Discussion

Reinterpretation of Finnmarkian deformation on western Sørøy, northern Norway: a comment

BRIAN A. STURT & DONALD M. RAMSAY

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The postulate by Krill and Zwaan (1987) that the magmatic rocks of the Seiland Province are uniquely pre-orogenic based on dyke relationships on Western Sørøy is rejected, as also are the stratigraphic implications made by those authors from that area.

B. A. Sturt, Norges geologiske undersøkelse, Postboks 3006, 7002 Trondheim, Norway; D. M. Ramsay, Department of Geology, University of Dundee, Dundee, Scotland, U.K.

We have read with interest but with a strong measure of bewilderment the contribution by Krill & Zwaan (1987) to this journal concerning the relationships between stratigraphy, tectonic structures, dykes and possibly plutons on Sørøy, western Finnmark.

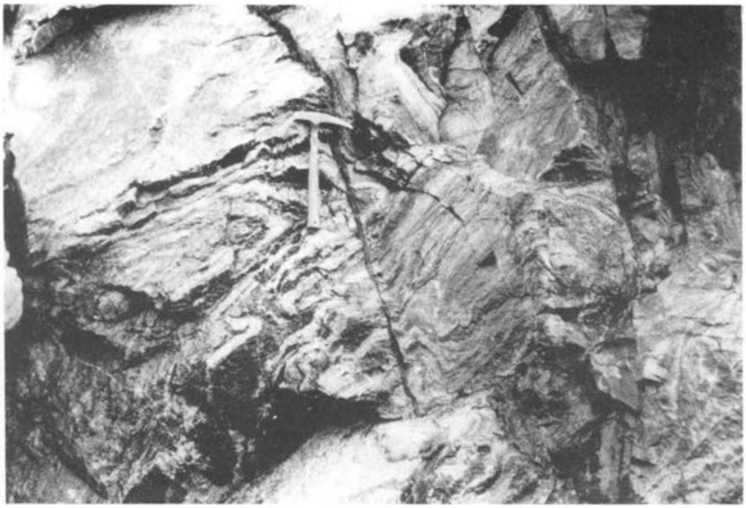
The basis of their argument is as follows:

(i) The described stratigraphy of Sørøy is not a continuous sequence as considered by Roberts (1968a), Ramsay (1971), Speedyman (1972, 1983), Sturt *et al.* (1978).
(ii) Dyke and fold relationships on W. Sørøy show unequivocally that the dykes are pre-fold and hence pre-tectonic.
(iii) Folds preserved in contact aureoles have a unique flow-fold mechanism in their production.

This leads Krill & Zwaan (op. cit.) to the conclusion that the igneous rocks of the Seiland Province are uniquely of pre-tectonic emplacement. This view we refute for the following reasons:

(i) The stratigraphy of Sørøy is in our view well established, and a clearly marked sedimentary transition can be seen between the Klubben and Storelv Groups on the road section, 2 km east of Sørvær, and in innumerable other localities along the extent of this boundary. In the Sørvær road section the transition is perfectly exposed both at road level and on the coast. This particular section is characterized by low strains and, as a result, sedimentary structures, especially current bedding, abound. These structures show a consistent sense of younging from the Klubben Group through a transition zone into the micaschists of the Storelv Group *per se*. Other such transitions are well marked, e.g. at Storelv (Ramsay & Sturt 1963) and in the Langstrand area (Roberts 1968a). At many places along this contact, however, the strains may be higher and sedimentary structures are difficult to find, although the characteristic lithologies of the transition zone can be unequivocally identified in most cases.
(ii) The contact between the Storelv and Falkenes Groups is also transitional in nature, and generally the lithological sequence is comparable in different areas. Sedimentary structures, however, are only sporadically preserved, owing to the nature of the original lithologies and orogenic strains.
(iii) The contact between the Falkenes Group and the Aafjord Group is again transitional in nature and similar sequences are preserved in different areas, while the lithologies rarely preserve any sedimentary structures.
(iv) The contact between the rocks of the Aafjord and Hellefjord Groups is somewhat more abrupt over much of the area, though as Roberts (1968a, 1968b) shows there is a clear transition between those groups in the Langstrand–Finfjord area. Locally abundant sediment structures in the HG consistently young away from the Aafjord Group.

We thus see no compelling reason or evidence to suspect that there is any major stratigraphic or tectonic break within this sequence. A similar



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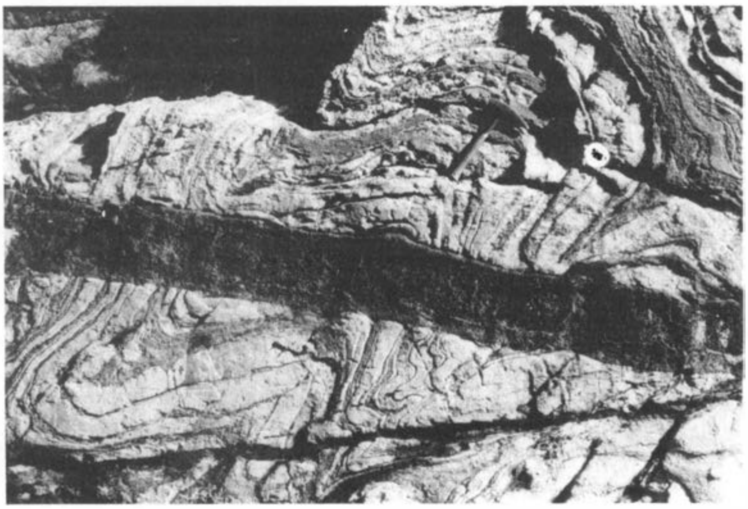

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Fig. 1a. Basic dyke cutting asymmetrical second generation F_2-folds. Note folded and boudined earlier basic sheet in centre-right of photo (ED 460203). *b.* Basic dykes cutting asymmetrical F_2-folds. Note chilled margin to the thicker dyke (ED 454276). *c.* Thin basic dyke cutting F_2-folds. The light-coloured bands close to hammer-handle are folded granitic sheets (ED 462278). *d.* Basic dyke cutting strongly attenuated and folded (F_2) banding. Note the pre-dyke deformed pegmatite (ED 460203).

lithostratigraphic succession has been observed in several nappes in the Kalak Nappe Complex across a wide areal extent of Finnmark and N. Troms (Ramsay et al. 1985).

In their note, Krill & Zwaan (op. cit., p. 16) cast doubts upon the relationships between the major plutons and the Sørøy stratigraphy and advance the view that 'the Falkenes Marble is too young to have undergone Finnmarkian deformation or to have been intruded by rocks of the Seiland Province'. This we must treat as a 'view' not based on critical assessment of evidence available in the literature or from Field observations. In the Husfjord area (S. Sørøy) Speedyman (1968, 1972, 1983) demonstrated how the various gabbros, diorites and nepheline syenite pegmatites intrude through the entire Sørøy stratigraphic sequence from the Klubben through to the Hellefjord Group. The contact relations of the Husfjord Plutonic Complex are well marked and in places well exposed and there can be *no doubt* concerning the intrusive nature through its stratigraphically almost complete sidewall. This complex is replete with xenoliths and rafts derived from the metasedimentary carapace. These clearly demonstrate the imprint of contact metamorphism and are now well-developed hornfelses. It is also clear that these contact meta-


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morphic effects were superimposed upon at least one phase of penetrative folding/foliation. Similar features can be seen in other plutons on Sørøy. The Hasvik gabbro, for example, in its upper portion (Robins & Gardner 1975) contains abundant inclusions of previously deformed, now hornfelsed, material derived from the psammites, semipelites and quartzites of the Klubben Group, which can be matched with xenolithic materıals in the Breivikbotn Gabbro (Sturt & Ramsay 1965). The Storelv Gabbro, in the Burfjord area, contains abundant xenoliths/rafts of previously deformed rocks derived from the Klubben and Storelv Groups (Sturt & Taylor 1971) and in the section from Donnesfjord to Kipperfjord similaı materials derived from the Klubben, Storelv, Falkenes and Aafjord Groups (Bjærknes 1975; Holland & Sturt 1970). Similarly, basic dykes/sheets may be observed at all levels of the stratigraphy, although, depending on the host-lithology, they may have undergone deformation and metamorphism which render them superficially difficult to identify.

(ii) With regard to the relationships between basic dykes and sidewall tectonic elements, which is the basic theme of Krill & Zwaan's (op. cit.) thesis, we consider that their conclusions are simply wrong. In establishing unequivocal relationships between dyke and sidewall structure it is necessary to establish the nature of the structural state of the host rock. This we consider has not been done in the case in question. Where dykes do predate folds, as reported by Krill & Zwaan, it is important to establish the age of these folds. We have recently had the opportunity to re-examine the sections described by Krill & Zwaan and would make the following observations:

(a) The folds which they describe as post-dating dyke emplacement are in fact second-generation (F2) structures, and congruous with large-scale F2 folds in the region.
(b) They fold a previous near bedding foliation (S1) and the axial plane cleavage is always a crenulation cleavage (S2). The sole cleavage observed in the dykes is generally margin-parallel and essentially parallel to the axial planes of the F2 folds, i.e. *S1 dyke = S2 metasediment*. The near bedding nature of S1 is a regional feature related to the recumbent large-scale folds and S1 is only observed as a markedly oblique structure in the hinges of F1 folds.
(c) The folds figured, by Krill & Zwaan, also fold the S_0/S_1 intersection lineation and in some cases a stretching lineation consisting of elongated retrograded sillimanite pods.
(d) Many basic dykes are markedly oblique to the axial planes of F2 folds and other dykes with variable orientation may trend up to 90° in the axes of such folds.
(e) F1 folds the well-developed S1 axial plane cleavage are transected by dykes, and a number of these are in turn folded by F2 fold structures (Figs. 1a, b, c, d).
f) There is little or no evidence for the selective preservation of current bedding against dykes, as claimed by Krill & Zwaan. Indeed, in the well-exposed section from Høyvik to Sørvær abundant sedimentary structures can be observed in the psammites/quartzites of the Klubben Group where strains are relatively low. This bears no obvious relationship to dyke margins and indeed the best sedimentary structures are usually most obvious in portions which are dyke-free.
(g) The preservation of current bedding in metamorphic rock systems does not imply an absence of penetrative deformation, but rather that the strains in metamorphic rock sequences deformed at middle crustal levels are notably inhomogeneous.
(h) Dykes, now in amphibolite facies, but with well-preserved igneous form including chilled margins, cut older blastomylonitic fabrics (Fig. 2).

The features and relationships outlined above are incompatible with the model of Krill & Zwaan (op. cit.).

(iii) Many of the best preserved dykes in western Sørøy occur within the contact metamorphic aureoles to the Breivikbotn and Hasvik gabbros and smaller plutons. This is closely related to the more competent nature of hornfelses and their ability to propagate joints over long distances during the regional deformation and intrusion hydrofracturing attending magma injection. This is the case for dykes which are either syn-genetic with a major pluton or intruded subsequently.

Dykes and inclined sheets of basic rock, 'granite' and pegmatite are spectacular features intruding the contact metamorphic rocks around the Breivikbotn and Hasvik gabbros. Primary features such as chilled margins, horns, matching marginal irregularities and other indications of dilation and xenoliths are generally well preserved, and many of the dykes show low effects of tectonic strains, particularly in the inner parts of the aureoles (Fig. 3). Further out, however, they demonstrate an increasing degree of tectonic strain. These dykes and sheets cut through a variety of earlier pre-hornfels tectonic structures, including folds, lineations, boudins, blastomylonites, metamorphic segregations, etc. A re-examination of critical exposures in the Hasvik aureole, during summer 1987, indicated that the contact metamorphism postdates two distinct folding episodes and hence it is necessary to revise our earlier opinions concerning the age relationships of this pluton, i.e. it is probably syn- to post-F2 in age.

Folds of both first (F1) and second (F2)

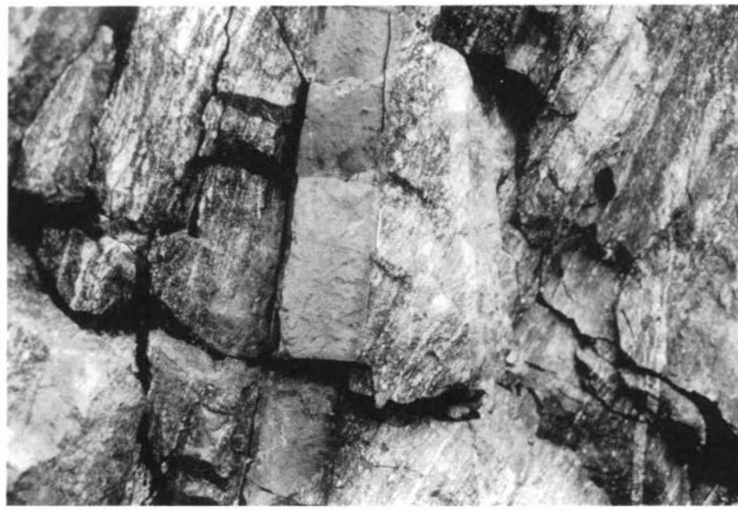

Fig. 2. Basic dyke, with chilled margin, cutting blastomylonitic fabric in strongly deformed pegmatite (ED 464243).

generations are excellently preserved and these belong essentially to Class IC (Ramsay 1967), i.e. modified buckle folds. The folds of both generations bear axial plane foliations though these may be difficult to detect in the highest grade hornfelses, owing to the pervasive development of granoblastic textures during the contact metamorphism. The folds, when traced through the aureoles into the envelope, show little change in style. The F2 folds generally display a congruous relationship to the larger-scale regional F2 folds, e.g. the Breivikbotn Anticline, thus forming an integral part of the regional movement plan.

Nowhere do the dominant fold sets exhibit features indicative of an origin via flowage consequent upon large-scale anatectic remobilization. In the inner parts of the aureoles the results of anatectic melting and mobilization are well displayed in appropriate lithologies by phenomena such as back- and net-veining of early dykes which can be seen together with modification of previously formed fold-structures. Small-scale flow folds are occasionally to be seen where bulk mobilization of variable compositioned multilayers occurs. Such folds invariably have highly irregular geometries with swirling patterns, and competent materials are considerably disrupted. We submit that Krill & Zwaan's (op. cit.) claim of major systems of anatectic-melt generated flow folds is completely mistaken, and must in addition cast doubt upon Zwaan's identification of such features in the Kvænangen area.

There are obviously a number of important questions to be asked regarding the relationships between the igneous rocks of the Seiland Province and the protracted tectonothermal evolution of the metasedimentary envelope. When we were actively working with these problems on Sørøy some 10–15 years ago, our thinking was very much constrained by the identification of Archaeocyathids in the Falkenes Group (Holland & Sturt 1970), which were considered to provide an early Middle Cambrian age for that group. These 'fossils' have been effectively discredited by Debrenne (1984) and hence this lower age constraint to the sequence has been removed. A recently quoted zircon age (Robins 1987) of 531 ± 2 Ma obtained from a nepheline syenite pegmatite in S. Seiland, if confirmed, effectively dates the emplacement of these rocks as at *latest* Middle Cambrian. If, as would appear reasonable, the nepheline syenites of the region are coeval, the major magmatism of the Seiland Province must be at least of that antiquity. This naturally casts doubt on some aspects of the tectonothermal modelling previously made by both ourselves and others in the region.

The removal of a lower age constraint to the Sørøy stratigraphy and the observation that the Husfjord and Hasvik Gabbros probably postdate

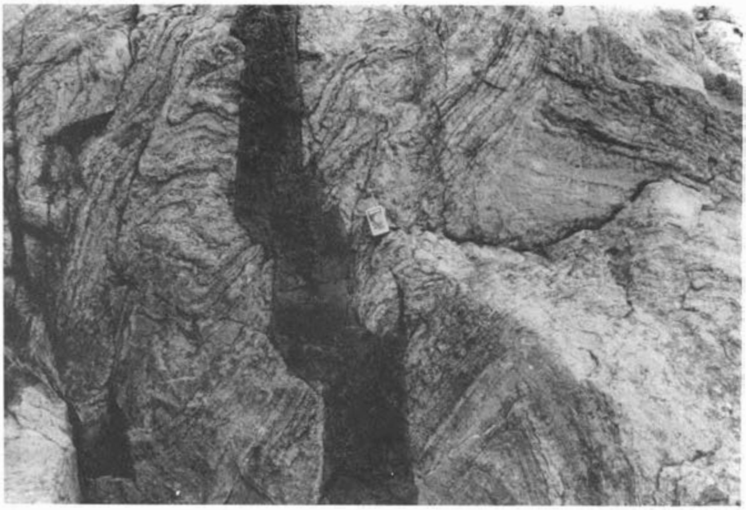

Fig. 3. Basic dyke, with chilled margin, cutting pre-hornfels folds (F_2) in aureole of Hasvik Gabbro. Note well-preserved horn and dilatational features (ED 457202)

what we identified as the F2 folding in the region, allow consideration of models where the emplacement of the plutons of the Seiland Province is effectively syn- to interorogenic. Earlier studies of the region may have oversimplified the structural development as the plutons and associated minor intrusions have both complex postemplacement strain histories and metamorphic developments. In addition to the polyphasal tectonothermal development prior to emplacement of the plutons and nepheline syenites there is good evidence, from geochronological studies, both in this area and others in the Scandinavian Caledonides for a major tectonothermal event towards the beginning of the Ordovician showing the polyphase nature of Caledonian orogenic development.

We accept that certain of the previous *mores* concerning the tectonothermal development of the Seiland Province require revision, and that this provides a considerable challenge for future research in the region. The postulate that the dykes of Western Sørøy are pre-tectonic (Krill & Zwaan op. cit.), however, is not one that can be sustained and does not serve any purpose in the present debate. We are, however, grateful to Krill & Zwaan for refocussing our attention on the evolution of the rocks of this geologically intriguing and scenically beautiful region.

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