

WEATHERING OF ENSTATITE TO TALC THROUGH A SEQUENCE OF TRANSITIONAL PHASES

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Abstract—Orthopyroxene (En_{85}) weathers initially by vacancy diffusion, and through this process hydration occurs and a sequence of biopyriboles develops, culminating in a talc-like layer silicate whose structure joins coherently to the orthopyroxene structure. Oxidation of Fe^{2+} to Fe^{3+} colors the altering pyroxene yellow. The 'talc' does not remain in structural coherence with the pyroxene after it has exceeded a few tens of nanometers in size; it is replaced by a mixture of talc and smectite. In some areas the mixture has an epitactic relation to the pyroxene, but commonly it fills faceted solution holes without crystallographic relation to the parent structure. Continued weathering extends the yellow zone at the periphery of the orthopyroxene, and the alteration product increases in smectite and decreases in 'talc.' During this stage of the reaction, MgO and SiO_2 are released to form colorless true talc around the altering pyroxene. Eventually, the yellow alteration may become a smectite pseudomorph after orthopyroxene or it may be changed entirely to a mixture of vein talc and iron oxides. The complete conversion of orthopyroxene to talc plus oxides thus takes place through three sequential mineral reactions without the development of a noncrystalline phase.

Key Words—Biopyribole, Enstatite, Smectite, Talc, Transmission electron microscopy, Weathering.

INTRODUCTION

During the weathering of rock, a chemical fractionation occurs. Certain elements are released by the minerals to solution, where they are available for use by plants, or are reprecipitated in the weathering profile, or transported elsewhere. The remaining elements are regrouped *in situ* to form various soil minerals. Bulk mineralogical and chemical studies have established the relative mobilities of various elements and the relationship between climate and weathering, but they have revealed little of the mechanism of rock-mineral breakdown or soil-mineral formation.

Berner and Holdren (1977) and Berner *et al.* (1980) using scanning electron microscopy showed that mineral solution during weathering proceeds along crystallographic directions, producing etch pits whose locations are inferred to be controlled by the positions of defects in the weathering crystal. New minerals are assumed to form by precipitation on the surface of the altering mineral (Keller, 1978). Idlefonse (1978) by X-ray diffraction and electron probe analyses found that hypersthene and amphiboles altered to a yellow mixture of nontronite, talc, and iron oxides in the lower parts of the weathering profile where the rock structure was preserved. In the upper part, where the rock texture was modified, smectite and vermiculite dominate.

From optical microscopy and X-ray diffraction analyses Basham (1974) described the progressive replacement of hypersthene by trioctahedral vermiculite during the weathering of a gabbro. The layer silicate occurred as yellow-brown pseudomorphs, biaxial ($-$), $2V = 10^\circ$ oriented with its 'c'-axis normal to the 'c'-axis of the pyroxene. Basham (1974, p. 197) concluded that a "close structural control of the development of vermiculite is exerted by the host lattice."

Using transmission electron microscopy, Eggleton (1975) and Eggleton and Buseck (1980) showed that the first stage of mineral weathering occurs essentially in the solid state and coincides with the formation of new minerals inside the altering crystal. Veblen and Buseck (1980) demonstrated that the metamorphic hydration of anthophyllite to talc proceeds via a series of intermediate biopyriboles of different chain width, all in topotactic relation to each other. The key to this process is the structural similarity of the 'I-beam' chains in the biopyriboles. Coalescence of chains may build up 2:1 layer silicates with minimal disruption of the structure. Veblen and Buseck's work and the description of the weathering of hedenbergite to nontronite (Eggleton, 1975) provide an essential background to the present study.

Nakajima and Ribbe (1980), in an electron microscope examination of pyroxene alteration, found that augite hydrated to amphibole and wider chain biopyriboles. Lamellae of orthoenstatite included in augite appeared to be more extensively altered, forming a

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14.5-Å clay mineral and complex biopyriboles. As had been reported in the earlier studies, the layer silicate developed with (001) parallel to (100) of the pyroxene/amphibole.

The process of mineral weathering cannot be seen *in situ*. The reactants and the weathering products can be identified, but the process itself can only be inferred after the synthesis of information from different experiments. We have examined the weathering of orthopyroxene at scales ranging from the unit cell to hand specimen. Inevitably, many experiments have been performed on material which cannot be described succinctly because it is a mixture of known minerals, undescribed phases, and voids. Furthermore, in attempting to characterize a process, transient phases assume great importance, but do not deserve a formal mineral name. Although it sometimes proves cumbersome, we have described the weathering of orthopyroxene in terms of the original mineral, and weathering products (2:1 and 2:2 layer silicates), and 'yellow material,' which is essentially everything else. 'Yellow material' is a mixture of the three recognized minerals *plus* complex intergrowths on the unit-cell scale of these minerals and other structures. It has no single composition and no unique X-ray diffraction or other properties.

OBSERVATIONS

Sample

A mafic rock composed largely of orthopyroxene, with minor clinopyroxene, amphibole, and spinel, is exposed in a road cut 20 km west of Waratah, northwest Tasmania, where the highway crosses the Heazlewood River. Weathering has reduced the outer surface of the rock to a friable mass of bronze-yellow flaky particles, some of which resemble bastite. Others are orange-yellow laths with striations parallel to their length, and some are clear lemon-yellow tabular objects which look like single crystals, but which prove to be layer silicates with several different layer spacings. Samples of fresh and weathered rock, as well as loose soil-like materials from the face of the cutting, were collected for study.

Optical microscopy

Thin sections of weathered but still coherent rock show a clear alteration sequence (Figure 1a–1d). The pyroxene grains first develop a striated margin, which extends inward until the whole grain has become yellow. The color progressively darkens, and many grains

with yellow centers have brown rims. The striae, which are ubiquitous during alteration, have widths below the resolution of the light microscope. As alteration proceeds further, the rock becomes veined by clear talc dotted with an opaque mineral (Figure 1d), and some pyroxene grains become rimmed with actinolite. The altered pyroxene grains split along the original (100) plane, and the resulting folia shrink by 16% in the direction normal to the parting surface and distort slightly (Figure 1b). Sections cut parallel to the parting show further striae parallel to the Z axis of the pyroxene. These sections develop a ladder structure which in more altered material coalesces with the vein talc (Figure 1c). The yellow 'crystals' and striated laths appear to have been released by mechanical break-up of the already altered orthopyroxenite.

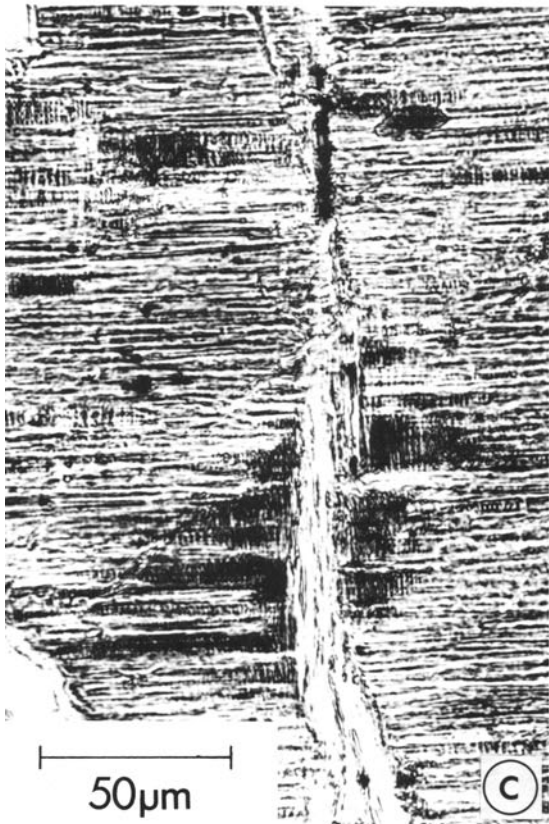
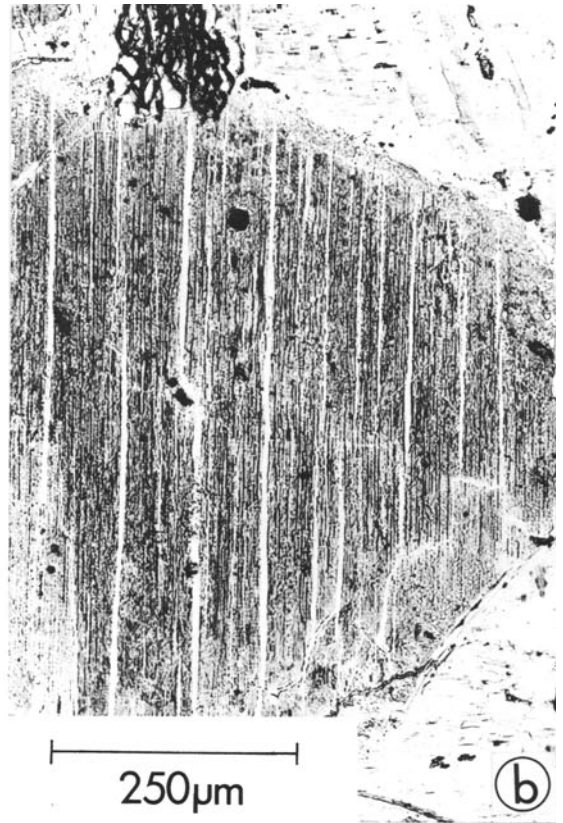
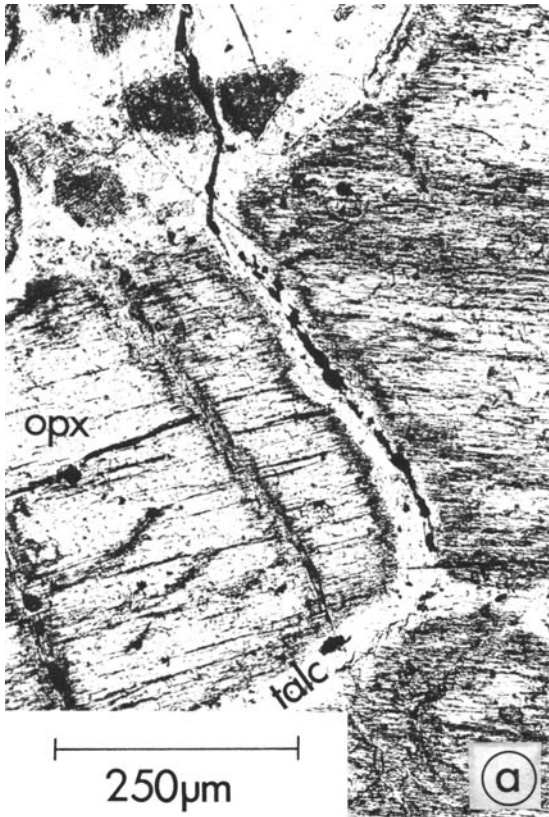
Electron microscopy

Transmission electron microscope observations were made on ion-beam-thinned material selected from optical thin sections using a JEOL 200B and a JEOL 100CX microscope equipped with tilt/rotate or double tilt side-entry goniometers.

Sections of partly altered orthopyroxene cut normal to [100] show that the initial alteration is to a 9-Å layer silicate, structurally coherent with the parent pyroxene. Such a topotactic reaction was proposed for the weathering of hedenbergite (Eggleton, 1975) and described by Veblen and Buseck (1980) for the hydration of anthophyllite. In this process, (001) of the pyroxene becomes (100) of the layer silicate, (100) becomes (001) of the layer silicate, and (010) retains those indices. Essentially, the I-beam chains of the pyroxene (parallel to Z) recombine following a relative shift of b/4 parallel to [010] to form infinite sheets parallel to the original (100) plane (Figures 2–4). The enlargement reveals columns of vacancies, or channels, parallel to [001] of the orthopyroxene where strips of various chain widths terminate. Veblen and Buseck envisage such channels as avenues for "high speed" diffusion. Growth of 'talc' from the strip of 3-chain structure as at A (Figure 5) can be achieved by exchanging the vacancy for the adjacent 3-chain strip of I-beams. This growth mechanism requires no coordination change for the tetrahedral or octahedral cations, no noncrystalline intermediate phase, and minimum bond-breaking. Thus, the pyroxene transforms entirely in the solid state, by releasing Mg and incorporating H, according to the reactions:

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Figure 1. Optical micrographs (plane polarized light) of the alteration of pyroxene to talc. (a) Initial development of a yellow rim around orthopyroxene crystals and the development of vein talc between grains. (b) [001] orthopyroxene section, heavily altered to yellow material. Shrinkage by about 16% is shown by the separation of the original orthopyroxene (100) parting. (c) [100] orthopyroxene section, altered to yellow material. Note the development of ladder structure with the 'rungs' of the ladders merging with the vein talc. (d) [100] orthopyroxene section, with further growth of vein talc and formation of magnetite in the talc.



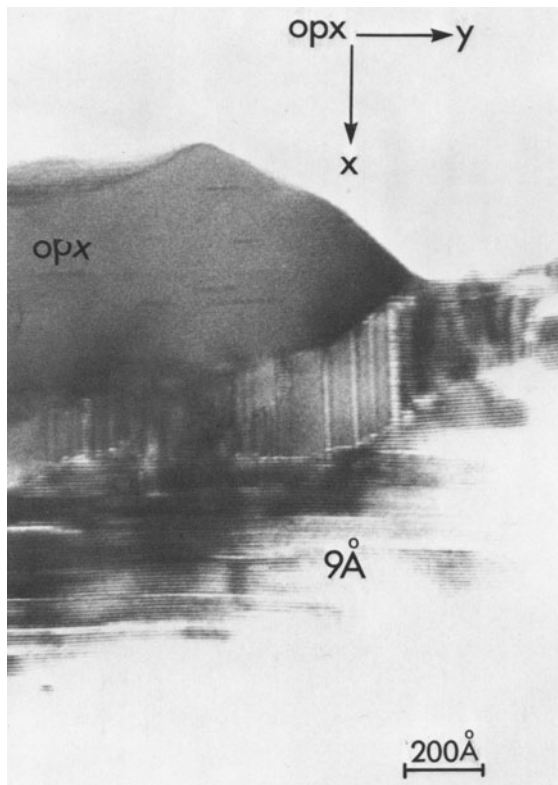
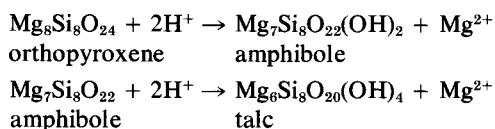


Figure 2. Orthopyroxene (opx) rimmed by a biopyribole complex (bpb) grading into 9-Å layer silicate.



Figure 3. Layer silicate (9-Å) in crystallographic continuity with a complex series of biopyriboles.



This is an idealized reaction; the actual minerals contain iron, and the pathway is more complex because of the oxidation of iron and because talc does not contain ferric iron in its octahedral sheet.

The second stage of alteration is the recrystallization of the initial 9-Å layer silicate into a mixture of 7-, 9-, and 14-Å layers (Figures 6–10). This process involves a volume decrease, as voids, wrinkles and split layers appear. The continuity with the pyroxene lattice is lost although it is common for the second-stage layer silicate to crystallize with (001) parallel to the (010) of pyroxene, as revealed by electron diffraction patterns. Eventually the pyroxene is consumed and replaced by a mixture of 9-Å and 14-Å layer silicates which make up 'yellow material.' Qualitative analysis by scanning electron microscopy with an energy dispersive analytical system shows that the 'ladder' structures (Figure 1c) which correspond to the second stage of alteration

(e.g., see Figure 9) have the highest iron content in the yellow material.

In the third stage of alteration, the yellow material is converted to a mixture of talc and iron oxides. Although we have not examined this process in detail in the electron microscope, we infer that the Mg flushed in the initial hydration of pyroxene diffused into the region surrounding the altering crystals where it exchanged with Fe^{3+} in the 'yellow material' to form talc. The texture of vein talc shows considerable separation of the layers where diffusion would be comparatively rapid (Figure 11).

X-ray diffraction

Cell dimensions of the orthopyroxene, determined by least-squares regression from 19 reflections measured by Guinier photography with a Si internal standard are $a = 18.27$, $b = 8.846$, $c = 5.197$ Å. The alteration product gave single crystal and powder diffraction patterns of a mixture of talc and smectite and orthopyroxene. The clear yellow plates show no pyroxene reflections, and the layer silicate reflections show disorder parallel to Z^* , and are broadened in the $hk0$ plane. The talc 00ℓ reflections were recorded to $\ell = 8$; only the first order was detected for the smec-

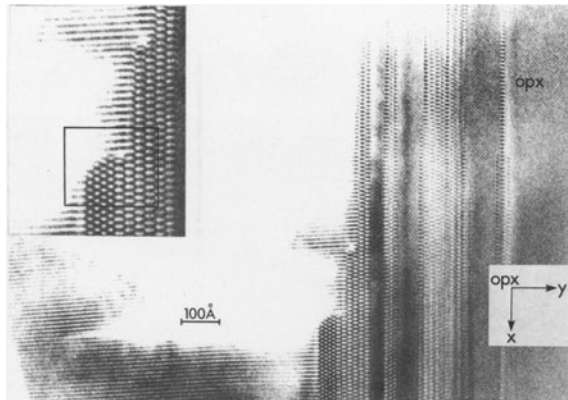


Figure 4. Layer silicate (9-Å) and biopyroxene alteration of orthopyroxene. The enlarged inset shows two channels formed at the termination of 3-chain 'zippers.'

tite. No evidence was found for interstratification of the two-layer silicates at the unit-cell scale from the X-ray diffraction data. Diffractometry of the loose crystals and pseudomorphs (Table 2) showed the presence of talc and a smectite, and a small amount of chlorite as revealed by a weak residual 14-Å reflection after heating beyond 300°C, and by a shoulder on the 17-Å peak of the glycolated sample. The X-ray diffraction results confirm the electron imaging that the alteration is a mixture of expanded and unexpanded 2:1 layers. The *b* cell dimension of the vein talc and of lowest 2V yellow 'crystals' were estimated from *d*(060) measured from 114.6-mm Debye-Scherrer photographs with Si as an internal standard.

Density

Particles collected from the weathered surface were gently disaggregated, washed, and sieved to 72 × 100 mesh. The least dense grains from this fraction have a density of 2.20 g/cm³ as measured by pycnometry applied to the heavy liquid in which the bulk of the grains remained suspended. These grains are mostly yellow-

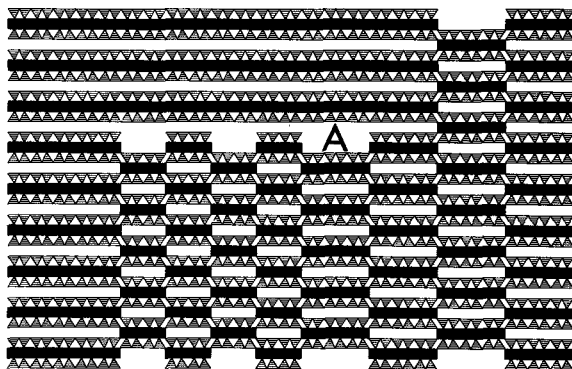


Figure 5. Diagram showing the I-beam structure of part of the region shown in Figure 4.

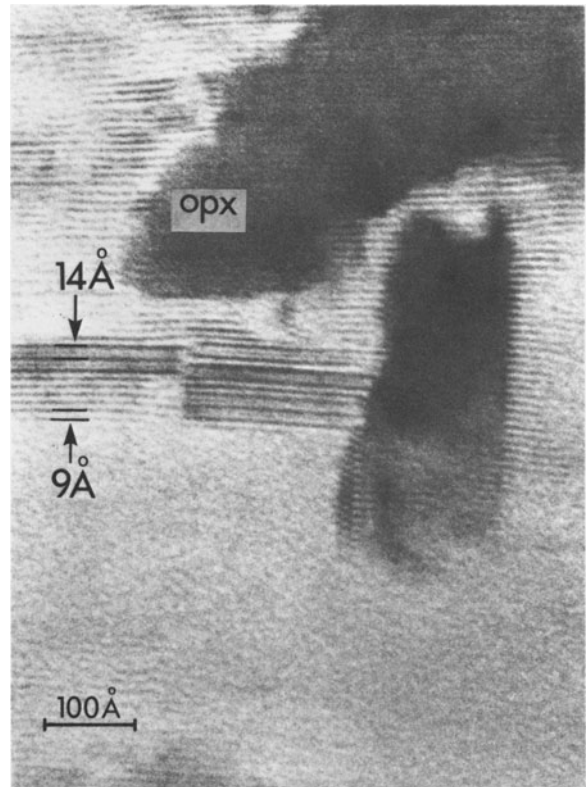


Figure 6. 9-Å and 14-Å layer silicates forming from orthopyroxene.

orange, and the fraction contains many clear yellow plates, such as were used in the above single-crystal studies, as well as more cloudy and semiopaque material.

Chemistry

The various weathering products were analyzed by an energy dispersive electron microprobe. The orthopyroxene, its yellow alteration product, and clear talc, were analyzed in polished section. The difficulty of obtaining a good polish on yellow material and vein talc in the presence of pyroxene, reduced the X-ray count rate and may have led to low totals. Because the analytical total is the only guide to water content, the quoted H₂O for the thin-section analyses must be regarded as uncertain. Selected yellow 'crystals' collected from the soil were also analyzed by electron probe. These 'crystals' have very smooth (001) surfaces, and their analytical totals are more reliable. As a check, single cleavage flakes were analyzed of coarsely crystalline pure talc from Mt. Windarra, Western Australia, for which a full chemical analysis was available. The analytical total by electron probe differed from 100% by exactly the analyzed water content.

Ferrous iron in the weathering products was determined by titration with K₂Cr₂O₇ following digestion in

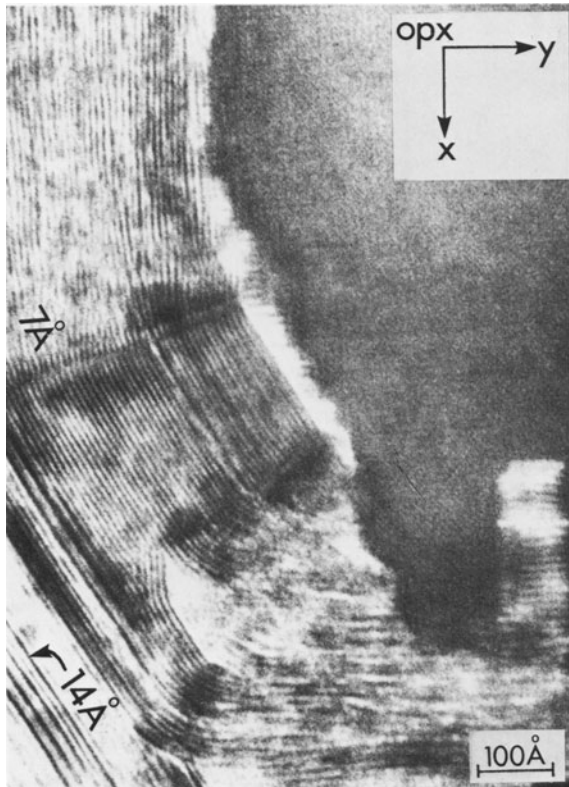


Figure 7. Growth of layer silicates following initial topotactic development of 9-Å layers in solution holes. 7-Å, 9-Å, and 14-Å sequences can be seen in the bent layers.

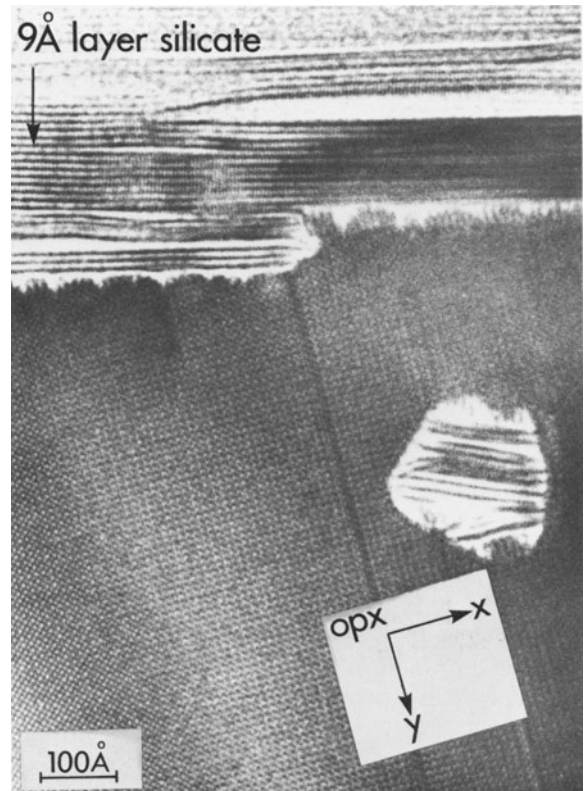


Figure 8. 9-Å layer silicate filling solution hole and crack in orthopyroxene.

Table 1. Analyses of orthopyroxene and alteration products.¹

	1	2	3	4	5	6	7	8
SiO ₂	55.78	53.93	57.35	53.94	46.58	49.03	59.84	0.00
Al ₂ O ₃	1.32	5.23	1.01	1.24	2.29	3.50	0.36	0.20
Cr ₂ O ₃	0.31	0.35	0.23	0.29	0.64	0.61	0.07	1.75
FeO	11.17	8.97						31.55
Fe ₂ O ₃			8.22	11.35	18.54	22.30	3.80	65.80
MnO	0.18	0.23						
MgO	30.35	26.40	26.13	23.19	20.29	16.28	29.17	—
CaO	0.97	4.90	0.59	0.68	0.36	0.40	0.00	—
Total	100.08	100.01	93.55	90.71	88.70	92.12	93.24	99.30
Si	3.89		3.92	3.89	3.78	3.69	3.99	
Al	0.11		0.08	0.11	0.22	0.31	0.01	
Cr	0.02		0.01	0.02	0.04	0.04	0.00	
Fe ²⁺	0.40							
Fe ³⁺	0.25		0.42	0.62	1.13	1.26	0.19	
Mg	3.18		2.68	2.51	2.45	1.83	2.90	
Ca	0.07		0.04	0.05	0.03	0.03	0.00	
H ₂ O	—		1.48	2.25	3.06	1.98	1.50	

1. Average of 7 orthopyroxene grains (Fe as FeO), structural formula to +24.

2. Exsolution lamella in orthopyroxene (Fe as FeO).

3. Average of 10 grains of yellow material in thin section ($7.8 < \text{Fe}_2\text{O}_3 < 11.2$).

4. Average of 6 grains of yellow material in thin section ($11.2 < \text{Fe}_2\text{O}_3 < 12.2$).

5. Average of 4 grains of yellow material in thin section ($16.9 < \text{Fe}_2\text{O}_3 < 19.3$).

6. Average of 4 yellow 'crystals' (Fe as Fe₂O₃). Empirical structural formula.

7. Average of 5 grains of vein talc (Fe as Fe₂O₃).

8. Magnetite in talc (FeO/Fe₂O₃ calculated to conform to magnetite) (+0.5TiO₂).

¹ Structural formulae of layer silicates based on 4 (Si + Al) except number 6. H₂O in structural formulae is by difference.

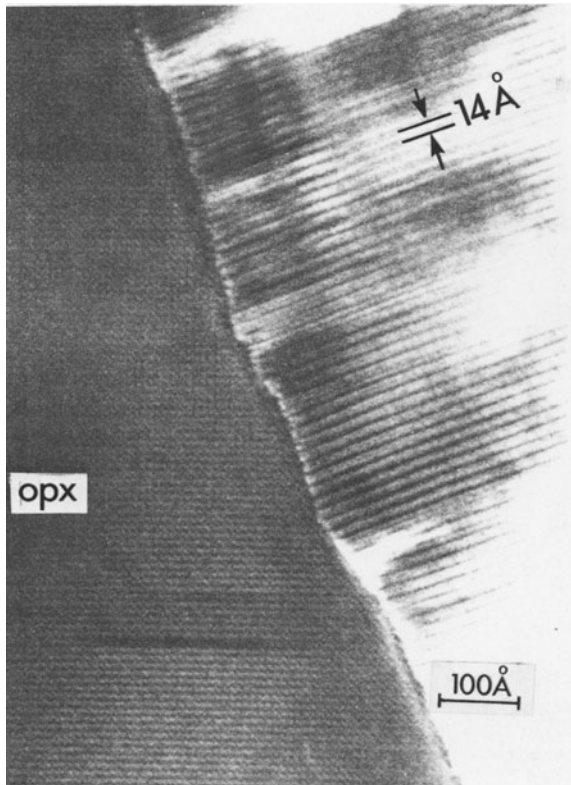


Figure 9. 14-Å layer silicate grown in a presumed solution channel in orthopyroxene. The 'ladders' of Figure 1c have a similar microstructure.

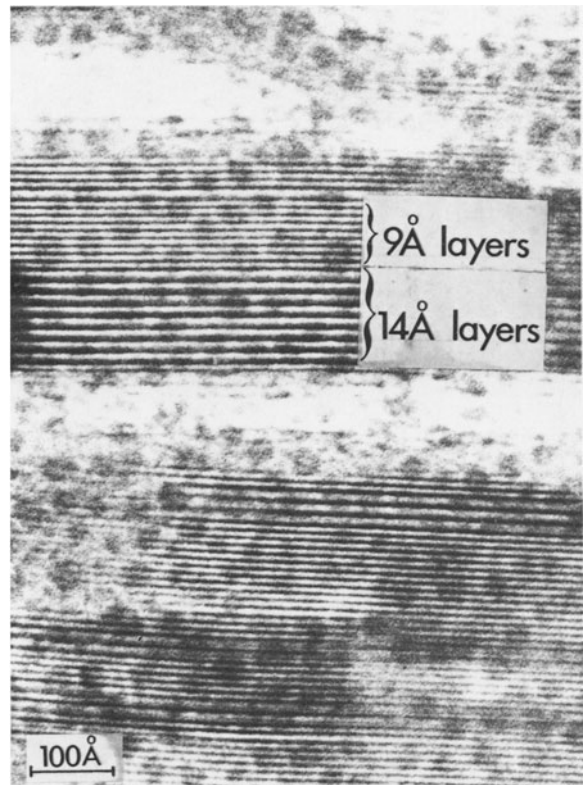


Figure 10. 9-Å- and 14-Å-layers in yellow material. The mottling is an artifact from ion-thinning.

HF. A density fraction $<2.3 \text{ g/cm}^3$, composed of yellow crystals, some bastite-like pseudomorphs, and about 3% nonmagnetic iron oxides has an FeO content of 0.3%. The density fraction $2.3\text{--}2.5 \text{ g/cm}^3$ contains 1.1% FeO. Thus, the iron in yellow material is ferric, and accordingly the electron probe analyses for Fe have been reported as Fe_2O_3 .

Table 1 lists average analyses of the orthopyroxene and its weathering products. These data show a de-

crease in divalent cations and an increase in trivalent cations with weathering, trends that have been commonly recorded (Loughnan, 1969). Figures 11 and 12 show the distribution of octahedral cations and Al among the phases analyzed. Ideal talc or smectite should have a total octahedral charge no greater than +6; if the yellow material is composed only of these two phases, the data points of Figure 11 would fall close to the line from 3 Mg to 2 Fe^{3+} . The scatter of analyses to the right of this line indicates the presence of 1:1 or 2:2 layers and relict pyroxene in some of the yellow material.

There is a roughly linear relation between the analytical total and 2V for the yellow 'crystals,' and decreasing 2V is interpreted as reflecting increasing smectite component. 'Crystals' of lowest 2V have the lowest density, and by using this density and the measured cell parameters to calculate the structural formula for yellow 'crystals', the structural formula for the smectite can be approximated. The high octahedral cation total of 3.13 is consistent with the X-ray diffraction observation that yellow 'crystals' contain some unexpanded 2:2 layers (chlorite).

The empirical structural formula (Table 1, column 6), determined from the chemical analysis, density, and

Table 2. X-ray diffraction data for orthopyroxene, talc, and smectite alteration product.

	a (Å)	b (Å)	d(001) (Å)
Orthopyroxene	18.27	8.846	5.197
Talc		9.175	9.4
Smectite 25°C		9.20	14.7
110°C			14.5
200°C			14.3
300°C			14.1
400°C			9.3
500°C			9.3
ethylene glycol			17.0



Figure 11. Vein talc, with only a few remaining expanded layers.

cell volume of the yellow crystals showed that all of the Al is in tetrahedral coordination. Accordingly, the structural formula of the less-altered yellow material was calculated on the basis of 4 (Si + Al). However, because the electron microscopy showed that yellow material is a mixture of 9-Å and 14-Å layer silicates with minor 7-Å layers, the structural formulae do not represent a single mineral. The average analyses in columns 3–5 of Table 1, which were grouped for averaging on the basis of similar Fe content, all show a cation charge in excess of 22, indicating the presence of 1:1 or 2:2 layers or residual orthopyroxene. Nonetheless, all analyses of yellow material show a tetrahedral to octahedral cation ratio close to 4:3, consistent with the conclusion from the electron microscopy that yellow material forms from, and is part of, the initial 9-Å layer silicate that developed topotaxially from the orthopyroxene.

The formula for the vein talc (Table 1, column 7) is calculated on the basis of 4 (Si + Al), and is close to ideal talc formula. The iron in the talc analyses may indicate the presence of residual smectite or finely divided magnetite. Analyses indicate that the grains in the vein talc are an Al-Cr-magnetite, but the grains are too small for an accurate analysis.

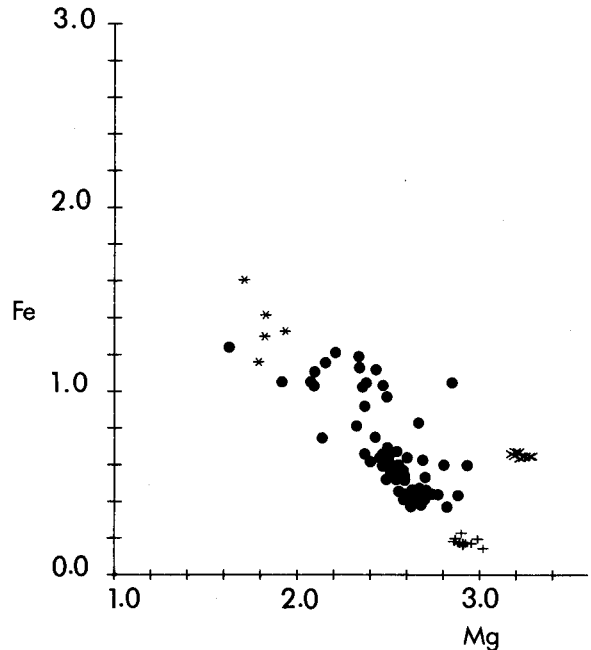


Figure 12. Relation between Mg and Fe for all analyses, calculated to 4 (Si + Al). (Mg + Fe) > 3, indicating some 1:1 or 2:2 layers with the 2:1 layer silicate, or some residual orthopyroxene. + = talc; × = orthopyroxene; * = 'crystals.'

REACTION

The chemical and structural characterization of each reaction product is essential to a full description of the reaction itself. Chemical formulae for the many biopyriboles that develop during the early stage of alteration are impossible to obtain. However, an estimate may be made of the first major product to form, namely, the 2:1 layer silicate that develops in continuity with the pyroxene. From the chemical data discussed above, this material should have (Si + Al) = 4, minimal inter-layer material (d(001) remains at 9 Å), and a minimum of octahedral cations, because to remain in structural coherence it must have a *b* parameter the same as that of the pyroxene (8.85 Å). It must also retain all the original iron of the pyroxene in oxidized form. The conditions suggest a composition of $\text{Ca}_{0.05}(\text{Fe}^{3+}_{0.65}\text{Cr}_{0.02}\text{Mg}_2)(\text{Si}_{3.89}\text{Al}_{0.11})\text{O}_{10}(\text{OH})_2$ which on formation from orthopyroxene would require the release of 1.18 MgO, with no change in volume. The domains of this layer silicate are nowhere large enough to be the only phase 'seen' by the electron microprobe; analyses of such material must include less-altered areas as well as original orthopyroxene. The few data points in Figure 12 scattered at constant Fe toward the pyroxene position may be of such mixtures.

The second stage of alteration is marked by the development of mixtures of 2:1- and 2:2-layer silicates with minor 1:1 layers, accompanied by a decrease in

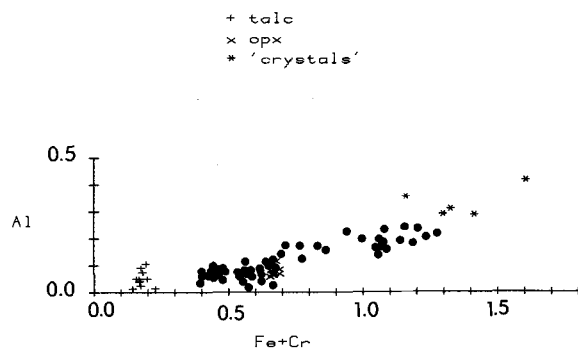


Figure 13. Relation between Al and (Fe + Cr) for all analyses.

volume of 16%, determined in thin section by measuring the proportion of gap space in crystals such as shown in Figure 1b. For topotactic transformation of pyroxene to smectite, 1.5 pyroxene becomes one layer of smectite ($1.5 \times d(100) \sim 14 \text{ \AA}$). In this example the transformation is not fully topotactic, and allowing for a 16% volume loss the equation becomes 1.74 pyroxene \rightarrow 1 smectite, with the release of SiO_2 and MgO . Comparison of the structural formulae of 1.74 orthopyroxene and the most altered material in thin section (analysis 5) shows that all of the Fe, Al, and Cr remain in the yellow material, whereas about equal proportions of MgO and SiO_2 are lost, presumably to form the vein talc.

The third stage of alteration is the conversion of yellow material to talc and, as described in the electron microscopy section, involves the exchange of Mg and Fe^{3+} in the octahedral layers of the 9- and 14- \AA layer silicates in the yellow material. From the microstructures, it appears that this final reaction takes place with little volume change implying a reaction: 1 smectite + $\text{MgO} + \text{SiO}_2 \rightarrow 1.5 \text{ talc} + \text{Fe}_3\text{O}_4$.

The reaction sequence may be written as follows, using the structural formulae from Table 1. Column 1 provides a formula for orthopyroxene (opx), column 5 for the smectite/chlorite yellow material (smc), and column 7 for talc. The structural formula for the first-found layer silicate is deduced above.

- (1) 1.74 orthopyroxene + 0.35 O_2 + 1.74 $\text{H}_2\text{O} \rightarrow$ 1.74 layer silicate + 2.05 MgO + 0.03 CaO
- (2) 1.74 layer silicate + 0.4 $\text{H}_2\text{O} \rightarrow$ 1.0 smectite/chlorite + 1.03 MgO + 0.06 CaO + 2.96 SiO_2
- (3) 1.0 smectite/chlorite + 1.9 MgO + 2.19 $\text{SiO}_2 \rightarrow$ 1.5 talc + 0.45 spinel + 0.64 H_2O + 0.18 O_2

These three reactions summarize as: orthopyroxene + 0.2 O_2 + 0.86 $\text{H}_2\text{O} \rightarrow$ 0.86 talc + 0.26 spinel, with the release of 0.68 MgO , 0.07 CaO , and 0.45 SiO_2

DISCUSSION

The complete transformation of enstatite to talc through a three-stage reaction is not the fate of all of the orthopyroxene. Some yellow material is released from the rock by mechanical disintegration and thereafter loses its magnesium, becoming the yellow 'crystals' of smectite/chlorite. The nature of the layer silicate that forms at this stage probably depends on the particular weathering environment. Only the steep, recently weathered, road cut was sampled, where the surface material would dry out quickly. Idlefonse *et al.* (1979) reported large crystals of vermiculite with optical properties similar to those of the 'yellow material,' but containing more aluminum, in the weathering profile of a gabbro. Because the gabbro has no phyllosilicate minerals from which vermiculite could have formed, they concluded that the mineral crystallized from "elements put into solution." Our observations suggest that vermiculite could have formed by the topotactic transformation of pyroxene or amphibole from the gabbro, as Basham (1974) found.

The availability of the various elements released during weathering is related to the mineralogical transformation sequence. Although we have not made trace-element analyses the differences in the behavior of the minor elements Mn and Cr point to the existence of different pathways. The orthopyroxene contains 0.2% MnO and 0.3% Cr_2O_3 . Yellow material has no MnO , and as much as a threefold increase in Cr_2O_3 . The spinel contains even more chromium. Presumably Mn was lost very early from the pyroxene and could not be accommodated by the layer silicate structure, but remained in solution to form dendritic coatings when the water evaporated.

The ability of minerals to weather by topotactic transformation in the solid state with no intervening noncrystalline phase is of great significance to any studies of leaching and mineral solution. Laboratory experiments of solution rates, abrasion pH, etc. assume large volumes of water reacting with the mineral surface. Doubtless this process occurs naturally whenever it rains, and for as long as the rock and soil remain wet, but the mineral in contact with water has already been hydrated on the unit-cell scale long before that rain shower. Indeed, liquid water may never wet anything except the layer-silicate alteration products, leaving the bulk of the weathering to be accomplished by water vapor diffusing through the crystal.

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REFERENCES

- Basham, I. R. (1974) Mineralogical changes associated with deep weathering of gabbro in Aberdeenshire: *Clay Miner.* **10**, 189–202.
- Berner, R. A. and Holdren, C. R. (1977) Mechanism of feldspar weathering: some observational evidence: *Geology* **5**, 369–372.
- Berner, R. A., Sjöberg, E. L., Velbel, M. A., and Krom, M. D. (1980) Dissolution of pyroxenes and amphiboles during weathering: *Science* **207**, 1205–1206.
- Eggleton, R. A. (1975) Nontronite topotaxial after hedenbergite: *Amer. Mineral.* **60**, 1063–1068.
- Eggleton, R. A. and Buseck, P. R. (1980) High resolution electron microscopy of feldspar weathering: *Clays & Clay Minerals* **28**, 173–178.
- Idlefonse, P. (1978) Mécanismes de l'altération d'une roche gabbroïque du Massif du Pallet: Doctorat Thèse, l'Université de Poitiers, 142 pp.
- Idlefonse, P., Copin, E., and Velde, B. (1979) A soil vermiculite formed from a meta-gabbro, Loire-Atlantique, France: *Clay Miner.* **14**, 201–210.
- Keller, W. D. (1978) Kaolinization of feldspars as displayed in scanning electron micrography: *Geology* **6**, 184–188.
- Loughnan, F. (1969) *Chemical Weathering of the Silicate Minerals*: Elsevier, New York, 154 pp.
- Nakajima, Y. and Ribbe, P. H. (1980) Alteration of pyroxenes from Hokkaido, Japan, to amphibole, clays and other biopyriboles: *N. Jb. Miner. Mh.* **6**, 258–268.
- Veblen, D. R. and Buseck, P. R. (1980) Microstructures and reaction mechanisms in biopyriboles: *Amer. Mineral.* **65**, 599–623.

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Резюме—Ортопироксен (En_{85}) выветривается сначала путем диффузии свободных мест и во время этого процесса происходит гидратация с образованием последовательных биопириболи, заканчивающихся талько-подобным слоистым силикатом, структура которого когерентно связывается со структурой ортопироксена. Окисление Fe^{2+} в Fe^{3+} окрашивает в желтый цвет изменяющийся пироксен. «Тальк» не остается в структурном согласии с пироксеном, если его размер превышает несколько десятков нанометров; он подменяется смесью талька со смектитом. В некоторых областях эта смесь имеет эпитактическое отношение к пироксену, но обычно она заполняет в растворе отверстия нерегулярной формы без кристаллографической связи с материнской структурой. Продолжительное выветривание увеличивает желтую зону на краях ортопироксена, а изменяющийся продукт увеличивается в смектите и уменьшается в «тальке». MgO и SiO_2 освобождаются во время этой стадии реакции, чтобы образовать бесцветный настоящий тальк около изменяющегося пироксена. Окончательно, продукт желтого изменения может превратиться в псевдоморф смектита после ортопироксена, либо может измениться полностью в смесь талька и окисей железа. Полная перемена ортопироксена в тальк и окиси происходит через три последовательные минералогические реакции, без образования некристаллической фазы. [Е.С.]

Resümee—Orthopyroxen (En_{85}) verwittert am Anfang durch Leerstellendiffusion. Durch diesen Prozess kommt es zur Hydratation, und es entwickelt sich eine Abfolge von Biopyribolen, die zu einem Talk-ähnlichen Schichtsilikat führt, dessen Struktur mit der Orthopyroxenstruktur zusammenhängt. Die Oxidation von Fe^{2+} zu Fe^{3+} färbt den sich umwandelnden Pyroxen gelb. Der "Talk" verliert seine strukturelle Ähnlichkeit mit dem Pyroxen, wenn er über einige Zahner von Nanometern groß wird; er wird dann von einer Mischung aus Talk und Smektit ersetzt. In manchen Bereichen hat diese Mischung eine epitaxische Beziehung zum Pyroxen. In den meisten Fällen füllt er jedoch facetierte Lösungshohlräume ohne kristallographische Beziehung zur Pyroxenstruktur. Durch weitere Verwitterung dehnt sich die gelbe Zone bis zum Rand des Pyroxens aus, und das Umwandlungsprodukt enthält dann immer mehr Smektit und immer weniger "Talk." Während dieser Umwandlungsstadien werden MgO und SiO_2 frei und bilden farblosen echten Talk um den ungewandelten Pyroxen. Gelegentlich führt die gelbe Umwandlung zu einem Smektit pseudomorph nach Orthopyroxen. Der Pyroxen kann aber auch vollständig in eine Mischung von Gangtalk und Eisenoxiden umgewandelt werden. Die vollständige Umwandlung von Orthopyroxen in Talk und Oxide verläuft somit über drei aufeinanderfolgende Mineralreaktionen ohne die Bildung einer nichtkristallinen Phase. [U.W.]

Résumé—L'orthopyroxène (En_{85}) est initialement altérée par diffusion de vide, et par ce procédé l'hydratation se produit, et une séquence de biopyriboles se développe, culminant en un silicate à couches, semblable au talc, dont la structure se joint de manière cohérente à la structure orthopyroxène. L'oxidation de Fe^{2+} en Fe^{3+} colore la pyroxène altérante en jaune. Le "talc" ne reste pas en cohérence structurale avec la pyroxène après que sa taille a excédé quelques dizaines de nanomètres, il est remplacé par un mélange de talc et de smectite. Dans certaines régions, le mélange a une relation épitactique avec la pyroxène, mais il remplit généralement des vides de solution à facettes sans relation cristallographique avec la structure mère. L'altération continue étend la zone jaune jusqu'à la périphérie de l'orthopyroxène, et le produit de l'altération accroît son contenu en smectite, et décroît son contenu en "talc." Pendant ce stade de la réaction, MgO et SiO_2 sont relâchés pour former un talc incolore autour de la pyroxène altérante. L'altération jaune peut éventuellement devenir une smectite pseudomorphe après l'orthopyroxène, ou elle peut être entièrement changée en un mélange de talc veinoux et d'oxides de fer. La conversion complète d'orthopyroxène en talc plus oxides se produit donc par trois réactions minérales en séquence sans le développement d'une phase non-cristalline. [D.J.]