The First Occurrence of Suolunite in Taiwan: Its Physical Properties, Chemical Composition, and Genesis

Kung-Suan Ho[1*], Ju-Chin Chen[2], Chen-Feng You[3], Shih-Chieh Hsu[4], and Ming-Huei Huang[1]

[1]Department of Geology, National Museum of Natural Science, Taichung, Taiwan 404, R.O.C.
[2]Institute of Oceanography, National Taiwan University, Taipei, Taiwan 106, R.O.C.
[3]Department of Earth Sciences, National Cheng Kung University, Tainan, Taiwan 701, R.O.C.
[4]Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan 115, R.O.C.

(Received October 22, 2008; Accepted March 16, 2009)

Abstract. The hydrated calcium silicate, suolunite, is an extremely rare mineral and was found in serpentinites near Shanyuan, of the southern Coastal Range in southeastern Taiwan. Its physical properties and chemical compositions were studied by x-ray diffraction, electron-microprobe analysis, thermal ionization mass spectrometry, and inductively coupled plasma mass spectrometry. Suolunite was associated with tobermorite and occurred as irregularly shaped veinlets in metasomatized rodingite and albitite. It is colorless, with white streaks, a vitreous luster, and white fluorescence under shortwave ultraviolet light. The average contents of SiO_2, CaO, and water obtained from three suolunite samples were 44.61, 40.98, and 13.62 wt%, respectively. Small amounts of Na, Mg, K, and Fe replace the Ca, and Al substitute for the Si to a minor extent. Calculation of the analytical data showed that suolunite from Taiwan has a simplified chemical formula of $Ca_{1.96}Fe_{0.01}Si_{1.99}Al_{0.01}O_5(OH)_2 \cdot H_2O$. In addition, trace amounts of Li, Sc, V, Cr, Mn, Co, Ni, Zn, Sr, Y, Zr, Nb, Ba, Ce, Nd, Dy, Hf, Pb, and Th also existed within the suolunite crystals. The isotopic composition of Sr in the three suolunite samples was markedly heterogeneous, with the $^{87}Sr/^{86}Sr$ ratios varying from 0.706895 to 0.709342. When these suolunite samples were heated to 320 °C for 1 h, some specimens lost their water and were transformed to xonotlite. Suolunite was formed in metasomatized rocks as a secondarily altered mineral due to interactions between calcium-bearing solutions and Ca-plagioclase. The conditions of formation imply hydrothermal activity at temperatures below 140 °C; these conditions are similar to those favoring the occurrence of tobermorite as suggested by Gabrovšek *et al.* (1993).

Keywords: : suolunite, genesis, serpentinite, southern Coastal Range, southeastern Taiwan.

INTRODUCTION

Suolunite is a hydrated calcium silicate which was named by Huang (1965) for the locality it was first found, Suolun, Inner Mongolia. It is an extremely rare mineral in nature. To the present day, this mineral has been found at seven localities in the world: Suolun, Ulanhot, and Xilinuole League, Inner Mongolia, China (Huang, 1965); Spa Kulasi, near Doboj, Bosnia, Yugoslavia (Stojanovic *et al.*, 1974); Shiraki, Toba City, Mie Prefecture, Honshu Island, Japan (Minakawa *et al.*, 1983); Wadi Semali, Al Khawd, near Muscat, Oman (Stanger and Neal, 1984); Lac de Gras, Northwest Territories (Chakhmouradian *et al.*, 2002) and Black Lake, Québec, Canada (Dunnell, 2001), and Shanyuan, Taitung, Taiwan (this study). In general, suolunite occurs as veins cutting through harzburgites in an ultramafic intrusive (Suolun, China), as precipitates from alkaline solutions in a narrow fault zone in basalt and gabbro overlying an ultramafic rock (Al Khawd, Oman), and as veins

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*Corresponding author. E-mail: ksho@mail.nmns.edu.tw or on cracks in serpentinite (Shiraki, Japan). In addition, acicular suolunite occurs as a secondary mineral, associated with strontium-apatite and barium phlogopite, in vesicles in the Lac de Gras kimberlites.

Suolunite is orthorhombic and has biaxial negative and a moderate refractive index (1.610~1.623). Its hardness on Mohs' scale is 3.5, and the calculated density is 2.67 g/cm^3. The available literature shows that the crystallographic parameters of the mineral are: a = 11.02~11.15 Å; b = 19.67~19.82 Å; and c = 6.00~6.08 Å (Gaines *et al.*, 1997). The detailed crystallography of this mineral was previously reported by Tseng *et al.* (1966), Gaines *et al.* (1997), and Ma *et al.* (1999). The purposes of this study were (1) to investigate the physical properties of suolunite crystals, (2) to analyze their chemical compositions, and (3) to constrain the genesis of the mineral. X-ray diffractometer (XRD), electron microprobe analysis (EMPA), thermal ionization mass spectrometry (TIMS), and inductively coupled plasma mass spectrometry (ICP-MS) were performed to characterize this rare mineral.

GEOLOGICAL SETTING

The Coastal Range is located in eastern Taiwan and is about 180 km long and up to 20 km wide (Fig. 1). About 12 Ma, the northern tip of the Luzon Arc began overriding the Asian continental margin (Teng, 1992), and

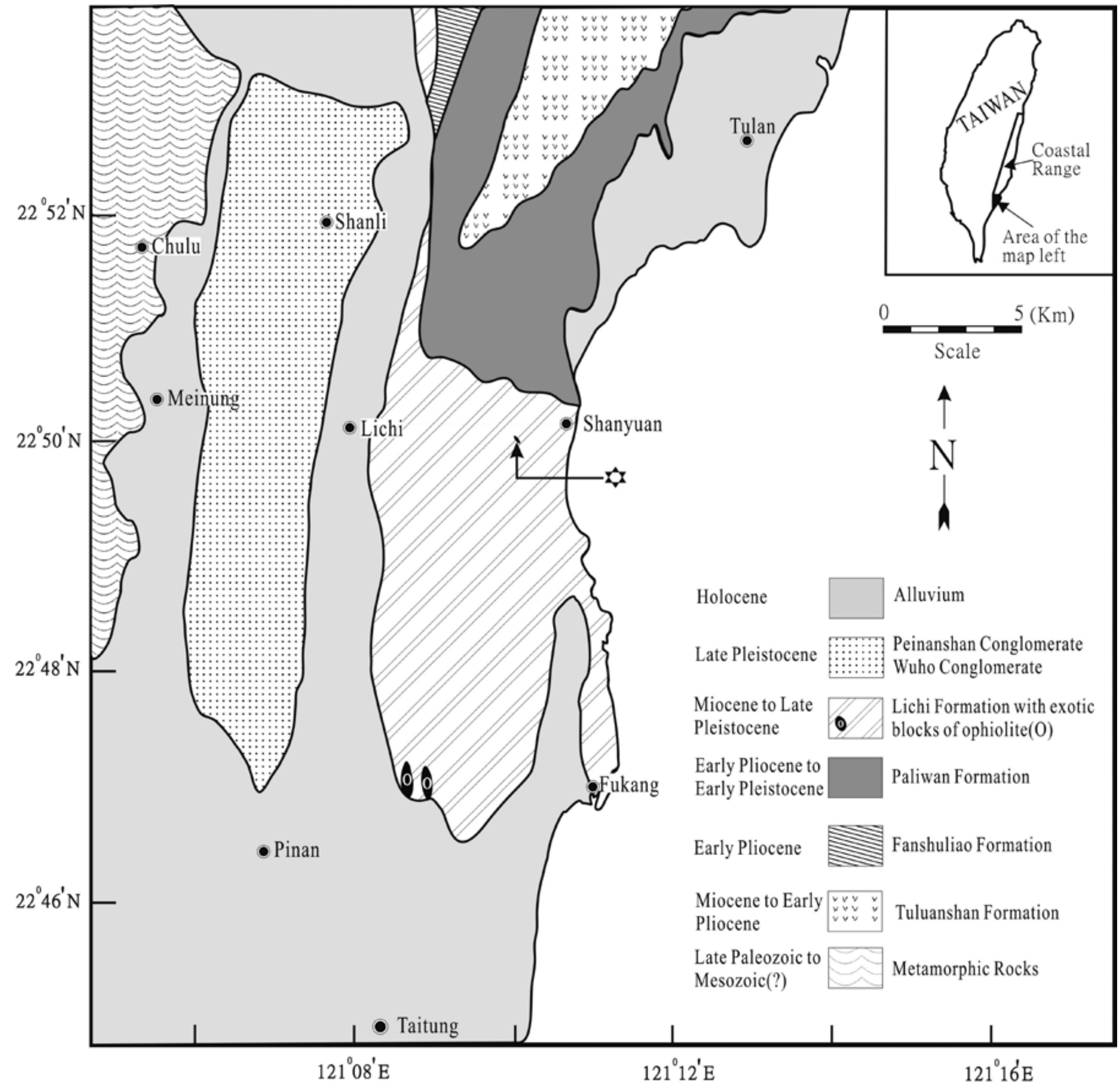

Fig. 1. Simplified geological map of the southern Coastal Range, southeastern Taiwan (after Wang and Chen, 1993). The open star (☆) indicates the locality where the suolunite samples were obtained.

the area of present-day Taiwan also began to experience compressional processes. During the Pliocene to Pleistocene, the collision event and accompanying continental crust compression caused an active orogeny, which developed regional uplifting to form the mountain ranges of Taiwan. The Coastal Range is part of the Philippine Sea Plate, and can be divided into three tectonostragraphic sequences (Fig. 1, Chen and Wang, 1996): (1) volcanic-arc sediments (Tuluanshan Formation and Kangkou Limestone), (2) orogenic sediments (Fanshuliao, Paliwan, and Peinanshan Formations), and (3) a subduction-collision complex (Lichi Mélange).

The Lichi Mélange consists mainly of a well-developed phacoidally cleaned mudstone which contains a variety of disseminated exotic blocks of sandstone, shale, tuffaceous sandstone, andesite, and ophiolite (Ho, 1977; Page and Suppe, 1981). An assemblage of basalt, basaltic breccia, diabase, gabbro, peridotite, serpentinite, and hornblendite is one of major lithologic categories of exotic blocks of the Lichi Mélange, which is similar to ophiolitic rocks formed in South China (Chen and Wang, 1996). Different models of the tectonic setting and formation mechanisms of the Lichi Mélange have been proposed including sedimentary olistostrom in the western forearc basin, a subduction complex in the Manila Trench, and a collision complex (Page and Suppe, 1981; Barrier and Angelier, 1986; Chen and Wang, 1996). Suolunite was found in serpentinites of the Lichi Mélange at approximately 22°50'N, 121°10'E and lies about 2 km to the west-southwest of Shanyuan, Taitung County (Fig. 1).

ANALYTICAL METHODS

The mineral phase of suolunite was identified on a Rigaku XRD with Cu-radiation according to standard powder methods. With 1° of divergence, a 0.001-inch (0.0254-mm) receiving slit, and a 1°/min scanning rate, each powdered sample was investigated through an angular range of 5°~60°. In order to observe the stability field of the mineral, 20 samples were heated at 1 atm pressure and temperatures varying from 100 to 450 °C for 1 h. In order to further understand the reaction rate, seven samples were heated to 360 °C for times varying from 1 to 7 h. XRD and heating experiments were performed at the National Museum of Natural Science, Taichung, Taiwan.

Three samples were obtained from the center of the veins in which suolunite had formed as a narrow layer. The major elemental compositions of these samples were determined using a 4-spectrometer ARL-SEMQ electron microprobe at the Central Geological Survey, Ministry of Economic Affairs, Taipei, Taiwan, and were corrected with the Bence and Albee correction procedures. Operating conditions were as follows: an electron beam current of 15 nA, an accelerating voltage of 15 kV, a beam diameter of 5 μm, and a counting time of 20 s for each element. Analyzed natural minerals, including wollastonite (WON8) and albite, were utilized as standards.

Minor and trace elements (including Al, Ba, Co, Cr, Cu, Cs, Fe, Hf, K, Li, Mg, Mn, Na, Nb, Ni, Pb, Rb, Sc, Sr, Th, U, V, Y, Zn, Zr, La, Ce, Pr, Nd, Sm, Eu, Tb, Dy, Ho, Er, Tm, Yb, and Lu) of the three samples were determined using solutions prepared by dissolving 0.25 g of mineral powder in a mixture of ultrapure hydrofluoric acid (HF) and nitric acid (HNO_3) in Teflon beakers under clean-room conditions. Solutions were analyzed using a Perkin-Elmer Elan 6100 ICP-MS at the Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan. Al, Fe, K, Mg, and Na measurements were calibrated using Merck ICP multi-element standard solution VIII; Ti was calibrated using Perkin Elmer pure-quality control standard 21, whereas calibration curves of the trace elements were constructed using US Geological Survey rock standards AGV-1, BCR-1, W-1, G-2, and BHVO-1 and the Geological Survey of Japan rock standard JB-1. Values for these rock standards were adapted from compilations by Govindaraju (1994). The precision was estimated to have been better than ± 5% for all ICP-MS analyses. The details of the analytical techniques were discussed by Ho *et al.* (2003).

In addition, the Sr-isotopic composition of the three suolunite samples was analyzed. The Sr fraction was separated by ion exchange chromatography, and the isotopic compositions were measured using a Thermo Finnigan TRITON TI TIMS instrument at National Cheng Kung University, Tainan, Taiwan. Isotopic ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$ and were relative to 0.710260 as the NIST SRM 987 standard. Precisions of Sr isotopic compositions were better than ± 0.000009 (2σ).

RESULTS AND DISCUSSION

Petrography

Suolunite occurs with other accompanying white minerals including calcite, aragonite, and tobermorite on the surface or in fractures of metasomatized rodingite and albitite, which are in a 30~60-cm vein cutting through serpentinite and can be traced over distances of more than 20 m (Plates A, B). Suolunite-bearing veins range in thickness from 0.1 to 6 mm and rarely occur alone; more often they form complicated networks (Plates C, D). Generally, colorless and granular suolunite fills in the central parts of the veins, whereas milky-white and fibrous tobermorite, another hydrated calcium silicate mineral, occupies the margins of most of the veins (Plates E, F). Other common features are veined cores of granular suolunite surrounded by a layer of fibrous tobermorite, with the outmost layer directly covered by calcite and aragonite. On the other hand, calcite and/or aragonite in veinlets cut metasomatized rocks inside the suolunite-tobermorite veins (Plate C). These textures indicate that the hydrated calcium silicates crystallized earlier than the aragonite and calcite.

Physical Properties

Suolunite is easily distinguished from other associated minerals on the basis of its color and occurrence. For example, suolunite is always colorless and transparent with a vitreous luster, is fine-grained and granular, and fills in the central parts of veins, whereas milky-white and fibrous tobermorite occupies the margins of most of the veins. In addition, suolunite is easily mistakenly identified as aragonite or calcite, but can be recognized in thin sections by its lower-order interference colors and white fluorescence under short-wave ultraviolet light.

The x-ray powder diffraction data of suolunite from Taiwan are listed in Table 1. They are similar to samples from the Oman area (Stanger and Neal, 1984), although there are some differences in the intensity of reflections for some crystalline faces. However, it is clear that the four strongest peaks of suolunite from Taiwan correspond to *d* values of 4.130, 3.173, 2.851, and 2.685 Å, respectively.

Table 1. X-ray powder diffraction data (2θ = 5°~60°) of suolunite from Shanyuan, southern Coastal Range, southeastern Taiwan compared to a sample from Oman

1		2		1		2	
d (Å)	I/I_1	*d* (Å)	I/I_1	*d* (Å)	I/I_1	*d* (Å)	I/I_1
5.122	16	5.126	18	2.109	11	2.108	25
4.965	5	4.972	9	2.079	9	2.078	15
4.130	100	4.133	100	2.063	9	2.064	24
3.705	4	3.708	4	2.032	4	2.033	22
3.173	64	3.173	81	1.994	17	1.994	47
3.119	3	3.125	2	1.887	12	1.888	37
2.851	45	2.849	62	1.850	13	1.851	38
2.786	2	2.788	3	1.808	3	1.809	9
2.685	39	2.687	85	1.764	5	1.764	9
2.642	16	2.647	51	1.706	6	1.705	68
2.555	18	2.558	37	1.681	4	1.681	15
2.496	15	2.495	23	1.653	2	1.652	4
2.473	9	2.473	20	1.617	5	1.617	6
2.431	15	2.431	25	1.611	7	1.613	32
2.334	13	2.331	26	1.586	12	1.587	18
2.223	23	2.224	25	1.581	9	1.580	13

1. This study
2. Suolunite from Oman (Stanger and Neal, 1984)

Stability of the Mineral at 1-atm Pressure

Data concerning the stability conditions of natural suolunite could not be found in the literature, except for one paper by Minakawa *et al.* (1983). Minakawa *et al.* (1983) suggested that suolunite could be transformed to xonotlite or wollastonite at temperatures of about 400 and 800 °C, respectively. But no detailed analytical data were available, including heating times, in that report.

We identified the XRD patterns of these samples using an incremental heating method. Suolunite samples were heated under controlled temperature conditions to determine the rates at which the crystals changed from the solid-phase. As a whole, suolunite remained stable at temperatures up to 310 °C for 1 h (Fig. 2). However, it should be noted that suolunite was partly altered to xonotlite at temperatures up to 320 °C. The amount of xonotlite was found to increase when the temperature exceeded 310 °C. When the sample was heated to 450 °C, the suolunite was completely transformed into xonotlite. At the same time, samples had a peculiar small peak with a *d* value of 2.9859 Å in the diffraction pattern, coinciding with the most intense peak of wollastonite ($CaSiO_3$). Experimental data indicated that the transformation rate was the fastest from 360 to 370 °C (Fig. 3). In addition, when the heating times varied from 1 to 7 h at 360 °C, various amounts of xonotlite were formed as shown in Fig. 4. It was observed that the percentage of the peak height ratio between suolunite and xonotlite of about 24.5% was measured after heating for up to 7 h.

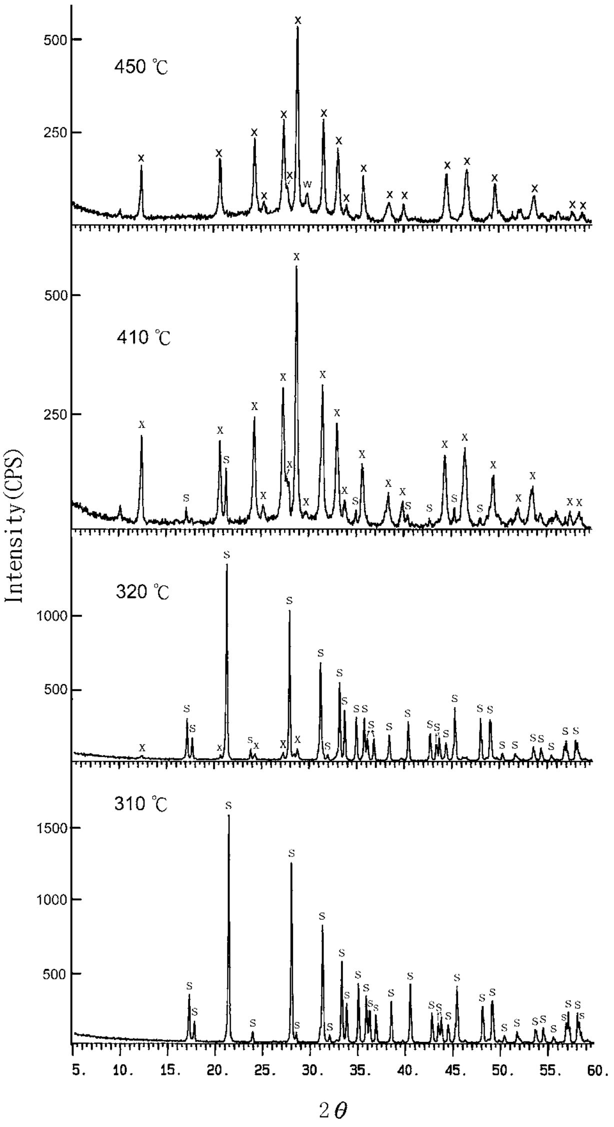

Fig. 2. Representative x-ray powder diffraction spectra of a suolunite sample after it was heated to 310, 320, 410, and 450 °C for 1 h. It can be seen that xonotlite was formed after the sample was heated to 320 °C. S, suolunite; X, xonotlite; W, wollastonite.

Chemical Composition and Sr-Isotope Data

Electron microprobe and loss on ignition (LOI) analytical results (Table 2) indicated that suolunite is essentially a hydrated calcium silicate hydroxide. Water contents for Taiwanese suolunites were relatively constant at 13.53~13.74

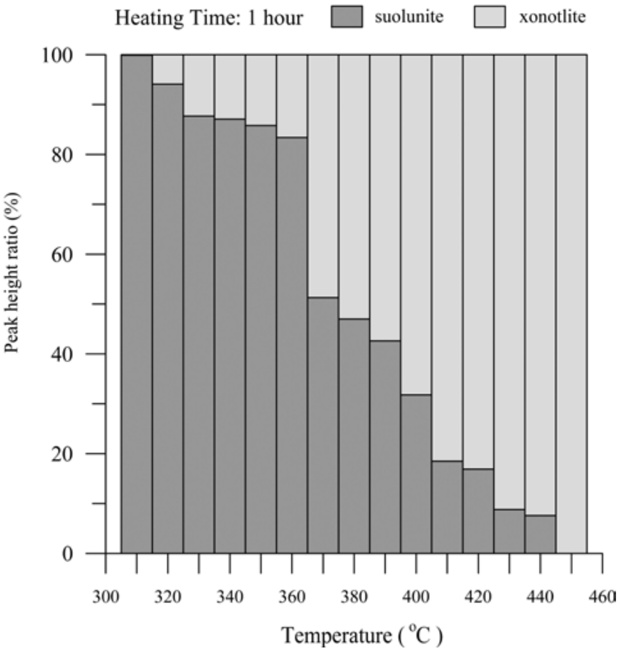

Fig. 3. Histogram showing the formation of xonotlite from a powdered suolunite sample as a function of heating temperature (310~450 °C) for 1 h.

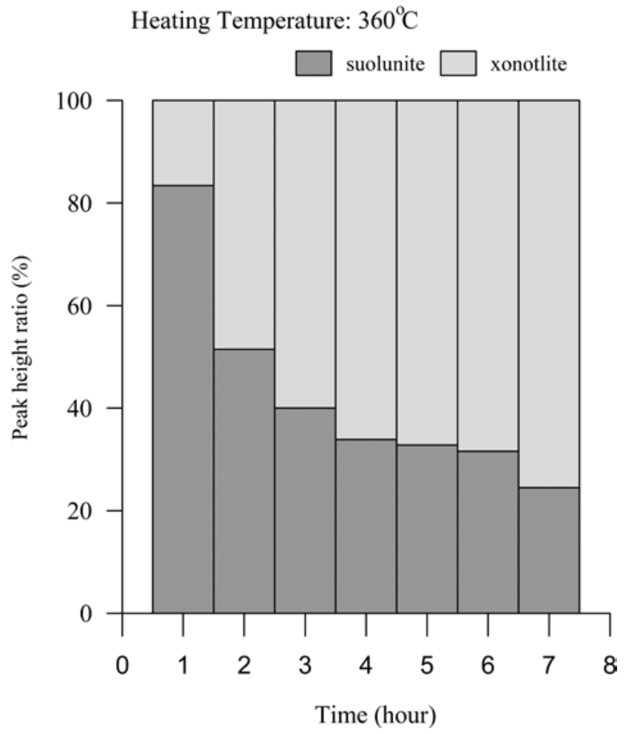

Fig. 4. Histogram showing the formation of xonotlite from a powdered suolunite sample as a function of heating time (1~7 h) at 360 °C.

wt%. Disregarding the water, the average contents of SiO_2 and CaO obtained from the three analyses were 44.61 and 40.98 wt%, respectively. Compared to samples from other localities, suolunite from Taiwan contains more silicon and less calcium and is much closer to the ideal chemical composition (Table 3). Chemical compositions of suolunite from Taiwan, given in column 1 of Table 3 were calculated on the basis of 14 atoms or ions of oxygen and hydroxide. The average composition derived from the three samples corresponds to $Ca_{1.96}Fe_{0.01}Si_{1.99}Al_{0.01}O_5(OH)_2\bullet H_2O$.

Suolunite contains almost no rare earth elements besides trace amounts of cerium (up to 0.72 ppm), neodymium (up to 0.67 ppm), and dysprosium (up to 0.03 ppm). In addition, some minor and trace elements, including Li, Na, Mg, Al, K, Sc, Fe, V, Cr, Mn, Co, Ni, Zn, Sr, Y, Zr, Nb, Ba, Hf, Pb, and Th, exist in the mineral (Table 2). The maximum concentrations of Na, Mg, Al, K, and Fe were 108, 172, 1301, 51, and 1379 ppm, respectively.

Selected analyses of the three suolunite samples showed that the Sr-isotopic ratios were rather heterogeneous (Table 2). The Sr isotopic composition data of TD-13 (0.709342) were similar to that of seawater ($^{87}Sr/^{86}Sr = 0.709234$, Faure, 1986), but samples of TD-02 ($^{87}Sr/^{86}Sr = 0.708135$) and TD-25 ($^{87}Sr/^{86}Sr = 0.706895$) had lower $^{87}Sr/^{86}Sr$ ratios. Essentially suolunite has variable Sr-isotopic compositions which probably represent crystallization products from different sources: mixing of various amounts of Sr from the host rock and fluid.

Associated Minerals and Mineral Genesis

The calcium-silicate-hydrate (Ca-Si-H) system is highly complex with over 30 stable phases reported (Shaw *et al.*, 2000). In Taiwan, suolunite coexists with tobermorite (Fig. 5), a rare hydrated calcium silicate, $Ca_5Si_6O_{16}(OH)_2\bullet 4H_2O$. The compositions in columns 4 and 5 of Table 2 correspond to tobermorite, which has higher Al and lower Ca compared to suolunite. Generally some Al^{+3} always substitutes for Si^{+4}; therefore, tobermorite has considerable amounts of Al_2O_3 (e.g., 3.90~4.75 wt%, Lo and Chen, 1981; 3.96~4.20 wt%, Livingston, 1988; and 2.40~5.70 wt%, Aguirre *et al.*, 1998). However, it was noted in this study that the composition of the tobermorite near the metasomatized rock was richer in aluminum and calcium and poorer in silica than that of tobermorite near the suolunite. Therefore, the high aluminum (Al_2O_3 = 6.54~7.16 wt%) contents found in Shanyuan tobermorite may be a special case and possibly not essential for tobermorite in general. Tobermorite usually occurs where hydrothermal fluids react with basic igneous rocks, e.g., in Taitung, Taiwan (Lo and Chen, 1981) and Skye, UK (Livingston, 1988). According to the results of Lo and Chen (1981), the tobermorite and associated secondary minerals, thomsonite and calcite, were

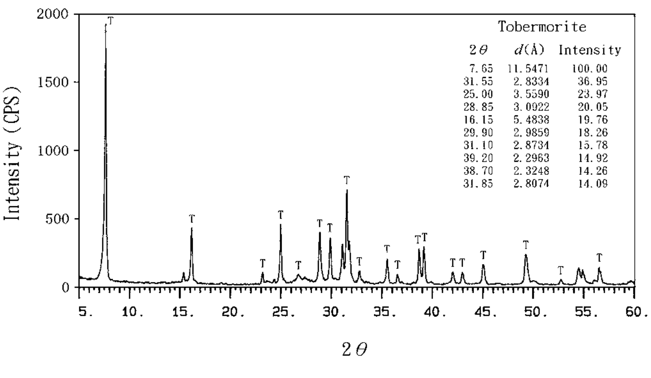

Fig. 5. X-ray pattern of tobermorite in the suolunite-tobermorite vein from the study area.

Table 2. Major and trace elements and Sr isotopic compositions of suolunites compared with tobermorites from southeastern Taiwan

Mineral	Suolunite			Tobermorite	
Sample No.	TD-02	TD-13	TD-25	1[a]	2[b]
(wt. %)					
SiO_2	44.76	44.59	44.55	44.10 ~ 45.23	45.44 ~ 49.49
CaO	40.82	40.86	41.12	35.49 ~ 35.77	32.64 ~ 36.82
Al_2O_3				6.54 ~ 7.16	3.90 ~ 4.75
L.O.I.	13.53	13.59	13.74		11.97 ~ 20.65
Total	99.11	99.04	99.41		
(ppm)					
Li	0.50	0.52	0.52		
Na	62	108	107		
Mg	67	144	172		
Al	968	746	1301		
K	33	51	39		
Sc	0.39	0.08	0.20		
V	2.09	1.92	1.98		
Cr	2.10	0.70	2.34		
Mn	1.76	0.58	1.91		
Fe	1073	1215	1379		
Co	0.97	0.85	0.85		
Ni	3.31	2.70	3.59		
Cu	bdl	bdl	bdl		
Zn	1.12	0.54	0.15		
Rb	bdl	bdl	bdl		
Sr	8.8	20.8	12.7		
Y	0.35	0.33	0.35		
Zr	4.33	4.15	4.16		
Nb	3.69	1.13	1.13		
Cs	bdl	bdl	bdl		
Ba	3.77	3.82	4.24		
La	bdl	bdl	bdl		
Ce	0.72	0.47	0.50		
Pr	bdl	bdl	bdl		
Nd	0.67	0.56	0.58		
Sm	bdl	bdl	bdl		
Eu	bdl	bdl	bdl		
Tb	bdl	bdl	bdl		
Dy	0.03	0.03	0.03		
Ho	bdl	bdl	bdl		
Er	bdl	bdl	bdl		
Tm	bdl	bdl	bdl		
Yb	bdl	bdl	bdl		
Lu	bdl	bdl	bdl		
Hf	0.02	0.01	0.02		
Pb	0.42	0.63	0.59		
Th	0.03	0.03	0.04		
U	bdl	bdl	bdl		
$^{87}Sr/^{86}Sr$	0.708135±25	0.709342±24	0.706895±24		

bdl: below the detection limit; Sources: [a] This study; [b] Lo and Chen (1981).

Table 3. Average major element compositions of suolunite from Taiwan compared to the ideal compositions and samples from other localities in the world

	(1)	(2)	(3)	(4)	(5)	(6)
Method	EMPA	Ideal			Wet	XRF
(wt.%)						
SiO_2	44.61	44.78	43.38	43.35	43.10	41.91
Al_2O_3	(0.19)				0.19	0.72
CaO	40.98	41.79	42.95	42.22	41.55	44.66
FeO	(0.16)				0.22	
MgO					0.07	0.29
Na_2O					0.06	0.39
K_2O					0.08	
H_2O	13.62	13.43	13.17	14.05	13.87	14.14
Total	99.56	100.00	99.50	99.62	99.14	102.11
Numbers of ions on basis of 14 (O, OH)						
Si	3.98					
Al	0.02					
Ca	3.92					
Fe	0.01					
OH	4.13					
H_2O	1.99					

(1) This study. Data of the ICP-MS analysis are labeled in parentheses.

(2) $Ca_2Si_2O_5(OH)_2 \cdot H_2O$.

(3) Suolun, Ulanhot, Xilinguole League, Inner Mongolia, China (Huang 1965).

(4) Kulasi, near Doboj, Bosnia, Yugoslavia (Stojanovic *et al.* 1974).

(5) Shiraki, Toba, Mie Prefecture, Japan (Minakawa *et al.*, 1983).

(6) Wadi Semali, Al Khawd, Baushar, Muscat, Oman (Stanger and Neal 1984).

crystallized from the pore solution, and these fluids were leached out from basaltic glass under very low temperatures.

In general, the crystallization sequence of hydrothermal solutions is very complicated, and mainly depends on temperature, pressure, composition, pH, redox potential (Eh), and chemical concentration (Wenk and Bulakh, 2004). Suolunite in Taiwan occurs as irregularly shaped veinlets in metasomatized rock. Based on XRD and petrographic observations, two types of metasomatized rocks of albitite (e.g., albite with minor analcime) and rodingite (e.g., grossular with minor diopside and chlorite) were identified, whereas unaltered serpentinite is dominantly chrysotile with minor lizardite and magnetite (Plates B, C, F). Serpentinization is a hydration reaction whereby water reacts with mafic minerals such as olivine and pyroxene, to drive hyper-alkalinity and produce lizardite, antigorite, and/or chrysotile (Palandri and Reed, 2004). Based on chemical evidence from Burro Mountain, CA, USA, Coleman and Keith (1971) concluded that only CaO is lost from an ultramafic body during serpentinization (i.e., an isochemical alteration). In contrast, serpentinization may occur as a constant-volume and metasomatism process, in which Si, Mg, Fe, Ca, and hydroxyl ions are leached out via the serpentinizing fluids (Raymond, 1995).

Since ground waters in ultramafic (or serpentinitic) terrain are normally low in silica and an independent silica source is required for suolunite generation, Stanger and Neal (1984) suggested that the most likely silica source is from Ca-plagioclase. Ca-rich plagioclase is one of the main constituent mineral in gabbroic rocks, the common precursor of rodingite. As a result of chemical interactions between Ca-plagioclase and the calcium-transporting aqueous solution that passes through it, the build-up of Ca^{+2} and OH^- at constant SiO_2 concentrations causes suolunite to precipitate. The reaction can be described by the following equation:

$$Ca^{2+} + 2OH^- + CaAl_2Si_2O_8 + 4H_2O \rightarrow Ca_2Si_2O_5(OH)_2{\bullet}H_2O + 2Al(OH)_3$$

During the reaction of Ca-plagioclase and fluid, silica is leached out from the original system, while the $Al(OH)_3$ component combines with residual Ca-plagioclase to produce various calcium aluminosilicates (Stanger and Neal, 1984). Therefore, the main secondary minerals often observed include grossular ($Ca_3Al_2(SiO_4)_3$), prehnite ($Ca_2Al_2Si_3O_{10}(OH)_2$), and chlorite ($(Mg,Al)_6(Si,Al)_4O_{10}(OH)_8$). In addition, Na purged from metasomatized rocks can in turn form nearby metasomatic albitites (Best, 2003).

The heating experiment in this study showed that xonotlite was formed after suolunite samples were heated to 320 °C for 1 h. It has a general formula of $Ca_6Si_6O_{17}(OH)_2$ and contains less water than suolunite. In addition, Gabrovšek *et al.* (1993) verified that xonotlite forms at higher temperatures than tobermorite, with the equilibrium phase boundary between these two minerals at approximately 140 °C. Huang (1965) suggested that xonotlite might also be produced by the dehydration of suolunite, but this mineral was not found in the present study. We, therefore, envisage formation of suolunite to have occurred in a low-temperature condition (< 140 °C), which is supported by the nature of the accompanying tobermorite phase. Tobermorite is stable over a range of ratios of Ca/Si of 0.8~1 (Shaw *et al.*, 2000). Compared with this coexisting mineral, suolunite may be formed at a narrow range of P-T and/or composition conditions and is therefore rather rarely distributed in nature.

CONCLUSIONS

Suolunite was found as a vein-forming mineral in serpentinite near Shanyuan, southern Coastal Range, southeastern Taiwan. The mineral is colorless, with a vitreous luster and appears as fine-granular aggregates. Electron microprobe and loss-on-ignition analyses revealed it was mainly composed of silicon (avg. SiO_2 of 44.61 wt%), calcium (avg. CaO of 40.98 wt%), and water (avg. H_2O of 13.62 wt%) with narrow chemical variations. It is the only natural hydrated calcium silicate with a CaO: SiO_2: H_2O composition of 1: 1: 1. In addition, minor and trace amounts of Li, Na, Mg, Al, K, Sc, Fe, V, Cr, Mn, Co, Ni, Zn, Sr, Y, Zr, Nb, Ba, Ce, Nd, Dy, Hf, Pb, and Th may also exist within suolunite crystals.

Dehydration of suolunite in a heating experiment indicated that it can be partly transformed to xonotlite in air at about 320 °C for 1 h. Some specimens were found to exhibit a typical structure until the temperature reached 450 °C. Suolunite in the present study was associated with tobermorite, aragonite, and calcite, but xonotlite was not found. We, therefore, inferred that suolunite may have formed as a result of a reaction between a calcium-bearing solution and Ca-plagioclase, and that the temperature of crystallization of suolunite was below 140 °C.

ACKNOWLEDGEMENTS

KSH wishes to thank K. W. Chung and K. M. Juang for their assistance in the field. The Sr isotopic analysis was carried out by C. H. Chen. S. H. Chung assisted with the electron microprobe analysis. The authors are most grateful for their kind assistance. Deep gratitude also goes to Prof. Y. H. Shau and an anonymous reviewer for their critical comments and constructive suggestions. This research was supported by the National Science Council, R.O.C. and the National Museum of Natural Science, Taichung, Taiwan.

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臺灣首次發現的直水矽鈣石：其物理性質、化學成分及成因之探討

何恭算[1] 陳汝勤[2] 游鎮烽[3] 許世傑[4] 黃敏惠[1]

1.國立自然科學博物館地質學組
2.國立臺灣大學海洋研究所
3.國立成功大學地球科學系
4.中央研究院環境變遷研究中心

直水矽鈣石又名索倫石，它是一種非常罕見的礦物，筆者在臺灣東南之海岸山脈南段杉原附近的蛇紋岩中發現。本文針對它的物理性質和化學成分，利用X光繞射儀、電子微探儀、熱離子質譜儀和感應耦合電漿質譜儀進行分析與研究。直水矽鈣石與雪矽鈣石一起伴生，並在異剝鈣榴輝長岩和鈉長岩等換質岩石內呈不規則細脈狀產出。礦物爲無色，具白色條痕和玻璃光澤，在短波段紫外線照射下會發出白色螢光。本文挑選三件直水矽鈣石標本分析結果顯示，其平均二氧化矽、氧化鈣和水含量分別爲44.61, 40.98 和13.62 wt.%。其晶體內另有少量的鈉、鎂、鉀和鐵取代鈣的位置，少量的鋁置換矽的位置。從分析數據計算臺灣直水矽鈣石的化學式爲$Ca_{1.96}Fe_{0.01}Si_{1.99}Al_{0.01}O_5(OH)_2\bullet H_2O$。此外，在直水矽鈣石中也賦存微量的鋰、鈧、釩、鉻、錳、鈷、鎳、鋅、鍶、釔、鋯、鈮、鋇、鈰、釹、鏑、鉿、鉛和釷等元素。至於鍶同位素組成則呈現相當的不均質，三件標本的$^{87}Sr/^{86}Sr$比值從0.706895變化至0.709342。當直水矽鈣石被加熱至攝氏320度且持續1小時後，部分標本會失去結晶水而轉爲另一種礦物—硬矽鈣石。直水矽鈣石在換質岩石內以次生換質礦物生成係因含鈣溶液與鈣斜長石作用的結果，推測其形成的溫度類似Gabrovšek *et al.* (1993)實驗測得雪矽鈣石產出的條件—低於攝氏140度。

關鍵詞：直水矽鈣石，成因，蛇紋岩，海岸山脈南段，臺灣東南。

Plate A. Suolunite-bearing white vein cutting through serpentinites near Shanyuan, southern Coastal Range, southeastern Taiwan. Field of view ~10 m across.

Plate B. Photograph of a polished slab of metasomatized rodingite (Rod) and serpentinite (Serp) from eastern Taiwan. White minerals in the metasomatized rodingite consist mainly of aragonite and calcite, with minor amounts of suolunite and tobermorite. The right-hand green part shows unaltered serpentinite, which is dominantly clinochrysotile with minor amounts of lizardite and magnetite.

Plate C. Photograph of a polished slab showing suolunite, tobermorite, calcite, and aragonite precipitated on the surface and a fracture of metasomatized rodingite. It can be seen that suolunite and tobermorite were always crystallized earlier than the other two. Abbreviations for this and other photographs or photomicrographs are as follows: S, suolunite; T, tobermorite; A, aragonite; C, calcite.

Plate D. Photograph of part of the thickest (~5 mm) suolunite vein found in sample TD-13. In general, the suolunite was characterized by its colorless and vitreous luster.

Plate E. Photomicrograph showing a single vein, approximately 3 mm thick, predominantly consisting of suolunite crystals which infill the fracture of the metasomatized rock. Crossed polarizers (left), plane polarizers (right).

Plate F. Photomicrograph showing finely granular suolunites with small needles of tobermorites in contact with metasomatized rock (Met). Crossed polarizers (left), plane polarizers (right).

Plate A

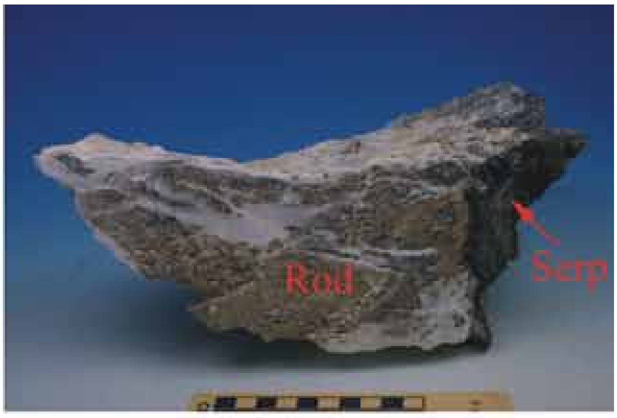

Plate B

Plate C

Plate D

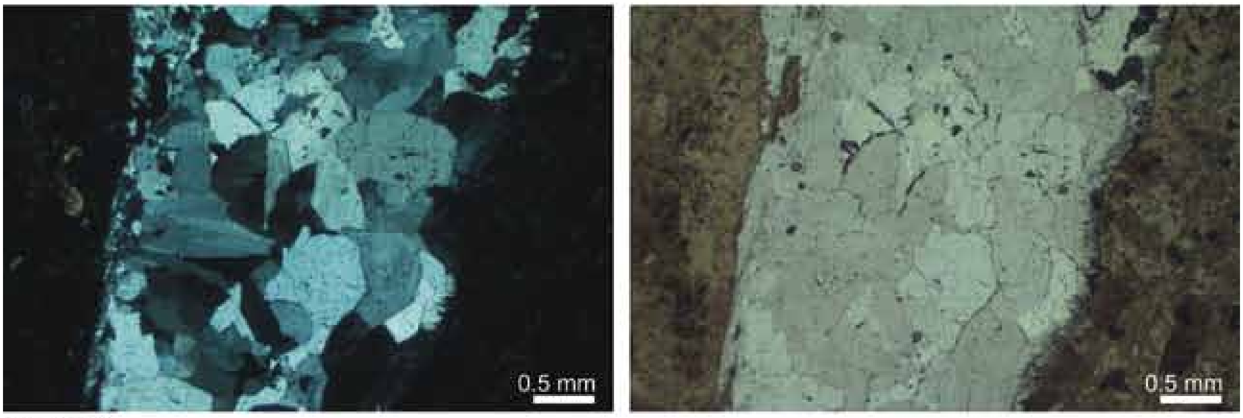

Plate E

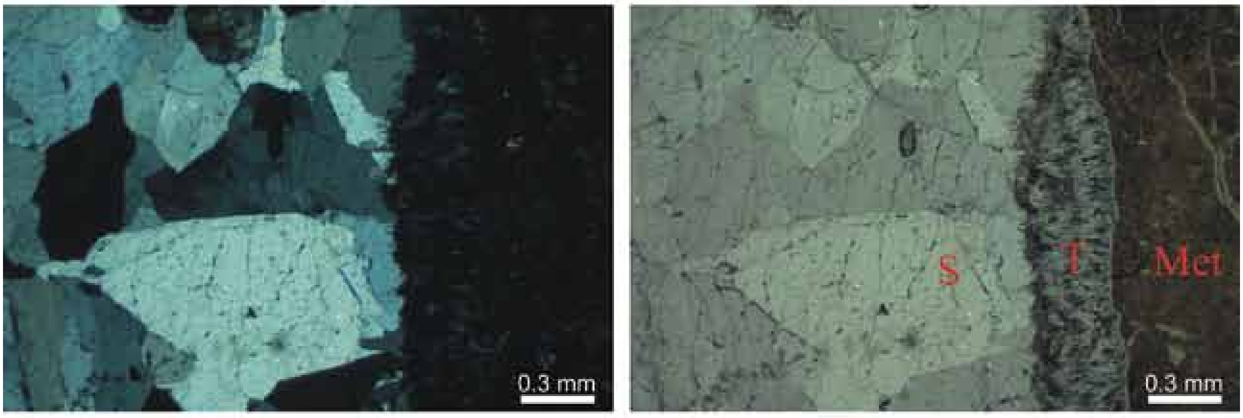

Plate F