CORRESPONDENCE

CONJUGATE FOLDS, KINKS, AND DRAG

SIR,—Professor Sherbon Hills (September–October issue, 1963) has criticized the suggestion that conjugate fold systems represent a brittle response to deformation. This erroneous suggestion was made by me eight years ago and it is a pity that it appears in Dr. Ramsay's otherwise excellent discussion of conjugate folds. Fortunately, Turner and Weiss (1963, pp. 475–6) in their recently published book state clearly the significant analogy between the conjugate folds found in thinly laminated rocks and the kink bands found in plastically deformed crystals. Thus, the kink bands in conjugate folds are local strain domains, in which the foliation is progressively rotated (External Rotation) with respect to the undeformed parts of the rock. The magnitude and size of External rotation depends on:—

(*a*) the magnitude of strain;
(*b*) the orientation of the foliation in relation to *P* max. and *P* min.;
(*c*) the constraint on the rock body.

During strain the foliation in the kink band rotates towards the *P* min. direction. The linear strain, ϵ, and external rotation, ω, are related by:—

$\frac{\cos x_1}{\cos x_0} = 1 - \epsilon$ (where x_0 and x_1 = angle between foliation (i.e. glide plane and *P* max. in unstrained and strained parts respectively)

angle of external rotation = $x_0 - x_1$.

Paterson and Weiss (1962) in their instructive experimental folding of rocks, show that conjugate folding and similar folding can be intimately associated processes. The similar folds (or Concertina folds) appear wherever the kink bands coalesce, and they become more and more common as strain proceeds. This sequence has not yet been described in natural samples—probably the upper limit for the compression that produced the conjugate folds near the Moine Thrust is 40 per cent, possibly much less. Also, although symmetrical folds have developed where the kink bands intersect, it may be noted that these folds are not Similar in figured examples (e.g. Johnson, 1956, Text-fig. 1*b* and *c*; Ramsay, 1962, Text-fig. 6).

I suppose that the misconception (that conjugate folds were other than flow phenomena) arose because of their frequent association with breccias (e.g. Johnson, 1956, 1960) and with " a good deal of shattering and jointing " (Sutton and Watson, 1958, p. 248), but no doubt the breccias and fractures developed late in, or after, the conjugate fold episode in the Moine Thrust belt.

Dr. Ramsay points out that conjugate folds may be regionally developed, and are not special features of fault zones as my papers may have implied. Large-scale conjugate folds are to be seen in the Jura, Andes, the Scottish Dalradian, and perhaps in the Rhine schist structures (with thetic and autithetic cleavages) described by Hoeppener (1955). The small-scale conjugate fold systems are more puzzling, at least so far as dynamic interpretation is concerned. They can form in response to secondary stress systems. For example, current interpretation of these folds in the Moine Thrust belt is that they formed in response to *P* max. oriented roughly perpendicular to the direction of thrust transport (Johnson, 1956, 1957, pp. 261–3; Sutton and Watson, 1958, pp. 249–250). Incidentally, Ramsay effectively corrects my failure of logic in referring to " local *irregular* compressive stresses . . . constant neither in direction nor sense " (Johnson, 1960, p. 155) as being responsible for the Moine Thrust conjugate folds. The stresses, in fact, must have been surprisingly constant in direction !

In the Valley and Ridge province of the Appalachians, I have seen conjugate fold systems that presumably developed as a result of a component of shear operating parallel to the bedding during the formation of a major,

https://doi.org/10.1017/S0016756800049864 Published online by Cambridge University Press

upright fold. It would be interesting to know whether comparable relations between small conjugates and major structures, folds, or thrusts exist elsewhere.

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10th December, 1963.

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THE MALVERN LINE

SIR,—Drs. Phipps and Reeve, knowing of my interest in the Upper Llandovery rocks and fossils of the Welsh Borderland kindly allowed me to see their paper before publication. They dispute the field evidence (Reading and Poole, 1961, 1962) for an unconformable junction of Silurian on Pre-Cambrian in the Gullet Quarry, maintaining that the west flank of the Malvern hills is marked by a continuous major fault.

Their arguments are based (1) on structural mapping, (2) on stratigraphical interpretation and (3) on their interpretation of the Gullet Quarry exposure.

To take the last point first, Reading and Poole's description of the Gullet Quarry exposure is complete and accurate leaving little to be added. In their second communication (published after Phipps and Reeve had submitted their manuscript) they state that undistorted fossils surround the boulders and that regularly stratified sediments are in contact with the Malvernian, whereas Reeve and Phipps found fossils only on the upper surface of the conglomerate band and imply that clay occurs everywhere at the contact between the boulders.

The mapping evidence propounded by Phipps and Reeve is inconclusive in spite of their claims that Groom's mapping " demonstrated unquestionably " a fault or that the western boundary line is " manifestly a fault ". Everyone who has mapped in the Welsh Borderland will agree that, with the very poor exposure available, the mapping is largely a matter of interpretation. Phipps and Reeve say that the " outcrop " of the western boundary of the Malvernian rocks from the top of North Hill to Colwall forms an unbroken line and they go on to argue that it appears beyond dispute that this line is the outcrop of a fault plane. Yet the only place where this line is today exposed is at the " sycamore tree exposure ", West Malvern, which, as Reading and Poole (1961, 1962) indicate, is clearly a stratigraphical junction. Phipps and Reeve do not mention this exposure at all, although it is the only currently exposed Malvernian/Llandovery contact apart from the one in the Gullet Quarry.

https://doi.org/10.1017/S0016756800049864 Published online by Cambridge University Press