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ANOMALOUS OPTICS IN LOW-GRADE CHLORITE FROM ATLANTIC CANADA

DAVID CRAW* AND REBECCA A. JAMIESON
Department of Geology, Dalhousie University, Halifax, Nova Scotia B3H 3J5

ABSTRACT

Two textures of optically negative chlorite and one of positive chlorite can be distinguished in low-grade metavolcanic rocks of the St. Anthony Complex, Newfoundland. Interlayered positive and negative chlorites also occur. The chlorites are all moderately magnesian, and coexisting different types have similar compositions. The negative chlorite is a low-temperature polytype. Recrystallization from negative to positive chlorite was induced by deformation during and after lower-greenschist-facies metamorphism. Interlayered and intermixed positive and negative chlorites in the matrix of undeformed metavolcanic rocks of the Dunn Point Formation, Nova Scotia, are cross-cut by veins of positive chlorite. Negative chlorite has recrystallized to positive chlorite owing to rising metamorphic temperature under conditions of the prehnite-pumpellyite facies. In the Dunn Point Formation, the negative chlorite is more magnesian than the analogous chlorite in the Newfoundland rocks, and it has recrystallized to the positive form at a lower temperature.

Keywords: chlorite, anomalous optics, metamorphism, deformation, St. Anthony Complex, Newfoundland, Dunn Point Formation, Nova Scotia.

SOMMAIRE

On peut distinguer deux textures de chlorite optiquement négative et une seule de chlorite positive dans les roches métavolcaniques faiblement métamorphisées du complexe de St. Anthony (Terre-Neuve). Les chlorites des deux signes se présentent aussi interfoliées. Toutes les chlorites examinées sont relativement magnésiennes, et les types différents sont de composition analogue où ils coexistent. La chlorite négative représente un polytype de basse température. Sa recristallisation en chlorite positive résulte d'une déformation pendant et après un épisode de métamorphisme dans le facies schiste-vert inférieur. On trouve la même association interfoliée de chlorites positive et négative, mais que recoupent des veinules de chlorite positive, dans la pâte de roches métavolcaniques non-déformées de la formation Dunn Point (Nouvelle-Ecosse). La recristallisation de la chlorite négative en chlorite positive est due à l'élévation de la température de métamorphisme dans les conditions du facies prehnite-pumpellyite. Dans ces roches, la chlorite négative est plus magnésienne que dans celles de Terre-Neuve et doit avoir recristallisé en chlorite positive à plus basse température.

(Traduit par la Rédaction)

Mots-clés: chlorite, anomalies optiques, métamorphisme, déformation, complexe de St. Anthony, Terre-Neuve, formation Dunn Point, Nouvelle-Ecosse.

INTRODUCTION

The optical properties of chlorite have been well studied, and the relationships between composition and optical properties determined by several authors (*e.g.*, Hutton 1940, Albee 1962, Miyashiro 1958). In particular, Albee (1962) presented a useful scheme to classify chlorite based on the relationship between iron/magnesium ratio and optical properties. Using Albee's scheme, the ratio Fe/(Fe+Mg) (hereafter designated F/FM) of most specimens of chlorite can be determined approximately from optic sign and interference colors in thin section. Optic sign is normally determined from sign of elongation using an accessory plate. Albee's method has been used extensively by petrographers over the last twenty years. In this paper, we describe deviations from accepted optical properties in chlorite from some low-grade metabasalts.

Most common low-grade metamorphic chlorite is ripidolite; this species may be optically positive or negative, with the change in optic sign occurring where $\beta = 1.630$ and F/FM = 0.52 (Albee 1962). At this changeover point, chlorite is effectively isotropic for the whole spectrum of white light, although very commonly some parts of the spectrum are not extinguished, resulting in purple interference-colors. If F/FM is between about 0.52 and 0.7 the chlorite is optically negative, with $\beta > 1.630$, and is isotropic for longer wavelengths of light, giving rise to abnormal blue interference-colors. If F/FM is beween about 0.3 and 0.52, the chlorite is optically positive, with $\beta < 1.630$, and is isotropic for shorter wavelengths, giving rise to abnormal red-brown interference-colors. However, we have observed in several low-grade metamorphic situations that chlorite flakes commonly are made up of interlayered or intermixed abnormal blue (−) and abnormal brown (+) chlorite.

Another type of dispersion observed in chlorite is bisectrix dispersion. This phenomenon appears as bluish or brownish fringes near the extinction position; the mineral goes into extinction for part of the spectrum only. The phenomenon arises because there is an angle, from zero up to about 10° between the *X* (and *Z*) directions of principal vibration for violet and red light. Not all chlorite specimens show this dispersion, and evidence presented below suggests that bisectrix dispersion is more prevalent in chlorite formed at lower temperatures.

Low-grade metamorphic rocks are very fine-grained, and chlorite is generally finely disseminated

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*Present address: Department of Geology, University of Otago, Dunedin, New Zealand.

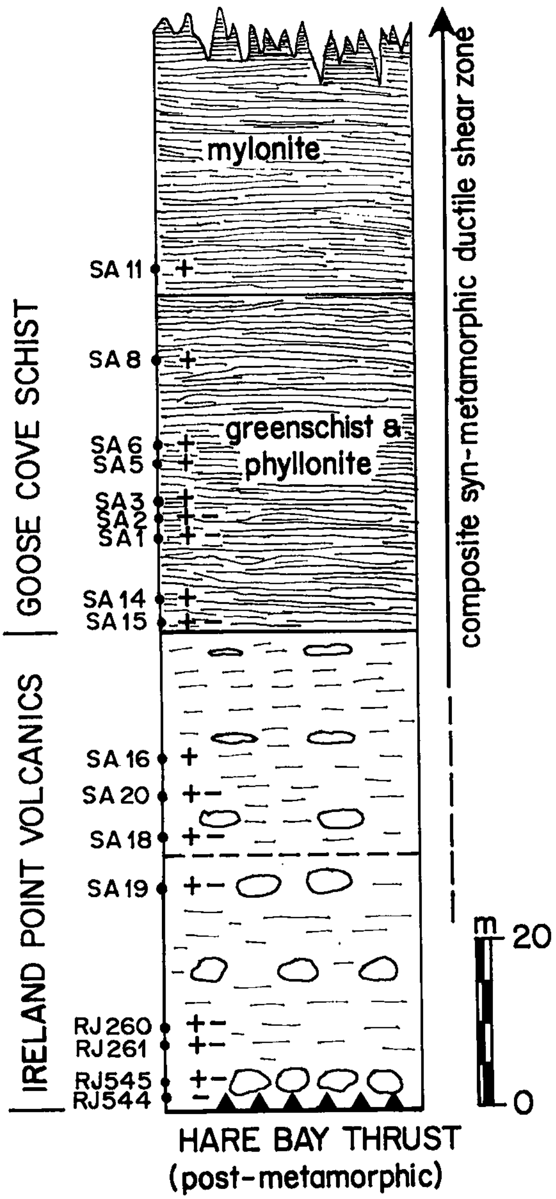

FIG. 1. Composite section from base of Ireland Point Volcanic Suite (Ireland Point) to middle of Goose Cove Schist (near Stark's Bight) (see Jamieson 1981 for locality map). Synmetamorphic strain increases up-section from undeformed pillow lavas (round ornament) through moderately flattened pillow lavas (elliptical ornament) to schists and mylonites (line ornament). Postmetamorphic deformation associated with Hare Bay Thrust has occurred inhomogeneously near the base of the section. Sample localities are shown on left side of the diagram. Optic sign(s) of chlorite in each sample is indicated (+ or − or both) beside each sample locality.

through the matrix and intimately intermixed with other fine-grained low-grade minerals. Hence, detailed study of the minerals is difficult. However, some rocks collected from the base of the St. Anthony Complex, northwestern Newfoundland (Jamieson 1981) contain abnormal blue and abnormal brown chlorite intermixed on an unusually coarse scale, and thus provide excellent subjects for a study of the problem. The data reported here show that these optically different chlorites have approximately the same composition; therefore, some other factor(s) must affect the optical properties of this mineral. Deformation is the most likely cause. Also, we present data from the Dunn Point Formation of Nova Scotia where positive and negative chlorites coexist in undeformed low-grade metavolcanic rocks. This variation in optical properties is probably due to some effect of temperature.

THE ST. ANTHONY COMPLEX

The St. Anthony Complex consists of a peridotite sheet underlain by metamorphosed igneous and sedimentary rocks that range from lower-greenschist facies (Ireland Point Volcanic Suite and the base of the Goose Cove Schist) to the granulite facies immediately beneath the peridotite. The total thickness of the section is about 500 metres. The entire St. Anthony Complex is a thrust slice emplaced along the postmetamorphic Hare Bay Thrust (Williams 1975). The rocks are described in detail by Jamieson (1981). The following discussion involves metavolcanic rocks from the Ireland Point Volcanic Suite and the Goose Cove Schist.

Deformation in the Goose Cove Schist has been intense, and the rocks have completely recrystallized, with up to three synmetamorphic foliations. The Ireland Point Volcanic Suite is relatively little deformed. The single foliation is inhomogeneously developed. The Ireland Point Volcanic Suite and the lower part of the Goose Cove Schist were all metamorphosed under lower greenschist-facies conditions. Differences in development of deformation textures and degree of foliation are a direct result of different amounts of strain in the rocks during metamorphism (Craw 1983). Strain increased up-section in the Ireland Point Volcanic Suite toward a structural discontinuity that marks the base of the Goose Cove Schist (Fig. 1). In addition, all of the St. Anthony Complex was affected by at least two phases of postmetamorphic deformation. These later phases of deformation were inhomogeneous and involved local folding and faulting. Some of this deformation was presumably related to the Hare Bay Thrust (Fig. 1).

Low-grade chlorites

Some rocks from the base of the Ireland Point

TABLE 1. TEXTURES AND OPTICAL PROPERTIES OF CHLORITE IN RJ545

TYPE	TEXTURAL ORIENTATION OF (001)	OPTIC SIGN	ANOMALOUS OR NORMAL	GRAIN SIZE	INTERFERENCE COLORS	BISECTRIX DISPERSION	EXTINCTION	PLEOCHROISM	OCCURRENCE
I	random; flake shapes poorly developed	-	anomalous	less than 0.1 mm	pale abnormal blue-first order grey/yellow	strong	undulose	too fine-grained to determine	small (0.1-0.5 mm)
II	parallel	-	anomalous	0.2-	deep abnormal blue	none	undulose	α = colorless β = γ = very pale green	large flakes defining S1, apparently recrystallized from I
III	semi-random (see Fig. 2)	+	normal	0.1 mm (up to 0.5 mm)	abnormal brown	none	sharp, parallel	α = β = very pale green, γ = colorless	in shear zones cross-cutting II as flakes parallel to 001 in II; in clusters adjacent to II, especially around calcite

Volcanic Suite show no sign of deformation, and these contain pools of randomly oriented negative chlorite only (*e.g.*, RJ544). However, most rocks from this level (Fig. 1) contain coexisting positive and negative chlorites (*e.g.*, RG545). Positive chlorite becomes progressively more common up-section, and this chlorite is progressively better-aligned in the foliation, which also becomes better-developed up-section. Negative chlorite is quite rare in the upper 40 metres of the Ireland Point Volcanic Suite and almost nonexistent in the upper 15 metres, immediately below the contact with the Goose Cove Schist. Almost all chlorite in the Goose Cove Schist is positive and lies parallel to pervasive foliation(s). Although most rocks from the zone of intermixed positive and negative chlorite are too fine-grained to allow analysis of individual chlorite flakes of different optic signs, one sample, RJ545, contains both types of chlorite in sufficiently coarse flakes for accurate analysis.

The sample studied (RJ545) is a variolitic pillow lava consisting predominantly of titanaugite laths in a devitrified groundmass. The groundmass consists of pools of albite and chlorite with very fine-grained (0.02 mm) actinolite, calcite and titanite, and minor hematite, sericite and epidote. Chlorite forms coarser pools up to 1 mm across, many of which are elongate parallel to (defining) the incipient foliation. It is in these larger pools of chlorite that mixed positive and negative chlorites occur.

Three different forms of chlorite can be identified in RJ545 on the bases of texture and optical properties (Table 1). Irregularly bounded pools of fine-grained randomly oriented flakes of type-I chlorite (*cf.* RJ544, see above) are scattered through the rock. Many of these pools are cross-cut by coarse-grained type-II chlorite, which has apparently recrystallized from type I and is strongly oriented in the incipient foliation. Both these types of chlorite are optically negative. Large flakes of type-II chlorite are cut by sigmoidal microshear zones (Fig. 2). Type-III chlorite (positive) has grown in or across many of these shear zones and is undeformed.

Some flakes of type-III chlorite occur interleaved with type-II chlorite on a 0.1 mm scale, with (001) cleavages parallel. In the latter texture, the two types can be distinguished in plane-polarized light by their different pleochroic schemes. Where there is no overlap of flakes, a faint Becke line is visible. If there is overlap of flakes, no Becke line is visible and a combined interference color, purple, is apparent under crossed polars. Since type-III chlorite has grown in and across deformation zones in type-II chlorite, it must postdate, and is presumably recrystallized from, type-II chlorite. This recrystallization resulted in more randomly oriented chlorite (type III), although some recrystallization was apparently mimetic (Figs. 2, 3).

Many chlorite pools oriented parallel to foliation have a core of calcite. Chlorite associated with the calcite (adjacent or intergrown) is almost invariably positive (type III). Some of the pools are "zoned", with positive chlorite around the central calcite and negative (type-II) chlorite on the outer edge of the pool, adjacent to the rock matrix (Fig. 4). In Figure 4 the positive chlorite is mainly mimetically parallel to the type-II chlorite, but in some similar pools the positive chlorite has grown more randomly than the well-aligned negative (type-II) chlorite.

Chemical composition in relation to optical properties

Microprobe analyses of chlorite were made in two pools of chlorite (type I) and five different composite

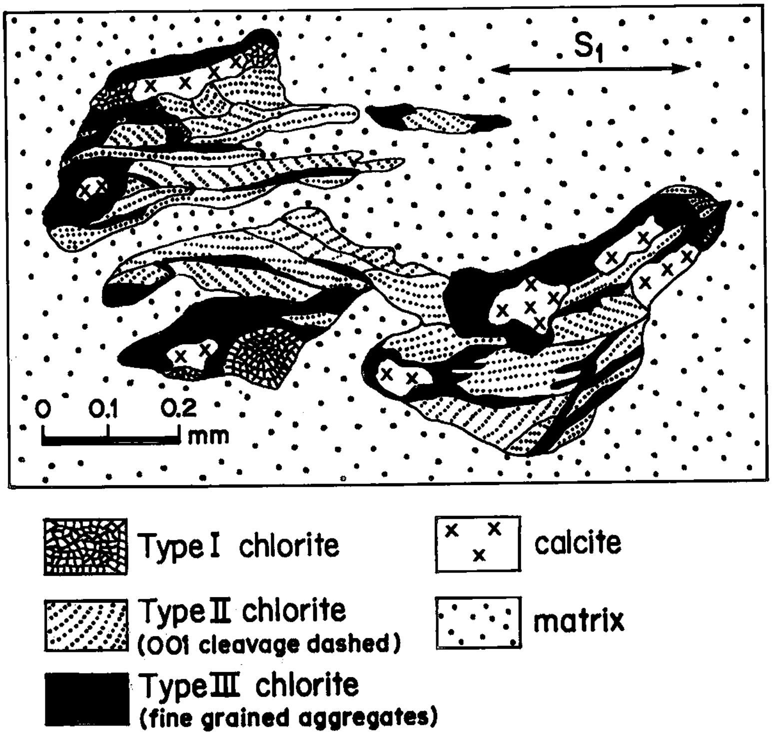

FIG. 2. Sketch from a thin section of sample RJ545 (Ireland Point Volcanic Suite), showing mutual relationships of chlorites of types I, II and III. Foliation = S_1.

grains (types II and II) in sample RJ545. The compositions (Table 2) show that there is no significant chemical difference between types II and III, but type I has slightly higher F/FM. Type-I chlorite was analyzed on a different day from type-II and type-III chlorites. Three analyses of each of types II and III were made for comparison during the session of analyses of type-I chlorite; all these compositions of type II and III chlorites fall within the ranges obtained during the first session of analyses.

A chlorite concentrate was obtained from sample RJ545. The coarsest flakes in this separate (0.05–0.1 mm) are presumably predominantly type-II chlorite. The intermediate index of refraction determined using these flakes is 1.614 ± 0.003. The value F/FM and this index of refraction were plotted on Albee's (1962) diagram relating composition and index of refraction (Fig. 5). The parameter F/FM is used in this paper rather than Albee's parameter Fe + Mn + Cr/(Fe + Mn + Cr + Mg) since Cr is below the detection limit of the microprobe in these chlorites, and Mn is very low and has no significant effect on the value of the parameter. We combine Fe^{2+} and Fe^{3+}, as did Albee (1962).

Type-III chlorite (same composition as type II) is plotted on Figure 5 at the same point as type II. Type-I chlorite was plotted on Albee's intermediate-index line at the appropriate composition. The resultant points all fall on the optically positive side of this diagram, showing that it is the positive (late-stage) type-III chlorite that is "expected" according to Albee's (1962) data.

The chlorite concentrate from RJ545 was used for X-ray-diffraction examination, which showed that the chlorite has a basal spacing typical of low-grade chlorite (14.2 Å). Chlorite reflections in the diffractogram are single symmetrical peaks, so that the three types of chlorite seem to have the same basal spacing. This spacing is consistent with the observed Al content of the chlorite (*cf.* Albee 1962).

Chemical compositions of chlorite in other samples from the Ireland Point Volcanic Suite and the Goose Cove Schist are plotted in Figure 5. These rocks are too fine-grained to liberate chlorite for determination of index of refraction. Therefore, points were plotted on Figure 5 on Albee's (1962) β-index line at the appropriate compositions (see above). The plotted points cluster on the positive side of the diagram, apart from RJ586 (Ireland Point Volcanic Suite), which is negative and therefore "ex-

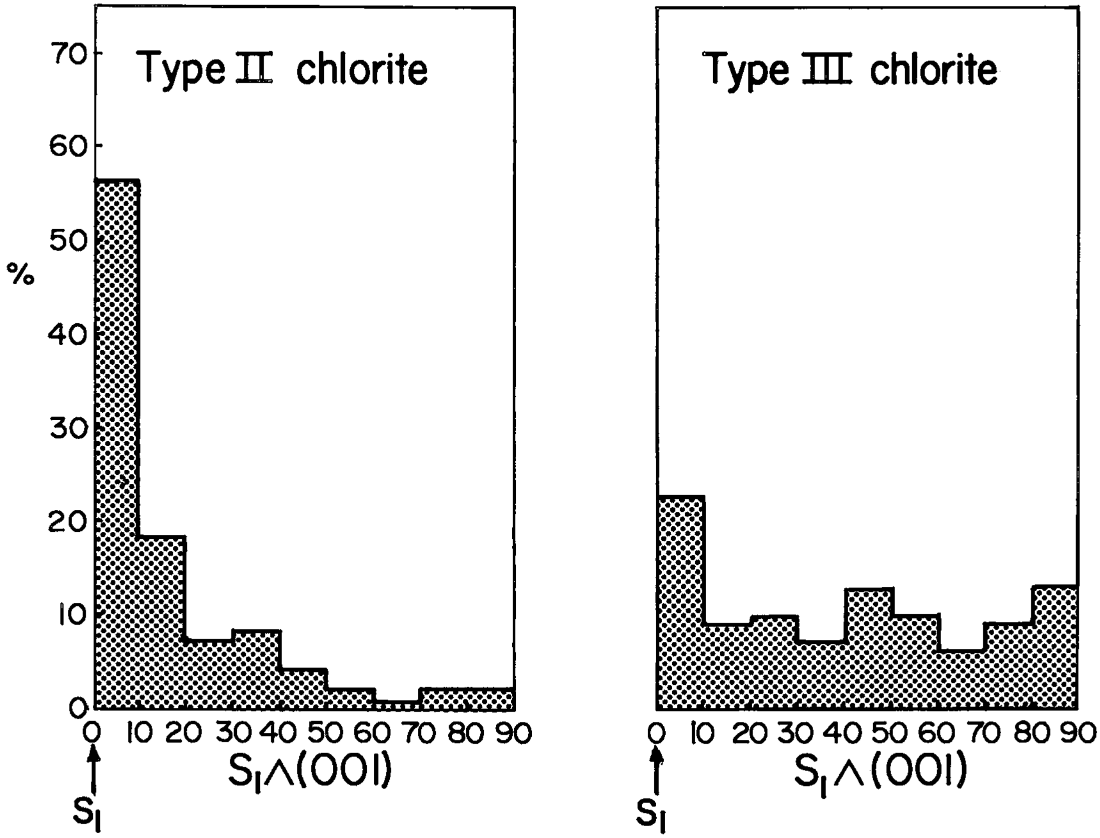

FIG. 3. Histogram showing distribution of angles between foliation (S_1) and chlorite (001) cleavage in RJ545 for (a) type-II chlorite (216 measurements), and (b) type-III chlorite (195 measurements). Thin section was cut perpendicular to S_1. Measurements were made on a flat-stage petrographic microscope.

pected". Thus in most rocks it is the negative chlorite that is "not expected" according to Albee's (1962) scheme.

The general up-section transitional appearance of positive chlorite at the expense of negative chlorite (Fig. 1, described above) reflects the recrystallization of the negative chlorite forms to give the positive forms. This recrystallization is complete in the upper parts of the Ireland Point Volcanic Suite and throughout the Goose Cove Schist. The recrystallization parallels the increase in deformation in the Ireland Point Volcanic Suite at constant metamorphic grade, and so is probably directly related to the deformation (see below).

Origin of anomalous chlorite

Anomalous negative chlorite was described by Albee (1962) from amygdules and veins in mafic igneous rocks. Albee attributed the anomalies to deficiencies in H, which balanced some of the charge of octahedral Al. However, there is no indication of any major deficiency of hydrogen in chlorite of the Ireland Point rocks, although H_2O can be obtained only by "difference" for microprobe analyses. Also, since there is no chemical difference between coexisting positive and (type-II) negative chlorite in RJ545, H deficiency can be ruled out as a cause for the anomalous negative chlorite in that rock.

More likely, the anomalous negative chlorite is a different polytype. Random rotations and linear shifts in the crystallographic stacking of the "talc" and "brucite" sheets in chlorite result in metastable polytypes, particularly at low temperatures of formation (Brown & Bailey 1962, 1963, Shirozu & Bailey 1965).

A type-III chlorite separate from sample SA6 (Fig. 1) yielded an X-ray powder pattern indicative of the IIb polytype of Brown & Bailey (1962). This identification was based on direct comparison of the SA6 powder photograph with a set of photographs of different chlorite polytypes kindly supplied by S.W. Bailey. The IIb polytype is the most common,

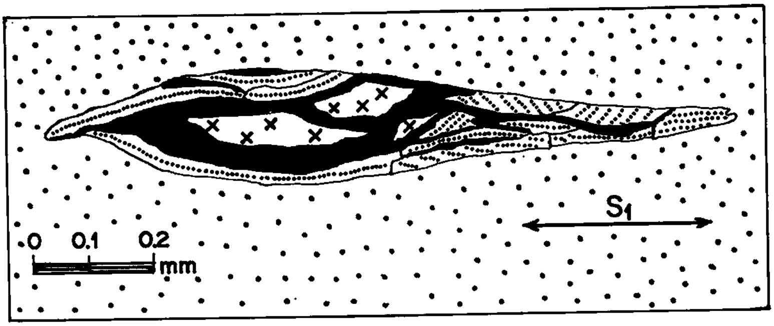

FIG. 4. Sketch from a thin section of sample RJ545, showing "zoning" of chlorite polytypes around a calcite pool. Foliation = S_1. Ornaments as for Figure. 2.

"stable", chlorite polytype (Brown & Bailey 1962), and is the polytype on which Albee's scheme of classification is based (A.L. Albee, pers. comm. to S.W. Bailey). The fine grain-size and fine scale of intermixing preclude separation of type-I and type-II chlorites for detailed X-ray analysis to determine their polytypes. The following discussion shows that on optical grounds the stacking arrangements (and, therefore, the polytypes) in type-I and type-II chlorites are different from each other and from type-III chlorite. From these data and the paragenesis data discussed in later sections, it seems likely that type-I and type-II chlorites are metastable polytypes (*cf.* Brown & Bailey 1962), although the exact nature of these polytypes remains obscure.

Bisectrix dispersion provides evidence for differences in stacking types between the first-formed chlorite and the recrystallized chlorite in RJ545. Since the directions of principal vibration are fixed to crystallographic axes in uniaxial minerals, such minerals cannot show bisectrix dispersion. In fact, it is only in monoclinic and triclinic minerals that

TABLE 2. CHLORITE COMPOSITIONS FROM LOW-GRADE METAVOLCANIC ROCKS

	RJ545, TYPE I		RJ545, TYPE II		RJ545, TYPE III		SFX5 -ve matrix	SFX5 +ve matrix	+ve veins
	Av.	Range	Av.	Range	Av.	Range			
SiO_2	28.6	27.7 - 29.6	28.9	27.3 - 30.0	29.2	28.8 - 29.7	30.6	31.4	28.1
TiO_2	0.00	0.00 - 0.00	0.00	0.00 - 0.00	0.00	0.00 - 0.00	0.00	0.00	0.00
Al_2O_3	19.3	18.2 - 20.2	18.5	17.4 - 19.3	18.3	17.9 - 18.7	18.9	18.1	21.8
FeO*	23.4	23.1 - 24.1	22.2	21.2 - 22.8	22.1	21.7 - 22.5	18.2	18.6	20.8
MnO	0.32	0.26 - 0.39	0.30	0.23 - 0.41	0.28	0.17 - 0.37	0.62	0.64	0.77
MgO	16.8	16.4 - 17.2	18.5	17.2 - 19.0	18.6	18.1 - 19.0	22.0	22.6	19.5
CaO	0.45	0.23 - 0.63	0.13	0.05 - 0.21	0.16	0.08 - 0.21	0.13	0.14	0.00
Na_2O	0.00	0.00 - 0.00	0.00	0.00 - 0.00	0.00	0.00 - 0.00	0.00	0.00	0.00
K_2O	0.00	0.00 - 0.00	0.00	0.00 - 0.00	0.00	0.00 - 0.00	0.00	0.00	0.00
Total	88.87		88.53		88.64		90.45	91.48	90.97
Si*	5.86		5.91		5.96		5.97	6.07	5.55
^{iv}Al	2.14		2.09		2.04		2.03	1.93	2.45
^{vi}Al	2.51		2.36		2.36		2.33	2.19	2.61
Ti	0.00		0.00		0.00		0.00	0.00	0.00
Fe*	4.01		3.79		3.77		2.97	3.01	3.43
Mn	0.06		0.05		0.05		0.10	0.11	0.13
Mg	5.13		5.63		5.66		6.41	6.50	5.72
Ca	0.10		0.03		0.03		0.03	0.03	0.00
Na	0.00		0.00		0.00		0.00	0.00	0.00
K	0.00		0.00		0.00		0.00	0.00	0.00
Total	11.81		11.86		11.87		11.84	11.84	11.89
F/FM	0.44		0.40		0.40		0.32	0.32	0.37

* Si + Al = 8.00. Average and range of compositions from RJ545 (Ireland Point Volcanic Suite) are presented for type-I (10 analyses), type-II (18 analyses) and type-III (18 analyses) chlorites. Representative compositions from SFX5 (Dunn Point Formation) are presented for matrix positive and negative chlorites and vein positive chlorite. Analyses were obtained using a Cambridge microprobe with energy-dispersion system. Operating conditions: accelerating voltage 15 kV; current 5 nA on Faraday cage; beam diameter 10 μm; analysis time = 100 seconds. Cations were calculated on the basis of 28 oxygen atoms (anhydrous). Fe* = all Fe as Fe^{2+}.

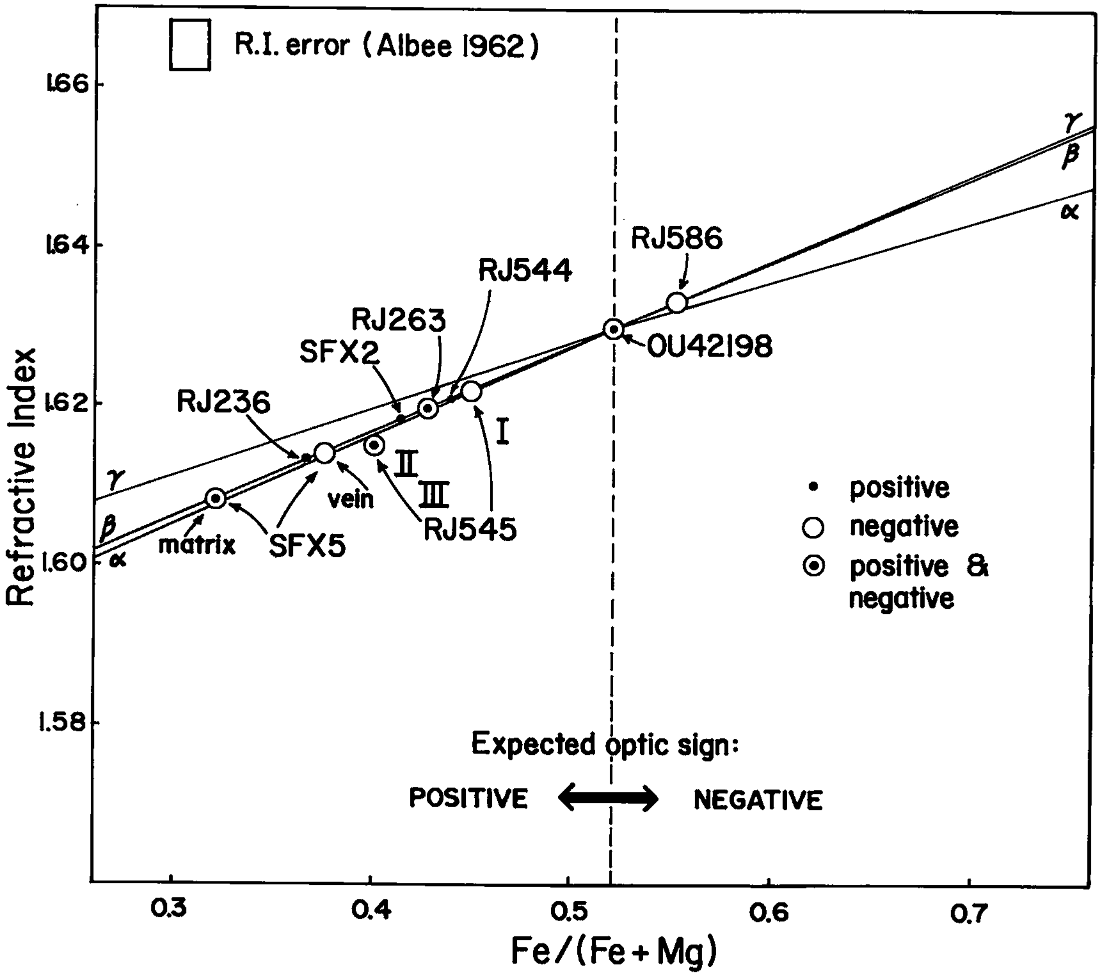

FIG. 5. Index of refraction *vs.* composition of chlorite, modified from Albee (1962). Data points from Ireland Point Volcanic Suite (RJ544, 545, 586), Goose Cove Schist (RJ263, 236), Dunn Point Formation (SFX 2 and 5) and Otago Schist (OU 42198). All Fe is calculated as FeO.

bisectrix dispersion can occur (*e.g.*, Phillips 1971). Chlorite that shows pronounced bisectrix dispersion therefore must be monoclinic or triclinic rather than pseudo-uniaxial. The recrystallized chlorites in RJ545 (types II and III) show no bisectrix dispersion. Therefore, they probably have a higher symmetry than the strongly dispersing type-I chlorite. Flakes of type-II chlorite are rarely sufficiently coarse and suitably oriented to yield interference figures. Undulose extinction distorts the resulting figures as well. However, figures obtained show that type-II chlorite is, or is close to, pseudo-uniaxial ($2V < 5°$). No figures were obtained for type-I and type-III chlorites. The difference in symmetry between type-I chlorite and the recrystallized chlorite is presumably a result of the different stacking-sequence within the chlorite structures. No such difference can be demonstrated between types II and III, but the difference in optic sign implies that some crystallographic difference does exist. Minor structural irregularities as outlined above could result in anomalous optical properties since there is only a very small difference (about 10% relative) in the α and γ indices of refraction between types I and II and type-III chlorites in RJ545.

CAUSES OF CHANGES IN OPTICAL PROPERTIES OF CHLORITE

Temperature

Intuitively, increasing temperature might be expected to be the main factor in recrystallization of early-formed metastable polytypes. Hayes (1970) suggested that the stable IIb polytype forms from metastable polytypes above about 150–200°C. However, there is no evidence for a differential in metamorphic temperature in the Ireland Point Volcanic Suite, although this greenschist assemblage is stable over a wide interval of temperature. Since increasing metamorphic temperature is almost invariably accompanied by deformation in metamorphic belts, the effect of temperature is difficult to document. The Dunn Point Formation, discussed below, may be an example of deformation-free temperature-dependent recrystallization of polytypes of chlorite.

Microscale, local causes of change in chlorite optics

Radioactive bombardment of the chlorite structure from included grains of zircon can cause inversion from positive to negative optics or *vice versa* (*e.g.*, Heinrich 1965). The effect is local, within grains, and approximately radial around the included zircon. The affected zone generally appears as a pleochroic halo. This type of inversion was not observed in the samples studied.

Oxidation of Fe^{2+} in the chlorite structure by weathering processes results in a radical change in optical properties. Oxidized chlorite closely resembles brown biotite (Brown 1967, Craw 1981a), *i.e.*, it is optically negative and has higher-order interference colors than unoxidized chlorite. Even incipient oxidation of positive chlorite causes apparently anomalous optical properties. Characteristically, this oxidation occurs along the cleavages of the chlorite, so that interlayered positive and negative chlorites can result. Oxidation appears as diffusely bounded brown stains along the chlorite cleavages, readily visible in plane-polarized light. To avoid this problem, only fresh samples with green chlorite were used in this study.

Deformation

The textures described above imply that deformation is the principal cause of recrystallization from negative to positive chlorite. The recrystallization accompanied the progressive development of foliation in the Ireland Point Formation under apparently static P–T conditions. Presumably, recrystallization of negative to positive chlorite in postmetamorphic zones of microshearing was also induced by defor-

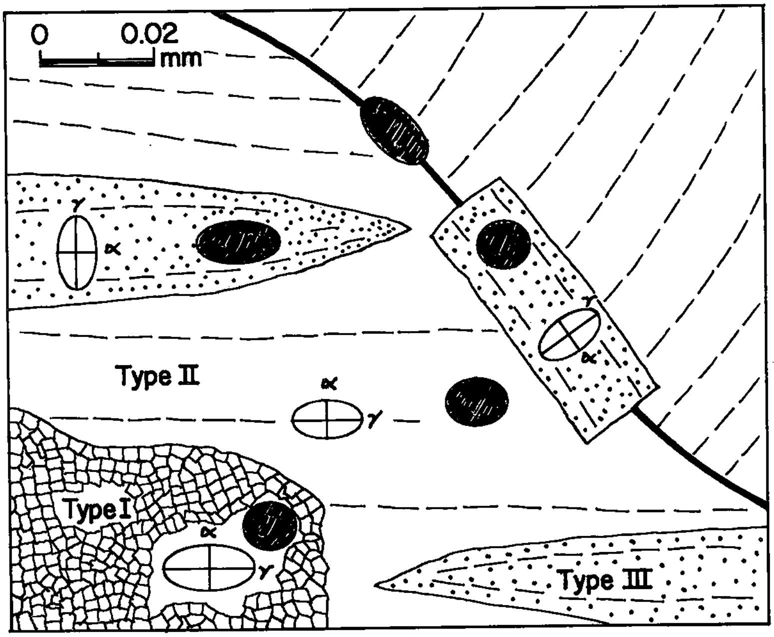

FIG. 6. Sketch of three chlorite polytypes in RJ545 (types I, II and III) (*cf.* Fig. 2). Type-II chlorite is crossed by a sigmoidal shear-zone. Sketches of sections through strain ellipsoids (black) and optical indicatrices (open ellipses) show relative changes in these geometric figures during recrystallization and increasing strain. Dimensions of ellipses are exaggerated and schematic only. Chlorite (001) cleavage is dashed. Foliation is horizontal.

mation. "Zoned" chlorite pools around calcite (Fig. 4) support this contention. Since calcite deforms readily, a local high-strain zone probably developed in and around the calcite as a result of a competency contrast between the calcite and the rest of the rock. High strain in this zone may have induced negative chlorite to recrystallize to a positive polytype.

Some recrystallization of chlorite could be due to direct compression of the phyllosilicate structure, resulting in a small (undetectable) change in basal spacing (*cf.* Crowley & Roy 1960, Hazen & Finger 1978). Compression perpendicular to (001) could result in a density increase in that direction, and perhaps a density decrease parallel to (001). Such density changes would cause minor changes in indices of refraction of the negative mineral so that α could increase (to become γ) and γ could decrease (to become α). The strain ellipsoid during synmetamorphic deformation and formation of foliation presumably had its short axis approximately perpendicular to the foliation now seen in the rocks. Thus the change in length of axes of the XZ section of the optical indicatrix of the flakes of negative chlorite parallel to the foliation would be opposite to changes in the XZ or YZ section of the strain ellipsoid during the deformation and hence consistent with the observed change in optical properties. Interlayered positive and negative chlorites, with (001) parallel to the foliation, may result from this process (Fig. 6).

The same process may have operated during formation of microshear zones in negative chlorite. However, it is more likely that positive chlorite recrystallized from grains of locally highly strained negative chlorite in an orientation that was energetically most favorable (*cf.* Shirozu 1963, White 1977, McClay & Atkinson 1977), not necessarily parallel to the host grain (Fig. 6). This could explain the wide variety of orientations of positive chlorite (Fig. 3). The concentration of orientations of positive chlorite parallel to the foliation probably reflects a tendency to mimetic crystallization in the negative chlorite (type II).

Two different styles of deformation have apparently been involved in recrystallization of chlorite in the Ireland Point Volcanic Suite and Goose Cove Schist. Ductile deformation occurred synmetamorphically, and strain increased up-section (Fig. 1). Up-section disappearance of metastable negative chlorite is presumably due to this ductile deformation. Near the base of the Ireland Point Volcanic Suite, where ductile strain was at a minimum, negative chlorite recrystallized but survived that deformation. Late- or postmetamorphic brittle deformation, which produced microshears (above), is best developed at the base of the section studied, where it may be related to the Hare Bay Thrust. Strain during this deformation has resulted in more local recrystallization of negative chlorite to positive chlorite.

DUNN POINT FORMATION, ANTIGONISH COUNTY, NOVA SCOTIA

The Silurian Dunn Point Formation consists of subaerial basalts, rhyolites, ignimbrites and intercalated reddish sedimentary horizons that possibly represent baked or lateritic soils. The rocks have been mapped and described by Benson (1974) and Boucot *et al.* (1974), and the petrological affinities discussed by Keppie *et al.* (1978). According to the latter authors, the volcanic rocks were erupted in an intraplate rift-zone. The volcanic rocks are overlain by shallow marine sediments (*e.g.*, Benson 1974).

Although the rocks show dips up to 70° and are cut by several faults, they are generally remarkably undeformed. Some samples contain both positive and negative chlorites. Hence the Formation is ideally suited for a study of intermixed chlorite polytypes in undeformed rocks.

General geology

A suite of samples was obtained from basic volcanic flows near the base of the Dunn Point Formation, in the type section at Dunn Point, Nova Scotia. These rocks are largely recrystallized to very fine grained (about 0.01 mm) low-grade metamorphic minerals, but primary textures are partly preserved. Interlocking laths of feldspar with feldspar phenocrysts up to 2 cm across are recognizable. No primary mafic minerals or their textures are preserved. Feldspar laths have been albitized and are riddled with fine-grained epidote, chlorite, calcite and quartz. Pools of chlorite (up to 0.5 mm) in feldspar interstices may replace devitrified glass. Titanite is common as scattered grains and clusters of grains throughout the rock. Hematite grains probably replace primary oxide phases. Chlorite, epidote, calcite and quartz veins are common, and vesicles contain chlorite, calcite and prehnite. Outcrops are extensively veined, mainly by epidote (veins up to 5 cm across) and calcite. No pumpellyite or actinolite was found in these rocks.

There is little evidence for deformation in the rocks. In outcrop, primary flow features, such as vesicular tops and rubbly tops and bases, are preserved and undistorted. Vesicles are still approximately spherical. No foliation is visible on mesoscopic or microscopic scales. The only mesoscopic structures present in the rocks are veins, set of tension gashes that are commonly filled with epidote, and slickensides on some joints and flow surfaces.

Chlorite polytypes

Most of the chlorite occurs in veins cross-cutting the rocks in a wide variety of (random?) orientations. Vein chlorite commonly shows "cocks-comb" textures or forms radiating clusters of flakes on vein walls, both indicative of open-space filling. Other veins contain chlorite flakes aligned approximately parallel to vein walls, but perpendicular veins nearby commonly show the same texture. Apparently undulose extinction in vein chlorite is a result of radiating textures, not deformation. Chlorite in the matrix of the rock mainly occurs as irregular pools containing randomly oriented flakes. Very fine chlorite grains are mixed with other metamorphic minerals in feldspar grains. All vein chlorite and much of the matrix chlorite are optically positive, with abnormal brown interference colors and very weak to nonexistent bisectrix dispersion.

Some of the matrix chlorite is optically negative and has abnormal blue interference-colors. Pools of randomly oriented fine-grained (about 0.02 mm) negative chlorite with strong bisectrix dispersion resemble the type-I chlorite of RJ544 and 545 in the Ireland Point Volcanic Suite (above). Coarser (up to 0.1 mm) flakes of negative chlorite without bisectrix dispersion also occur. The latter flakes commonly contain interlayered positive chlorite; positive chlorite dominates over negative chlorite in some flakes. Thus chlorite textures in these rocks resemble those described from the Ireland Point Volcanic Suite (above) except that there is no incipient foliation in the Dunn Point Formation.

Microprobe analyses of the Dunn Point Formation chlorites show that both polytypes have a magnesian composition (Table 2, Fig. 5) and hence that the positive polytype is "expected" as in the Ireland Point Volcanic Suite. Coexisting positive and negative chlorites in the matrix, and fine-grained negative chlorite, all have the same compositions. However, positive chlorite in the veins is slightly less magnesian than the matrix chlorite. This difference in composition probably reflects a chemically evolving metamorphic system.

Discussion

It is apparent from the above descriptions that recrystallization from negative to positive chlorite polytypes is not a result of compressive shear-deformation in the Dunn Point Formation, as it probably was in the Ireland Point Volcanic Suite. Textures imply that the Dunn Point Formation was undergoing syn- to postmetamorphic extension or tectonic relaxation when recrystallization of polytypes occurred, and that this tectonism was of minor importance. More likely, recrystallization of the chlorite polytype in the matrix occurred in response to increasing metamorphic temperature in these rocks (*cf.* Hayes 1970). Vein chlorite recrystallized during or after the metamorphic maximum as the rocks became more fractured.

Lack of index minerals in the Dunn Point Formation makes determination of metamorphic grade difficult. The matrix assemblage epidote - chlorite - albite - quartz - sericite - titanite - hematite - calcite implies prehnite-pumpellyite or lower-greenschist facies conditions (*e.g.*, Miyashiro 1973, Schiffman & Liou 1980), although the assemblage is not diagnostic. The notable absence of actinolite in the rocks and the presence of prehnite in vesicles tend to indicate the prehnite-pumpellyite facies, although the evidence is tenuous. Certainly, it seems that the Dunn Point Formation was not metamorphosed at a higher temperature than the Ireland Point Formation. Thus deformation-free recrystallization of the optically negative polytype chlorite has apparently occurred owing to increasing temperature. The temperature was at or below the temperature of metamorphism of the Ireland Point Volcanic Suite, yet recrystallization of chlorite in the Ireland Point Volcanic Suite required deformational impetus. The reason for this apparent anomaly probably lies in the compositional differences of the chlorites. Negative chlorite in the Dunn Point Formation is more magnesian (Fig. 5) and, therefore, probably recrystallizes to the "expected" polytype more readily than negative chlorite in the Ireland Point Volcanic Suite. Thus, a lower temperature of recrystallization of the positive polytype is to be expected.

Further evidence for the compositional dependence of temperature of recrystallization of chlorite polytypes comes from the Meguma Group of southern Nova Scotia, a weakly deformed slate terrane (*e.g.*, Schenk 1970, Keppie & Muecke 1979). Biotite-zone chlorite compositions are very close to the positive–negative boundary: F/FM = 0.52 (J. Cullen, pers. comm.), and these very flakes commonly show both positive and negative polytypes interlayered. Similarly, chlorite from the biotite zone of the Otago Schist terrane of New Zealand (*e.g.*, Craw 1981b), with compositions near F/FM = 0.52, almost invariably contain both positive and negative polytypes interlayered. Apparently, these "unexpected" polytypes can persist at least to the biotite zone if their composition is close to that of the changeover in the optic sign. The effect of later deformation on stable polytypes is not known; could deformation cause formation of metastable polytypes from stable polytypes of chlorite with a composition near F/FM = 0.52?

CONCLUSIONS

Anomalous optics in chlorites in low-grade metamorphic rocks are probably a result of metastable stacking-sequences. Recrystallization to "expected" chlorite polytypes can be induced by a rise in temperature or application of stress. Hence anomalous optics disappear with prograde metamorphism or progressive deformation, or both. Anomalous and "normal" polytypes coexist during the recrystallization.

The temperature or amount of strain required to recrystallize chlorite to "expected" polytypes will vary according to the composition of the chlorite. Thus chlorite with a composition near the positive–negative boundary (F/FM = 0.52) may retain anomalous optics to relatively high temperatures (or amounts of strain), *e.g.*, up to the biotite zone. Relatively magnesian negative chlorite (F/FM = 0.32) of the Dunn Point Formation recrystallized to a positive polytype under conditions of the prehnite-pumpellyite facies. Less magnesian negative chlorite of the Ireland Point Volcanic Suite (F/FM = 0.4) recrystallized to negative chlorite under lower greenschist-facies conditions but recrystallized again to the "expected" positive polytype under both ductile and brittle deformation. Hence recrystallization of early-formed metastable chlorite polytypes is governed by temperature, strain and composition of the original chlorite. Albee's (1962) classification scheme should be used with caution in low-grade metamorphic rocks.

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