approximately to the west, that is, roughly *parallel* to the earlier-formed fold axes. This parallelism of nappe transport and fold axes could have arisen either (1) through rotation of the axes during simple shear, a phenomenon that is receiving increasing attention

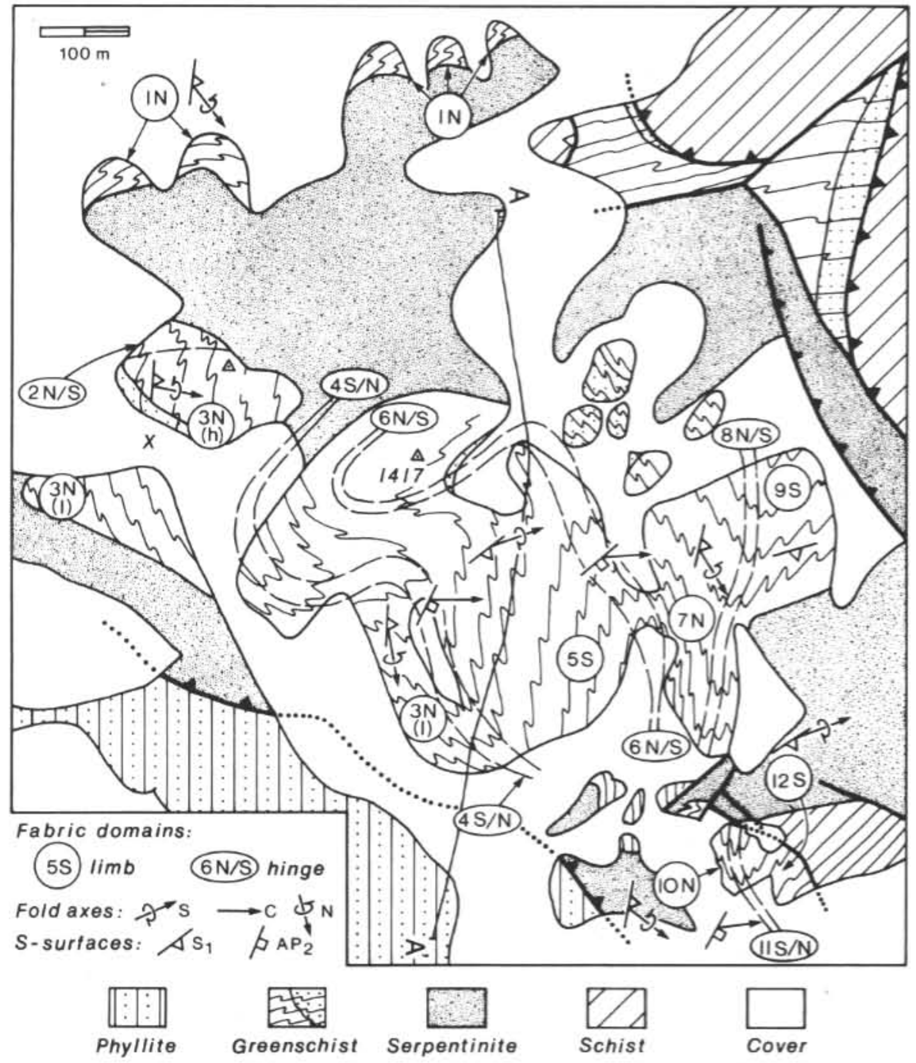


Figure 1. Geologic map of the summit area of Monte Reventino, based on field mapping at 1:5,000. The ornamentation in the greenschist outcrop area shows schematically the trace of $S_1$ banding and the orientation of minor $F_2$ folds; retrograded greenschist is dotted. Structure symbols are domain means from Table 1. The gross outcrop pattern is controlled by the gentle eastward dip of thrust contacts and of axial surfaces in the greenschist $F_2$ folds. The sharply curving traces of domains 4S/N and 6N/S near the 1,417-m summit are due to gentle, late refolding that has locally flattened the $AP_2$ axial surfaces so that they crop out roughly along contour lines.

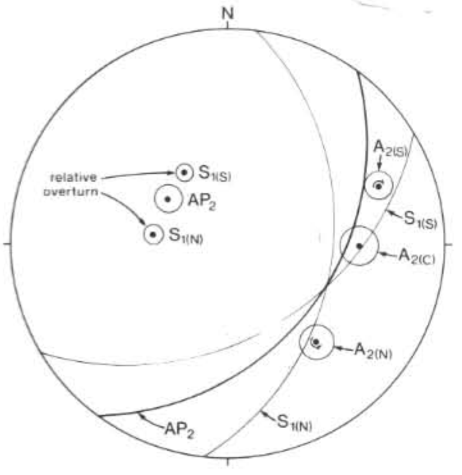


Figure 3. Summary of greenschist structural data; plotted here are the mean values for each of the three groups of domains (N, C, and S), as listed in Table 1. The unusual trimodal distribution of $A_2$ fold axes is the basis for determining the direction of tectonic transport during an episode of nappe movement that postdated formation of the $F_2$ folds. Lower-hemisphere, equal-angle projection.

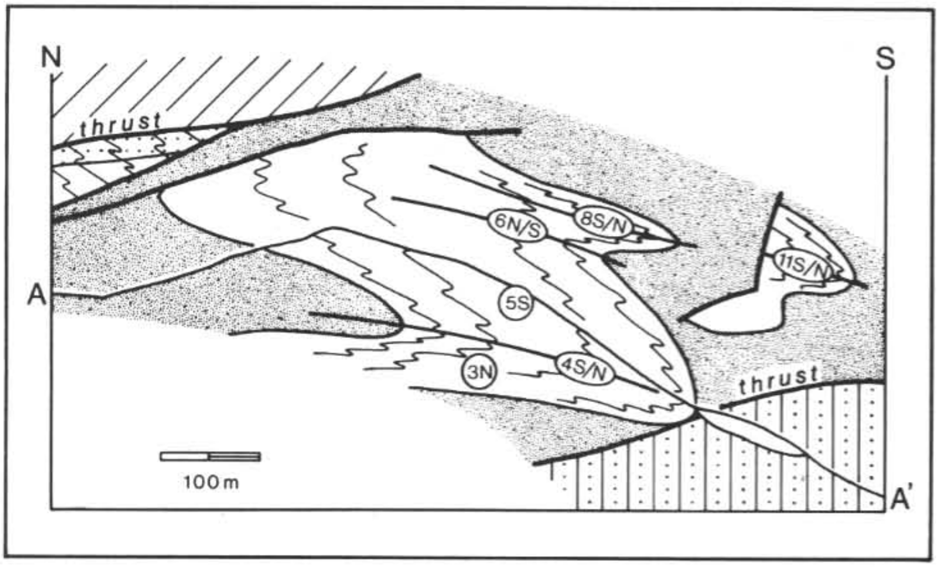


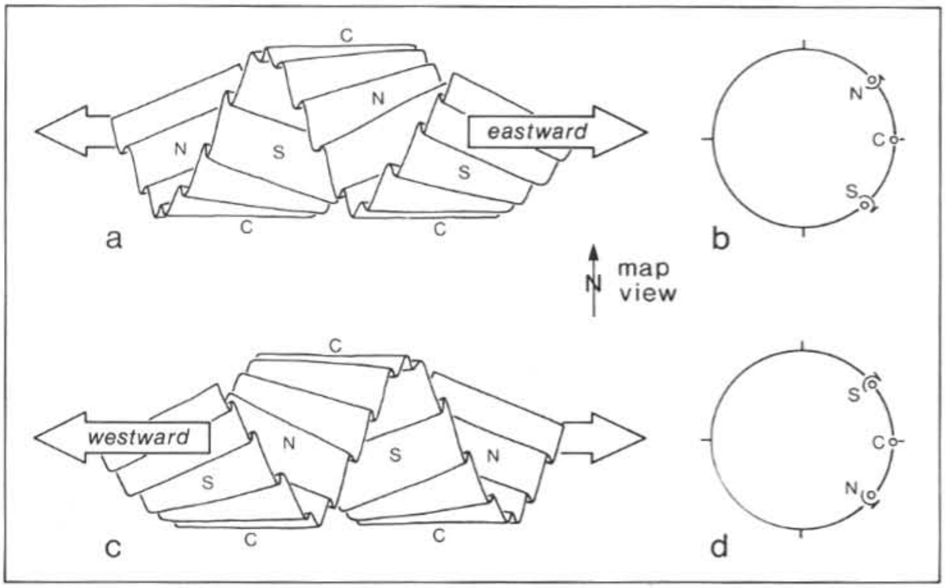
Figure 2. Profile of the main folded greenschist mass, projected onto a plane normal to the major $A_2$ fold axes. Symbols as in Figure 1. A-A′ is the intersection of the profile and the topographic surface; the nonlinear trace of the profile on Figure 1 results from the fact that the projection plane strikes due north and dips 65°W.

Figure 4. Twisting of $F_2$ folds in the greenschist. This mechanism is proposed to account for the observed pattern of minor $A_2$ fold axes. Prior to nappe movement, an undistorted pile of folds is in a recumbent position (not shown) with east-trending axes. The subsequent fold distortion and the resulting orientation of minor fold axes are shown in (a) and (b) for eastward thrusting, and in (c) and (d) for westward thrusting. The pattern of minor fold axes at Monte Reventino (Fig. 3) corresponds to (d) and thus leads one to the conclusion that thrusting was directed generally westward.

TABLE 1. FABRIC DATA FOR THE MONTE REVENTINO GREENSCHIST

| Domain | $D_R$ (°) | $I_R$ (°) | N | R | K | $\alpha_{95}$ (°) | Azimuthal distribution, uniform | Angular distribution, Fisherian |
|---|---|---|---|---|---|---|---|---|
| Fold axes ($A_2$) | | | | | | | | |
| 1N | 141.9 | 32.1 | 13 | 12.30 | 17.3 | 10.2 | Yes | Yes |
| 3N | 130.5 | 21.4 | 28 | 22.99 | 5.3 | 12.9 | No | Yes |
| 3N(h) | 103.5 | 18.7 | 16 | 15.26 | 20.3 | 8.3 | Yes | Yes |
| 3N(1) | 168.1 | 18.0 | 12 | 11.31 | 16.0 | 11.1 | Yes | Yes |
| 7N | 147.6 | 26.4 | 18 | 16.96 | 16.3 | 8.8 | Yes | Yes |
| 10N | 127.1 | 36.6 | 5 | 4.92 | 51.2 | 10.7 | Yes | Yes |
| All N-limb domains | 137.7 | 26.7 | 64 | 56.52 | 8.4 | 6.5 | Not determined | |
| 6N/S | 97.3 | 34.2 | 21 | 18.11 | 6.9 | 13.0 | Yes | Yes |
| 4S/N | 89.6 | 25.2 | 13 | 12.18 | 14.7 | 11.1 | Yes | Yes |
| 11S/N | 83.2 | 17.6 | 11 | 10.55 | 22.2 | 9.9 | Yes | Yes |
| All hinge domains | 91.1 | 27.4 | 45 | 40.40 | 9.6 | 7.3 | Not determined | |
| 5S | 67.8 | 17.6 | 24 | 23.14 | 26.8 | 5.8 | Yes | Yes |
| 12S | 69.1 | 14.6 | 12 | 11.66 | 32.6 | 7.7 | Yes | Yes |
| All S-limb domains | 68.3 | 16.6 | 36 | 34.79 | 28.9 | 4.5 | Not determined | |
| Foliations (poles to $S_1$ on dominant limbs of asymmetric minor $F_2$ folds) | | | | | | | | |
| 1N | 276.6 | 50.9 | 14 | 12.41 | 8.2 | 14.7 | Yes | Yes |
| 3N | 273.2 | 54.7 | 27 | 25.45 | 16.8 | 6.9 | Yes | Yes |
| 7N | 280.6 | 48.1 | 28 | 26.11 | 14.3 | 7.4 | Yes | Yes |
| 10N | 280.2 | 54.3 | 9 | 8.71 | 28.5 | 9.8 | Yes | Yes |
| All N-limb domains | 277.5 | 51.7 | 78 | 72.57 | 14.2 | 4.4 | Not determined | |
| 5S | 319.0 | 48.9 | 24 | 23.16 | 27.5 | 5.7 | Yes | Yes |
| 9S | 343.2 | 45.2 | 20 | 19.07 | 20.5 | 7.3 | No | Yes |
| 12S | 324.9 | 47.0 | 13 | 12.81 | 65.2 | 5.1 | Yes | Yes |
| All S-limb domains | 329.1 | 47.7 | 57 | 54.59 | 23.2 | 4.0 | Not determined | |
| Axial planes (poles to $AP_2$ of symmetric minor $F_2$ folds) | | | | | | | | |
| 6N/S | 312.3 | 42.6 | 8 | 7.87 | 55.4 | 7.5 | Yes | Yes |
| 4S/N | 295.3 | 61.1 | 4 | 3.94 | 58.7 | 12.0 | Yes | No |
| 11S/N | 300.8 | 59.8 | 4 | 3.94 | 53.6 | 12.6 | Yes | No |
| All hinge domains | 306.6 | 51.8 | 16 | 15.53 | 31.9 | 6.6 | Not determined | |

*Note:* $D_R$, $I_R$: declination and inclination of resultant (mean) vector; N: number of measurements; R: length of resultant vector; K: precision parameter; $\alpha_{95}$: semi-angle of cone of 95% confidence. Distributions for means not determined because of space limitations in program.



(Kvale, 1953; Christie, 1963; Bryant and Reed, 1969; Sanderson, 1973; Escher and Watterson, 1974; Carmignani and others, 1978), or (2) through a change in the direction of nappe movement.

The plane of simple shear movement during nappe transport was approximately parallel to the axial surfaces of the greenschist folds. The greenschist is a strong member in a weak matrix of sheared serpentinite. The limb of each major fold cuts diagonally up through the planes of simple shear and was thus acted upon by a torque; this torque was in opposite directions on opposite limbs of major folds. The effect of these opposite torques was to distort the pile of major greenschist folds in the fashion shown in Figure 4, with deformation of the weaker serpentinite controlled by the strong greenschist. Because the minor $A_2$ axes lay in the axial plane $AP_2$ before fold distortion, and since this distortion involved shear and rotation on planes approximately parallel to $AP_2$, the minor $A_2$ axes fall close to the $AP_2$ trace after the deformation (Fig. 3).

The important point is that because of the greater strength of the greenschist, rigid-body rotation was more important than internal deformation of the major fold limbs. If the greenschist and the serpentinite had had the same strength, the fold pile would have been deformed by homogeneous simple shear, and the major fold limbs would not have rotated.

## DETERMINATION OF MOVEMENT DIRECTION

What makes this distortion kinematically informative is that the minor fold axes provide markers that record the rotation of the major fold limbs, and simple shear in the two opposing senses produces opposite patterns of fold distortion (Fig. 4). Eastward transport of the overriding nappe deflects minor N-folds into the northeast quadrant, whereas westward transport deflects them to the southeast. Thus, in cases where this process has occurred, the pattern of distorted minor fold axes can be used to infer the approximate transport direction of the overriding block. At Monte Reventino, this technique indicates that the overriding nappe moved in a roughly westward direction.

## TIMING

At Monte Reventino, the question immediately arises whether the fold distortion really occurred at the same time as nappe emplacement. This question can be answered in the affirmative because of the presence, in a few places, of chlorite schist formed by retrograde metamorphism of the greenschist (as is demonstrated by mineral relicts and by the fact that the foliation and the minor folds in the greenschist can be traced into the adjacent chlorite schist with no change in style or orientation). The soft, easily degraded chlorite schist probably also underlies areas of soil, because several of these areas have adjacent chlorite schist outcrops. Such soil-covered areas are surrounded by massive greenschist that crops out prominently.

Chlorite schist is found as an alteration product of the greenschist immediately beneath the overlying nappe of pre-Mesozoic mica schist (Figs. 1, 2); this is interpreted to mean that retrograding of the greenschist occurred during final emplacement of the overlying nappe. Chlorite schist (including areas of soil cover) is also found at several places along the axial surfaces of major folds in the greenschist. As shown in Figure 4, the axial surfaces of major folds are planes where the rotation direction of major fold limbs reverses; these planes would thus be loci of shearing within the greenschist. This shearing would facilitate passage of fluids, which explains the concentration of retrograde metamorphism along the axial surfaces. Although there could possibly have been more than one episode of retrograde metamorphism, the presence of chlorite schist both on the axial surfaces of major folds and beneath the overlying nappe provides strong evidence that nappe emplacement and fold distortion were contemporaneous. Thus it appears to be valid to use the distortion of the greenschist folds to determine the direction of of tectonic transport during nappe emplacement.

Identical chlorite schist also occurs just north of the soil-covered gap in the greenschist labeled X in Figure 1. This topographically recessed gap suggests that the massive greenschist is absent here. The gap separates greenschist bodies both clearly belonging to domain 3N, but with different $A_2$ fold-axis orientations. Subdomain 3N(h), which is adjacent to hinge domain 2N/S, shows an $A_2$ orientation close to that of the hinge domains, while subdomain 3N(l), well away from the hinge area, shows $A_2$ axes strongly rotated in the sense typical of N-limb domains (Table 1). This difference accounts for the nonuniform azimuthal distribution of $A_2$ axes in the composite domain 3N. These observations suggest that the major fold limb of domain 3N was broken into two parts by stretching as the limb was rotated during nappe emplacement. This interpretation accounts for the differing orientations of $A_2$ in subdomains 3N(h) and 3N(l), for the absence of greenschist in the gap, and for the retrograde metamorphism of greenschist flanking the gap; as in the case of the axial surfaces, retrograde metamorphism would have been facilitated by fracturing and shearing localized at the site of rupture of the 3N limb.

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