THE CHLORITE SERIES OF FLAGSTAFF HILL AREA, CALIFORNIA: A PRELIMINARY INVESTIGATION

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Abstract—The results of X-ray diffraction, DTA, i.r. spectroscopy, and chemical tests are presented for some chlorites typical of the Flagstaff Hill area. The area is notable for the large variety of chlorite types occurring in considerable quantities. Chlorite, in this area, is found as veins, as pseudomorphs, and as individual crystals. Textures vary from massive, fine-grained aggregates to books which are more than 20 mm in width. Crystals more than 5 mm in size occur in parallel groupings at rock interfaces. Judging from 45 chlorite samples studied, sheridanite is most abundant; clinochlore and ripidolite are common. Penninite and its Cr–chlorite equivalent are less abundant. The parent rock is an irregularly shaped ultramafic body surrounded by low-grade schists and located very close to a granodiorite stock. The original ultramafic rocks have been highly altered by metamorphism and metosomatism into assemblages comprised mainly of serpentine, talc, hornblende, and chlorite with relics of olivine, pyroxene, and other less abundant original minerals. Much of the exposed rock is essentially monomineralic, mostly consisting of various polytypes of serpentine. Preliminary investigation indicates that the area merits much more study because of the opportunity for readily observing the various chlorite types and determining their genesis, alteration sequences and weathering characteristics. The area, being easily accessible, could also serve as an adequate source for samples to be used as reference standards.

INTRODUCTION

ALTHOUGH the investigation of the chlorite minerals of the Flagstaff Hill area is in its preliminary stages, the results thus far are presented for the following purposes: to suggest the area as an adequate source for chlorite samples usable as reference standards; to propose that the area should be fruitful for information on the genesis, alteration, and weathering characteristics of the different chlorite minerals; to describe unusual serpentine minerals present and show that they bear further investigation. The first purpose is considered important because it has been difficult to secure good samples of the different chlorite types in the United States, especially in the West, although most of the more common clay minerals are readily available in rather pure form.

The chlorite types are discussed below under the headings of the principal investigation procedures including differential thermal analysis, i.r. spectra, and X-ray diffraction. The minerals, other than chlorites, will be discussed briefly. A few thin sections, studied for a preliminary understanding of the history of alteration of rock, provided no

means for distinguishing between the chlorites.

Names used herein reflect a tentative classification of the chlorite types devised for this investigation

Location and access

The study area is in western El Dorado County about 25 miles northeast of Sacramento, California (see Fig. 1). Access is by partially paved road from the village of Pilot Hill. The valley west of Flagstaff Hill was inundated in 1956 to form Folsom reservoir.

Flagstaff Hill, part of the low foothills of the Sierra Nevada, is characterized by a rough, hilly topography with a maximum local relief of about 300 ft. Hilltops are approximately 1450 ft above sea level. The semi-arid climate has resulted in a dense cover of manzanita, scrub oak, and chamisal (Adenostema).

Previous work

The mining history and mining geology of the area have been described by Wells *et al.* (1940) and by Cater *et al.* (1951). Attention was first called to the chromite deposits in the general area about 1853, and during 1892 a few pockets of chromite were worked. There was profitable mining of

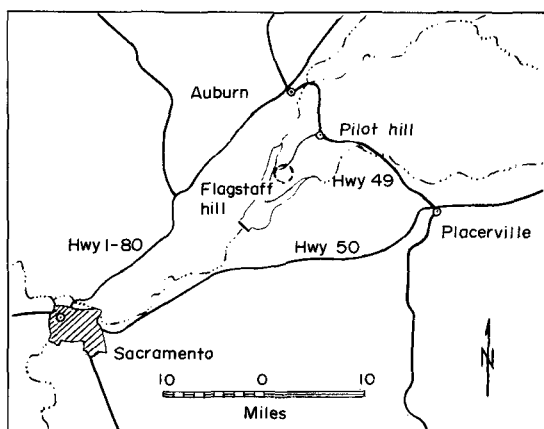*Dept of Civil Engineering.
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Fig. 1. Location of the Flagstaff Hill area, El Dorado County, California.

chromite from 1915 to 1918, and mining was resumed during 1936 after construction of a concentration plant and continued to 1946.

Both Wells *et al.* (1940), and Cater *et al.* (1951) mention the chlorite schists in the area. Surprisingly, kammererite is the only chlorite type listed for the area in the most recent edition of *Minerals of California* (1966). A report on contact metamorphic effects on an ultramafic body in the vicinity of the present area has recently been published in abstract form by Springer (1971).

Geology

The chlorite occurs in a north-northwest trending, steeply eastward dipping, approximately tabular body of ultramafic rock about 3/4 of a mile wide and 4 miles long. The various mineral assemblages within the body include the alteration products — serpentine, talc, and various chlorite polytypes.

The ultramafic body, in which chlorite and other products of its alteration are found, is one of a number of "Alpine type" tectonically emplaced bodies found along a major fault zone in the Sierra Nevada foothills. Here, the ultramafic rocks are surrounded by low-grade metamorphosed (greenschist facies) andesitic volcanic rocks (Middle and Upper Jurassic Amador Group) and slate (Upper Jurassic Mariposa Slate). Metamorphism and deformation took place during latest Jurassic or early Cretaceous time, with the ultramafic body probably being emplaced during this deformational episode.

The ultramafic body contains abundant olivine and pyroxenes. Sufficient relics attest to the pre-alteration rocks being peridotite, dunite and pyroxenite. Chromite is an abundant accessory

in these rocks. Dioritic dikes within the body have been metamorphosed to assemblages of actinolite, oligoclase and epidote.

Unlike ultramafic bodies elsewhere in the foothills, this one is in close proximity to the Folsom granodiorite pluton, undoubtedly part of the Cretaceous or latest Jurassic intrusive series which presently underlies the greater part of the Sierra Nevada (Bateman and Wahrhaftig, 1966). It is reasonable to attribute the unusual mineral assemblages in part to the contact metamorphic, metasomatic and hydrothermal effects from the nearby pluton.

The most abundant and pervasive alteration product in the body is serpentine, derived from olivine and pyroxene. In thin section, some of the serpentine can be seen to have partially replaced olivine preferentially along more susceptible crystallographic planes. Attesting to mobility of its constituents, some serpentine occurs in veins in which the long axis of the mineral is normal to vein walls.

Complex alteration of the body has involved silification, steatization, chloritization, and carbonation (resulting in magnesite). More work is necessary to determine the degree of influence to the present assemblages of the probable geologic events subsequent to the ultramafic body's emplacement and the intrusion of dioritic dikes. These events include: low-grade regional metamorphism; contact metamorphism and metasomatism associated with granitic intrusion; and subsequent hydrothermal emanations from the cooling pluton.

Gillery (1959) has suggested that under certain conditions serpentine may be an intermediate phase and chlorite a more stable end product of what is regarded as the serpentinization process.

CHLORITE MINERALS

The chlorite minerals vary in form, depending upon whether the chlorite represents in-place alteration of rock, vein replacement material, or crystal growth in seams. The observed chlorite morphology includes platy and blocky chlorite as replacement material (e.g. sample 15 and sample 38), books in veins with books normal to vein walls (e.g. sample 5), crystals in vesicular seams (e.g. sample 27), and matrix containing chromite (e.g. sample 3) (see Table 5 for description of samples.)

The size of chlorite books varies from very fine-grained masses to more than 20 mm in width, and individual crystals more than 6 mm across. Some seams of platy chlorite are more than one meter wide.

Ripidolite and Cr–chlorite can usually be

differentiated by color, unlike sheridanite, clinochlore, and penninite which cannot ordinarily be distinguished visually. Discussion of the characteristics of chlorite types as determined by the several methods of analysis follows.

Differential thermal analysis. Air-dried chlorite samples were crushed to material passing a No. 200 sieve. Thermograms were made using a DuPont 900 Thermal Analyzer. A heating rate of 20°C per min through a range from room temperature to 1125°C was used with an alundum reference. A T-scale of 2 mV per in. and a ΔT scale of 0·02 mV per in. were used. For this investigation samples weighing about 0·08 g were firmly packed in platinum crucibles which were then placed in the heating elements so that they rested on the thermocouples. The apparatus was calibrated by using internal standards at the given heating rate.

The four types of chlorites tested appear to be clearly differentiated by this method of investigation, except in the region of the sheridanite-clinochlore classification interface. Typical thermograms for the chlorite types are shown in Figs. 2 and 3. The penninite (curve A) and ripidolite (curve B) samples, Fig. 2, give comparable reaction intensities but different patterns. Clinochlore (curve A) and sheridanite (curves B and C), Fig. 3, also give comparable reaction intensities but, again, quite different patterns. The sheridanite sample gives an additional endotherm at about 810°C. The endothermic reaction which occurs from about 625°–690°C actually appears to consist of two possible reactions. Which predominates appears to depend in part on the morphology of the chlorite and, hence, on the sample grain size. There appears to be little consistent data available from the results of differential thermal analyses of chlorite minerals. This is largely because of the lack of standard testing procedures. Heating rates, sample particle size and density, and procedures for recording peak position all may vary.

Differential thermal data for six chlorite types, investigated by Calliere and Henin, are given by Mackenzie (1966), and additional data are given by Grim (1968). Differential thermal data for 10 samples, representing 4 chlorite types, are given in Table 1. All temperatures given are those of the peak temperatures and not the commencement of the peak. The exothermic reaction peaks observed for the chlorite samples from Flagstaff Hill area appear to be significantly higher than those given by Mackenzie (1966) and Grim (1968), but only slightly higher than those given by Martin (1955). This discrepancy may be due to the heating rate used (20°C per min) being higher than the more customary rate of 10°–15°C per min. It has been observed that these chlorite minerals are very resis-
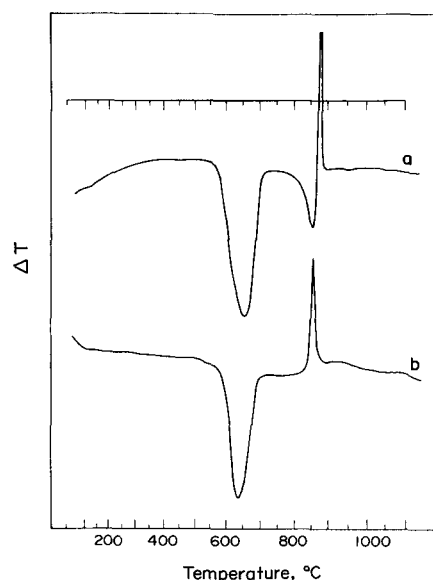

Fig. 2. DTA curves for A—penninite, sample 4; B—ripidolite, sample 31.
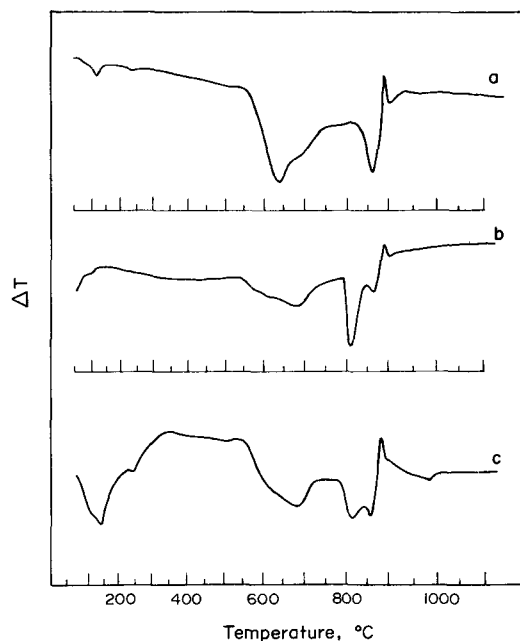

Fig. 3. DTA curves for A—clinochlore, sample 38; B—sheridanite, sample 15; C-weathered chloritic "soil", sample 25.

tant to heat treatment, X-ray basal reflection intensities being scarcely diminished upon heating of samples to 550°C.

Table 1. Differential thermal data for four chlorite types

Sample	Type	Endothermic peaks						Exo.	Endo.
		°C r.i.*	°C r.i.	°C r.i.	°C r.i.	°C r.i.	°C r.i.	°C r.i.	°C r.i.
4	Penninite	—	—	—	655 s	—	855 m	880 s	—
1	Penninite	—	—	—	655 s	—	855 m	875 s	890 w
38	Clinochlore	120 w	240 f	640 m	690 m	—	865 m	890 w	900 w
42	Sheridanite	—	—	645 m	—	—	865 m	890 w	905 w
15	Sheridanite	—	—	625 w	685 w	810 m	865 w	890 w	900 w
17	Sheridanite	—	—	—	690 s	790 m	860 w	885 w	—
25	Sheridanite†	135 m	245 f	630 w	680 m	810 m	855 m	885 w	—
13	Sheridanite	115 w	—	625 m	675 w	810 m	865 w	890 m	—
9	Ripidolite	—	—	—	665 s	—	845 f	865 s	—
31	Ripidolite	—	—	635 s	—	—	—	860 s	—

*r.i. — relative intensities; s — strong; m — moderate; w — weak; f — faint.
†Weathered chlorite material consisting of unaltered plates of sheridanite in a matrix of altered material.

The additional endotherms which occurred from 115°C to 135°C (Table 1 and Curve C of Fig. 3) for some of the chlorite samples may be attributed to adsorbed water because none of the samples were preheated, nor were they subjected to humidity control. All data below 200°C should be disregarded with respect to the chlorite mineral characterizations. The weathered chlorite material (curve C of Fig. 3) consists largely of unaltered plates of sheridanite in a matrix of altered material, referred to as "soil". The sample was about 18 in. below the surface of the ground and contained numerous rootlets.

I.R. absorption spectra. The chlorite samples used to obtain i.r. spectra were air dried and ground to particles passing a No. 200 sieve. No additional grinding was done even though many investigators, such as Lyon (Chapt. VI, Rich and Kunze, 1964), have cautioned against poor results being obtained when the wave length of light approximates mean particle size. A portion of sample 4, passing a No. 200 sieve, was additionally ground in an alcohol bath continuing the grinding until the material dried, then repeating the process two more times. Three of the rather weak absorption peaks were slightly enhanced by the additional grinding, otherwise no change in the spectrum was observed. I.R. absorption spectra were obtained using potassium bromide discs containing about 0·15% of the sample.

A Perkin-Elmer 337 grating i.r. spectrophotometer, having a light frequency response varying from 4000 to 400 cm⁻¹ (wave Nos. from 2·5 to 25·0 μm) was used. Machine settings combined fast scan rate using normal slits with an air-reference beam attenuator. The amount of peak drift due to the use of the rapid scan was determined with the aid of a standard polystyrene sample spectrum.

The i.r. spectra, which appear to be typical for the four types of chlorites from the Flagstaff Hill area, are shown in Fig. 4. The spectra represented by the curves include: curve A — sheridanite, sample 15; curve B — ripidolite, sample 31; curve C — clinochlore, sample 38; and curve D — penninite, sample 4. The Cr–chlorite spectrum was observed to be similar to curve D, the spectrum for penninite.

I.R. absorption data are given in Table 2 for eight chlorite samples which are believed to be typical of the Flagstaff Hill chlorite series. It appears that each chlorite type may be differentiated by its distinct spectral pattern in this manner, except in the region of the sheridanite–clinochlore classification interface. It can be seen that generally clinochlore is differentiated from sheridanite in
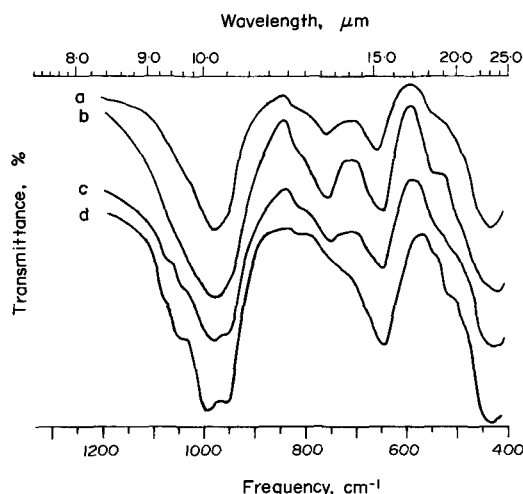

Fig. 4. The i.r. spectra in the region 8·3 to 25 μm for A — sheridanite, sample 15; B — ripidolite, sample 31; C — clinochlore, sample 38; D — penninite, sample 4.

Table 2. Positions of i.r. absorption bands in chlorite samples, arranged in order of increasing Si content

Sample	Type		Frequency (cm⁻¹), wavelength (μm), and relative degree of absorption										
31	Ripidolite	cm⁻¹	—	—	985 s*	—	824 f	760 m	655 m	552 m	—	455 f	425 s
		μm			10·15		12·14	13·16	15·27	18·12		22·0	23·5
32	Ripidolite	cm⁻¹	1084 f	—	984 s	—	824 f	755 m	652 m	548 m	—	453 f	425 s
		μm	9·22		10·16		12·14	13·25	15·34	18·25		22·1	23·5
27	Sheridanite	cm⁻¹	—	—	985 s	—	824 f	758 m	657 m	551 f	—	460 f	435 s
		μm			10·15		12·14	13·19	15·22	18·15		21·7	23·0
15	Sheridanite	cm⁻¹	—	—	988 s	—	830 f	757 m	661 m	557 w	—	—	437 s
		μm			10·12		12·05	13·21	15·13	17·95			22·9
42	Sheridanite	cm⁻¹	1085 w	1037 f	988 s	957 s	824 w	758 m	657 s	552 f	—	—	434 s
		μm	9·22	9·64	10·12	10·45	12·14	13·19	15·22	18·12			23·0
38	Clinochlore	cm⁻¹	1083 w	1052 f	988 s	955 s	822 w	757 m	656 s	552 f	523 f	—	434 s
		μm	9·23	9·51	10·12	10·46	12·17	13·21	15·24	18·12	19·12		23·0
4	Penninite	cm⁻¹	1085 f	1040 m	998 s	957 s	822 f	—	648 s	550 f	523 w	490 f	438 s
		μm	9·22	9·62	10·02	10·45	12·17		15·43	18·18	19·12	20·4	22·8
3	Cr-chlorite	cm⁻¹	1085 f	1052 m	998 s	957 s	824 f	—	647 s	—	523 w	493 w	438 s
		μm	9·22	9·51	10·02	10·45	12·14		15·46		19·12	20·3	22·8

*Relative degree of absorption: s – strong; m – moderate; w – weak; f – faint.

the region of $9 \cdot 2 \, \mu$m wavelength, and that penninite gives another distinct pattern. These results are comparable to spectra observed by Tuddenham and Lyon (1959) for chlorite minerals containing varying amounts of Al and Si in tetrahedral positions in the crystal structure of a magnesium chlorite series.

It appears that sheridanite can be differentiated from ripidolite in the spectral region of $18 \, \mu$m wavelength by the absorption intensity observed, and that penninite is differentiated by a shift of the spectrum in the region of $15 \cdot 0$–$15 \cdot 5 \, \mu$m, as observed by Stubican and Roy (1961).

A method has been suggested by Tuddenham and Lyon (1959) for the determination of the total iron content of chlorite minerals from the wave length of the strong absorption band nearest $10 \, \mu$m. The frequency of this strong band decreases as the radius of the ion linking the SiO_4 tetrahedra increases (Saksena, 1961). The usefulness of the method was limited for the chlorite samples investigated because the strong absorption band near 10 μm was quite broad. According to Saksena (1961) the $10 \, \mu$m band includes modes from two group species; symmetric Si–O stretching vibrations, and asymmetric Si–O stretching vibrations, which are near the same frequency, giving rise to a broad absorption band. The absorption band near $9 \cdot 2$ μm may be a mode from a third group species; a doubly degenerate Si–O stretching vibration. As observed by Tuddenham and Lyon (1959), clinochlore and penninite can generally be differentiated from sheridanite and ripidolite by the presence of an absorption band near $9 \cdot 2 \, \mu$m, when there is a substitution of Al for Si in tetrahedral formula positions of about $1 \cdot 2$–$1 \cdot 3$.

The i.r. spectra observed for chlorite minerals included moderate to strong absorption peaks at about $2 \cdot 82$, $2 \cdot 92$ and $6 \cdot 14 \, \mu$m. The first two peaks are attributed to O–H stretching bonds and the latter is attributed to H_2O bending bonds (Lyon, 1964). The absorption spectra observed in this region were strong in every case because the materials were not oven dried.

There has been considerable difficulty in differentiating between sheridanite and clinochlore chlorite types, as will be discussed in the following section. The i.r. absorption spectra for the chlorite types herein classified as clinochlore appear to match rather well the data given by Veniale and van der Marel (1969) for clinochlore.

X-ray diffraction. The chlorite samples were prepared by reducing air dried material to particles passing a No. 200 sieve. Generally, the material appeared to be rather insensitive to the effect of grinding. The diffraction peak intensities were affected far more by chlorite type than by size

of books or sieve size used. Pressed powder samples of ripidolite and sheridanite tended to give comparable (002) reflection intensities, as did clinochlore and penninite; however, the latter two comparable intensities were only about three-fourths as high as the former. Generally, powder samples of chlorite which were loosely packed gave basal reflections having about one-half the intensity of the densely packed (pressed) material, and samples oriented on glass slides gave basal reflections about $1 \cdot 5$ times that of the pressed material. The data listed in Table 3 were secured using very loosely packed powder samples.

A Picker X-ray diffractometer was used with an ordinary scan rate of $1° 2 \, \theta$/min and with a rate of $1/4° 2 \, \theta$/min for more precise measurement of reflection spacings. A $1°$ divergence slit and $1°$ scatter slit were used in conjunction with a $0 \cdot 002$ in. receiving aperture. Nickel-filtered copper radiation was used.

The results from typical diffraction patterns for four different chlorites are given in Table 3. Machine settings included a count rate of 400 cps, with a 3 sec time constant, except for more precise measurement of basal reflections and (060) reflection spacings. The spacing and relative intensity of the first five basal reflections were determined using a count rate of 2000 cps, with a 1 sec time constant, and the spacing of the 060 and $00 \cdot 10$ reflections were determined using a count rate of 400 cps, with a 3 sec time constant, each with a scan rate of $1/4° 2 \, \theta$/min. The reliability of d-values presented to $0 \cdot 0001$ Å were established by using a $0 \cdot 002$ in. receiving aperture in combination with slow-speed scan. The goniometer alignment and powder position were checked at regular intervals using quartz as an internal standard. The position of the basal reflection orders with respect to increasing diffraction angle was also helpful. The α_2 reflections also need to be considered when multiple reflections are encountered as the diffraction angle exceeds about $30° 2 \, \theta$. The d-values given in Table 3 are considered accurate to within $0 \cdot 001$ Å, except for the d (060) and d (00·10) values which are considered accurate to within $0 \cdot 0002$ Å.

It can be seen from Table 3, and Table 5, that each chlorite type has a distinct set of basal-reflection relative intensities, helpful in identifying the chlorite type. The $(I_{(002)} + I_{(004)})/I_{(003)}$ ratios, and the $I_{(003)}/I_{(005)}$ ratios, for the chlorite samples are given in Table 5. Thus, using the procedure given by Petruk (1964), it is possible to determine the number of heavy atoms, predominantly Fe, in the unit-cell octahedral layers of the chlorite samples. Although nearly all of the chlorite samples appear to have asymmetrical distribu-

Table 3. X-ray powder data observed for four chlorite types

Indices	Sample 31 Ripidolite		Sample 15 Sheridanite		Sample 38 Clinochlore		Sample 4 Penninite	
	d (Å)	I	d (Å)	I	d (Å)	I	d (Å)	I
001	14·14	54†	14·16	78†	14·19	31†	14·31	68†
002	7·071	148†	7·080	147†	7·094	50†	7·156	103†
003	4·714	43†	4·720	72†	4·729	31†	4·770	74†
020	4·640	3	4·621	4	4·614	7	—	—
110*	—	—	4·607	8	4·602	9	4·607	7
004	3·535	89†	3·540	96†	3·547	39†	3·578	64†
005	2·828	22†	2·832	43†	2·838	28†	2·862	36†
131; 20$\bar{2}$	2·597	13	2·585	12	2·583	12	2·587	9
13$\bar{2}$; 201	2·558	9	2·544	15	2·540	20	2·544	19
132; 20$\bar{3}$	2·453	9	2·439	13	2·438	17	2·447	17
13$\bar{3}$; 202	2·387	9	2·381	10	2·381	10	2·386	11
006	2·357	2	2·360	3	—	—	—	—
133; 20$\bar{4}$	2·263	8	2·259	8	2·260	9	2·263	9
134; 20$\bar{5}$	2·070	3	2·068	3	2·070	2	2·076	3
007	2·020	4	2·023	11	2·027	8	2·044	13
13$\bar{5}$; 204	2·006	14	2·001	18	2·004	19	2·009	22
135	1·886	7	1·883	7	1·883	6⟩	1·886	7
20$\bar{6}$			1·880	7	1·875	5⟩		
136; 205	1·823	5	1·821	4	1·821	6	1·827	6
310; 240*	1·748	2	—	—	1·739	2	1·742	3
136; 20$\bar{7}$	1·727	3	1·714	2	1·717	4	1·727	3
13$\bar{7}$; 206	1·661	5	1·659	4	1·664	5	1·668	5
137; 20$\bar{8}$	1·563	11	1·564	14	1·564	11	1·572	17
060; 330*	1·5477	6	1·5401	8	1·5393	12	1·5384	6
062; 331	1·510	2	1·502	4	1·502	3	1·508	2
063+	—	—	1·464	2	1·461	2	1·464	3
0, 0, 10	1·4141	11	1·4159	6	1·4188	5	1·4311	6
064+	1·401	3	1·404	2	—	—	1·415	3
208+	1·391	10	1·391	15	1·393	13	1·404	14

*Indices suggested by Lister and Bailey (1967).
†Data using high count rate, slow speed scan.

tion of the heavy atoms in the two types of octahedral layers comprising the unit cells, the ripidolite and sheridanite samples from Flagstaff Hill area are readily differentiated from one another and from the clinochlore and penninite samples by the observed $(I_{(002)} + I_{(004)})/I_{(003)}$ ratios.

A typical diffractogram for clinochlore from the Flagstaff Hill area, sample 38, is shown in Fig. 5. The powder sample was scanned from 4° 2 θ to 68° 2 θ at a rate of 1° 2θ/min. The first 34° 2 θ of the scan, which only included five very strong basal reflections, is not shown on the diagram. It is necessary, because of strongly preferred orientation in the loosely packed powder, to scan the high-angle side of the (003) reflection at slow speed to observe the (020) and (110) reflections. The data for the entire scan are given in Table 3.

More X-ray diffraction peaks were resolved than are ordinarily listed for chlorite minerals, such as in the tabulation by Brindley (Chapt. 6, Brown, 1961). Also some of the multiple reflections are separate, as with the (135) and (206) reflections for sheridanite and clinochlore, which ordinarily are shown to be combined as a single peak. A number of additional reflections at higher 2 θ angles also appeared to be multiple reflections; however, no further investigation was made because of the broadness and relatively low intensity of these reflections. For example, the (060) reflections for penninite and clinochlore were partially obscured by the (330) reflections, and possibly ($\bar{3}$30) reflections. Figure 5 was presented in part to show the problems involved in identifying the multiple and weak chlorite reflections. Where it is conventional (Grim, 1968) to show only 3 reflections between the 1·82 and 1·57 Å reflection others, such as Steinfink (Borg and Smith, 1969), show as many as 9 reflections in the same spacing
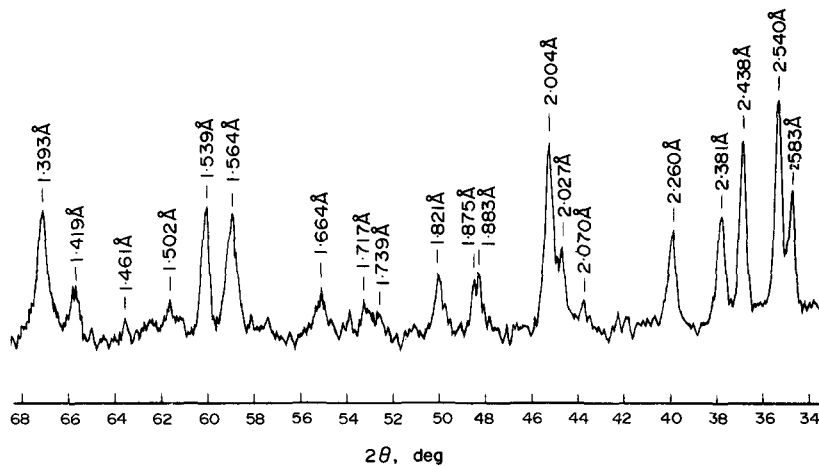
Fig. 5. X-ray diffractometer trace for clinochlore sample 38, from 34°2θ to 68°2θ, using a scan rate of 1°2θ and count rate of 400 cps, time constant of 2 sec, 1° divergence and scatter slits and 0·002 in. receiving aperture.

for some chlorites. Some of the possible additional reflections also are given by Lister and Bailey (1967). According to Bailey (personal communication) the chlorite series from the Flagstaff Hill area all appear to be of the common IIb structural type.

The 45 chlorite samples were classified according to Foster's scheme (1962). The Fe/(Fe + Mg) ordinate values were determined using the procedure developed by Shirozu (1960) whereby the (060) reflection spacing is precisely determined. The abscissa values, for formula positions occupied by Si, were found using the relationship, developed by Brindley (1961), between the structural positions occupied by Si or Al, and the computed

(001) basal reflections. The first order basal reflections were calculated from the 5th and 10th order basal reflections which were precisely derived with the aid of slow-speed scans.

The classification of the chlorites is shown in Fig. 6. An additional sample of penninite, which was also classified, is presented to show that the penninite samples are also of variable composition.

Correlation of the results of differential thermal analyses, i.r. spectra, and X-ray data suggest that for these chlorite minerals Brindley's relationship, between Al^{IV} content and (001) basal reflection spacing (Chapt. VI, Brown, 1961), gives a reliable classification. However, the results of differential thermal analyses and infrared spectra
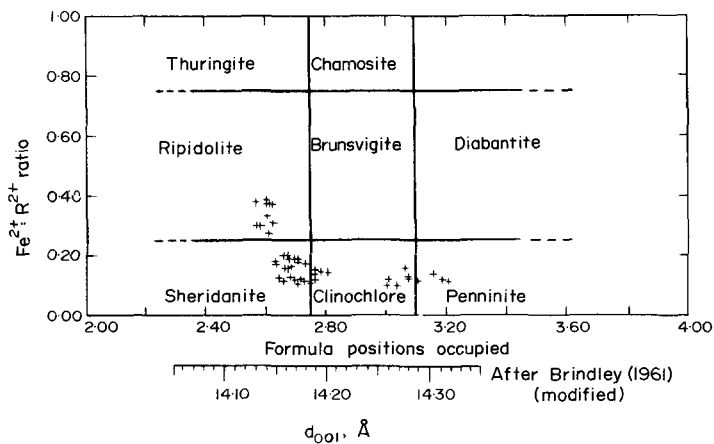

Fig. 6. Classification of the chlorite types using the scheme proposed by Foster (1962).

Table 4. Chemical analyses (percentage) of four typical chlorite samples from Flagstaff Hill area

	Sample 31 Ripidolite	Sample 15 Sheridanite	Sample 38 Clinochlore	Sample 4 Penninite
SiO_2	25·8	27·9	30·5	33·9
Al_2O_3	18·3	25·2	17·3	14·6
Fe_2O_3	4·1	0·0	2·9	2·7
FeO	21·3	10·6	6·1	2·1
MgO	20·3	24·2	32·8	34·6
H_2O_+	8·7	10·8	11·5	12·3
Total	98·5	98·7	101·1	100·2
H_2O_-	0·3	0·4	0·8	0·3
Number of ions (half-cell)				
Si	2·64	2·69	2·87	3·17
Al	1·36	1·31	1·13	0·83
Al	0·85 ⎱	1·55 ⎱	0·79 ⎱	0·77 ⎱
Fe^{3+}	0·32 ⎰ 6·09	— ⎰ 5·88	0·21 ⎰ 6·08	0·18 ⎰ 5·94
Fe^{2+}	1·82	0·86	0·48	0·17
Mg	3·10	3·47	4·60	4·82
(OH)	6·29	7·08	7·39	7·73

Trace elements include: sample 31 < 0·1% Mn, Cr, Ti, Ni (each); sample 15 0·1 + % Ni and < 0·1% Mn, Cr, Ti (each); sample 38 0·2% Cr; sample 4 0·2% Ni and < 0·1% Mn, Cr (each).

suggest that there is a rather abrupt change in chlorite structure when the (001) basal reflection is about 14·170 Å rather than the 14·185 Å implicit in Foster's classification scheme.

The ripidolite chlorite types may be differentiated from the sheridanite types generally by determination of the specific gravity of the minerals, using ASTM Test Designation D854-58. A chlorite classification scheme including the specific gravity of the chlorite minerals has been presented by Hey (1954). The specific gravity of selected chlorite samples is listed in Table 5 with other data relevant to the identification and classification of the samples.

Chemical composition. The chemical composition of four typical chlorite samples was determined by using several different methods of analysis and correlating the results. The total iron contents, and the trace elements given in Table 5, were determined by fluorescence radiation methods. The total Si, Al, Fe, and Mg contents were determined by conventional chemical methods and also by atomic absorption spectrophotometric methods of analysis. The ferrous iron contents were determined with the use of orthophenanthrolene.

The half-cell ion contents of the chlorite samples, given in Table 5, were computed according to the method shown by Foster (1962). The results of the chemical analyses are considered to be suffi-

ciently accurate for the proper classification of the chlorite samples in spite of lack of experience in silicate analysis procedures. It appears that the massive materials comprising samples 31 and 15 contain small amounts of impurities. Low H_2O+ values were derived for sample 31 from weight loss on ignition, 110°–1050°C.

Sample 31 (ripidolite) contained only 8·7% H_2O+ whereas sample 9 (ripidolite) from nearby contained about 9·3% H_2O+. Both values are low according to data given by Foster (1962). A comparison of data results derived using the procedure given by Petruk (1964) with the results of chemical analyses indicate that both samples 15 and 31 contain more heavy atoms in the unit-cell octahedral layers than are consistent with comparable chlorite mineral structures. Small amounts of magnetite, chromite, and goethite, which may be present, have been observed in other chlorite samples from the area.

The classification of the chlorite samples according to cation content determined from chemical analyses correlates very well with the classification procedure entailing the use of X-ray diffraction data. Thus, the classification of chlorite types presented in this paper is believed to be acceptable.

Associative minerals

Samples of the most common minerals were collected from the Flagstaff Hill area for identifica-

Table 5. Classification of chlorites from Flagstaff Hill area

Sample	Structure	$\frac{I(002)+I(004)}{I(003)}$	$\frac{I(003)}{I(005)}$	Type	$d(060)$ Å	$d(00·10)$ Å	sp. gr.
6	Blocky	5·06	2·86	Ripidolite	1·5452	1·4134	2·84
7	Blocky	5·35	3·00	Ripidolite	1·5454	1·4148	
9	Blocky	4·87	3·02	Ripidolite	1·5457	1·4147	2·88
28	Platy	4·79	3·20	Ripidolite	1·5442	1·4143	
31	Blocky	5·52	2·78	Ripidolite	1·5477	1·4141	2·91
32	Platy	5·64	2·25	Ripidolite	1·5473	1·4145	
33	Blocky	5·71	2·36	Ripidolite	1·5466	1·4142	
35	Platy	4·92	3·13	Ripidolite	1·5450	1·4131	
43	Platy	6·53	2·23	Ripidolite	1·5477	1·4131	
44	Blocky	5·35	2·56	Ripidolite	1·5475	1·4141	
8	Blocky	3·71	3·59	Sheridanite	1·5407	1·4171	
12	Blocky	3·89	4·06	Sheridanite	1·5405	1·4150	2·84*
13	Platy	3·27	3·58	Sheridanite	1·5399	1·4159	2·74
15	Platy	3·38	3·33	Sheridanite	1·5401	1·4159	2·72
16	Blocky	3·59	2·90	Sheridanite	1·5410	1·4157	
17	Blocky	3·84	3·73	Sheridanite	1·5416	1·4159	2·78
19	Blocky	3·71	3·89	Sheridanite	1·5385	1·4174	2·75
20	Small blocks	3·06	3·63	Sheridanite	1·5382	1·4170	
21	Platy	3·25	3·28	Sheridanite	1·5410	1·4172	
22	Platy	3·40	3·35	Sheridanite	1·5388	1·4152	
24	Small crystals	3·56	3·28	Sheridanite	1·5411	1·4163	
25	'Soil'	3·41	3·04	Sheridanite	1·5403	1·4165	2·69
26	Blocky	3·57	3·77	Sheridanite	1·5405	1·4148	2·85*
27	Crystals	3·37	3·25	Sheridanite	1·5384	1·4157	
30	Books	3·02	3·49	Sheridanite	1·5388	1·4165	
34	Platy	3·50	3·13	Sheridanite	1·5401	1·4161	
36	Platy	3·64	3·13	Sheridanite	1·5416	1·4161	
40	Small books	2·63	4·00	Sheridanite	1·5381	1·4171	
41	Platy	2·98	3·55	Sheridanite	1·5403	1·4178	
42	Large books	3·02	3·49	Sheridanite	1·5384	1·4177	
1	Veinlet	2·30	5·43	Clinochlore	1·5377	1·4270	2·68
2	Books	2·57	5·00	Clinochlore	1·5400	1·4280	
5	Veinlet	2·62	3·19	Clinochlore	1·5390	1·4281	
10	Books	2·30	4·78	Clinochlore	1·5386	1·4281	
11	Small books	3·00	3·57	Clinochlore	1·5387	1·4187	
14	Small books	2·99	3·50	Clinochlore	1·5397	1·4193	
18	Small books	2·92	4·61	Clinochlore	1·5396	1·4199	2·74
23	Blocky	2·48	4·88	Clinochlore	1·5383	1·4262	2·61*
29	Books	2·33	4·40	Clinochlore	1·5377	1·4261	
37	Small books	3·16	3·10	Clinochlore	1·5399	1·4188	2·74
38	Books	2·93	4·00	Clinochlore	1·5393	1·4188	
39	Platy	2·93	4·42	Clinochlore	1·5382	1·4184	
45	Blocky	2·15	4·58	Clinochlore	1·5382	1·4290	
4	Large books	2·26	4·70	Penninite	1·5384	1·4311	2·63
3	Blocky matrix	2·25	6·66	Cr–chlorite	1·5394	1·4305	

*Impure.

tion purposes to tie in rock units with those of the geologic map of the area prepared by Wells *et al.* (1940). Wells *et al.*, described the prevalent rocks as being partially altered peridotite, dunite, lherzolite, and saxonite, which suggests the presence of olivine and various pyroxenes. No orthopyroxenes were observed in any of the samples despite efforts to find this mineral implied as present by the rock types listed.

The associative minerals were identified by X-ray diffraction and, in some cases, were verified by thin-section study. A complete listing of the minerals identified, in approximate order of prevalence, is given in Table 6.

Hornblende occurs as possible pseudomorphs after diallage. The (310) reflection of 3·128 Å

Table 6. Associative minerals of the Flagstaff Hill area·

Mineral	Relevant observations
Common minerals:	
Hornblende	occurs as uralite and ordinary hornblende
Diopside	present as diallage
Augite	found in massive deposits
Forsterite	present in all altered peridotites and dunites
Epidote	provides matrix for some amphibolites
Antigorite	very common as platy and fibrous material
Talc	trioctahedral variety
Chromite	blebs and pods scattered throughout area
Magnetite	variable concentrations of octahedral crystals
Fairly common minerals:	
Magnesite	occurs as pure plates and mixed with talc
Grossularite	present as crystals and as massive rock
Tridymite (Type M)	yellow-green subtranslucent plates
Goethite	after pyrite
oligoclase	in metadiorite dikes
Andesine	diorite rock bounding area
Trace minerals:	
Muscovite	remnants in ripidolite sample 44
Vermiculite	on weathered surfaces of saxonite
Quartz	found in dike alteration zone
Uvarovite	occurs with Cr–chlorite on chromite
Mixed-layer mineral	4-layer regular-spacing mineral

corresponds more closely to hornblende than to actinolite.

Serpentine is by far the most common mineral found in the area, and antigorite appears to be the predominant type of serpentine although there are indications that crysotile is intermixed with much of the antigorite. Samples of pure antigorite were obtained having both platy and fibrous (picrolite) varieties. Some of the fibrous material includes needles more than 20 cm long. Identification of both forms as antigorite was verified using X-ray diffraction patterns and checked with the aid of i.r. spectra (Stubican and Roy, 1961).

An unusual mixed-layer mineral occurs in altered peridotite–dunite rock near the Pillikin Mine pit 3. The mineral appears to be a 4-layer regular-spacing mineral (Table 6) which appears to consist of 3 layers of antigorite $(d_{(001)} = 7 \cdot 25$ Å) and 1 layer of talc $(d_{(002)} = 9 \cdot 35$ Å). The X-ray diffraction pattern includes a very strong reflection at $7 \cdot 78$ Å and a weaker one at $3 \cdot 89$ Å. The mineral occurs in combination with antigorite and forsterite.

Thermal reaction products

Representative samples of the four chlorite types were heated in covered containers in an electric furnace to determine the structural water contents of the minerals. The mineral contents of the fired products were then investigated. The reaction products derived at 1050°C varied according to the chlorite type as follows: the major constituents in sample 4, penninite, and sample 38, clinochlore, were spinel and forsterite; the major constituent in sample 15, sheridanite, and sample 31, ripidolite, was spinel with only a small amount of olivine. A portion of sample 15 was then heated to 1165°C to observe mineral generation in the fired product. The resulting material consisted mainly of Fe-rich spinel and enstatite, with some Fe-rich olivine and some corundum. The spinel (220) reflection is combined with the enstatite (160) reflection at $2 \cdot 864$ Å to form the strongest diffraction peak in the X-ray diffraction pattern.

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Résumé – Les résultats de la diffraction des rayons X, de l'ATD, de la spectroscopie i.r. et d'essais chimiques, relatifs à certaines chlorites typiques de la zone de Flagstaff Hill, sont présentés dans ce travail. Cette zone est connue pour sa grande variété de types de chlorites présentes en quantités considérables. La chlorite, dans cette zone, se trouve sous forme de veines, de pseudomorphes et de cristaux individuels. Les textures varient d'agrégats massifs à grains fins, jusqu'à des empilements feuilletés qui ont plus de 20 mm de large. Les cristaux de plus de 5 mm apparaissent en groupements parallèles aux interfaces rocheuses. Si l'on en juge sur 45 échantillons de chlorite étudiés, la shéridanite est la plus abondante; le clinochlore et la ripidolite sont communs. La penninite et son équivalent chlorite chromifère sont moins abondants. La roche mère est une masse ultramafique de forme irrégulière entourée de schistes et située très près d'un bloc de granodiorite. Les roches ultramafiques originelles ont été fortement altérées par le métamorphisme et le métasomatisme en des assemblages composés principalement de serpentine, de talc, de hornblende et de chlorite avec des reliquats d'olivine, de pyroxène et de minéraux originels moins abondants. Une grande partie de la roche exposée est essentiellement monominérale, consistant principalement de divers polytypes de serpentine. Les premières recherches indiquent que la zone de Flagstaff Hill mérite une étude beaucoup plus poussée à cause des facilités qu'elle offre pour observer les divers types de chlorite et déterminer leur génèse, les séquences et les caractéristiques de l'altération. Cette zone, facilement accessible, pourrait également servir de source d'échantillons de référence.

Kurzreferat – Die Ergebnisse der Röntgenbeugung, DTA, UR-Spektroskopie und chemischen Tests werden für einige Chlorite, die typisch für die Flagstaff Hill Gegend sind, dargelegt. Die Gegend ist bekannt für die grosse Vielfalt von Chloritarten, die in beträchtlichen Mengen vorkommen. Chlorit in dieser Gegend findet sich in Adern, als Pseudomorphe und als Einzelkristalle. Die Gefüge variieren von massiven, feinkörnigen Anhäufungen bis zu buchartigen Gebilden von mehr als 20 mm Breite. Kristalle von einer Grösse von mehr also 5 mm kommen in Parallelgruppierungen an Gesteingrenzflächen vor. Aus der Untersuchung von 45 Chloritproben ergibt sich, das Sheridanit nm meisten verbreitet ist und dass Clinochlor und Ripidolit häufig vorkommen. Penninit und sein Cr-Chlorit Äquivalent sind weniger reichlich. Das Muttergestein ist ein unregelmässig geformter ultrabasischer Körper, der umgeben ist durch geringhaltige Schiefern, und sich sehr nahe an einem Granodioritlager befindet. Die ursprünglichen ultrabaschen Gesteine wurden durch Metamorphismus und Metasoma-

tismus bedeutend verändert in Ansammlungen hauptsächlich von Serpentin, Talk, Hornblende und Chlorit mit Resten von Olivin, Pyroxen und anderen weniger reichlich vorhandenen ursprünglichen Mineralen. Ein Grossteil des entblössten Gesteins ist hauptsächlich monomineralisch und besteht meist aus verschiedenen Polytypen von Serpentin. Vorkäufige *Untersuchungen* deuten daruf him, dass die Gegend genaueres Studium verdient da die Gelegenheit einer direkten Beobachtung der verschiedenen Arten von Chloriten besteht, mit Bestimmung ihrer Genese, Änderungsfolgen und Verwitterungseigenschaften. Die leicht zugängliche Gegend sollte ferner eine geeignete Quelle für Proben darstellen, die als Bezugsnormen Verwendung finden können.

Резюме — Приводятся результаты рентгенографических исследований, дифференциально-термического анализа, инфракрасной спектроскопии и химических испытаний нескольких типовых хлоритов района Флагстафских гор. Этот район известен своим большим разнообразием хлоритов, встречающихся в больших количествах. В этих горах его находят в виде прожилок, в виде псевдоморфоз и в виде одиночных кристаллов. Строением хлорит очень разнообразен — от массивных мелкозернистых агрегатов до чешуйчатых масс шириной более 20 мм. Кристаллы размером более 5 мм встречаются в параллельных группировках на поверхностях раздела горных пород. Судя по изученным 45-ти штуфам хлорита в нем больше всего шериданита, меньше клинохлора и рипидолита, а содержание пеннита и эквивалента хлорита-Cr в нем незначительно. Основной горной породой является ультрамафический агрегат нерегулярной формы, окруженный низкокачественным сланцем и находящимся очень близко к гранодиоритной массе. Исходная ультрамафическая горная порода была изменена метаморфическим и метасоматическим процессами в соединения состоящие главным образом из серпентина, талька, роговой оболочки и хлорита со следами оливина, пироксена и других редковстречающихся самородных минералов. Бо́льшая часть горных пород на поверхности земли является по существу мономинеральной, состоящей главным образом из различных политипов серпентина. Предварительное исследование указывает, что этот вопрос заслуживает добавочного изучения, так как имеется возможность рассмотрения хлорита различных типов и определение их генезиса, последовательности изменений и характеристики выветривания. Эта область легко достигаема и может служитъ источником получения штуфов для использования в качестве эталонов.