

# A reappraisal of chloritoid-bearing phyllites in the Forland Complex rocks of Prins Karls Forland, Spitsbergen

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**ABSTRACT.** In the Forland Complex chloritoid is restricted to the grey and green phyllites which characterize the Scotia and Peachflya groups. The textures and compositions of the rocks and constituent minerals are described and discussed in an attempt to assess how metamorphism, deformation, and chemistry have influenced the stability of chloritoid.

THE Scotia and Peachflya groups of the Forland Complex, Prins Karls Forland, Svalbard (fig. 1) are characterized by the presence of chloritoid phyllites. The Forland Complex (Harland *et al.*, 1979) which consists of Late Precambrian to Early Palaeozoic rocks has been subjected to low grade Caledonian (*sensu lato*) metamorphism and deformation ( $D_1$ ) followed by higher level refolding and thrusting ( $D_2$ ). The presence of chloritoid in these rocks has been noted previously by Tyrrell (1924) and described in detail by Atkinson (1956). The latter concluded that chloritoid grew only in certain grey and green phyllites, was confined to zones of intense movement along thrust faults, and was in discordance with the regional pattern of metamorphism. More recent investigations by the author (Manby, 1978) and Morris (1979) have shown some of these conclusions to be at variance with the field evidence. Textural and mineralogical evidence presented here outlines the relative chronologies of metamorphism/deformation in the Forland Complex and demonstrates that the appearance of chloritoid in these rocks is consistent with the regional pattern of metamorphism. Rock and mineral compositions of a number of chloritoid and non-chloritoid phyllites are also examined in an attempt to assess the factors influencing the stability of chloritoid.

### *Mineral assemblages and textures*

In this and subsequent sections a number of mineral abbreviations are used as follows:

chl = chlorite, mv = muscovite, q = quartz,  
act = actinolite, trem = tremolite, ab = albite,  
ctd = chloritoid, py = pyrite, ph = pyrrhotite,  
pyr = pyrophyllite, czo = clinozoisite, zo = zoisite,  
slp = stilpnomelane.

The mineral assemblages of the Forland Complex phyllites, determined by thin section and XRD analysis are fully represented by (1)  $q + mv + ctd \pm py/ph$  (chlorite only as a retrograde phase), and, (2)  $q + mv + chl \pm ctd \pm py/ph \pm czo/zo$ .

Pyrophyllite was detected in XRD traces of two samples and paragonite in one. Albite has not been found and the opaques which account for less than 1% modal volume are invariably pyrite and/or pyrrhotite.

In most thin sections chloritoid occurs as single crystals, only occasionally are bow-tie or rosette bundles found (fig. 2a). Where  $D_2$ - $F_2$  folds are not developed single chloritoid crystals show a variety of orientations relative to the  $D_1$ - $S_1$  slaty cleavage.  $S_1$ , defined by the preferred orientation of muscovite and chlorite, wraps around the chloritoids which are frequently boudinaged. Pressure shadows border many chloritoids; these and the low pressure areas between boudin segments are filled with quartz + muscovite  $\pm$  chlorite aggregates. In most sections chloritoid is part retrograded and in a few is completely pseudomorphed by quartz + chlorite aggregates. Where chlorite and chloritoid seem to coexist the chlorite more often appears as flakes in the foliation. Only in one specimen (3959) are pre- $S_1$  chlorite rhombs found in addition. However, even in this case the rock has a mylonitic fabric and the sparse but large (1-2 mm) chloritoids are partially replaced by chlorite. Usually where chlorite and chloritoid occur together the latter develops only as tiny needles or rosettes. Seams of opaques are commonly seen paralleling or cross-cutting the  $S_1$  foliation at low angles. In some cases the seams wrap around the chloritoids and appear

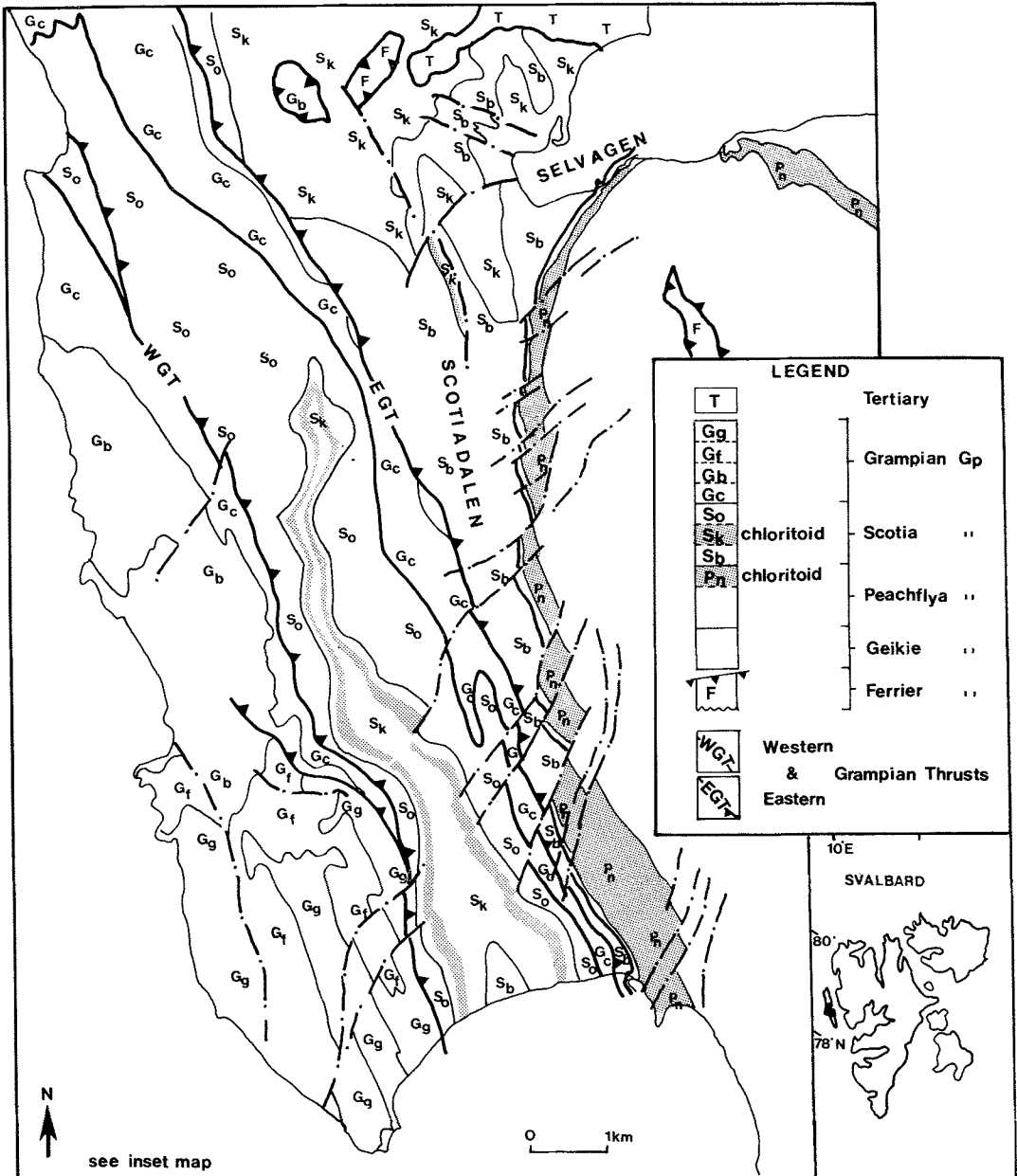


FIG. 1. Geology of Central Prins Karls Forland and outcrop of chloritoid rocks.

to be pressure solution surfaces. A significant loss of material (mostly quartz) has occurred along these surfaces as chloritoid grains impinge upon one another with extensive impaction fractures (fig. 2b). In other cases the seams of opaques are more planar (fig. 2c) and are thought to represent combined shear/pressure solution surfaces, particularly as the

rock fabrics are phyllonitic/mylonitic. All chloritoids show marked strain effects with no tendency to recovery recrystallization.

In addition to the more familiar hour-glass form of inclusions many chloritoids preserve a relict foliation. Rosettes of chloritoid with planar trails of inclusions show clearly that these inclusions are

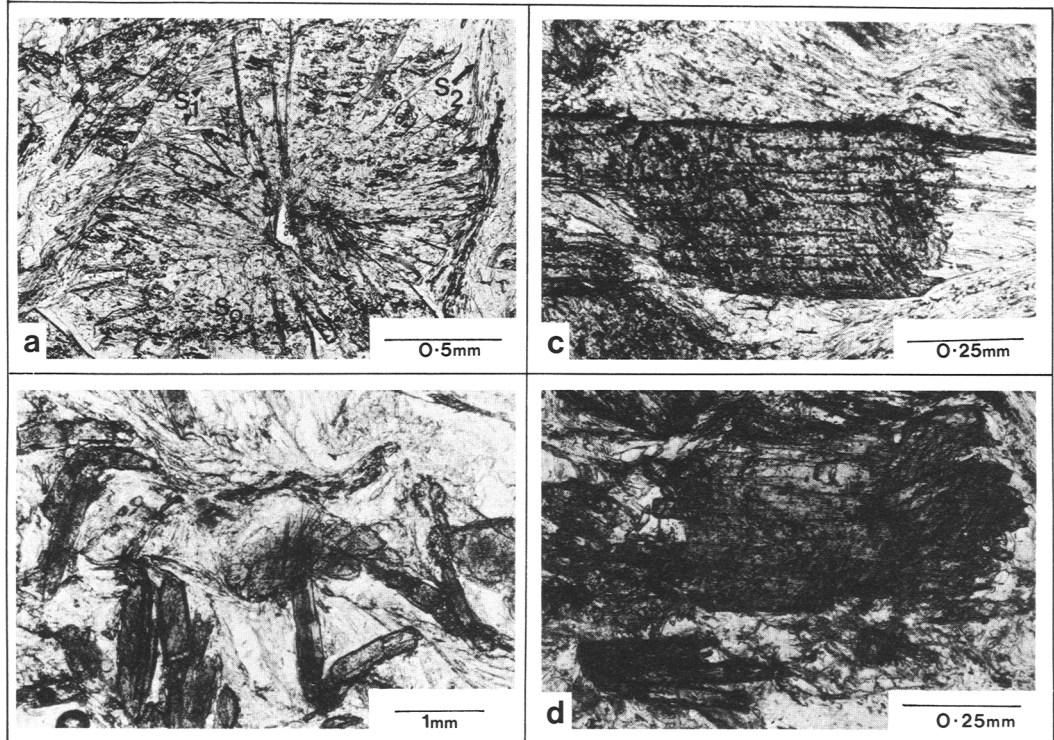


FIG. 2. Textures in chloritoid phyllites: (a) pre- or early-tectonic chloritoid rosette preserving relict ( $S_0$ ) foliation as inclusion trails; (b) impacted and fractured chloritoids. Spaced foliation running NW-SE is  $S_2$  crenulation cleavage; (c) single chloritoid (partially retrograded) with  $S_1 \neq S_0$  against pressure solution-shear plane; (d) early syn-tectonic chloritoid with sigmoidal (rotated) inclusion trails.

not crystallographically controlled (fig. 2a). The internal fabric ( $S_1$ ) in the rosettes is discordant with the external fabric ( $S_0$ ). Single crystals not uncommonly contain inclusion trails which are curved (fig. 2d) indicating growth synchronous with deformation.

#### *Metamorphism-deformation relations*

Throughout the 6.5 km sequence of Forland Complex rocks little change in metamorphic grade is evident. Although restricted to carbonate semipelites and psammites the presence of biotite indicates that even the youngest Forland Complex rocks experienced biotite grade conditions. Toward the Ferrier Group (fig. 1) rocks become more schistose and biotite increases in abundance and grain size. The continued stability of assemblages chlorite + muscovite + quartz, chloritoid + muscovite + quartz in pelites and actinotite + chlorite + albite in metabasic rocks combined with the lack of garnet (and staurolite) in rocks of

appropriate composition suggest conditions did not exceed biotite grade. The prevailing *PT* conditions that can be deduced from these assemblages are discussed below.

The textural relations described show chloritoid growth to have occurred both pre- and syn-tectonically in relation to the  $S_1$  foliation. The  $S_1$  foliation is axial planar to the Forland Nappe, a large imbricate fold structure with a SW transport direction. Many rocks within the nappe, including the chloritoid phyllites, show extensive deformation and retrogression associated with nappe emplacement. The mylonite-phyllonite fabrics and planar opaque seams are indicative of high shear strains and the pressure solution surfaces possibly indicate loading following nappe imbrication. The latter in particular would suggest temperatures at this point must have been below those necessary for phyllosilicate recrystallization (below 300°C). It is concluded therefore that  $D_1$  deformation although partially synchronous with metamorphism effectively brought it to a close.

### Mineral chemistry

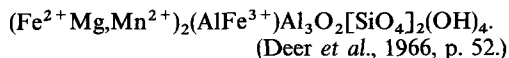
Analyses of muscovite, chlorite, and chloritoid have been carried out on a number of the Scotia and Peachflya phyllites using the EDS electron microprobe in the Department of Earth Sciences, University of Cambridge and the Jeol JSM 35/Link 860 EDS microprobe at Goldsmiths' College, London.

**Muscovite.** Representative muscovite analyses from the chloritoid phyllites are given in Table Ia. All muscovites are  $2M_1$  types (determined from XRD traces) and show limited solid solution with paragonite. Many are also phengitic with Si:Al ratios in excess of 3:1 and corresponding  $Al^{VI}$ -(Fe,Mg) substitution.

**Chlorite.** Chlorite analyses from three samples are given in Table Ib and their averaged compositions plotted in fig. 3b along with the chloritoids. According to Hey's scheme (1954, in Deer *et al.*, 1966, p. 233) the chlorites are generally of ripidolitic

type.  $Fe^{3+}$  has not been determined in the chlorites (or chloritoids) and is not thought to be present because of the occurrence of pyrite-pyrrhotite mixtures in most rocks.

**Chloritoid.** Representative chloritoid analyses are given in Table Ic and averaged values plotted in fig. 3. The compositional range of chloritoids from the Forland complex does not depart significantly from the formula:



The maximum range of substitutions amongst the exchangeable cations found in these rocks (Manby, 1978) includes:

- (1) Replacement of  $Fe^{2+}$  by  $Mg^{2+}$  up to 27 atom %.
- (2) Replacement of  $Fe^{2+}$  by  $Mn^{2+}$  up to 5 atom %.

$Al^{VI}$ - $Fe^{3+}$  substitution has not been determined

TABLE I Representative partial EDS probe analyses of (a) muscovite, (b) chlorites and (c) chloritoids in Forland Complex phyllites. Averaged chlorite and chloritoid analyses from specimens 3007, 3002, 3959 plotted in Figure 3b.

	(a) White Micas				(b) Chlorites								
	2790	2795	3007	3002	3002	3002	3002	3007	3007	3007	3959*	3959	3959
SiO <sub>2</sub>	46.75	46.19	44.93	45.82	26.64	25.68	25.02	25.28	26.89	24.16	22.03	22.54	22.67
TiO <sub>2</sub>	0.37	-	-	0.14	-	-	-	-	-	-	-	-	-
Al <sub>2</sub> O <sub>3</sub>	38.10	35.97	37.45	38.44	25.31	24.29	24.35	25.13	25.31	24.48	22.70	23.16	23.31
FeO	0.48	1.65	0.88	0.59	19.87	19.71	19.77	29.25	28.45	29.54	28.09	29.12	30.46
MnO	-	-	-	-	-	-	-	-	-	0.23	0.21	0.22	0.12
MgO	-	-	-	-	16.51	16.07	16.65	8.04	7.76	8.22	9.18	9.24	9.63
CaO	0.21	-	0.16	0.26	-	-	-	-	-	-	-	-	-
Na <sub>2</sub> O	1.06	0.96	1.69	2.41	-	-	-	-	-	-	-	-	-
K <sub>2</sub> O	8.43	7.80	7.00	5.46	-	-	-	-	-	-	-	-	-
TOTAL	95.40	92.57	92.11	93.62	88.33	85.75	85.79	87.70	88.41	86.63	82.31	84.69	86.82

3007 Chlorites in chl + q aggregates - retrograde.

3002 Chlorites as fibres on margins of pressure shadow.

3959\* Pre S<sub>1</sub> Rhomb.

3959 Chlorites define S<sub>1</sub>

#### (c) Chloritoids

	2795	2795	2795	2795	2938	2915	2915	3007	3007	3007	3007	3002	3002	3002	3959	3959	3959
SiO <sub>2</sub>	24.91	29.21	24.77	24.73	30.53	24.41	24.57	24.75	25.67	25.22	24.36	26.33	25.38	25.21	24.30	23.12	23.40
Al <sub>2</sub> O <sub>3</sub>	36.50	39.66	40.77	41.92	43.21	39.07	40.33	38.69	40.93	40.60	40.20	41.33	41.24	41.31	40.01	36.56	39.53
FeO	25.71	20.21	25.54	24.57	20.45	26.61	26.11	24.85	25.53	23.92	24.71	21.75	22.40	24.01	25.27	26.56	25.98
MnO	0.52	0.33	0.44	0.54	0.29	0.53	0.43	0.59	0.44	0.40	0.42	0.41	0.43	0.33	0.39	0.46	0.19
MgO	3.82	1.62	1.67	1.75	4.19	0.84	0.67	3.21	1.66	2.56	1.60	2.79	2.54	1.94	1.63	2.48	1.48
TOTAL	91.44	91.63	93.33	92.02	98.64	91.44	92.12	92.10	94.23	92.70	91.79	93.6	91.69	92.80	91.60	89.18	90.58

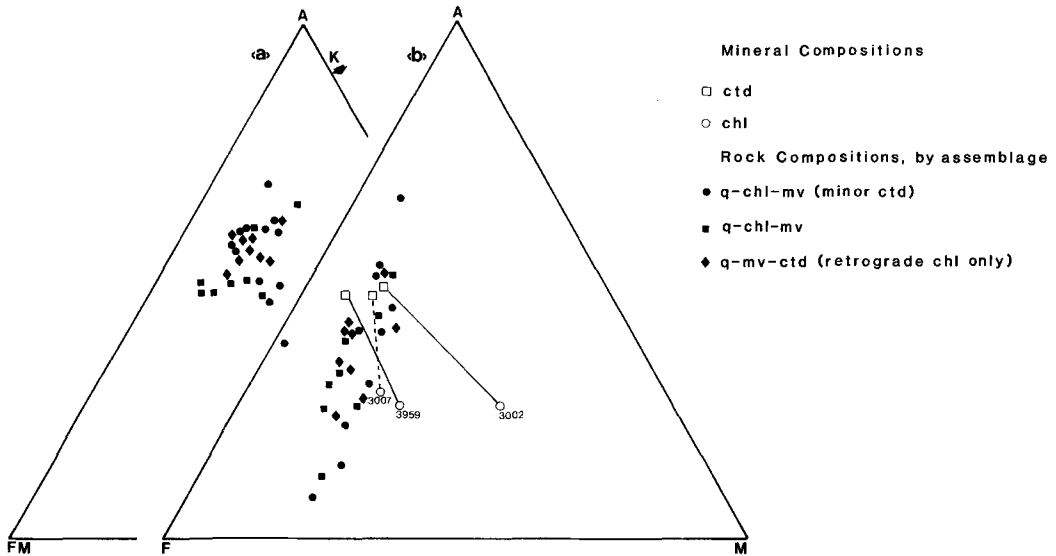


FIG. 3 (a and b). Uncorrected whole-rock (Hoschek) AFK and AFM plots of chloritoid and non-chloritoid phyllites from the Forland Complex. Tie lines join co-existing chlorite and chloritoid compositions (averaged analyses) in 3002 and 3959. Dashed line indicates chloritoid and retrograde chlorite composition in 3007.

because pyrite and pyrrhotite are present in most rocks and all Fe is therefore assumed to be in the Fe<sup>2+</sup> state. The Fe-Mg substitutions are the most significant and have in a few cases been found to vary by 7 atom % in the same sample. No chloritoids traversed showed significant chemical zoning.

*Rock compositions*

Analyses of twenty-eight chloritoid and non-chloritoid phyllites have been carried out using plasma source AA spectroscopy at Kings College, London. All samples are high in alumina, have high Fe/(Fe + Mg) ratios and are low in alkalis (Table II). ACF and AFM diagrams (fig. 3a and b) show these rocks to plot within the same compositional field, albeit wide.

*Discussion*

The association of chloritoid with chlorite, muscovite, and quartz is consistent with an intermediate ΔT/ΔP (Barrovian) type of metamorphism (Winkler, 1976) which affected these rocks. Compositionally the phyllites conform to the now well-established requirements for chloritoid growth having relatively high alumina contents, high Fe/(Fe + Mg) ratios and low alkalis (Hoschek, 1969). The initial sediments from which the phyllites were formed were almost certainly marine clays with a volcanogenic component consisting of

mixtures of chlorite (detrital?), kaolinite, mica/illite, and montmorillonite. The common sympathetic chloritoid + quartz association with muscovite ± chlorite would suggest that chloritoid-producing reactions were largely of the type:

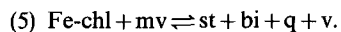


The most likely Al silicate is one of the mica/illite group (cf. Siedel and Okrusch 1975). Reactions of the type

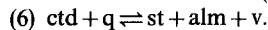


(Hoschek, 1969; Frey, 1978) were of lesser importance.

Published experimental data relating to the stability field of chloritoid are given in fig. 4. The continued stability of the ctd + mv + q ± chl assemblages and lack of staurolite or garnet demonstrates that conditions within the Forland Complex could not have exceeded those defined by reactions.



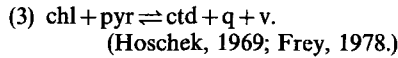
(Hoschek, 1969.)



(Richardson, 1968.)

The lack of garnet in some less aluminous pelites of the Ferrier Group suggests conditions below the 525–560 °C and 4.0–7.25 kbar field delimited by reaction 5. PT conditions for the younger Gramplan Group are more difficult to establish and rely on unsatisfactory experimental data for the lower

stability limit of biotite. Clearly, however, conditions at this level must have exceeded those for reaction curve 1 but were probably below the point where this curve intersects that for reaction 3, indicating a minimum temperature in the 380–400° region. The chloritoid assemblages in the Scotia Group (2 km deeper) show conditions must have exceeded those where the pyrophyllite dehydration curve (Kerrick, 1968) intersects curve 3.



Assuming these approximations have some validity then geothermal gradients between 18–23°C/km can be derived for the Forland Complex rocks (fig. 4).

The discussion so far has assumed that the chloritoid–chlorite assemblages have achieved equilibrium, a conclusion supported to an extent by their uniformity and lateral continuity. Texturally, equilibrium associations are difficult to recognize because of retrograde reactions and the extensive post-crystalline deformation that has occurred.

Microprobe traverses of chlorite, chloritoid and muscovite failed to reveal any significant compositional zoning in the porphyroblasts. Of these, chlorites show the most marked inter-specimen compositional variation (fig. 3b). Within section

3959 pre-S<sub>1</sub> chlorite rhombs have very similar compositions to the S<sub>1</sub> foliation chlorites suggesting re-equilibration of the chlorite from pre- to syn-tectonic crystallization events. Although a distribution coefficient of 0.24 can be calculated for Fe–Mg between chlorite and chloritoid for this sample it is not known whether chloritoid can re-equilibrate so readily as would appear to be the case for chlorite.

Although a proportion of the alumina in the rocks analysed is accounted for by muscovite, chloritoid and chlorite in particular show a marked ability to accommodate large variations in the Al/(Fe + Mg) ratios (fig. 3b). However, the modal abundances of chlorite and chloritoid appear to be unaffected by variations in Al<sub>2</sub>O<sub>3</sub> at constant Mg/(Mg + Fe) contrary to the suggestion by La Tour *et al.* (1980). Whole-rock Mg/(Mg + Fe) ratios for chloritoid-bearing phyllites from the Forland Complex are all below 0.30 and for any given alumina content chloritoid ( $\pm$  chlorite) should be stable (cf. La Tour *et al.*, 1980). Nevertheless many rocks with the requisite compositions (figs. 3a and b) do not contain chloritoid.

Texturally a range of stages can be recognized in the retrogression of chloritoid to chlorite. The incompetent phyllosilicate-rich rocks of the present study have clearly responded readily to shear and

TABLE II Major element analyses of chloritoid & non-chloritoid phyllites from the Forland Complex

Sample	G1	G2	G3	G4	G5	G6	G7	G2795	G2606c	G2915	G2938	G2978	G2980	G2992
SiO <sub>2</sub>	55.52	55.39	58.68	54.27	56.93	57.83	58.32	58.71	61.12	57.04	55.04	54.54	53.43	55.87
Al <sub>2</sub> O <sub>3</sub>	28.76	26.69	26.57	27.12	26.17	24.52	23.34	23.98	24.96	26.27	27.79	26.16	26.52	24.67
FeO	8.25	6.06	6.90	8.23	6.96	8.23	8.98	7.45	4.73	6.35	8.10	8.20	8.52	8.10
MnO	0.10	0.06	0.06	0.11	0.07	0.15	0.14	0.16	0.08	0.16	0.21	0.11	0.12	0.10
MgO	1.17	0.84	1.47	1.27	1.39	1.35	1.54	1.42	0.99	1.14	1.40	1.08	1.34	1.23
CaO	0.21	0.23	0.18	0.18	0.21	0.23	0.25	0.33	0.32	0.36	0.42	0.44	0.35	0.37
K <sub>2</sub> O	2.87	3.80	3.51	3.54	3.43	3.17	2.96	3.59	5.50	3.51	2.59	2.37	3.13	4.14
Na <sub>2</sub> O	1.69	1.68	1.60	1.03	1.56	1.00	0.06	0.95	0.75	0.99	0.73	0.51	0.69	0.76

Sample	M3003	M2748	M3959	H3957	H3988	G2995	G2989	G2820	G2891	G2899	G2984	G2990	G2994	G2998
SiO <sub>2</sub>	76.58	57.81	58.28	59.78	49.14	60.61	54.70	54.49	60.12	55.82	50.09	56.24	56.61	58.50
Al <sub>2</sub> O <sub>3</sub>	8.68	19.60	22.46	22.20	23.92	21.31	26.39	22.96	23.49	21.51	29.30	20.37	21.80	21.58
FeO	4.69	9.62	6.92	8.05	5.90	4.36	3.25	8.83	6.22	7.77	5.13	7.81	9.37	5.74
MnO	0.10	0.33	0.02	0.04	0.02	0.02	0.01	0.01	0.05	0.01	0.03	0.02	0.05	0.01
MgO	0.99	1.35	1.32	1.76	1.04	1.01	0.68	1.44	1.46	1.26	0.68	1.37	1.88	1.06
CaO	1.43	0.45	0.21	0.22	0.23	0.22	0.20	0.22	0.21	0.70	0.26	0.28	0.23	0.23
K <sub>2</sub> O	1.40	1.84	3.86	4.53	1.85	2.88	5.61	5.09	3.96	5.47	2.74	3.83	1.00	4.10
Na <sub>2</sub> O	0.23	0.44	1.53	0.79	0.90	1.33	0.83	0.66	1.41	1.97	0.72	0.84	2.75	0.74

Totals not given as H<sub>2</sub>O<sup>+</sup>, H<sub>2</sub>O<sup>-</sup> have not been determined.

(See Fig. 3 for key to symbols).

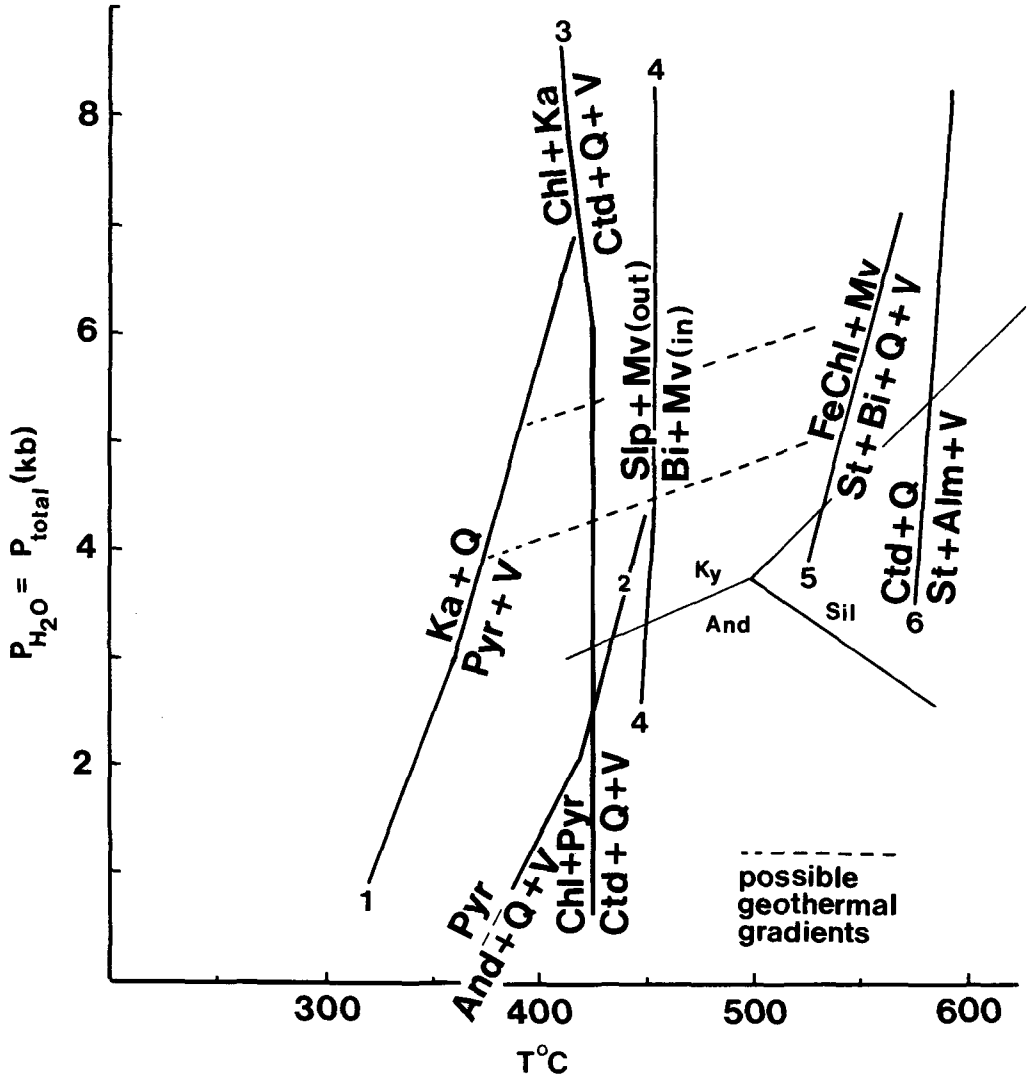


FIG. 4. Summary of relevant published experimental data relating to stability of chloritoid in the Forland Complex. 1. Thompson (1970), 2. Kerrick (1968), 3. Hoschek (1969), 4. Winkler (1976), 5. Richardson (1968). Approximate *PT* conditions for Forland Complex metamorphism is defined by the two possible geothermal gradients. Mineral abbreviations used are as follows: Ka = kaolinite, Pyr = pyrophyllite, St = staurolite, Alm = almandine, Ky = kyanite, And = andalusite, Sill = sillimanite, V = vapour.

flattening strains imposed during fold/nappe generation. Deformation of this nature in low-grade rocks is invariably accompanied by movement of fluid phases ( $H_2O$  predominantly) and reverse reactions (chloritoid to chlorite) are initiated. During  $D_1$  the elevated  $P_{H_2O}$  thus imposed would either have suppressed the chloritoid-forming reaction or alternatively destabilized earlier formed chloritoid, replacing it with chlorite + quartz in a foliated assemblage. The presence of

reduced iron phases (pyrite/pyrrhotite) rule out the effect of elevated  $f_{O_2}$  values as a destabilizing influence on chloritoid.

*Conclusions*

From its common association with quartz + muscovite + chlorite, chloritoid in the Forland Complex is thought to have been produced by reactions similar to that of Siedel and Okrusch

(1975). In the light of experimental data the mineral assemblages are indicative of metamorphic conditions in excess of 4–5 kbar/380–400 °C. The occurrence of chloritoid in rosettes or random orientations demonstrates some pre-tectonic growth with respect to  $S_1$  and those with curved (rotated) inclusion trails, syntectonic growth. Mg/(Mg + Fe) ratios of not much in excess of 0.30 in the rocks of this study might well define an upper limit for chloritoid stability over a range of  $Al_2O_3$  contents without necessarily affecting the modal abundance of chlorite–chloritoid (cf. La Tour *et al.*, 1980). Deformation-enhanced  $P_{H_2O}$  may well have destabilized chloritoid, favouring chlorite + quartz assemblages in many of the Forland Complex rocks. Further sampling of the Forland Complex phyllites will be carried out to investigate the influence of deformation on chloritoid stability.

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