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# Pyrophyllite mineralization of the Tanmai deposit, Quang Ninh Province, northern Vietnam – A result of a reconnaissance survey –

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Hideo HIRANO, Masahiro AOKI, Sadahisa SUDO and NGUYEN Van Quy (2001) Pyrophyllite minerelization of the Tanmai deposit, Quang Ninh Province, northern Vietnam – A result of a reconnaissance survey –. *Bull. Geol. Surv. Japan,* vol. 52 (11/12), p.581-598, 8 figs., 5 tables, 2 plates, 2 appendix-figs., 2 appendix-tables.

**Abstract:** The Tanmai pyrophyllite deposit, Quang Ninh Province, was studied geologically and mineralogically. The deposit consisting of five pyrophyllite bodies, is classified into five alteration zones: kaolin, pyrophyllite, siliceous, diaspore and alunite. All of them are characterized by low iron content. The original rocks are volcanics of rhyodacitic composition such as tuff, volcanic breccia, lava and sheeted intrusive rocks. Siliceous zone originated from felsic intrusive rocks and massive lava.

The sequence of the alteration is estimated as follows: kaolin zone formed earlier under lower temperature, and pyrophyllite- and siliceous- zones followed at higher temperature. The contrast in the permeability of the original volcanics resulted in the difference of mineral composition; a pyrophyllite zone from high permeability and a siliceous zone for low permeability units. The diaspore zone has formed as fissure-filling veins selectively in the siliceous zone. This sequence of the formation probably progresses with temperature. Vein-filling diaspore + pyrophyllite in the siliceous zone has precipitated in a hydrothermal solution under decreasing $P_{H_2O}$ caused by vertical fissure systems. The brittle nature of the siliceous zone has developed a vein-filling diaspore. The pyrophyllite zone being the majority of the Tanmai deposit has formed at a temperature of 260-290℃, estimated by the experimental data. Finally, alunite precipitated in the declining stage of hydrothermal activity.

## 1. Introduction

Large pyrophyllite deposits are distributed along the Eastern margin of the Asian continent, associated with Mesozoic felsic volcanic rocks (Sudo *et al.,* 1988). The southern end of this zone reaches Vietnam (Kamitani and Sudo, 1996). The largest pyrophyllite deposits is in northern Vietnam. It has been estimated 45 million tons of reserves and produces annually 20,000 tons (Tran, 1988; ESCAP, 1990). Despite beeing the largest and economically important deposit, a mineralogical study has not been carried out. The internal structure of the ore deposit and mineralization process are still undefined.

In February 2001, the authors (H. H., M. A, and N. V. Q) completed a reconnaissance survey at the Tanmai pyrophyllite deposit, which is located in the northeastern part of the the pyrophyllite ore-field in Quang Ninh Province, northern Vietnam (Fig. 1). We observed alteration zoning within the deposit and deduced the original volcanic rocks from their texture, on which the alteration process to pyrophyllite was reconstracted. In this paper, we describe the pyrophyllite ores petrographically, and discuss the alteration process of the Tanmai deposit.

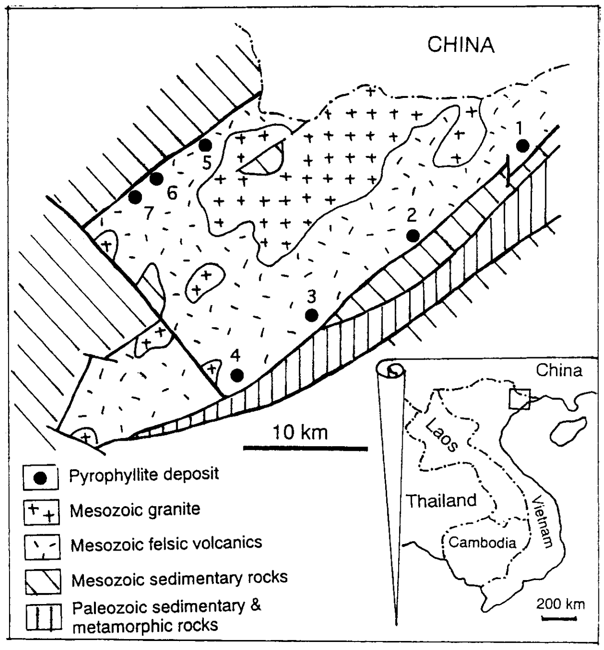


Fig. 1 Distribution of pyrophyllite deposits in northern Vietnam (simplified from ESCAP, 1990).
1, Tanmai; 2, Truc Baison; 3, Pinhho; 4, Lang Lom; 5, Chepha; 6, Ban Trong; 7, Nalang. Heavy lines show faults.

Keywords: hydrothermal alteration, pyrophyllite, industrial mineral, Tanmai

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## 2. Geology and outline of the mine

In the northern part of Vietnam, seven pyrophyllite deposits including the Tanmai deposit is recognized in an elliptic volcanic basin 60 km long in diameter (Fig, 1). All deposits are located along the border of the basin, which hosts the Son Hiem Suite comprised of felsic volcanic rocks and clastic sedimentary rocks of Jurassic to Cretaceous age (ESCAP, 1990). The alteration is thought to have occurred along the marginal faults of the volcanic area (Tran, 1990; ESCAP, 1990). The major constituent minerals of each deposit is different: the northeastern deposit is composed of pyrophyllite and kaolin (kaolinite and dickite), and southwestern deposit is characterized by pyrophyllite and sericite (Table 1). No precious and base metal mineralization has been reported from these areas.

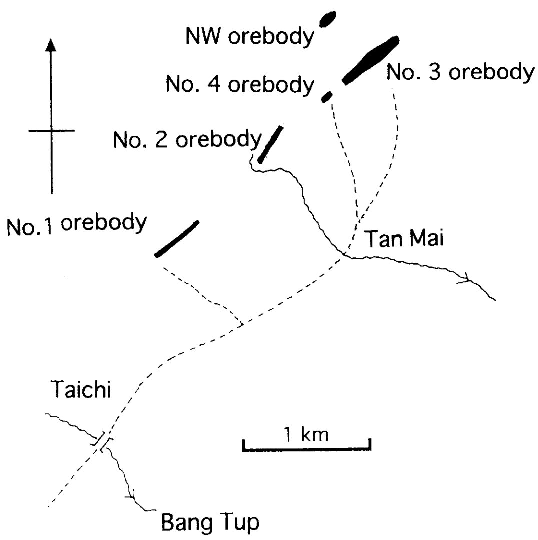



Fig. 2 Distribution of the Tanmai pyrophyllite ore deposit. Five ore bodies are arranged in the northeast - southwest direction.

In 1974, a pyrophyllite deposit was discovered in the Tanmai area by the Geological Organization 911 under a prospect survey for refractory raw materials. From 1980 to 1985, a detailed survey including trenching and drilling was carried out (ESCAP, 1990). After the exploitation survey, production of pyrophyllite ore at the Tanmai deposit started in 1990. It is the only operating pyrophyllite mine now in Vietnam.

**<Tanmai area>** Geology of the Tanmai deposit and adjacent areas are of felsic volcanic rocks, such as rhyolite, porphyritic rhyodacite, felsite, and shale and sandstone of late Jurassic to early Cretaceous age, J3 to K1 (ESCAP, 1990). Five pyrophyllite bodies have been identified in the Tanmai area that crop out on the southern slope from 100 to 400 m above sea level. All were lenticular and distributed in the northeast-southwest direction for about 2.5 km (Fig. 2 and Table 2). This direction is concordant

Table 1 Pyrophyllite deposits in Quang Ninh Province, Vietnam.

| | Mine name | Major mineral | Operation |
|---|---|---|---|
| 1 | Tanmai | pyrophyllite, kaolin, alunite, quartz | working |
| 2 | Truc Balson | pyrophyllite, kaolin, quartz | not exploited |
| 3 | Pinhho | sericite, pyrophyllite, quartz | not exploited |
| 4 | Lang Lom | pyrophyllite, sericite, quartz | not exploited |
| 5 | Chepha | pyrophyllite, sericite, quartz | not exploited |
| 6 | Ban Trong | pyrophyllite, kaolin, quartz | not exploited |
| 7 | Nalang | sericite, quartz | not exploited |

Table 2 Tanmai pyrophyllite ore body.

| Ore body | Size (length x width x height m) | Reserves (Mt) | Operation | Mineral |
|---|---|---|---|---|
| No. 1 | 500 x 10 x 20 ? | 0.2 | not exploited | |
| No. 2 | 250 x 20 x 20 (excavated)<br>250 x 20 x 20 ? | 0.4 | open pit, underground | pp, ka, qt, dia, al |
| No. 3 | 400 x 100 x 150 ? | 12 | open pit | pp, ka, qt, dia, al |
| No. 4 | 100 ? x 20 ? x 20 ? | 0.08 | not exploited | |
| NW body | 80 x 20 ? x 40 ? | 0.13 | not exploited | pp, ka, qt, graphite |

Abbreviations: al, alunite; dia, diaspore; gr, graphite; ka, kaolinite-dickite; p, pyrophyllite; qt, quartz.

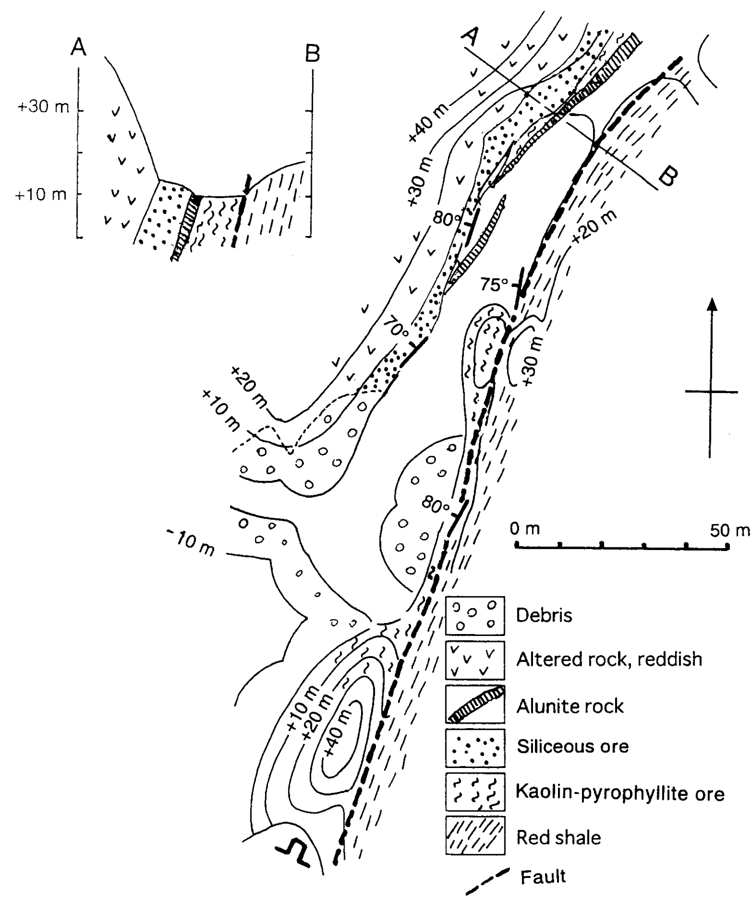



Fig. 3 Geologic sketch map of the Tanmai No. 2 pyrophyllite deposit and its cross section

with the strike of the surrounding sedimentary rocks.

## 3. Ore deposit

The Tanmai pyrophyllite deposit consists five lenticular ore bodies (Fig. 2). Among them, the northwest body is 360 m northwest of the No. 3 ore body, showing the different ore horizon of Nos. 1, 2, 3 and 4 ore bodies. We surveyed three ore bodies; No. 2, No. 3 and NW ore bodies. Pyrophyllite bodies show partly their original structure, such as bedding planes. We presumed the internal structure of ore bodies, from the primary structures. Geological sketch maps for Nos. 2 and 3 ore bodies are shown in Figs. 3 and 4 with their cross sections. The ore bodies are products of advanced argillic alteration with a special chemical composition, low in iron content less than 1.5 weight percent in the total $Fe_2O_3$ (Tran, 1988; ESCAP, 1990). The ore bodies consist of five zones: kaolin, pyrophyllite, diaspore, alunite and siliceous. Alteration zones and ores will be described later.

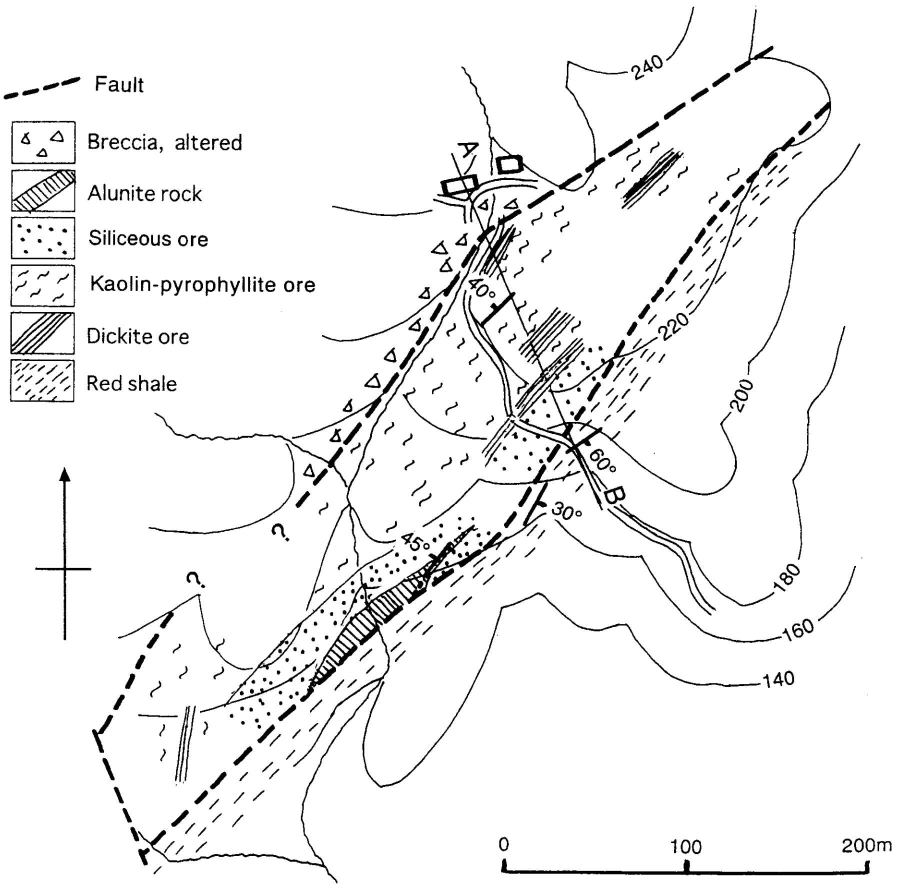
The annual ore production is about 20,000 tons with 90 percent of the ores are shipped to domestic cement factories as raw material for white cement which high aluminous one is sent to ceramic companies.

### 3.1 Original rocks of ores

Rock specimens collected from ore bodies and their surrounding are recrystallized by argillic alteration but have partly preserve their original structure and texture. Under an optical microscope, we recognize phenocrysts, groundmass texture, pumice, lithic fragments, and glass shards of volcaniclastic rocks. According to field occurrence and textures of the altered rocks, we could the distinguish following rock types: felsic tuff, felsic volcanic breccia, felsic lava, felsic intrusives and clastic sedimentary rocks (shale and sandstone). A description for the specimens is given in Appendix Table 2. The petrography of typical rocks is as follows:

**<Felsic tuff>** Felsic tuff, majority of the original rock of pyrophyllite ores, shows stratification parallel to the bedding plane. It is composed of a glass matrix, lithic and crystal fragments of quartz, feldspar and mafic minerals. Felsic tuff from the NW ore body, contains fragmental shale, changed to a patch of graphite aggregates.

**<Felsic volcanic breccia>** This is one of the major original rocks of the pyrophyllite deposit. Typical volcanic breccia is distributed along the northwestern boundary of No. 3 ore body, which contains large fragments of felsic volcanic rocks of 1 to 50 cm in diameter.



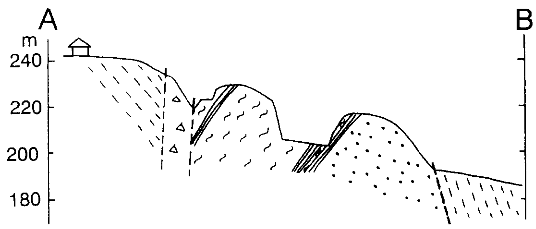




Fig. 4 Geologic sketch map of the Tanmai No. 3 pyrophyllite deposits and its cross section

**<Felsic lava>** It rather difficult to distinguish lava from other rock types under an optical microscope because of hydrothermal alteration. Some lava may show similar texture to tuff breccia and intrusive rocks. One sample of pyrophyllite-kaolin ore from No. 3 orebody shows a relic texture of perlitic fracture, which is common in rhyodacite lava and compact glass of welded tuff a in rhyodacite composition.

**<Felsic intrusive rock>** It is massive without a distinct platy structure on their outcrops of Nos. 2 and 3 ore bodies. The felsic intrusive rock cuts the bedding or compressed foliation of tuffaceous sediments (Fig. 5, Photo B in Plate 1 sample no. 21702). Under a microscope, small intrusives and lava of rhyolitic to dacitic (felsic) composition are characterized by a porphyritic texture with quartz phenocryst and fine-grained or glassy groundmass. The phenocryst size and distribution are mostly uniform within the unit (Photo D in Plate 1). Some of "porphyritic rhyodacite" described by ESCAP (1990, p. 46) may correspond to this intrusive rock.

**<Shale and sandstone>** Shale and sandstone are distributed near the ore deposit. They alternate with each other showing a distinct sedimentary structure. Its reddish color is caused by iron oxides, hematite and goethite. However, a black one is also observed near the pyrophyllite ore deposit. Their strike is constantly northeast to southwest with variable dips, northeastward or southwestward.

### 3.2 Ore and iron-rich altered rock

We classified the altered rocks into six categories at the quarry based on their rock facies, hardness, waxy touch, color and manner of its cracks. A term "kaolin" in this paper means kaolinite and/or dickite. Representative ores and altered rocks are analyzed by X-ray diffraction (XRD) and differential thermal analysis and thermogravimetry (DTA-TG). The results are shown in Figs. 6 and 7. Some minerals related to the pyrophyllite mineralization are listed in Table 3.

**<Dickite ore>** Dickite ore is a compact, homogeneous, fine-grained and translucent rock, showing commonly

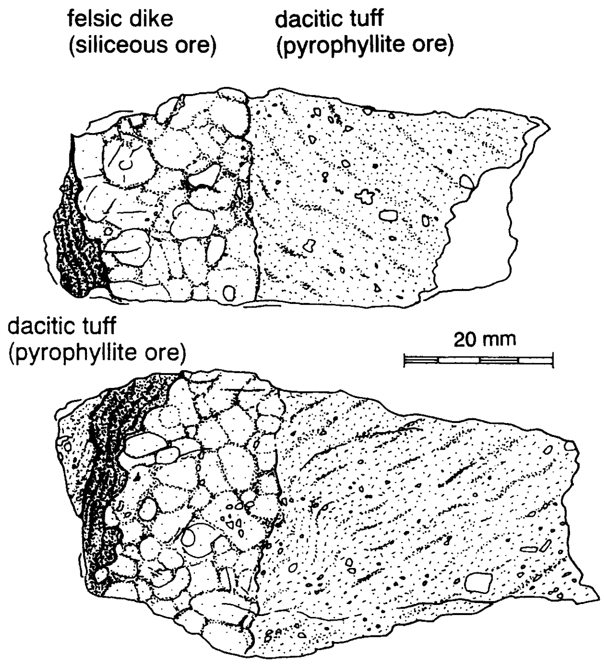



Fig. 5 Sketch for a sliced specimen collected from No. 3 ore body. Felsic dike (siliceous ore) intruding in the dacitic tuff (pyrophyllite ore). Fissures in the siliceous ore is filled with diaspore and pyrophyllite. Specimen no. 21702

pale ivory or light gray. It occurs usually as vein in pyrophyllite-kaolin ores. Dickite is the dominant mineral associated with kaolinite and relic quartz (specimen No. 21812A in Fig. 6). The DTA curves of kaolin show two strong endothermic peaks between 500 and 700 °C due to dehydration and decomposition of the kaolin structure (specimen No. 21812A in Fig. 7). Under a microscope, fragmental or phenocrystic quartz grains are observed in a homogeneous matrix of kaolin minerals, indicating that some parts of the dickite "vein" may have replaced in origin from pyrophyllite-kaolin ores. The dickite ore belongs to the 1st ore grade for ceramics, which contains more than 35 wt% $Al_2O_3$. The dickite ore output is small as 1 to 2 percent of the total ore production in this area. It is used as high quality ceramic raw materials for domestic industries.

**<Pyrophyllite-kaolin ore>** Pyrophyllite-kaolin ore is waxy, translucent and greenish yellow. A Japanese term "Roseki" corresponds to this type of ore. Its major constituent minerals are pyrophyllite, kaolin (kaolinite and dickite) and quartz (specimen no. 21704 in Fig. 6). Pyrophyllite-kaolin ores show a weak endothermic peak and no exothermic peak (DTA-curves for specimen nos. 21812B, 21803 in Fig. 7) and also show a smaller loss of weight during dehydration comparing with dickite ore under dehydration (TG-curves in Fig. 7). Dumortierite occurs as thin films in the No. 3 ore body. Pyrophyllite-kaolin ore commonly contains fragmental quartz crystals which is a relic phenocryst of the magma stage. This ore is the majority of the Tanmai deposit and shipped to ceramic industries, especially to cement factories. The

Table 3 Alumina content of some minerals.

| Mineral name | Chemical formula | $Al_2O_3$ wt% (hydrous basis) | $Al_2O_3$ wt% (anhydrous basis) | $Al_2O_3$ / ($Al_2O_3$ + $SiO_2$) in weight |
|---|---|---|---|---|
| corundum | $Al_2O_3$ | 100.0 | 100.0 | 1.000 |
| diaspore | $AlO(OH)$ | 85.0 | 100.0 | 1.000 |
| andalusite | $Al_2SiO_5$ | 62.9 | 62.9 | 0.629 |
| kaolinite | $Al_2Si_2O_5(OH)_4$ | 39.5 | 45.9 | 0.629 |
| dickite | $Al_2Si_2O_5(OH)_4$ | 39.5 | 45.9 | 0.629 |
| alunite | $KAl_3(SO_4)_2(OH)_6$ | 36.9 | 42.5 | 1.000 |
| sericite | $KAl_2(Si_3Al)O_{10}(OH,F)_2$ | 38.4 | 40.2 | 0.459 |
| anorthite | $CaAl_2Si_2O_8$ | 36.7 | 36.7 | 0.459 |
| pyrophyllite | $Al_2Si_4O_{10}(OH)_2$ | 28.3 | 29.8 | 0.298 |
| albite | $NaAlSi_3O_8$ | 19.4 | 19.4 | 0.221 |
| orthoclase | $KAlSi_3O_8$ | 18.3 | 18.3 | 0.221 |
| quartz | $SiO_2$ | 0 | 0 | 0 |

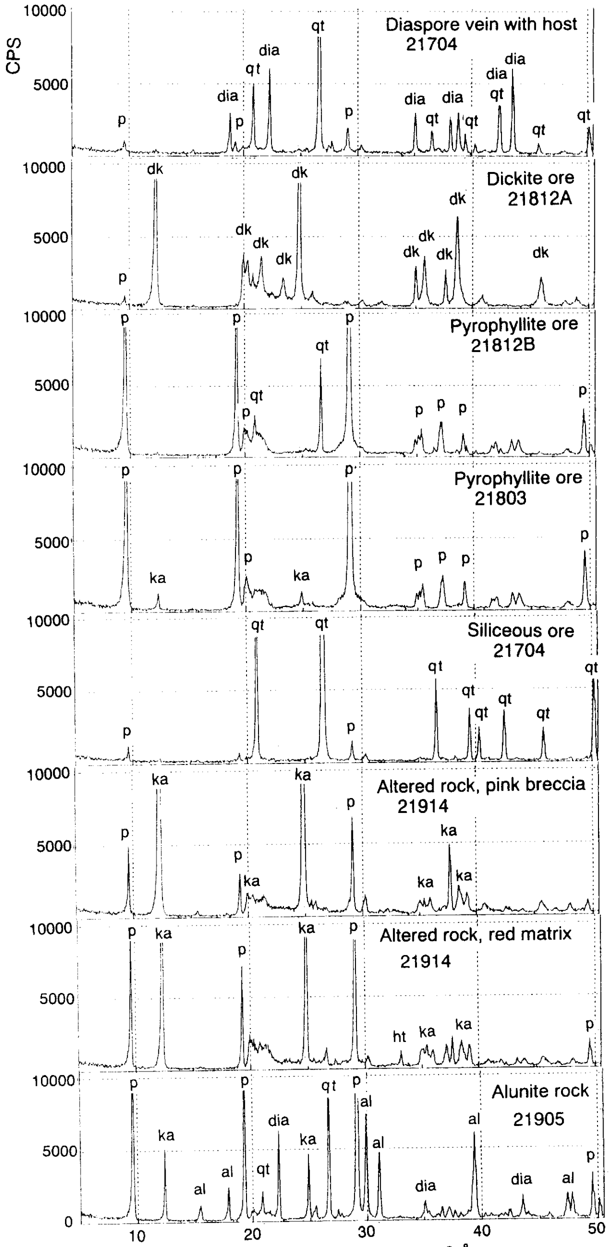



Fig. 6 X-ray powder diffraction patterns of ores and altered rocks from the Tanmai pyrophyllite deposit. Abbreviations: al, alunite; dia, diaspore; dk, dickite; ka, kaolinite; p, pyrophyllite; Q, quartz. Analytical condition: X-ray, Cu-Kα; Voltage, 40 kV; Current 100 mA; slit, 0.2 mm; step, 0.02 ° .

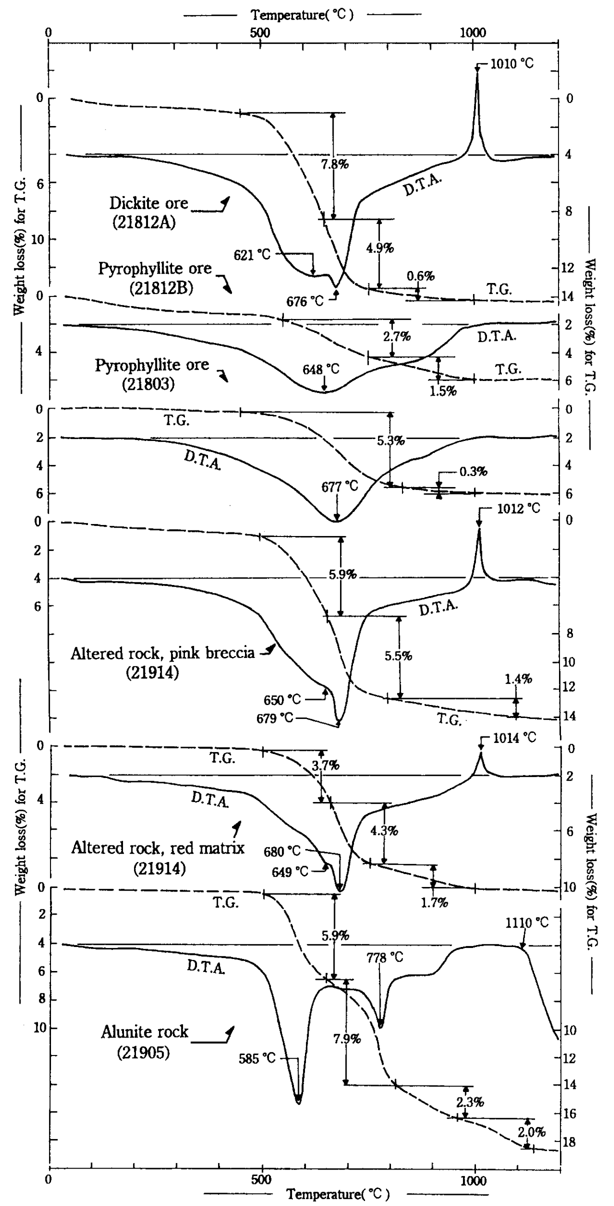



Fig. 7 DTA-TG curves for some advanced argillic alteration products of the Tanmai deposit.
Analytical condition: Amount of sample, 50 mmg.; Reference material, Annealed $Al_2O_3$; Grain size of sample, 200-100 micron; Furnace atmosphere, air; Sample holder, Pt crucible; Thermocouples, Pt-Pt90/Rh10; Heating rate, 20 ° /min; Packing density, loosely packed.

ore from the NW orebody commonly contains a small patch of graphite aggregates, which was migrated as fragmental shale during the volcanic activity. Pyrophyllite-kaolin ores contain kaolin, pyrophyllite and quartz in various chemical compositions. Most pyrophyllite-kaolin ore containing more than 28 wt % of $Al_2O_3$ and less than 35 % of $Al_2O_3$ belongs to the second grade.

**<Siliceous ore>** Siliceous ore occurs as a massive, hard, compact, white to light colored rock. It is present as zones in No. 3 ore body and the No. 2 ore body, apparently associating with alunite rock and diaspore-bearing ore (Figs. 4 and 5). It contains quartz, pyrophyllite and kaolin with small amounts of rutile. No vuggy silica, being common in the rocks altered by highly acid solution, is found in this siliceous zone. Overgrowth of quartz crystals is sometimes observed under a microscope. Some siliceous ore containing more than 19 wt % $Al_2O_3$ belongs to the third ore grade. The original rock of the siliceous ore is mainly intrusive rocks of rhyodacitic composition (e.g. quartz porphyry) and massive lava.

**<Diaspore ore>** Diaspore ore is characterized by diaspore, which can be recognized with the naked eye by their perfect cleavage. The ore contains mainly pyrophyllite and kaolin with various amounts of diaspore and quartz. This ore mainly occurs as a veinlet of diaspore-pyrophyllite or diaspore-kaolinite assemblage in and near the siliceous ore of the Nos. 2 and 3 ore bodies. This ore is not separated from other rock types under processing because of their limited production.

**<Alunite rock>** Alunite rock is soft, rough and pink to ivory. This rock contains alunite, pyrophyllite, kaolin with quartz and diaspore. Alunite rock occurs as narrow zones at the southeastern border of No. 3 ore body and in No. 2 ore body.

It contains low iron less than 1 % total $Fe_2O_3$ (Table 21, p. 48, ESCAP, 1990). The cement industry is the major consumer of the Tanmai ores and requires raw materials of low alkali and low iron contents (less than 1 % of total alkali oxide and less than 0.5 % $Fe_2O_3$ for white cement). Pure alunite, however, contains a high alkali component up to 11.4 % $K_2O$. Therefore, alunite rock should be eliminated from the ore products before shipping to the cement factories.

**<Iron-rich altered rock>** Altered rock near the pyrophyllite deposit is red to violet caused by the concentration of fine-grained iron oxides. The difference in color between the altered rock and ore is the content of iron oxides. Altered rock contains considerable amounts of iron above the limit for ceramic raw materials. Groundmass and phenocrystic feldspar are replaced by aggregates of kaolin, pyrophyllite with small amounts of hematite etc (specimen no. 21914 in Fig. 6).

### 3.3 Alteration zoning and their formation

According to field and microscopic observation of the ores, five alteration zones are tentatively recognized (Table 4).

**<Kaolin zone>** Mineral assemblage is characterized by kaolin without pyrophyllite, associating various amounts of quartz. This zone sporadically distributed in the pyrophyllite zone as a remnant and vein as a retrogressive alteration product. The zone's constituent minerals are fine-grained as shown in Photo B on Plate 2 suggesting recrystallization at a relatively lower temperature.

**<Pyrophyllite zone>** This zone is characterized by pyrophyllite without diaspore. Mineral assemblage is pyrophyllite, pyrophyllite+kaolin, and pyrophyllite+kaolin+quartz. This zone is widely spread over most areas of the ore bodies and their surrounding rocks, which are altered volcanic rocks higher in iron content. Under a microscope, aggregates of pyrophyllite envelops small domains of kaolin-quartz aggregate indicating that pyrophyllite zone replaces kaolin zone. Dickite veinlets occur in the pyrophyllite zone showing its later formation than pyrophyllite zone.

**<Siliceous zone>** This zone is characterized by silicification including overgrowth of a relic crystal of quartz. The mineral assemblage of this zone is similar with the pyrophyllite zone except for larger amounts of quartz. The siliceous zone corresponds originally to shallow intrusive rocks and massive lavas which should have been relatively impermeable compared with tuff and volcanic breccia.

**<Diaspore zone>** It is characterized by diaspore. Typical mineral assemblages are diaspore+pyrophyllite and diaspore+kaolin. This zone develops mostly as fissure-filling veinlets in the siliceous zone as shown in Photo C on Plate 1.

**<Alunite zone>** This zone is characterized by considerable amounts of alunite. It develops at the southeastern border of No. 3 ore body and in No. 2 ore body. The constituent minerals are medium-grained alunite, pyrophyllite and quartz.

Table 4 Alteration zone of the Tanmai pyrophyllite deposit.

| Alteration zone | Characteristic mineral | Texture, occurrence |
|---|---|---|
| Kaolin zone | kaolin (kaolinite and/or dickite) and quartz | fine-grained |
| Pyrophyllite zone | pyrophyllite and quartz or kaolin | medium-grained |
| Siliceous zone | quartz and pyrophyllite | mineral assembl. similar to those of pyrophyllite zone |
| Diaspore zone | diaspore and pyrophyllite or kaolin | medium-, coarse- grained, vein |
| Alunite zone | alunite, pyrophyllite and diaspore or quartz | medium-grained |

## 4. Discussion

### Formation of alteration zoning

Five alteration zones are tentatively recognized in the Tanmai pyrophyllite deposit. The alteration is essentially an extraction of iron, alkali and alkali-earth elements from volcanic rocks of rhyodacite composition caused by a hydrothermal reaction. The alteration is thought to have occurred along the marginal faults of the volcanic area (Tran, 1988; ESCAP, 1990). The high permeability nature of the tuff and volcanic breccia have provided for a favorable place for intense alteration.

The mode of occurrence of alteration minerals suggests the sequence of the hydrothermal reaction as follows: the kaolin zone formed earlier in a progressive stage under a relatively lower temperature. The pyrophyllite zone and a siliceous zone formed with increasing temperature. The difference in permeability of the volcanics may have resulted in two zones: the pyrophyllite zone from high permeability units and siliceous zone from low permeability ones. The diaspore+pyrophyllite crystallized within the veins particularly in and around the siliceous zone. This sequence of formation can be explained by the increase in temperature. Finally alunite precipitated in the waning stage of the hydrothermal activity and alkali elements were added to the pyrophyllite zone.

Main mineralogical transition from lower to higher temperature is presented in the system $Al_2O_3$-$SiO_2$-$H_2O$ as follows:

kaolinite + 2 quartz = pyrophyllite + $H_2O$ (1)
2 kaolinite = pyrophyllite + 2 diaspore + 2 $H_2O$ (2)
pyrophyllite + 6 diaspore = 4 andalusite + 4 $H_2O$ (3)

The stability fields have been established by experimental and thermodynamic works for the system of $Al_2O_3$-$SiO_2$-$H_2O$ (e.g., Kennedy, 1959, Hemley, *et al.*, 1980). Their results are represented in Table 5 and Fig. 8. It should be noted that the equilibrium curves for kaolin dissolution shown in reactions (1) and (2) are nearly parallel to the pressure axis under the condition, $P_{total}$= $P_{H_2O}$ =10 to more than 100 MPa (0.1 to more than 1 kb) as shown in Fig. 8. This means kaolin dissolves essentially at almost the same temperatures for a substantial depth interval from 400 m to more than 4,000 m. It is also noteceable that the decrease in $P_{H_2O}$ under a constant Ptotal is very effective for decomposition of kaolinite presented by the dashed lines in Fig. 8.

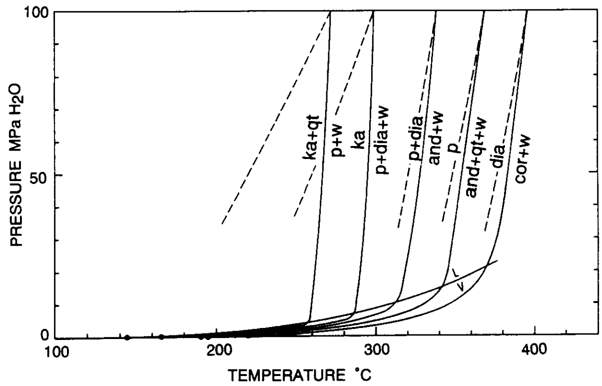



Fig. 8 Pressure-temperature curve in the system $Al_2O_3$-$SiO_2$-$H_2O$ at low water pressures. Dashed curves correspond to 100 MPa total pressure at the indicated $P_{H_2O}$. (Hemley *et al.*, 1980)

Based on the above reactions, we can estimate some physical conditions for the formation of the Tanmai pyrophyllite deposit.

Reaction (1) indicates the first appearance of pyrophyllite at a higher temperature than 260℃, which corresponds to the transition from the kaolin zone to the pyrophyllite zone described in this report.

Reaction (2) shows the extinction of kaolinite at a higher temperature than 290℃. According to reaction (2), diaspore coexists with pyrophyllite at a temperature higher than 290℃. The mineral assemblage of diaspore and kaolinite is stable at a temperature lower than 290℃ because diaspore without pyrophyllite can be stable at a lower temperature than 290℃ (for example Kennedy, 1959, Fig. 2, p. 568).

Reaction (3) indicates the first appearance of and alusite at a higher temperature than 320℃ at $P_{H_2O}$ = 1 kb. We can estimate that the maximum temperature didnot exceed 320℃ at the Tanmai ore deposit, because no andalusite has been reported from the pyrophyllite deposit. The assemblage of pyrophyllite and kaolinite makes up the majority of the Tanmai ore deposit. This assemblage indicates that the majority of the Tanmai pyrophyllite deposit has been formed at the temperature from 260 to 290℃.

We will discuss the vein-filling occurrence of diaspore + pyrophyllite in the siliceous zone of the No. 2 and No. 3 ore bodies. It may be chemically unlikely that diaspore, a

Table 5 Dehydration reaction in the $Al_2O_3$-$SiO_2$-$H_2O$ system. Data from Hemley *et al.*, 1980.

| | Dehydration reaction | Equilibrium temperature at $P_{total}$ = $P_{H_2O}$ = 0.1 to 1 kb |
|---|---|---|
| (1) | kaolinite + 2 quartz = pyrophyllite + $H_2O$ | 260 °C |
| (2) | 2 kaolinite = pyrophyllite + 2 diaspore + 2 $H_2O$ | 290 °C |
| (3) | pyrophyllite + 6 diaspore = 4 andalusite + 4 $H_2O$ | 320-340 °C |

high-alumina mineral, apparently prefers a silicic environment of the alteration. The assemblage of diaspore and pyrophyllite may not mean precipitation at a higher temperature than the surrounding pyrophyllite-kaolinite assemblage because of their thin fissure-filling occurrence. If partial $P_{H_2O}$ of the hydrothermal system is lower than the total pressure, the hydrothermal fluid may have the opportunity to precipitate as the assemblage, diaspore+pyrophyllite shown in Fig. 8. The decrease in $P_{H_2O}$ under constant $P_{total}$ in natural hydrothermal systems is realized by several processes: for instance, introduction of other gaseous phases such as carbon dioxide and pressure release caused by hydraulic fracturing.

Natural fracturing is commonin subvolcanic and geothermal regions (e.g. Phillips, 1972; Sibson, 1990; Tamanyu *et al.*, 1998). The brittle nature of the siliceous zone of the Tanmai pyrophyllite deposit may have preferentially prepared a vein-like mineralization of diaspore + pyrophyllite.

**Deeper part of No. 3 ore body**

The siliceous zone of the Tanmai deposit associates the mineral assemblage of diaspore + pyrophyllite in some places, which shows the highest temperature assemblage of the alteration in the Tanmai deposit. Geological Organization 911 described the cross sections of the No. 3 ore body, where an ore body deeper than 50 m from the surface is mainly composed of volcanic breccia. The "volcanic breccia" named by Geological Organization 911 may correspond to "microquartz" named by ESCAP (1990), which contains sheets of diaspore- and pyrophyllite-zones (ESCAP, 1990, Fig. 26, p. 48). Judging from the vertical position, occurrence and mineral assemblage, the volcanic breccia or the microquartz refferred by previous papers may correspond to the siliceous zone of the present report.

## 5. Conclusion

The Tanmai pyrophyllite ore deposit is an alteration product, originally from felsic volcanic rocks of the Mesozoic age such as rhyodacitic tuff, volcanic breccia, lava and sheeted intrusives. The altered rocks are tentatively classified into five zones; kaolin, pyrophyllite, siliceous, diaspore and alunite. All of them are characterized by low iron contents. The original rock of the siliceous zone is an intrusive rock and massive lava of rhyodacitic composition. The mineral assemblage of diaspore+pyrophyllite indicates the highest temperature of the formation ranges from 290 to 320°C assuming under $P_{total}=P_{H_2O}$. The diaspore zone is closely associated with a siliceous zone in this area suggesting the brittle nature of the siliceous zone and hydraulic fracturing have favorably prepared the vein -like formation of a diaspore zone.

**Acknowledgements:** We acknowledge Mr. Nguyen Manh Hung, Director and Mr. Luong, Chief geologist of the Geological Organization 911 for guiding us to the deposit. Mr. M. Kanamaru, Director of Vietnam JICA Office for providing a vehicle for the site survey to the Tanmai area. Messrs. T. Nogami and K. Fukuda of the Geological Survey of Japan who quickly prepared a total of 40 thin sections on the collected specimens for microscopic observation. Constructive comments given by Dr. M. Sasada is also acknowledged.

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Appendix Table 1 Mineral composition of collected samples from the Tanmai pyrophyllite deposit.

| no. VT- | sample no. | Locality | ore/rock | p | ka | dia | al | qt | py | ht | others |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 217-01 | SE part of Tanmai no. 3 ore body | alunite rock, white & pink | ○ | ○ | | ○ | ○ | | | |
| 2 | 217-02 | Tanmai no. 3 ore body | siliceous ore, white (siliceous dike in pyrophyllite-kaolin ore) | ○ | △ | △ | ○ | △ | | | |
| 2 | 217-02 | Tanmai no. 3 ore body | pyrophyllite-kaolin ore, yellow | ○ | ○ | △ | ○ | ○ | | | |
| 3 | 217-03 | SE part of Tanmai no. 3 ore body | pyrophyllite-kaolin ore | ○ | ● | | | | | | |
| 4 | 217-04 | SW part of Tanmai no. 3 ore body | siliceous ore, white | ○ | | | | ● | | | |
| 4 | 217-04 | SW part of Tanmai no. 3 ore body | yellow vein in siliceous ore | ○ | | ● | | ○ | | | |
| 5 | 217-05 | Between no. 3 and NW bodies | black shale, including apatite nodule | △ | | | | ● | | | △ chl<br>△ser |
| 6 | 217-06 | NW ore body | pyrophyllite-kaolin ore, pale brown | ● | △ | | | ○ | | | △ gr |
| 7 | 217-07 | NW ore body | kaolin ore, white | ● | ○ | | | ○ | | | |
| 8 | 217-08 | Tanmai no. 3 ore body | pyrophyllite ore, light gray | ○ | ● | △ | | | | | ○ chl |
| 9 | 218-01 | Tanmai no. 3 ore body | pyrophyllite-kaolin ore | ○ | ● | | | ○ | | | △ chl |
| 10 | 218-02 | Tanmai no. 3 ore body | pyrophyllite ore, gray | ○ | | | | ● | △ | | |
| 10 | 218-02 | Tanmai no. 3 ore body | siliceous ore, white | ○ | △ | | | ● | | | |
| 11 | 218-03 | Tanmai no. 3 ore body | siliceous ore, white | ● | ○ | | | ○ | | | |
| 11 | 218-03 | Tanmai no. 3 ore body | yellowish pyrophyllite ore, in siliceous ore | ● | ○ | | | | | | |
| 12 | 218-04 | Tanmai no. 3 ore body | kaolin ore, white, phyllitic | ● | ○ | | | | | | △ chl |
| 13 | 218-05 | Tanmai no. 3 ore body | pyrophyllite-kaolin ore | ● | ○ | | | | | | |
| 14 | 218-06 | Tanmai no. 3 ore body | pyrophyllite-kaolin ore | ● | | | | ○ | | | △ chl |
| 15 | 218-07 | Tanmai no. 3 ore body | pyrophyllite-kaolin ore | ● | | | | ○ | | | |
| 16 | 218-08 | Tanmai no. 3 ore body | weakly altered rock?dark gray | ○ | △ | | | | | | ● chl |
| 17 | 218-09 | Tanmai no. 3 ore body | weakly altered rock? red | ○ | | | | ○ | | △ | △ chl |
| 17 | 218-09 | Tanmai no. 3 ore body | reddish breccia in weakly altered rock? | ○ | | | | ○ | | | |
| 18 | 218-10 | Tanmai no. 3 ore body | weakly altered rock? reddish | ● | | | | ○ | | △ | |
| 18 | 218-10 | Tanmai no. 3 ore body | siliceous rock, pale violet breccia in weally alt. rock | ○ | | | | ● | | △ | |
| 19 | 218-11 | Tanmai no. 3 ore body | pyrophyllite ore with pyrite vein | ● | ○ | | | | ○ | | △ chl |
| 20 | 218-12A | Tanmai no. 3 ore body | dickite ore, transparent | △ | ● | | | | | | |
| 21 | 218-12B | Tanmai no. 3 ore body | pyrophyllite ore, greenish yellow | ● | | | | ○ | | | |
| 22 | 218-13 | SE to no. 3 ore body | red shale | △ | | | | ● | | ○ | △ chl<br>△ ser |
| 23 | 219-01 | Tanmai no. 2 ore body | pyrophyllite-kaolin ore, pinkish | ○ | | | | ● | | | △ chl<br>△ ser |

Appendix Table 1 (Continued)

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 23 | 219-01 | Tanmai no. 2 ore body | yellow pyrophyllite vein in pyrophyllite-kaolin ore | ● | | | | △ | | | ○ ser |
| 24 | 219-02 | Tanmai no. 2 ore body | siliceous ore, pink | ○ | ○ | △ | | ● | | | |
| 25 | 219-02' | Tanmai no. 2 ore body | quartz vein | | | | | ● | | | |
| 26 | 219-03 | Tanmai no. 2 ore body | siliceous ore with quartz vein | | ○ | △ | | ● | | | |
| 27 | 219-04 | Tanmai no. 2 ore body | kaolin/ siliceous ore | ● | ○ | △ | | ○ | | | △rutile |
| 28 | 219-05 | Tanmai no. 2 ore body | alunite rock | ● | ○ | △ | ○ | ○ | | | |
| 29 | 219-06 | Tanmai no. 2 ore body | quartz vein | | | | | | | | |
| 30 | 219-08 | Tanmai no. 2 ore body | pyrophyllite-kaolin ore, pink | ○ | ● | | | ○ | | | |
| 30 | 219-08 | Tanmai no. 2 ore body | dickite vein in pyrophyllite-kaolin ore | ○ | ● | | | | | | |
| 31 | 219-09 | Tanmai no. 2 ore body | kaolin ore | ● | ○ | | | ○ | | | ○ ser |
| 32 | 219-10 | Tanmai no. 2 ore body | red tuff, weakly altered | ○ | ○ | | | ● | | △ | △relic ser |
| 33 | 219-11 | Tanmai no. 2 ore body | pyrophyllite ore, pink | ○ | ● | | △ | | | | |
| 34 | 219-12 | Tanmai no. 2 ore body | white kaolin -pyrophyllite ore | ○ | ● | | | | | | △ chl |
| 34 | 219-12 | Tanmai no. 2 ore body | red shale, weakly altered | ○ | ● | | | | | △ | △ chl |
| 36 | 219- 13 | Tanmai no. 2 ore body | pyrophyllite ore, pink | ○ | ● | | | | | | ○ chl |
| 37 | 219-14 | Tanmai no. 2 ore body | red tuff, weakly altered | ○ | ○ | | | △ | | △ | |
| 38 | 219-14 | Tanmai no. 2 ore body | white breccia (pyrophyllite-kaolin ore) in red tuff | ○ | ● | | | | | | |
| 38 | 219-15A | Tanmai no. 2 ore body | alunite rock, pink & white | ○ | ○ | △ | ● | | | | |
| 39 | 219-15B | Tanmai no. 2 ore body | dickite ore | ○ | ● | | | | | | |

Abbreviation: al, alunite; dia, diaspore; gr, graphite; ht, hematite; ka, kaolinite-dickite; p, pyrophyllite; py, pyrite: ser, sericite; qt, quartz.

Relative amounts of minerals: ● Abundant; ○ common; △ miner, trace

Appendix Table 2 Description of the samples from the Tanmai pyrophyllite deposit.

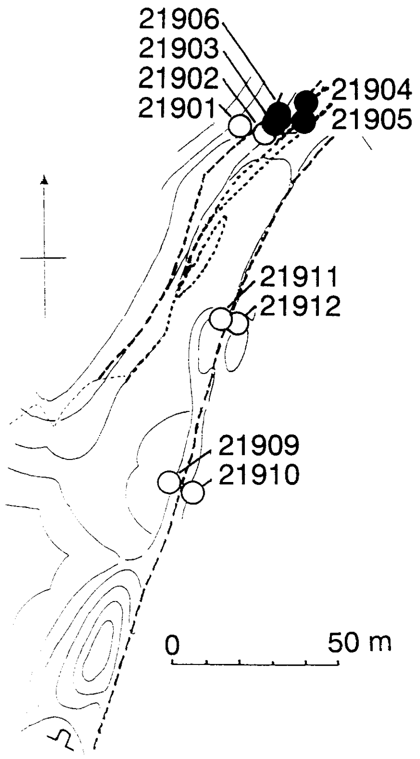
| No | Sample no | Locality | Feature | Microscopic observation | Alteration |
|---|---|---|---|---|---|
| 2 | 217-02 | Tanmai no. 3 ore body | Pale brown pyrophyllite ore cut by white siliceous ore | Original rock of kaolin ore is tuff having laminated matrix with quartz crystal fragments. Vein-like white siliceous rock is quartz porphyry comosed of homogeneous matrix with phenocrystic feldspar and quartz | Pyrophyllite ore is composed of p, al, ka with diaspore and titanite. Siliceous intrusives are composed of qt, ka, al and p with dia. Feldspar crystals in intrusives are completely altered to p and dia. P-dia veins occur in siliceous intrusives. |
| 4 | 217-04 | Tanmai no. 3 ore body | Massive siliceous white rock, associated with pale brown veinlet of diaspore and pyrophyllite | Siliceous rock is quartz porphyry intruding into tuff. It shows homogeneous matrix with phenocrystic feldspar and quartz | White rock composed of dk, ka and qt with few rutil. Pale brown vein is composed of dia in center and p in margin of vein |
| 8 | 217-08 | Tanmai no. 3 ore body | Light gray pyrophyllite ore, phyllitic | Fine-grained tuff, containing small amounts of compacted glass fragment | Mainly composed of ka and p with chlorite, sometimes containing yellow spots which are composed of mixtures of dia and p. Fine-grained rutile crystal is also observed as alteration products |
| 9 | 218-01 | Tanmai no. 3 ore body | White pyrophyllite ore | Tuff contains glass fragments and volcanic breccia. No quartz crystal is found | Specimen is composed of three parts; milky, blue and transparent. Milky parts are p and ka associated with dk. Blue parts are composed of dk and chl with few rutile, and clean transparent part, dk. |
| 11 | 218-03 | Tanmai no. 3 ore body | White siliceous ore with yellow pyrophyllite vein | Fine-grained homogen. lava showing relic of perlitic fracture, which is often observed in rhyo-dacilitic lava | Siliceous ore composed of fine-grained qt and ka with pyrophyllite. Yellow vein is composed of p with small amounts of ka. |
| 16 | 218-08 | Tanmai no. 3 ore body | Weakly altered dark gray porphyritic rock | Dacitic tuff, containing quartz and feldspar crystal fragments, and compacted glass fragments | Quartz and feldspar crystal fragments are altered to aggregate of pyrophyllite. Some relic quartz is also observed in the center of pyrophyllite aggregate. Matrix is composed of aggregates of chlorite and pyrophyllite with few rutile. |

Appendix Table 2 (Continued)

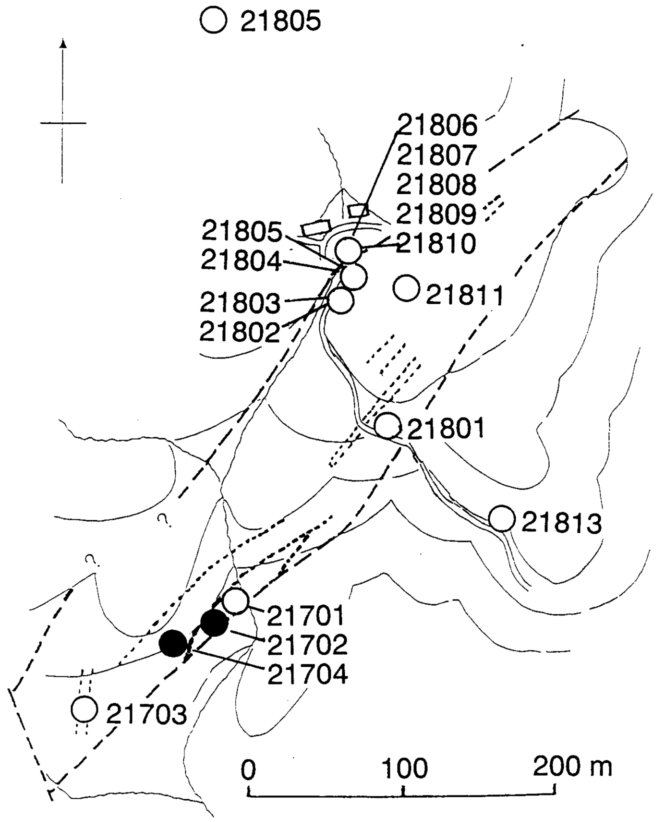
| | | | | | |
|---|---|---|---|---|---|
| 17 | 218-09 | Tanmai no. 3 ore body | Altered rock, red | Lapilli tuff composed of red matrix with pink lapilli. Matrix shows fine-grained red color. Lapilli is composed of glass with quartz crystal fragments | Weakly altered red matrix and pink breccia. Breccia changes to aggregates of pyrophyllite with kaolinite. Relic crystal of quartz scarcely observed. Matrix are composed of pyrophyllite, chlorite and hematite. Idiomorphic tourmaline occurs in matrix |
| 19 | 218-11 | Tanmai no. 3 ore body | Pyrophyllite ore (white) with pyrite vein | Tuff with pyrite vein. Tuff contains white volcanic breccia | White pyrophyllite ore contains of ka (80%) and p (20%) with kaolinite clot replacing qt crystal. Pyrophyllite veinlets occur along the fractures of pyrite crystals. |
| 20 | 218-12A | Tanmai no. 3 ore body | Dickite ore | Transparent vein, homogeneous and fine-grained. | Vein composed of homogeneous aggregates of fine-grained dickite with small amounts of pyrophyllite. |
| 22 | 218-13 | 200 m South-east to Tanmai no. 3 ore body | Red shale, weakly altered | Composed of sub-angular quartz grain and red matrix showing lamellae structure. It includes feldspar cryastal, detrital muscovite and lithic fragments showing laminated hematite grains,. | Altered red shale. Hematite, chlorite and blue tourmaline occurs in the matrix. Fragmental cryastal of feldspar altered to fine-grained clay minerals. |
| 23 | 219-01 | 1 m East to Tanmai no. 2 ore body | Pale violet pyrophyllite ore with pyrophyllite vein. Hanging wall of siliceous ore | Intrusive rock (quartz porphyry ) showing phenocrystic quart, feldspar (altered) and ferromagnesian phase (probably amphibole or biotite). | Pale violet altered rock ore with pyrophyllite vein. Matrix is composed of qt and p. Vein consists of p and sericite with few quartz. Trace amounts of rutile and titanite also observed |
| 26 | 219-03 | Tanmai no. 2 ore body | Siliceous ore with quartz vein | Light gray intrusives showing porphyritic texuture, homogeneous matrix | Light gray siliceous rock with quartz vein. Matrix is composed of quartz aggregates. Veinlets in siliceous ore shows zonal arrangements of qz-->ka-->dia, from bourder to central of the vein. |
| 27 | 219-04 | Tanmai no. 2 ore body | Kaolin ore, light gray | Heterogeneous tuff, containing 30 % of total fragments of glass and crystals of quartz, feldspar and mafic minerals. | Kaolin ore, light gray. Zonal arrangement in vein from center to margin, diaspore --> pyrophyllite--> kaolinite+quartz. Matrix: kaolinite+quartz. Few rutile occurs in matrix. |

Appendix Table 2 (Continued)

| | | | | | |
|---|---|---|---|---|---|
| 28 | 219-05 | Tanmai no. 2 ore body | Phyllitic alunite rock, occuring between siliceous zone and kaolin zone. | Crystal tuff, containing of fragmental quartz + feldspar (15 % ) and compacted glass fragment | Pinkish alunite, phyllitic. Coarse grained diaspore and alunite occur along the foliation. Matrix is composed of pyrophyllite and alunite with small amounts of diaspore. |
| 30 | 219-08 | Tanmai no. 2 ore body | Pink pyrophyllite ore and cutting dickite vein | Crystal tuff, containing fragmental quartz (10 % ) and compacted glass fragment. Lamellae structure in the matrix is also observed. | Pinkish pyrophyllite ore with dickite vein. Matrix is composed of dickite and quartz. Dickite vein contains relic fragments of quartz crystal showing replacement origin of the dickite "vein" |
| 32 | 219-10 | Tanmai no. 2 ore body | Red tuff, altered. Footwall rock of orebody. | Tuff containing compacted glass fragment. Quartz and feldspar crystal fragments are few. Detrital mica is also exist. | Altered reddish tuff, consisting of fine-grained of quartz and prophyllite |
| 33 | 219-11 | Tanmai no. 2 ore body | Pyrophyllite ore, pink. Bottom of the orebody | Crystal tuff, containing fragmental crystal (15 % ) of quartz + feldspar and compacted glass fragment | Pink pyrophyllite ore. Feldspar crystal fragments completely altered to pyrophyllite, and quartz crystal fragments change to kaolinite+quartz. Glass fragments altered to aggregate of pyrophyllite and kaolinite. |
| 37 | 219-14 | Tanmai no. 2 ore body | Altered tuff, includs white breccia (pyrophllite ore). Collected from stock yard of the mine site | Vitric tuff, containing lots of glass fragments (Ca. 30%) and also lithic fragments showing laminated texture of hematite, homogeneous rock and pumice. | Altered red tuff containing white breccia of pyrophyllite ore. Alteration degree of matrix and fragments are essentialy same and composed of pyrophyllite and kaolinite. Small scale zoning is also observed around quartz crystal. |
| 39 | 219-15B | Tanmai no. 2 ore body | Dickite ore, collected from stock yard of the mine site | Homogeneous dickite vein containing quartz crystal fragment. | Dickite vein composed of dickite with pyrophyllite. Volume ratio of kaolinite and pyrophyllite is 80:20. Fragment quartz surrounded by the halo of kaolinite and quartz. |




Appendix Fig. 1 Sample location map (Tanmai No. 2 ore body). Solid circles showing diaspore bearing sample locations.




Appendix Fig. 2 Sample location map (Tanmai No. 3 ore body). Solid circles showing diaspore bearing sample locations.

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# ベトナム北部タンマイ鉱床のパイロフィライト化作用
## －予察調査結果－

平野英雄・青木正博・須藤定久・グエン バン クイ

## 要　旨

ベトナム北部のタンマイパイロフィライト鉱床は5つの鉱体で構成され，うち2鉱体が開発されている．鉱床の原岩は珪長質火山岩で，鉱床は鉄分の少ない変質岩からなる．変質岩をその構成鉱物から，カオリン帯，パイロフィライト帯，珪化帯，ダイアスポア帯，アルーナイト帯に区分することを試み，その生成順序と物理条件を推定した．最初にカオリン帯が形成された．熱水の温度上昇に伴い，パイロフィライト帯と珪化帯が，それぞれの原岩透水率の違いにより形成された．ダイアスポア帯は珪化帯中の割れ目に沿って形成されているが，その産状から熱水の温度上昇よりは，むしろ垂直的な割れ目の生成にともなう $P_{H_2O}$ の低下が原因で生成されたらしい．アルーナイト帯は熱水活動の末期に形成された．鉱床の主体をなすパイロフィライト帯の形成温度は，その鉱物組み合わせからおよそ260-290℃と見積もられる．

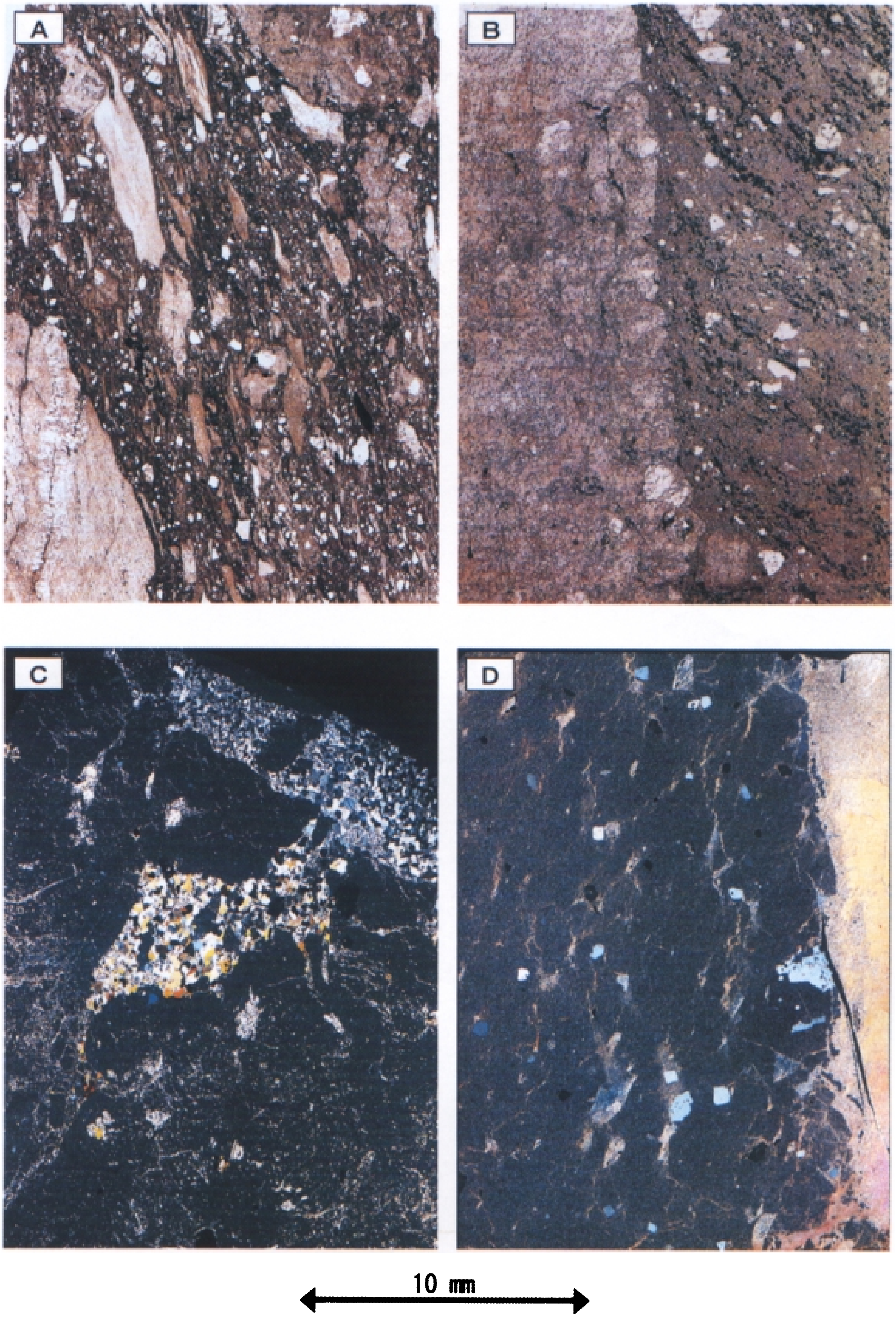


**Plate 1** Photographs of representative rocks from the Tanmai pyrophyllite deposit.
**A**, Vitric tuff containing many lithic and glass fragments. Altered rock. Open-polarized light. Sample no. 21914; **B**, Left half represents Quartz porphyry intruding into laminated tuff. Quartz porphyry altered to siliceous ore and laminated tuff altered to pyrophyllite ore. Open-polarized light. Sample no. 21702; **C**, Host rock of veinlet originated from a massive lava or dike showing porphyritic texture. Vein-filling diaspore + pyrophyllite in the siliceous zone of No. 2 orebody. Cross-polarized light. Sample no. 21704; **D**, Porphyritic texture with a homogeneous matrix. pyrophyllite vein is shown at the right margin of the photo. Altered rock. Cross-polarized light. Sample no. 21901.

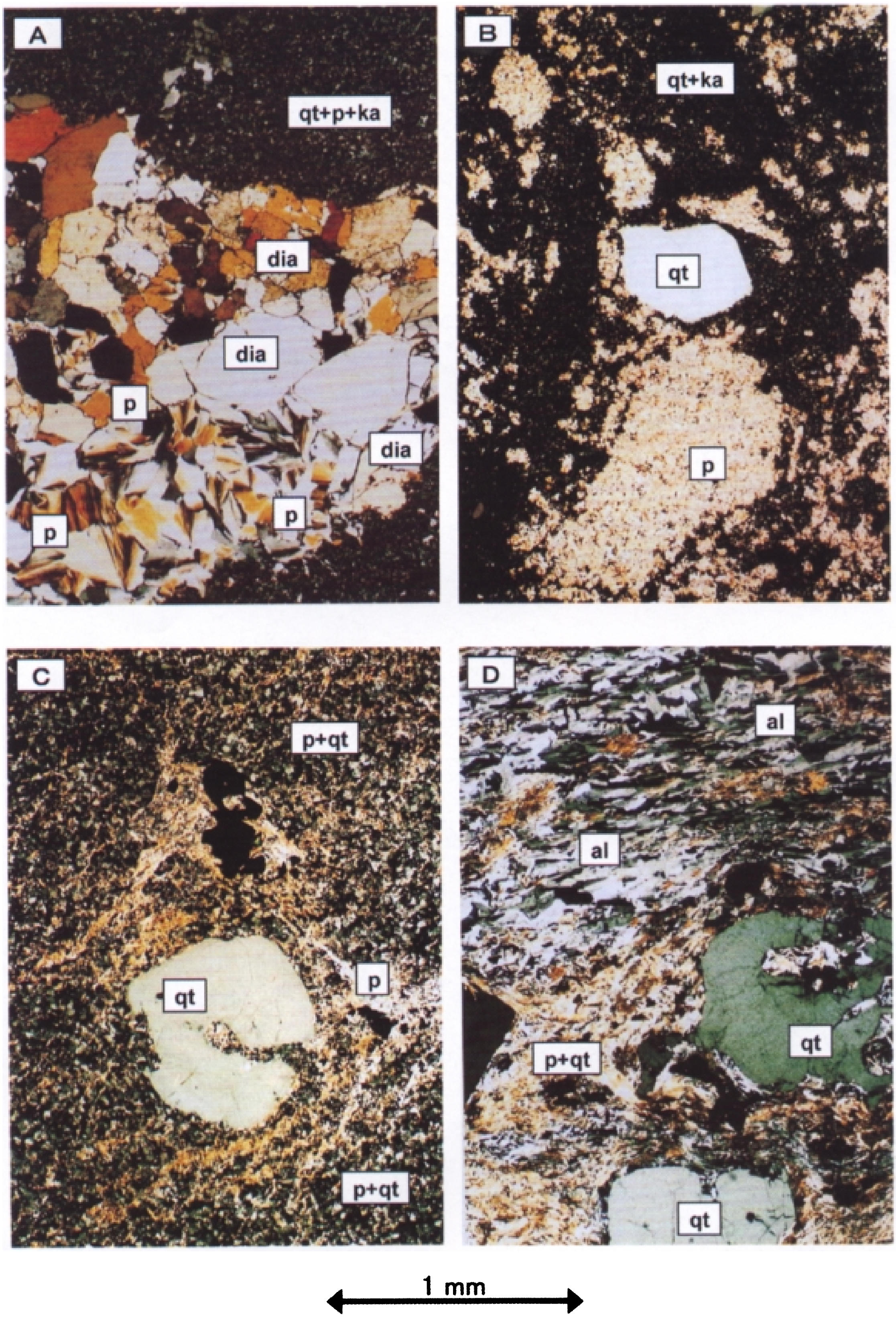


**Plate 2** Photomicrographs of representative rocks from the Tanmai pyrophyllite deposit.
**A**. Siliceous ore and veinlet of diaspore + pyrophyllite. Cross-polarized light. Sample no. 21704; **B**, Kaolin zone replaced by a pyrophyllite zone. Phenocrystic feldspar is replaced by an aggregate of pyrophyllite. Siliceous ore. Cross-polarized light. Sample no. 21803; **C**, Relic phenocrystic quartz and rutile (dark red) from a mafic mineral in the pyrophyllite zone. Altered rock. Cross-polarized light. Sample no. 21901; **D**, Alunite-rich (upper part) and pyrophyllite-rich parts in the alunite zone. Alunite rock. Cross-polarized light. Sample no. 21905.