GEOLOGIE EN MIJNBOUW VOLUME 55 (1-2), p. 41-45 1976

THERMAL ANISOTROPY – A FACTOR CONTRIBUTING TO THE DISTRIBUTION OF CALEDONIAN METAMORPHIC ZONES IN THE SW SCOTTISH HIGHLANDS?

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SUMMARY

The distribution of metamorphic zones in the SW Scottish Highlands may have been influenced by the bulk thermal anisotropy of the regional structure.

DISTRIBUTION OF METAMORPHIC ZONES

The distribution of zones of regional metamorphism in the Scottish Highlands is well known through the work of Elles and Tilley (1930), Barrow (1912), and Kennedy (1948). Tn the SW Scottish Highlands (Fig. 1) the zonal map was constructed by Elles and Tilley. The thermal structure of the Highlands as revealed by Caledonian metamorphism was first discussed by Kennedy. He attributed the metamorphism to a "thermal anticline", the higher metamorphic grades occurring in the Central Highlands near the culmination of the thermal dome. This configuration is also reflected in the distribution of radiometric cooling ages (Watson, 1964; Dewey and Pankhurst, 1970). The thermal dome extends into the SW Highlands as a ridge-like continuation, traced by a thin garnet grade zone along the southeast shore of Loch Fyne (Fig. 1) as far as the Isle of Gigha (Graham, 1974).

The zonation follows the NE – SW trend of the major structures but it is not symmetrically positioned with respect to the root of the Tay Nappe or the broad antiform formed by the flat-lying part of the nappe (Fig. 1 and Fig. 3b). The isograds' outcrop distribution thus cannot be attributed to post-metamorphic folding and the highest grade rocks actually coincide with the trace of the Tarbert Monoform (Fig. 3b) – the primary flexure of the Tay Nappe near its root (Roberts and Treagus, 1964). It is emphasised that there is no simple lithological control for this distribution because suitable lithologies for the development of index minerals *are* present throughout the region. Since the highest grade of metamorphism in the Highlands was achieved after, or at the close of the primary deformation (Johnson, 1963; Rast, 1963) accompanying nappe formation, it seems possible that the geometry of the nappe structure may itself have influenced the location of metamorphic zones. Such control might be affected by the anisotropy of the structure with respect to heat conduction, an idea expressed elsewhere by Wenk (1970) and den Tex (1975).

ANISOTROPY WITH RESPECT TO HEAT CONDUCTION

Although no data on the thermal properties of the SW Highlands schists are known to the writer, it is not unreasonable to assume that the penetrative first schistosity throughout the region renders the rocks thermally anisotropic. The schists also show very well developed mineral lineations resulting from the preferred orientation of the mica's long axes within the schistosity surfaces, so that thermal anisotropy should thus be that much more marked in the plane of minimum and maximum thermal conductivity. The orientations of the schistosity and the mineral lineation on the schistosity are well known throughout the region (Borradaile, 1972, 1973; Roberts, 1974; Simpson and Wedden, 1975) and their spatial relations are shown schematically in Figure 2.

The schistosity is axial planar to the major first folds, the Loch Awe Syncline and the Tay Nappe, and the northeasterly pitching mineral lineation on the schistosity maintains fairly constant high angles with the subhorizontal *major* fold axes. The angle, designated α in Figure 2, generally exceeds 70° so that the anisotropy of the fabrics of the tectonites is almost at its maximum in a NW-SE, cross-strike section.

The thermal anisotropy of a tectonite depends on the anisotropy of the component minerals and their degree of preferred orientation. The better the preferred orientation, the greater the thermal anisotropy of the tectonite. In the case of schists the maximum thermal anisotropy should approach that of its component micas which are very anisotropic with respect to heat conduction. Muscovite, for example, has thermal conductivities in the ratios 6.30 : 5.84: 1.00 (Clark, 1966).

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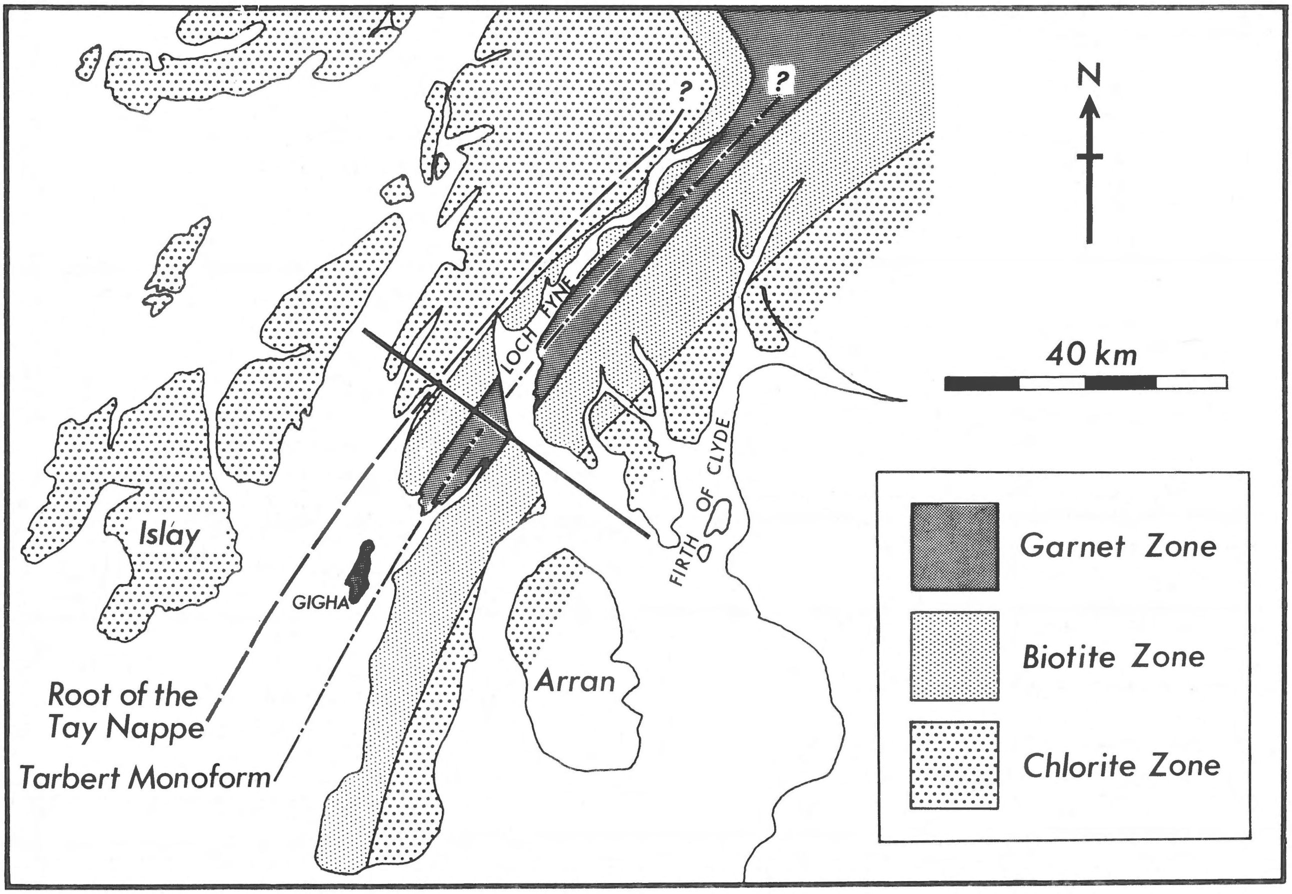

Fig. 1
Zones of Caledonian regional metamorphism in the SW Scottish Highlands and the axial traces of some major structures. The heavy line indicates the position of the profile given in Figure 3.

The most thorough investigation of the thermal anisotropy of schists has been made by Wenk and Wenk (1969) although some data were previously available (Clark, 1966; Munjal and Fatt, 1969). The degree of fabric anisotropy of the schists studied by Wenk and Wenk is not given but, for the purposes of argument, it seems appropriate to use as a model for the Highland schists their most thermally anisotropic schist. That showed conductivities in the ratio 2.64 : 1.00 between the lineation-parallel and schistosity-normal direction. Taking this value for the thermal anisotropy of the SW Highland schists in the plane of the cross-strike section (Fig. 3), the mean vertical thermal conductivity of the rocks has been calculated by using the regional schistosity and mineral lineation orientations as indicators of the conductivity-ellipsoid orientations. (In fact the diffusivities have been used instead of the conductivities because the densities and specific heats of the rocks are unknown parameters). The results of the calculations are presented in Fig. 3a. The solid line represents the mean vertical diffusivity of the structure indicated in Figure 3b, *below* the present level of erosion. The broken line represents the mean vertical diffusivity for the structure of the region as far as it can be reasonably reconstructed above the present level of erosion.

DISCUSSION

There is a clear correlation between the zone with high values of the expected mean diffusivity in a vertical direction and the zone showing higher metamorphic grade. Furthermore, the more rapid increase in the diffusivities on the northwest margin of the "diffusivity high" (Fig. 3a) corresponds to closely spaced isograds along Loch Fyne (Fig. 1),

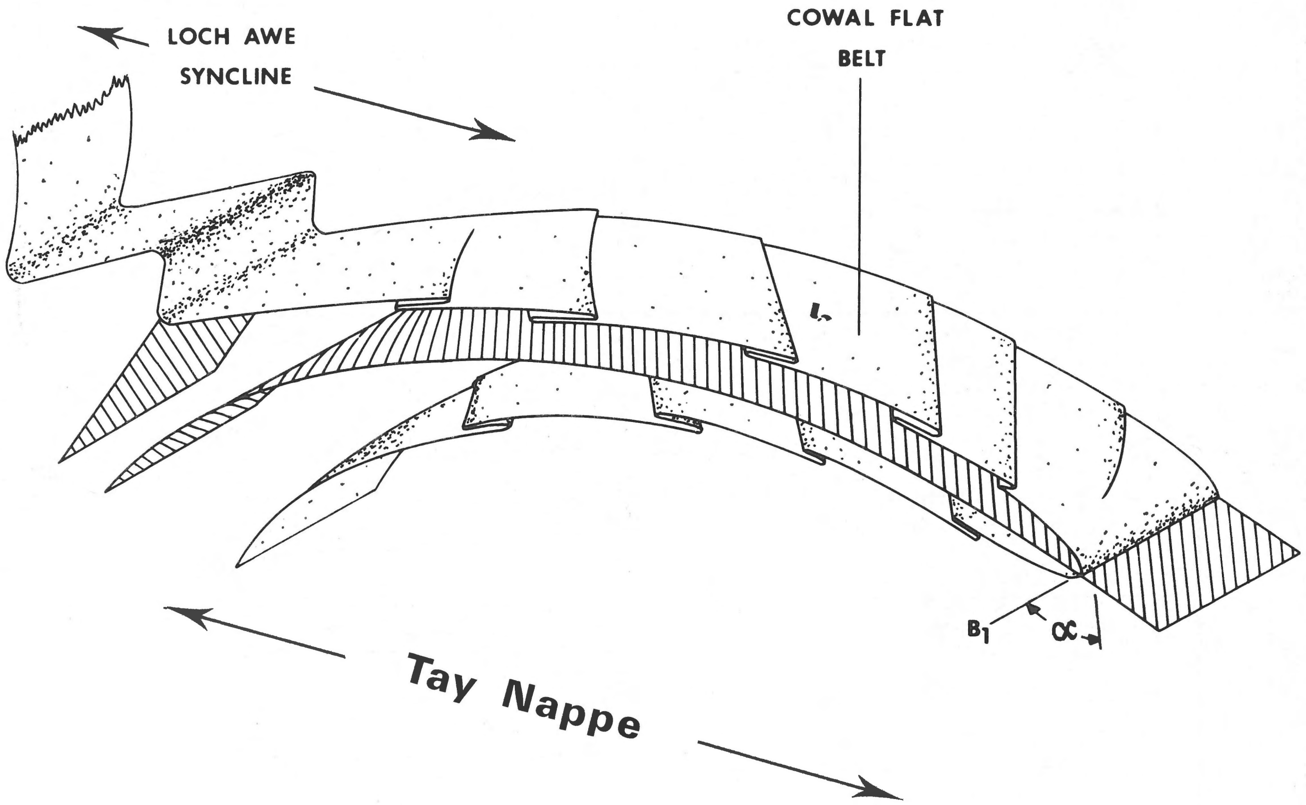

Fig. 2
Schematic representation of the orientation of the axial planar schistosity (hachured planes) and the mineral lineation on the schistosity (given by the direction of the hachuring) through the region. The angle α between the mineral lineation and the *major* folds' axes (B_1) is more than 70° in general. The angle is reduced in the diagram to facilitate visualisation.

while the more gentle decrease in diffusivity on the southeast margin corresponds with a much wider biotite zone in the near surface "Cowal flat belt" of the Tay Nappe (Fig. 2b).

This discussion glosses over problems such as the heterogeneity of the rocks and their almost certainly decreased thermal anisotropy at the temperatures of metamorphism. Nevertheless, given the relative time relations of metamorphism and nappe formation and the marked tectonite fabric anistropy, the bulk thermal anisotropy must have exerted an influence on the heat flow pattern at the time of metamorphism. Unfortunately, the magnitude of this influence cannot be calculated without further assumptions concerning the boundary conditions to the crustal segment under consideration and the time during which the thermal energy responsible for metamorphism was available. The writer proposes that the "heat source" lay under a much larger area than that suggested by the present widths of the higher grade zone, the isothermal surfaces having been locally deflected upwards along the steeper part of the Tay Nappe, which represents the zone of least thermal resistance in the vertical direction.

ACKNOWLEDGEMENTS

The writer wishes to acknowledge Prof.Dr. C.G. Egeler, Dr. M.R.W. Johnson, Dr. J.P. Platt, Prof.Dr. W.P. de Roever, Dr. H.E. Rondeel and Dr. L.J.G. Schermerhorn for their helpful and critical discussion.

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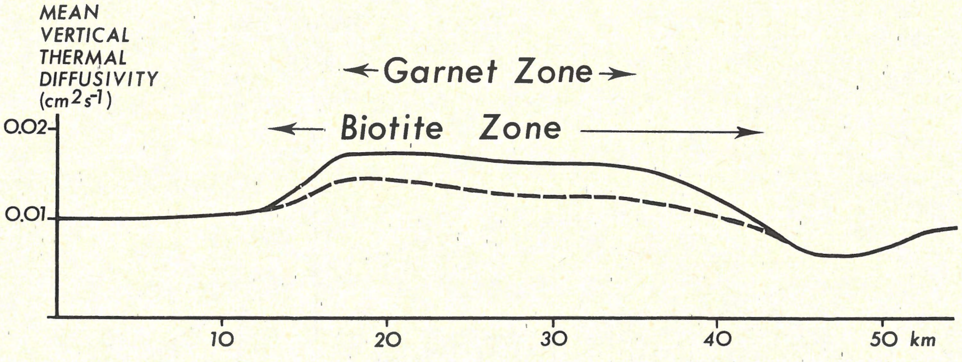

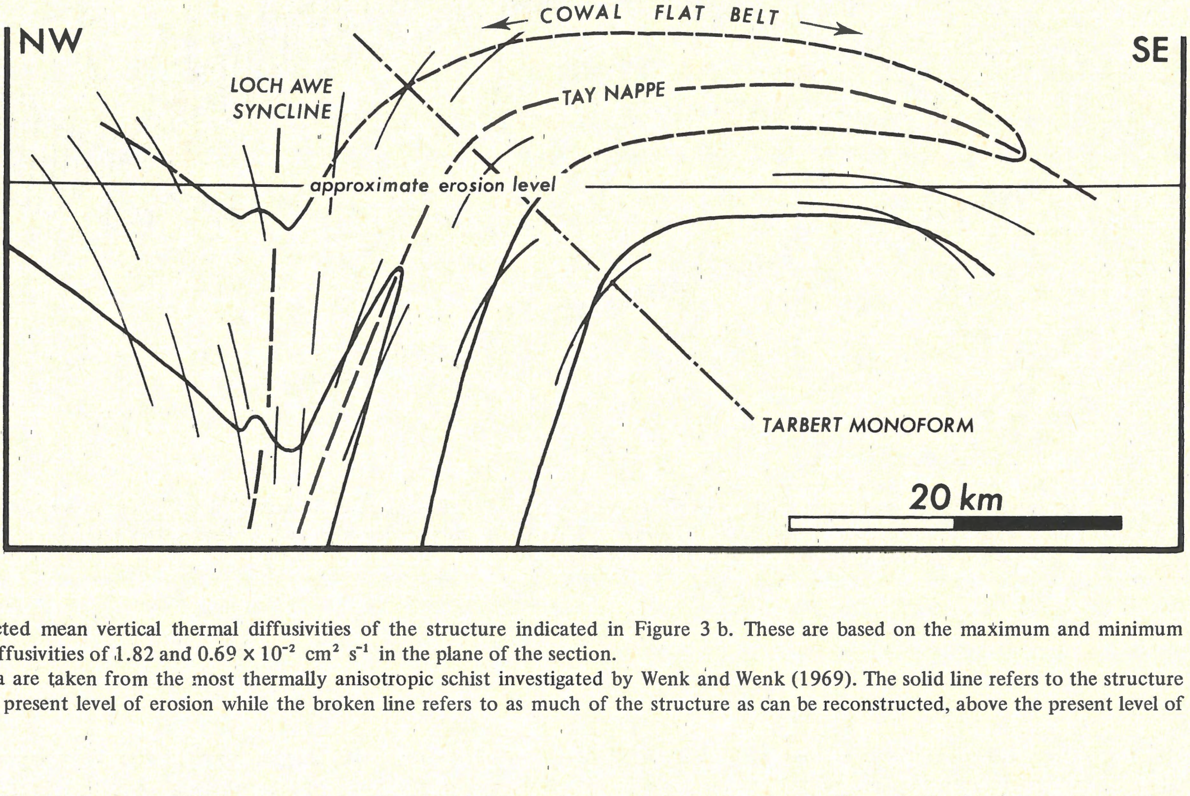

Fig. 3a
The expected mean vertical thermal diffusivities of the structure indicated in Figure 3 b. These are based on the maximum and minimum thermal diffusivities of 1.82 and 0.69 x 10^{-2} cm^2 s^{-1} in the plane of the section.
Those data are taken from the most thermally anisotropic schist investigated by Wenk and Wenk (1969). The solid line refers to the structure below the present level of erosion while the broken line refers to as much of the structure as can be reconstructed, above the present level of erosion.

Fig. 3b
A profile through the major fold structures of the SW Scottish Highlands along the heavy line given in Figure 1. The faint, discontinuous lines indicate the orientation of the axial planar schistosity.

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