Chapter 6  
INTERPRETATIONS  

Having described the geologic setting (pp. 6 - 10), petrography (pp. 16 - 68) and the structural geometry (pp. 69 - 164) of the area, an attempt is now being made to unravel its tectonic and metamorphic evolution.

The kinematic analysis is based on the standardised principles after Sander as modified by later work, and the conditions and controls of metamorphism is being interpreted by comparison of the observed mineral assemblages and textural relations with the currently available experimental data.

6.1 Nature and origin of the folds

Folds belonging to all the phases are disharmonic (q.v. p. 88) on all scales from macroscopic to microscopic (pp. 73, 104, 112, 117, 128, 131ff.; fig. 170, 171, p. 161), often showing crumples in their inner arcs and even reversals of closures (p. 117; fig. 82, p. 107; fig. 91, 92, p. 113f.; fig. 104 - 106, p. 123; p. 128). Some of them clearly illustrate the 'competence law' (q.v. p. 135) (p. 130, fig. 116, p. 127; p. 135, fig. 128, p. 140). In most of them the layer thicknesses measured parallel to their axial surface traces (q.v. p. 103) are not constant (pp. 103f., 117, 129, 131, 133). The F3 and F4 folds are associated with axial surface cleavage fans (pp. 119, 143); cross, longitudinal and rotational or radial (h01) (q.v. p. 129f.) and diagonal (0kl) joints (p. 150); and boudinage (pp. 80 ff.). In the microscopic scale, some quartz grains show a slight increase in their grain size from core of the fold outwards.
All these folds, therefore, initiated by buckling. Thereafter they have undergone 'flattening' (Ramsay, 1962; 1967, p. 387), flow (q.v. p. 86) and/or slip as evidenced from the presence of folds of classes 1C and 3 (q.v. p. 104) (pp. 104, 112, 131), folds with irregularly varying layer thicknesses (pp. 105 ff., 115 ff., 128 ff., 131 ff.), gleibretts (q.v. p. 78) (pp. 104 ff.) and axial surface slip (p. 133).

6.2 Mutual relations of fabric elements in space

This is best obtained from the mesoscopic analysis (pp. 74 ff.). The $S_1$ banding (pp. 74 ff.) is the form surface (q.v. p. 72) for the $F_1$ folds (pp. 103 ff.) which exhibit a very prominent axial surface (q.v. p. 75) schistosity $S_2$ (pp. 78, 104). The $S_2$ schistosity (pp. 76 ff.) is the form surface for all the other folds $F_2$, $F_3$ and $F_4$ (pp. 111 ff.) with axial surfaces $S_3$, $S_4$ and $S_5$ respectively (pp. 78f.). The $S_1$ surface is difficult to be examined in its plan view and lineations if any on it could not be studied. The $S_2$ surface shows a variety of lineations: mineral lineations (pp. 79f.), axes of mesoscopic folds and puckers (p. 80), boudin lines (pp. 80 ff.) and traces of other surfaces: $S_1$, $S_3$, $S_4$ and $S_5$. The very strong mineral lineation usually parallels the axes of the $F_2$ folds (pp. 79f.). Strong mineral lineation paralleling the axes of the $F_4$ folds have also been noted (p. 80). The axes of higher order (q.v. p. 70) folds and crenulations on the limbs and hinges of the $F_2$, $F_3$ and $F_4$ folds follow the $F_2$, $F_3$ and $F_4$ fold axes respectively. Some conjugate puckers (p. 80, fig. 44, p. 67) on the mica flakes in the pegmatites are symmetric to the $F_3$ fold axes. The intersect-
Interpretations

Superposition of the folds:
The $F_1$ and $F_2$ folds have not been encountered at the
same location, hence their mutual relation is not available
directly. Each of them, however, is closely associated with the
$F_3$ folds. On unrolling the $F_3$ folds, the fabric axes (q.v. p. 81)
of the $F_1$ and $F_2$ folds are incompatible in space. The $F_1$ and $F_2$
folds also differ in style (q.v. p. 85) (pp. 85, 103 ff.). The
$F_1$ folds are always compressed, tight (q.v. p. 86) folds and often
reclined (q.v. p. 76). Their axial surface schistosity $S_2$ is
folded into the $F_3$ open (q.v. p. 86) folds (pp. 78, 116, 166).
The $F_2$ isoclines are always low plunging inclined folds (p. 115).
Their axial surfaces $S_3$ is parallel to $S_2$ (except at the hinges
of $F_2$) which is folded into the $F_3$ folds.
The $F_3$ mesoscopic folds are homogeneous with the macro-
scopic regionally dominant folds of the area with axial surfaces
trending roughly N.E.-S.W.. These folds are open (q.v. p. 86) to
close (q.v. p. 91), and almost upright with axes plunging at
moderate angles due N.E. or at low angles due S.W.
The $F_4$ folds are warps on the macroscopic scale but
grade up to close folds in the mesoscopic scale. Their axes and
axial surfaces are transverse to those of the $F_3$ folds.

6.3 Mutual relations of fabric elements in time

The axial surface schistosity $S_2$ of the $F_1$ folds is the
form surface of the regional $F_3$ folds (pp. 78, 116, 166), i.e.
the $F_1$ folds have been bodily rotated during $F_3$-folding. The $F_1$
folds being of the flexural type (p. 166), the $S_2$ schistosity must
have developed well after the initiation of the \( F_1 \) folding. The \( F_1 \) folds are thus distinctly earlier than the \( F_2 \).

The \( F_2 \) folds with their axial surfaces \( S_2 \) always parallel to \( S_2 \) (except at the hinge of \( F_2 \)) (pp. 78, 112) must have also been bodily rotated during the \( F_2 \)-folding and are therefore distinctly earlier than the \( F_2 \). As already stated the \( F_1 \) and \( F_2 \) folds have not been observed at the same location (p. 167) and hence their mutual relation is not available directly. But the \( F_1 \) folds have a very well developed axial surface schistosity \( S_2 \) which is the most prominent and penetrative planar element in all scales. Such schistosity has not been observed along the axial surfaces of the \( F_2 \) folds. Also the \( F_1 \) folds usually occur as intrafolial folds (q.v. p. 75) and are much sheared along their axial surface schistosity \( S_2 \) most probably during the flexural-slip \( F_2 \)-folding, while the \( F_2 \) structures usually show more entire fold form and do not occur as intrafolial features. The \( F_1 \) folds are hence likely to be earlier than the \( F_2 \).

The \( F_3 \) folds are the most penetrative structures in all scales and must have developed at the peak of tectonic activity. These are most probably synchronous with the \( F_4 \) folds, the best evidence in this regard is the ellipsoidal boudins arranged rhomboidally along the \( F_2 \) and \( F_4 \) fold axes (pp. 82, 166 f.)

6.4 Metamorphism

The various mineral assemblages encountered in the metasediments and the associated metabasites within the area studied have been described in details (pp. 23, 40, 47, 53). All the mineral assemblages are confined within the limits of the

In the pelitic metasediments (pp. 23 ff.), almandine occurs only sporadically and in very small proportions. Staurolite is totally absent in the entire area. Kyanite is common as tiny subhedral blades but rare as perphyroblasts. Sillimanite is more abundant occurring as acicular prisms and tiny needles. In some specimens sillimanite, kyanite, muscovite, microcline and quartz are very closely associated, muscovite showing a wartlike, symplectic intergrowth with quartz (p. 28, fig. 22, p. 30), as also a cuneiform intergrowth with fibrolitic sillimanite (p. 28, fig. 20, 21, p. 29). The cuneiform intergrowth of muscovite with sillimanite fibres is best explained as due to the breakdown of muscovite in the presence of quartz (cf. Evans, 1965; Evans & Guidotti, 1966; Althaus & Hirsch in Winkler, 1967, p. 74):

\[
\text{muscovite} + \text{quartz} \rightarrow \text{microcline} + \text{sillimanite} + \text{water}
\]

\[
\text{KAl}_2(\text{AlSi}_2\text{O}_10)(\text{OH})_2 + \text{SiO}_2 \rightarrow \text{KAlSi}_2\text{O}_8 + \text{Al}_2\text{SiO}_5 + \text{H}_2\text{O}
\]

The symplectic intergrowth of muscovite and quartz is believed to have formed by potash feldspar reverting to muscovite and quartz partially using up the aluminium-silicate phase:

\[
\text{microcline} + \text{kyanite} + \text{water} \rightarrow \text{muscovite} + \text{quartz}
\]

and/or

\[
\text{KAlSi}_2\text{O}_8 + \text{Al}_2\text{SiO}_5 + \text{H}_2\text{O} \rightarrow \text{KAl}_2(\text{AlSi}_2\text{O}_10)(\text{OH})_2 + \text{SiO}_2
\]

Muscovite is known to form retrogressively (Miyashiro, 1973, p. 226). The assemblage thus appears to be either on or close the quartz + muscovite breakdown curve (fig. 173, p. 170). Similar
Fig. 173
STABILITY FIELDS OF Al₂SiO₅ POLYMORPHS (After Richardson, Gilbert & Bell, 1969) and MUSCOVITE + QUARTZ BREAKDOWN CURVE (After Evans, 1965)
co-existence of sillimanite, muscovite, K-feldspar and quartz has been described by Evans & Guidottl (1966) in W. Maine, U.S.A., although the K-feldspar phase described there is orthoclase. The peak of metamorphism in this area is hence uppermost amphibolite facies (cf. Binns, 1964, 1965) or amphibolite-granulite transition facies (cf. Thompson & Horton, 1968). The former is preferred in the present area considering the assemblages in the intimately associated metabasites described below. The widespread occurrence of microcline instead of orthoclase may be due to disphrophoresis (cf. Eskola, 1952), for which no definite textural evidence could be found here. Preference of microcline over orthoclase on grounds of composition have also been suggested (cf. Evans & Guidottl, 1966 and Binns, 1964, in Miyashiro, 1973, p. 225). The kyanite here seems to have been metastably dragged into the sillimanite field (cf. Richardson, et. al., 1969, pp. 268-270; Miyashiro, 1973, p. 225). No textural evidence of sillimanite to kyanite retrogression has been found. The muscovites described above have not been distinguished from paraconite or phengite or their intergrowths.

The associated calc-silicate metasediments (pp. 40 ff.) and the marbles (pp. 47 ff.) do not furnish any additional information on the nature of metamorphism (cf. Harker, 1932; 1950, pp. 252-261; Turner, 1968, pp. 309-314, 316-320).

The little epidote may be relict from the lower grade during progressive metamorphism or due to diaphthoresis, the textural evidence for the latter being not clear. Some biotite is due to incipient retrogression. These assemblages are typical of the middle amphibolite facies (cf. the pelitic metasediments of the upper amphibolite facies, just described, p. 171) containing only green hornblendes and no pyroxenes. Both pyroxenes and brown hornblendes are characteristic of the upper amphibolite facies in the Scottish Highlands (Wiseman, 1934) and the Broken Hill, Australia (Sinna, 1964, 1965).

The estimated P-T gradient is definitely above the $Al_2SiO_5$ triple point at 5.5 kbar & 622°C (Richardson, et. al., 1969, pp. 259, 264, 270; Miyashiro, 1961; 1973, pp. 71 ff., fig. 3-3), to the high temperature side of Kyanite sillimanite univariant curve (Richardson, et al., 1968) and on the muscovite + quartz breakdown curve. Thus at the peak of metamorphism the conditions were ca. 700°C and ca. 6 kbar pressure (cf. Miyashiro, 1973, pp. 89-91, fig. 3-12), (fig. 173, p. 170).

6.5 Igneous activity

Basic, ultramafic and acidic rocks have been described (pp. 51 ff., 59 ff., 62 ff.).

The metabasites constitute the dominant lithologic unit within the present area occupying ca. 60% of its areal extent (p. 16, fig. 2, in pocket). These are hornblende-quartz-plagioclase assemblages (p. 53) which could have formed either from basic igneous rocks — plutonic or volcanic, or from impure calcareous sediments. The large volume of these rocks exhibit a
wide range of textures from very coarse to very fine grained, but
have monotonously uniform composition (pp. 51, 53) in striking
contrast to the very heterogeneous composition of the associated
metasediments (pp. 17, 24, 38, 42). Their contacts with the meta-
sediments, including the very thin pure marble band occurring
within them (pp. 52, 73, fig. 2, in pocket) are very sharp (p. 74).
They are less likely to be metamorphosed sediments. Some specimens
exhibit relict igneous textures (p. 59, fig. 36 - 38, p. 58)
suggestive of volcanic origin. Their strictly concordant nature
with the associated metasediments and the occurrence within them
of the thin marble band in a totally undisturbed disposition are
evidences against a forceful intrusion. These were hence originally
basaltic or andesitic lava flows contemporaneous with the sediments.
They have been folded (pp. 72 ff., 89 ff.) and metamorphosed (pp.
171 f.) alongwith the sediments.

The metaultramafites (pp. 59 ff.) are clearly intrusive
bodies occurring as detached pods and patches elongated and aligned
along the regional schistosity S2, and rotated by the F5 and F4
folds. They are post-S2 pre-F3 i.e. early syntectonic.

The acidic rocks include gneissic granites, pegmatites
and quartz veins (pp. 62 ff.). The larger body of granite N.W. of
vil. Sheopura (lat. 26°16'6" N., long. 74°18'7" E.) is a concordant
lenticular body strongly foliated and lineated parallel to the
enclosing metabasic and neighbouring metasedimentary country rocks.
The foliation is parallel to the S2 in the surrounding rocks (p. 77
and the lineation to the F5 fold axes in that sector (p. 63). This
is hence strictly syntectonic. The entire body is very homogeneous
in composition and its contacts with the enclosing rocks very
sharp, evidences if favour of intrusion rather than granitisation. Effects of migmatisation are, however, very common in the entire area (pp. 18, 33 f., 62). The psammopolitic metasediments have been feldspathised by introduction of microclines together with tourmaline (pp. 33 f.) and the calc-silicate metasediments and metabasites intricately intruded by pegmatites (pp. 39, 118).

Feldspathisation and pegmatite permeation must have started early and continued over a long period as is evidenced from the folding of pegmatites and quartz veins by all the fold phases $F_1$ through $F_4$ (pp. 103 ff.).

6.6 Time relations between deformation, metamorphism & igneous activity

The bulk of metamorphic recrystallisation is post-$F_1$ syn-$F_2$ pre-$F_3$ (pp. 160 ff.) but it must have continued till the last phase of folding $F_4$, as is evidenced by the presence of mineral lineations paralleling the $F_4$ fold axes (pp. 80, 164). The abundance of joints related to the stress patterns of the $F_3$ and $F_4$ folds (p. 150) indicate that the recrystallisation dwindled with the cessation of folding movements.

The basic lava flows are contemporaneous with the sedimentation (p. 173) during the geosynclinal stage. Acidic igneous activity commenced with quartz veining and pegmatite permeation at the earliest deformational stage ($F_1$-folding) and continued throughout the orogenic stage till the $F_4$-folding (p. 174). The ultramafic intrusions took place at the peak of tectonic activity post-$S_2$ pre-$F_3$ (p. 173), followed by the granitic intrusions syn-$F_2$ (p. 173).