General comments on the identification of chlorites in thin sections

E. P. SAGGERSON AND L. M. TURNER

Department of Geology, University of Natal, King George V Avenue, Durban, Natal 4001, South Africa

ABSTRACT. Although a 'chlorite' is usually simple to recognize in thin section because of its characteristic colour, form, and often very low or anomalous interference colours, the identification of the various species is more difficult and requires both chemical and X-ray work for accurate determination. Roy and others have demonstrated that chlorites are polymorphous and occur in two structural groups, the normal 14 Å chlorites and the 7 Å septechlorites (Nelson and Roy, 1958). Many chlorite varieties may be found in both structural states, low-temperature end-members and compositionally extreme end-members favouring the septechlorite structure, especially antigorite, amesite, chamosite, greenalite, and cronstedtite. Phillips (1964) subsequently proposed that six variables, Y, R^{3+}, R^{2+}, Σ, H, plus the appropriate structural designation, must be fixed to define completely a variety of the chlorite group and from this he developed a numerical system of classification. Unfortunately these specific chemical and structural properties cannot be directly recognized by normal optical methods.

CHLORITES are Mg, Fe, Al phyllosilicates with a layered structure similar to the micas, of tabular habit, occurring in flaky and scaly aggregates. In thin section they exhibit mottled extinction and range from colourless to green, Mn and Cr varieties displaying orange, orange-brown, pink, or lavender colours. Members of the chlorite family are monoclinic or triclinic and therefore biaxial, yet because the refractive indices of the two rays in (001) sections are so close, the optic axial angle (2V) is very small. For most purposes chlorites may, therefore, be considered to be uniaxial, with positive and negative varieties. The septechlorite, antigorite, however, has 2V 20-60°. They may occur in all environments and their composition is thus closely related to that of the original rocks or minerals from which they have formed. Chlorite is characteristic of low-grade metamorphosed pelitic sediments and basic igneous rocks or as an alteration product of other ferromagnesian minerals. In igneous rocks it occurs most commonly as a late-stage crystallization product especially in amygdales, whereas in sedimentary rocks it is a common detrital component, often associated with clay minerals in a mixed-layer structure.

Varietal names are related to chemical composition and structure, the scheme presented by Hey (1954) recognizing the importance of the Fe/(Fe + Mg) ratio as well as the substitution of Si for Al in tetrahedral coordination. Many attempts have been made to relate the chemical composition of chlorites to their optical properties, e.g. Winchell (1936), Hey (1954), and Albee (1962). Hey (1954) presented a two-dimensional scheme (see fig. 1) showing the relationships between refractive index, birefringence, density and composition, and separating oxidized chlorites from orthochlorites on the basis of the Fe_2O_3 content, which exceeds 4% in the former. A third axis to Hey's diagram to indicate Fe^{3+} substitution in tetrahedral and octahedral sites (cf. Nelson and Roy, 1958, p. 721) would demonstrate the relationship between the four main compositional series listed by Phillips and Griffen (1981) viz.:

Amesite	Antigorite series
Pseudothuringite	Brunsvigite series
Klementite	Delessite series
Thuringite	Strigovite series.

Albee preferred to discard varietal names and to base routine petrographic identifications on optic sign and interference colours relating these to Fe/(Fe + Mg) ratios (Table I). He recognized, however, that chlorites in ultramafic rocks, and amygdales and veins may depart from his generalizations. Deer et al. (1966) further commented that pleochroism is generally exhibited more strongly by chlorites with higher iron content.

A consequence of Hey's scheme is that the increase in Fe/(Fe + Mg) ratio and oxidation state is accompanied by an increase in refractive index and a general increase in absorption (pleochroism) from colourless (Mg-Al-rich varieties) to green (Fe-rich members); those displaying anomalous interference colours being those with extremely low birefringence where $\varepsilon \simeq \omega$. Aluminous chlorites can also be identified in terms of the scheme. Albee's scheme is useful for general purposes when dealing with mafic and ultramafic assemblages and though
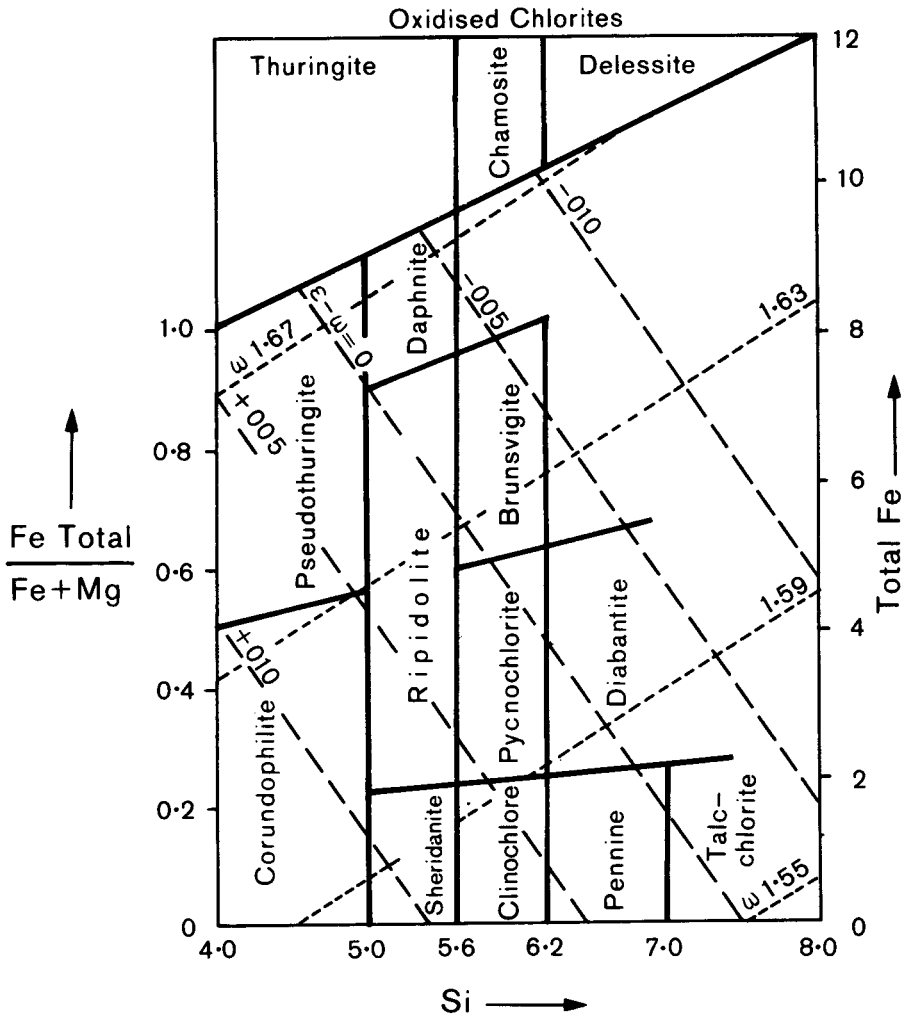
FIG. 1. Relationship between optical properties and chemical composition in the chlorites (from Hey, 1954).

he recognizes the importance of the Al content of chlorites as a reflection of their rock association, it is not provided for in his generalized optical scheme (Table I), where only a medial value of 2.6 to 2.7 atoms per 10 cations for Al is used. In order to accommodate this limitation, we have attempted to combine the main features of both Hey's and Albee's schemes with the revised nomenclature of Phillips and Griffen (1981) into fig. 2 and Table II from which the following generalizations can be made.

1. Colourless chlorites will be Mg-rich varieties. Green chlorites will be Fe-rich varieties.

2. Chlorites with very low relief will be Mg-rich, Al-poor varieties.

Chlorite with relatively high relief will be Fe-rich varieties.

3. Green chlorites with anomalous brown interference colours are likely to be pycnochlorite (basic rocks) or prochlorite (ripidolite) (pelitic rocks).

4. Green chlorites with anomalous blue interference colours are likely to be antigorite (talc-chlorite), talc-chlorite, diabantite, or brunsvigite.

5. Chlorites with high first-order interference colours will be Mg-Al-rich varieties.

6. As stated by Deer et al. (1966, p. 237), 'the division of the main types of chlorite according to optic sign puts pennine, clinochlore,

prochlorite (ripidolite), sheridanite, and corundophilite as positive, and diabantite, brunsvigite, thuringite, chamosite, and delessite as negative'.

In the writers' experience, chlorites displaying anomalous blue interference colours are commonly classified as pennine. Fig. 2 indicates that this is not necessarily the case, as chlorites of various compositions may exhibit this optical phenomenon and this is substantiated by EPMA analysis (pers. comm. from referee). From our own thin-section studies it has thus been possible to estimate that a chlorite with anomalous brown interference colours, optically positive sign R.I. > 1.63 and

TABLE I. *Optical properties and chemical composition of the chlorites (after Albee, 1962)*

Composition	Mg	Mg–Fe	Fe–Mg	Fe
δ	normal	anomalous brown	anomalous blue	normal
2V	(+)	(+)	(−)	(−)
Orientation	fast	fast	slow	slow
R.I.	1.56–1.60	1.60–1.63	1.63–1.65	1.65–1.69

TABLE II. *Optical properties, chemical composition, and rock associations of the chlorites (based on Hey, 1954; Albee, 1962; Deer et al. 1966)*

| Colour	R.I.	Orientation	2V	Interference colours	δ	Composition		Common rock associations
↑ colourless to general increase in green and pleochroism	1.65–1.73	slow	(−)	normal	> 002	Si,Al	Fe	Fe-sediments, ironstones, ores, pegmatites, veins, amygdales
	1.62–1.65	slow	(−)	normal	002–007	Si		
		slow	(−)	anomalous blue	< 002	Al	Fe/Mg	Fe-pelites, granitoids, quartzofeldspathic gneisses
		fast	(+)	anomalous brown				
		fast	(+)	normal	002–010			
	1.59–1.63	slow	(−)	anomalous blue	< 002	Si		
		fast	(+)	anomalous brown		Al	Mg/Fe	Basic, pelitic
		fast	(+)	normal	002–010			
	1.56–1.60	slow	(−)	anomalous blue	< 002	Si	Mg	Ultrabasic, carbonates, calc-silicates
		fast	(+)	anamolous brown				
		fast	(+)	normal	002–016	Al		Basic
	1.55–1.59	slow	(−) (20–60°)	normal	000–008	Si	Mg	Ultrabasic, carbonates, calc-silicates
		slow	(−)	anomalous blue	< 002			
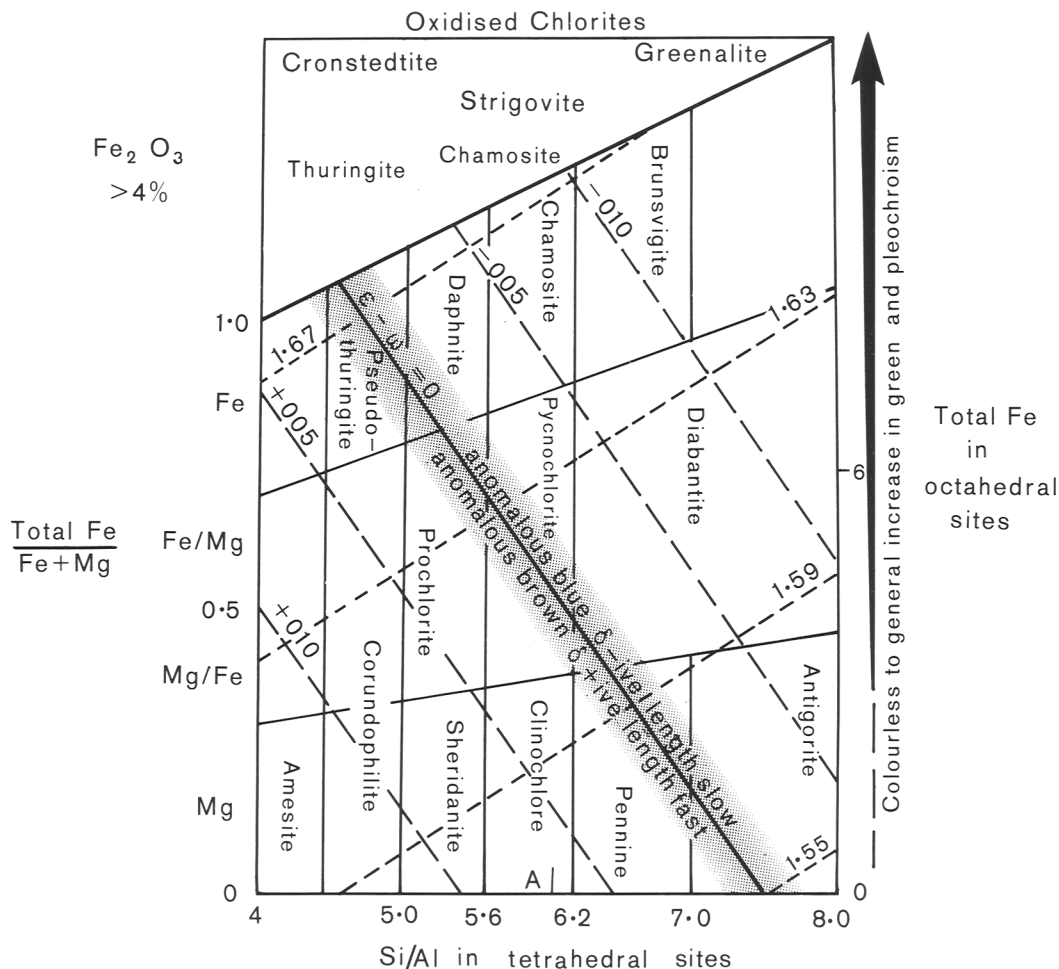
FIG. 2. Relationship between optical properties and chemical composition in the chlorites after Hey, 1954, Albee, 1962, and Phillips and Griffen (1981). A ≈ Albee's medial value of 2.6 to 2.7 atoms per 10 cations for Al used. Shaded area ≃ field of anomalous interference colours. Note that chlorites in the field to the left of the line $\varepsilon - \omega = 0$ are positive and those to the right are negative.

strong green pleochroism is most probably an Fe-Al-rich chlorite (as may be found in association with garnets, cordierites, and biotites in pelitic rocks) and *not* a Mg-Fe chlorite as suggested by Albee's scheme (Table I). On the other hand in terms of fig. 2, metamorphosed ultramafic rocks may be expected to contain Al-poor, Mg-Si-rich chlorites with anomalous blue interference colour, negative sign and R.I. < 1.60, whereas Mg-Al-rich chlorites show higher interference colours. Differences in R.I. (relief) between 1.65 and 1.55 (M → L) can be distinguished in thin section with a trained eye, as can the intensity of green colour and pleochroism. For intermediate values and the oxi-

dized equivalents of ortho(ferrous)-chlorites the distinction is more difficult and recourse to more sophisticated methods may be necessary. Additional properties such as polysynthetic twinning and inclined extinction may also be useful in delimiting chlorite varieties, e.g. clinochlore.

There is no simple way of identifying the chlorites and the use of simple optical methods is fraught with uncertainty. The recognition of the approximate chemical varieties of chlorite and classifying them by name can be accomplished providing care is given to the recognition of colour, relief, and birefringence, as well as the rock and mineral association. Albee's scheme based on Mg/Fe ratios

is useful for general purposes when dealing with metamorphosed basic rocks but the importance of Al/Si ratios as given by Hey are nevertheless relevant and cannot be ignored in the optical identification of common chlorites.

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