Geol. Mag. **123** (*4*), *1986, pp. 455–458. Printed in Great Britain*

CORRESPONDENCE

'Structural evolution in the Moine of northwest Scotland: a Caledonian linked thrust system?' by R. W. H. Butler – a criticism and discussion

SIRS – We are glad to acknowledge the provision by Dr Butler of a pre-publication copy of his paper (Butler, 1986) on the structural evolution and form of the Scottish Moine, and thank both him and the editors of the *Geological Magazine* for the opportunity of an early comment on his model. Dr Butler proposes a linked thrust model for the northwest part of the Scottish Caledonides which is similar to, and a development of, that advanced by Soper & Barber (1982), Rathbone, Coward and Harris (1983) and Butler & Coward (1984). Any attempt to present a unified account of such complex rocks is stimulating and welcome, especially since many workers permit the detail and complexity of the Moine to obscure important major structures and their interpretation.

Problems in accepting his model without demur arise from what is perhaps an over-emphasis on the validity of balanced cross-sections in this type of terrain, while Dr Butler's lack of personal knowledge of the Moine has led him to present a somewhat misleading simple interpretation. In addition, certain structures are represented for which no published evidence or explanation is cited.

We feel that valid criticisms can be directed at Dr Butler's model on four counts: (1) the accuracy of the geological information used; (2) the assumptions made in the balancing of the sections; (3) the neglect of metamorphic patterns; (4) the employment of an approach based almost wholly on high level thrust-tectonic models with scant regard for the other complex and interrelated processes involved in the evolution of this ductile reworked terrain.

(1 a) It is not clear if the geological basis of the schematic cross-sections through Sutherland (Butler, 1986, Fig. 3a) and the Moine of the southwest Highlands (Fig. 3c) are the result of re-interpretation of existing maps, new fieldwork or discussions with geologists working in these areas. Many of the structures shown in these cross-sections do not appear on previously published maps or cross-sections. For example, the positions of the slides shown as constituting the proposed 'Knoydart Duplex' (figs 1, 3c) are unexplained, but are entirely new, representing a far more extensive system than that originally envisaged by Powell (1974). Similarly if, as Dr Butler states, the Sutherland cross-section is based upon existing published maps, it should be made clear that many of these were geologically surveyed in the late nineteenth and early twentieth centuries, and that they are incorrect in many areas. It is important, for example, that far greater amounts of Lewisian basement are present at outcrop than has been previously recognized (R. E. H.). This unpublished work has made it clear that a number of Lewisian inliers below the Naver slide in the Sutherland section lie along probable Caledonian ductile thrusts, as mentioned by Dr Butler, but the great majority form originally NW-facing Caledonian fold cores with complex sheath-like geometries. The cross-section based upon new and detailed fieldwork carried out in Sutherland (Barr, Holdsworth & Roberts, in press) bears only a superficial resemblance to Dr Butler's figure 3a. We therefore cannot agree that this section and accompanying restoration (Fig. 3b) are well constrained, as implied by Dr Butler.

(1 b) It is possible that the steep belt folds in the southern part of the northern Highlands (fig. 3c) detach above a shallowly dipping decollement zone (possibly the Moine thrust) at depth (e.g. see Roberts *et al.* 1985). In order to produce a section which will entirely balance/restore, Dr Butler has had to propose a deep-level system of blind thrusts and backthrusts which pass upwards into the steep belt folds (fig. 3c, d). This is entirely an artifact of the high-level thrust model and there is not a single piece of geological evidence to support the existence of these deep structures; we feel that to show features of this kind imparts an unjustified accuracy to a schematic cross-section.

(2) An assumption of Caledonian plane strain within the cross-sections is a pre-requisite for balancing and restoration but, as mentioned by Dr Butler, is likely to be incorrect. More seriously, a number of less clearly stated, underlying assumptions present further doubts as to the validity of the restorations:

(i) There is no obvious geological reason why a uniform foreland dip can be assumed to affect all of this portion of the N Highlands.

(ii) Balanced sections of the kind presented must, by definition, lie parallel to the direction of tectonic transport (Dahlstrom, 1969), but no field-based evidence is presented to justify the positioning of the cross-sections (see fig. 1).

(iii) An assumption of a constant direction of thrust transport is implicit in the form of the sections presented, but our fieldwork in Sutherland indicates a progressive change in the plunge azimuth of Caledonian mineral extension lineations from 150–160° to 100–110° from the Naver slide rocks to the Moine thrust mylonites (Barr, Holdsworth & Roberts, in press). This implies a progressive change, with time, from NNW- to WNW-directed thrust transport. This feature alone reduces the validity of the restoration presented by Dr Butler through this area.

(3) Dr Butler gives insufficient attention to the regional metamorphic patterns developed within the northern Highland Moine. These are complex as most of these rocks have suffered variable levels of regional metamorphism and, in many areas, migmatization, during Precambrian and Caledonian phases of mid-crustal deformation (Barr, 1985, and references therein). Any wholly valid regional tectonic model should explain the pattern imposed by these events. The effects of overprinting and disruption of pre-existing, contemporary and evolving isograds during Caledonian ductile thrusting are particularly relevent in this respect. This information is available in published and unpublished work (Powell *et al.* 1981; Barr, Holdsworth & Roberts, in press).

(4) The northern Highland Moine is presented by Dr Butler in such a way as to suggest that it is a terrain dominated by thrusts. Those unfamiliar with ductile terrains of this type should not infer that this is immediately obvious on first encountering such areas. At present exposure levels within these complex metamorphic rocks, it is folds, not thrusts (ductile or otherwise), that are predominant. We agree that a foreland propagating thrust *model* is generally applicable to the Caledonian structure of the northern Highland Moine, but this would not have been seen to be

valid without detailed analysis of: (i) stratigraphy; (ii) deformation patterns and the evidence for reworking; (iii) complex fold geometries; (iv) mineral lineations and inferred transport directions; (v) strain variations; (vi) basement–cover relationships; (vii) metamorphic patterns; (viii) radiometric evidence. Data collection directed to this end over several decades has contributed to an enormous volume of published and unpublished work which has enabled Dr Butler to write his paper. It seems to us that this data-base has to a degree passed unacknowledged or has only been used in a selective manner.

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22 January 1986

Reply

SIRS – I welcome the opportunity to reply to this latest in an occasional series of discussions of Moine geology by the Liverpool group. Here they raise a number of general points while apparently not disagreeing with the overall model for Caledonian structural evolution in the Moine as a linked thrust system. As stated in the original article (Butler, 1986), this model derives from reinterpretations of Moine geology by Powell (1974), Soper & Barber (1982), Rathbone, Coward & Harris (1983) and Butler & Coward (1984), but examines the three-dimensional variations in thrust system geometry at greater length. The cornerstone to the examination was the use of two balanced cross-sections based on the references cited in the article (Butler, 1986) and by field studies, detailed in the westernmost Moine along the Moine thrust and of a reconnaissance nature along the section lines themselves. The assumptions necessary for the construction of balanced sections and the potential pitfalls of using the techniques within metamorphic terrains were also outlined in the article. The correspondents have a common misconception about the purpose of using such techniques. Balanced sections are not designed primarily to provide unique solutions to structural problems but rather clearly demonstrate the implications the particular solutions have for structural geometry and evolution within the thrust belt as a whole. One of these implications will be the amount of orogenic contraction required to form the structural geometry adopted on a cross-section. The sections through the Moine (Fig. 3 of Butler, 1986) imply large displacements, values which can only otherwise be obtained by circumstantial evidence such as offsets of individual pre-existing markers (orogenic fronts, facies variations or metamorphic patterns, etc.). These statements made, let us now consider the specific points raised by the commentators.

The first criticism is directed at the geological basis of the cross-sections, particularly through the Sutherland area (Fig. 3a, b of Butler, 1986). This uses data collected on reconnaissance traverses with detailed mapping in the vicinity of the Moine thrust, supported by reinterpretation of sections by Soper & Barber (1982) and the old Survey maps. Obviously our knowledge of the region will be significantly advanced by the eventual publication of Holdsworth's data. I note with interest the correspondents' assertion that more Lewisian slices exist within the Sutherland region than was indicated on my sections. Their presence would suggest more thrusts and hence a greater value for the orogenic contraction across Sutherland, more in keeping with the higher value obtained across the southwest Moine. I also find Holdsworth and co-workers' proposal that the Lewisian inliers lie in the cores of 'sheath-like' folds interesting. The present usage of the term 'sheath fold' (Cobbold & Quinquis, 1980; Holdsworth & Roberts, 1984) implies generation within a simple shear zone which displays penetrative, although not necessarily homogeneous, strain. My own observations of the Borgie Lewisian inlier on the Sutherland coast suggest that Caledonian strains are relatively low with presumably Proterozoic pegmatitic textures and granite sheets as well preserved as on the Caledonian foreland. I would propose that the Borgie and many other Lewisian inliers are carried and are bounded by a network of shear zones. In thrust belt terms this geometry is identical to thrust-bounded horses within an imbricate fan or duplex. Unfortunately this type of model has been misunderstood in Caledonian geology where the distinction between thrusts as brittle faults and shear zones (slides) has long been made. While this may be important on a small scale in understanding local fault zone processes, on a large scale there seems to be no justification. To characterize particular fault zones on the basis of their width can be highly misleading when analysing their large scale linked nature. However, when broader zones of simple shear climb ramps, the original lithological boundaries will be passively rotated towards the shear plane, generating folds. This geometry has long been recognized, for example at the base of the Morcles nappe in the Alps (Ramsay, Casey, & Kligfield, 1983). The presence of such folds does not argue against the thrust system model, indeed it supports it. The model differs from that proposed by Holdsworth and co-workers in that it implies a sequence of progressive propagation and displacement on the shear zones across Sutherland rather than simultaneous deformation across the presently 30 km width. I believe that the progressive deformation model more completely explains the structural complexity in the region together with the trend of shear zone metamorphism from amphibolite facies with migmatization in the east (Soper & Brown, 1971) to lower greenschist along the Moine thrust and increasingly cataclastic deformation within the Moine thrust belt (Butler, 1982, 1986). The correspondents offer no evidence against this hypothesis.

Let us now consider the criticisms of the section through the southwest Moine (Fig. 3c, d of Butler, 1986). This section was based again on reconnaissance studies by the author, relying heavily on previous work most notably by Powell (1974) and supported by the accounts of Johnstone, Smith & Harris (1969), the 1:63360/50000 geological maps (Geological Survey of Great Britain, 1971, 1975) together with a recent profile through the steep belt by Roberts & Harris (1983).

The extent of the Knoydart 'duplex' is evident on the sections and maps of Powell (1974). The author's own observations east of Kinloch Hourn suggest that there are other thrust-sense shear zones within this duplex but, as their geometry has yet to be established, they were not included on the cross-section. The correspondents do not dispute the exposed structure of the steep belt; indeed it was largely based on an account by two of them (Roberts & Harris, 1983) as acknowledged in the original article. Of critical importance is that the steep belt folds deform not only the Sgurr Beag slide (e.g. the Glenshian synform) but also the Knoydart duplex. Thus the folds must detach along the Moine thrust or be truncated by it. Metamorphic grounds dictate that the steep belt must predate the rather lower grade structures within the Moine thrust belt including the present Moine thrust itself. The commentators do not dispute the author's preferred choice of the steep belt folds now detaching along the hanging-wall to the Moine thrust and reflecting a locally reduced propagation ability during the early life of the thrust. They are correct in recognizing that the sub-surface structure of the steep belt as illustrated on the cross-section (Fig. 3c of Butler, 1986) is a requirement of the adoption of an excess area balancing routine. This solution was chosen to minimize the restored width of the Knoydart thrust (slide) and, as clearly stated in the original article, alternative models would require greater amounts of orogenic contraction. However, the adopted model requires shear zones at depth as indicated on the section and other options of more pure shear deformation across the steep belt would demand modifications of this model. This discussion illustrates the predictive quality of balanced section techniques since the proposed model suggests structures which may be found in adjacent areas of the Moine.

Potentially the most serious criticism made by the commentators concerns the consistency of thrust transport direction and the validity of assuming plane strain. Note that this only questions the use of two-dimensional restorations but need not rule out a linked thrust system model. They propose that mineral lineations show a directional variation of about 50°. This need not imply an actual variation in transport direction since, as Mertz & Siddans (1985) have recently documented, mineral lineation trends can develop oblique to the direction of maximum extension of the finite strain ellipsoid. The interpretation of linear mineral orientations requires detailed microstructural analysis since they could be preferentially modified by secondary recrystallization or annealing (e.g. Law, Knipe & Dayan, 1984). The commentators offer no substantiating microstructural evidence to support their implication that their mineral lineations have survived such processes unmodified. Alternatively the lineations could indeed lie parallel to the maximum finite extension direction but be the products of superposition of two distinct tectonic events. Holdsworth & Roberts (1984) have documented apparently pre-Caledonian N–S trending sheath folds within the Moine. These structures together with any other pre-existing structures (e.g. linear and planar fabrics) could be passively rotated by varying amounts towards the later, WNW-directed shear direction of Caledonian thrusting. It may be difficult to separate these features from any entirely Caledonian fabric elements. Finally, regionally uni-directional thrust systems can develop oblique fabric trends by local rotations caused by locally inhibited thrust propagation or displacement (Coward & Potts, 1983). All these factors render the interpretation of linear and planar fabrics in terms of shear zone kinematics problematic on local scales. If they are correct in asserting variable Caledonian thrust directions a number of problems arise. Some of the commentators (Roberts *et al.* 1985) have previously implied that the Caledonian structure of the southwest Moine is a product of WNW–ESE compression, presumably developing simultaneously with at least part of the Sutherland thrust systems. Thus at particular periods the Naver–Sgurr Beag thrust sheet will have experienced divergent transport requiring strike-parallel extension in, for example, the Ross-shire area. Holdsworth and co-workers do not provide the necessary corroborative evidence to test this assertion of divergent transport. In the absence of evidence to the contrary and supported by my own studies of thrust transport direction in the western Moine and Moine thrust belt (see also Evans & White, 1984), I constructed the sections parallel to the general Caledonian transport direction in northwest Scotland, namely ESE/SE–WNW/NW. The other general points concerning the deep structure of the Moine thrust and the use of Caledonian metamorphic patterns within the Moine were discussed in the original article (Butler, 1986; see also Butler & Coward, 1984).

Finally I am glad to acknowledge the immense body of work, regrettably largely unpublished, which has been carried out in the Moine. Naturally any truly valid model of Caledonian tectonic evolution will have to embrace all these multidisciplinary studies. However, it is increasingly being realized in the Moine as well as in many other 'internal' zones of orogenic belts, that most of the orogenic contraction has been accommodated by displacements on thrust-sense shear zones. The inability to completely integrate the high shear strains across the individual thrust zones (e.g. Rathbone, Coward & Harris, 1983) using conventional strain markers requires the use of large-scale restoration methods such as those adopted in foreland thrust belts and introduced to the Moine in the original article. Unless this type of large-scale approach is adopted in three dimensions, the interpretation and correlation of radiometric, metamorphic, stratigraphic and structural data will always be ambiguous.

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22nd January 1986