

Rengeite, $\text{Sr}_4\text{ZrTi}_4\text{Si}_4\text{O}_{22}$, a new mineral, the Sr-Zr analogue of perrierite from the Itoigawa-Ohmi district, Niigata Prefecture, central Japan

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ABSTRACT

Rengeite, $\text{Sr}_4\text{ZrTi}_4\text{Si}_4\text{O}_{22}$, is a new member of the perrierite–chevkinite group found in the jades from the Itoigawa-Ohmi district, central Japan. It is monoclinic, $P2_1/a$, $a = 13.97(1)$, $b = 5.675(7)$, $c = 11.98(1)$ Å, $\beta = 114.26(8)^\circ$, $V = 866$ Å³ and $Z = 2$. The six strongest lines in the X-ray powder diffraction pattern are 3.12 (s) (40-3), 3.05 (vvs) (31-3), 2.99 (vs) (311), 2.84 (s) (020), 2.74 (s) (004), 2.20 (s) (31-5). Electron microprobe analysis gave SiO_2 22.58, TiO_2 29.88, ZrO_2 9.49, Nb_2O_5 0.24, Ta_2O_5 0.07, Al_2O_3 0.20, FeO 0.10, CaO 0.43, SrO 34.32, BaO 0.13, La_2O_3 0.00, Ce_2O_3 0.38, Pr_2O_3 0.10, Nd_2O_3 0.29, Sm_2O_3 0.04, total 98.25 wt.%, corresponding to $(\text{Sr}_{3.62}\text{Ca}_{0.08}\text{Ce}_{0.03}\text{Nd}_{0.02}\text{Ba}_{0.01}\text{Pr}_{0.01})_{\Sigma 3.76}(\text{Zr}_{0.84}\text{Ti}_{0.09}\text{Al}_{0.04}\text{Fe}_{0.02}\text{Nb}_{0.02})_{\Sigma 1.01}\text{Ti}_{4.00}\text{Si}_{4.11}\text{O}_{22}$ on the basis of $\text{O} = 22$. The unit-cell parameters and chemical composition imply that rengeite is the Sr and Zr-analogue of perrierite or high- β analogue of strontiochevkinite. It is transparent, dark brown with adamantine lustre. Its streak is pale greenish brown, and no cleavage was observed. The hardness is VHN_{100} 606–698 kg mm^{-2} (Mohs 5–5.5). The calculated density is 4.12 g cm^{-3} . It is strongly pleochroic from pale green to pale greenish brown where the *REE* contents are <1 wt.% and pale violet to greenish brown where the *REE* contents are between 3 and 10 wt.%. It occurs as anhedral grains in close association with titanite, zircon and tausonite in a pebble of blue titanian omphacite-jadeite rock from the seashore of Oyashirazu, Ohmi Town, in a boulder of lavender-coloured Ti-bearing jadeite from the bed of the Kotaki-gawa river, Itoigawa City, and in a boulder of green jade from the bed of the Hime-kawa river, Itoigawa City, Niigata Prefecture, central Japan. Rengeite is considered to have crystallized by interaction between pre-existing minerals (rutile, anatase, titanite and zircon) and Sr-rich metamorphic fluid during later stage activity of high-*P/T* metamorphism. The name is for Mt. Renge near the locality and the Renge metamorphic belt where jadeite deposits are found.

KEYWORDS: rengeite, new mineral, jadeite, perrierite, Renge metamorphic belt, Japan.

Introduction

THE Itoigawa-Ohmi district is the famous locality for jade in Japan (Kawano, 1939). The district is located in the easternmost part of the Renge belt (Nishimura, 1998) which is the oldest of the high-*P/T* metamorphic belts in the Japanese Islands and

extends from northern Kyushu to the Itoigawa-Ohmi district, a distance of 850 km. The Renge belt is typically associated with meta-ophiolite sequences (470 to 340 Ma) including serpentinite. It is also characterized by ages of 330 to 280 Ma and the association of glaucophane-schist and epidote-amphibolite facies schists. During mineralogical and petrological research on jade from the Itoigawa-Ohmi district, we noticed anhedral grains of an interstitial mineral with high refractive indices and distinctive pleochroism

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were revealed in a pebble of blue jade. A preliminary microprobe analysis showed that the mineral is a *REE*-bearing Sr-Ti-Zr silicate, compositionally similar to strontiochevkinite found in fenites from the Paraná Basin carbonatite, Paraguay, by Haggerty and Mariano (1983). Subsequently, X-ray diffraction (XRD) study proved the β angle to be closer to that of perrierite than that of strontiochevkinite. Perrierite is dimorphous with chevkinite. The mineral data and the name have been approved by the IMA Commission on New Minerals and Mineral Names (no. 98-055). The type specimens of rengoite are deposited at the National Science Museum, Tokyo, under the registered number NSM M-27921 and at Fossa Magna Museum, Itoigawa, Niigata, under the catalogue No. FMM00715.

Occurrence

The Itoigawa-Ohmi district of the Renge belt is characterized by a serpentinite melange with high-*P/T* type schists, jade, albitite, rodingite, metagabbro and hornblende zoisite rock, etc., and various fragments of Palaeozoic accretionary complexes composed of greenstone, limestone, chert and mudstone, etc. (Nakajima *et al.*, 1992). Rengoite was first found in the blue jade from the Oyashirazu shore, Sea of Japan, Ohmi Town. Subsequently, other occurrences of rengoite were found in lavender jade from the bed of the Kotaki-gawa river, Itoigawa City and the Oyashirazu shore, and in green jade from the bed of the Hime-kawa river, Itoigawa City (Fig. 1).

Rengoite in the blue jade

The rengoite-bearing blue jade (FMM00715) which was found at the seashore of Oyashirazu, is a small pebble, ~5 cm diameter. The specimen is a dense blue greyish rock. It includes prismatic crystals <5 mm long, composed of acicular dark bluish titanian omphacite and dark brownish sodic amphibole corresponding to eckermannite and nyböite. Under the microscope, the major components are jadeite, titanian omphacite and sodic amphibole associated with minor titanite, zircon, rutile and/or anatase, strontium-apatite, tausonite and rengoite. Rengoite as anhedral grains ~0.5 mm across occurs interstitially within jadeite grains (Fig. 2*a,b*). The physical and chemical data for rengoite were obtained from this specimen.

Rengoite in the lavender jade

The rengoite-bearing lavender jade (FMM00716), which was found at the Oyashirazu shore, is a boulder ~30 cm in diameter, and is white to greyish purple. Under the microscope, the specimen is composed of essentially pure jadeite and Ti-bearing jadeite with minor amounts of rutile, titanite, zircon, an undetermined Sr-Ti silicate, native copper and rengoite. The specimen is characterized by the existence of rounded brownish rutile grains <3 mm in diameter rimmed by titanite coronae. The rengoite in this specimen is closely associated with rutile, titanite and zircon (Fig. 2*c,d*).

The other rengoite-bearing lavender jade (FMM01309) was found in the bed of the Kotaki-gawa river. It is a boulder ~50 cm in diameter, submitted by Mrs K. Ito of Kotaki Bussan Co. Under the microscope, it is composed of essentially pure jadeite, Ti-bearing jadeite and natrolite with minor constituents of lamprophyllite, titanite, zircon, rutile, tausonite, undetermined Sr-Ti silicate and rengoite. The specimen is characterized by the existence of nearly euhedral jadeite crystals in the natrolite matrix. The rengoite in the lavender jade comprises a fan-shaped aggregate of prismatic crystals <0.3 mm long with euhedral jadeite crystals (Fig. 2*e*).

Rengoite in the green jade

The rengoite-bearing green jade (FMM01310) was found in the bed of the Hime-kawa river. It was given to the first author by Mrs K. Ito for study of the jade. The specimen is a translucent greyish green boulder ~50 cm in diameter. Under the microscope, it is composed of essentially pure jadeite and omphacite with minor titanite, zircon and rengoite. The rengoite in the green jade occurs as elongate aggregates (~9 mm) of anhedral crystals in close association with titanite (Fig. 2*f*). The microhardness data for rengoite were obtained from this specimen.

Physical and optical properties

The rengoite is transparent dark greenish brown with adamantine lustre. It shows a strong pleochroism; from pale green to pale greenish brown in *REE*-poor areas ($\Sigma REE < 1$ wt.%) and pale violet to greenish brown in *REE*-rich areas (ΣREE 3 to 10 wt.%). These different areas may coexist in a single grain and the boundary

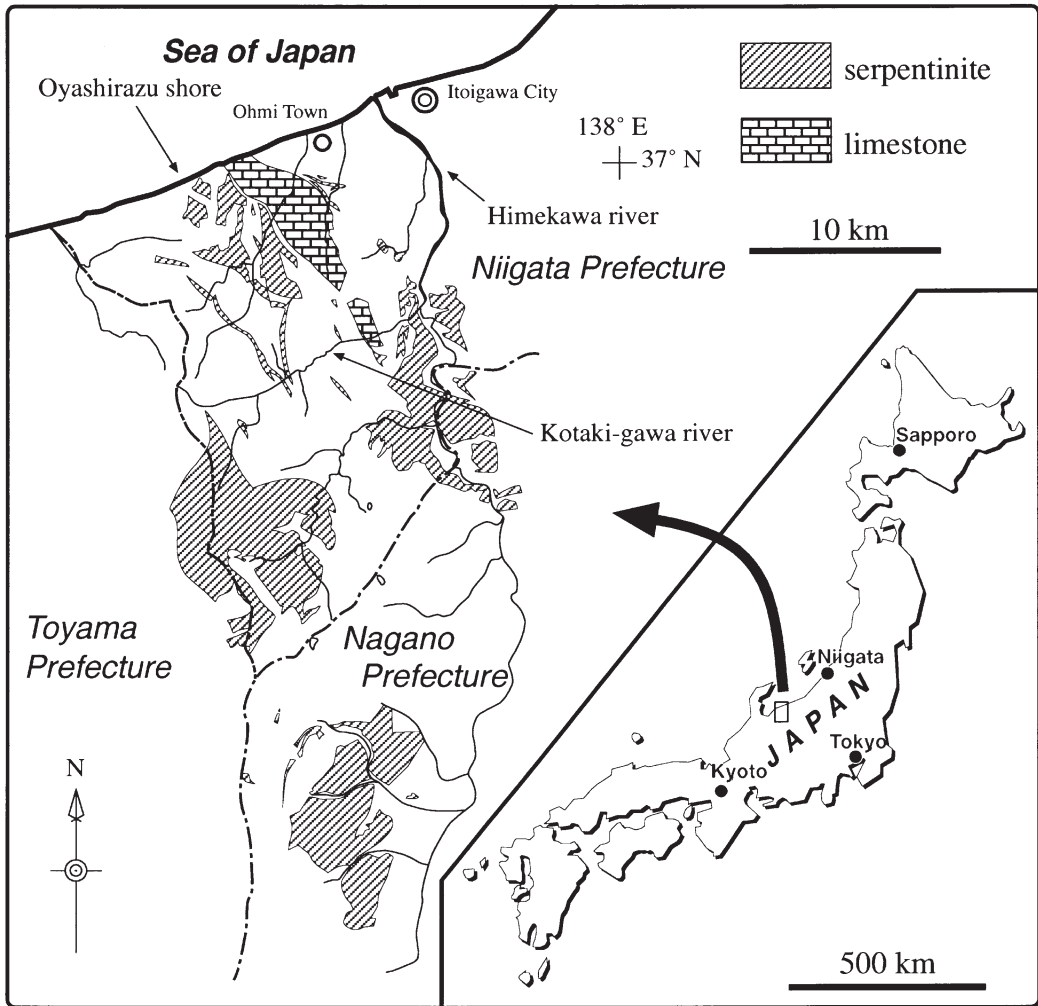


FIG. 1. Index map of the Itoigawa-Ohmi district (modified from Komatsu, 1990).

between them may be irregular (Fig. 2*b*). No cleavage was observed. The Vickers microhardness is 606–698 kg mm⁻² (100 g load), corresponding to 5–5.5 on the Mohs scale. The density could not be measured due to the lack of material, but the calculated density is 4.12 g cm⁻³. There is no fluorescence in the either long- or short-wave ultraviolet radiation. Rengeite is optically biaxial positive. The refractive indices are higher than titanite, though they could not be measured because they are too high for normal liquid.

Chemistry

An electron microprobe using wavelength dispersion methods (JEOL JXA-8800, beam diameter 2 to 3 μm, 15 kV accelerating voltage, 20 nA probe current, and standard ZAF correction) was used for chemical analysis of rengeite. The standards used were sillimanite (Al), wollastonite (Si and Ca), TiO₂ (Ti), Zr (Zr), Fe₂SiO₄ (Fe), Nb (Nb), Ta (Ta), SrF₂ (Sr), BaF₂ (Ba) and REEP₅O₁₄ (REE). Backscattered electron images (Fig. 2*b*) and chemical analysis demonstrate that the

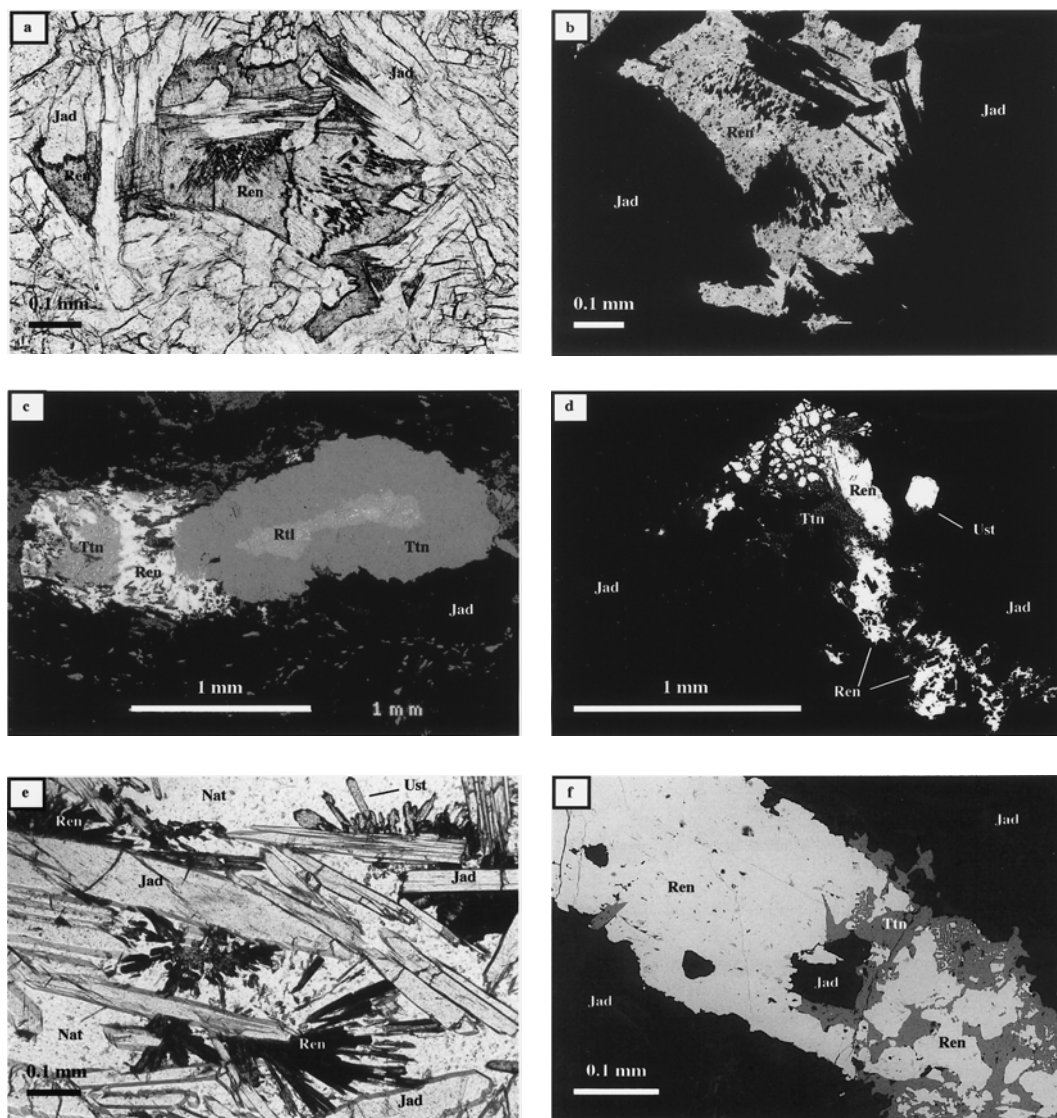
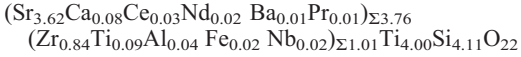
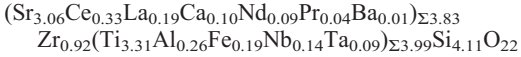


FIG. 2. (a) Photomicrograph (PPL) of reneite shows interstitial crystals between subhedral jadeite in the blue jade (FMM00715) from the Oyashirazu seashore. (b) Back-scattered electron (BSE) image of reneite shows compositional heterogeneity of *REE* within the grains in the blue jade (FMM00715) from the Oyashirazu seashore. (c) BSE image of reneite shows its close association with titanite and rutile in the lavender jade (FMM00716) from the Oyashirazu seashore. (d) BSE image of reneite shows its close association with zircon and titanite in the lavender jade (FMM00716) from the Oyashirazu seashore. (e) Photomicrograph (PPL) of reneite shows fan-shaped aggregates with jadeite and natrolite in the lavender jade (FMM01309) from the riverbed of the Kotaki-gawa river. (f) BSE image of reneite shows its close association with titanite in the green jade (FMM01310) from the bed of the Hime-kawa river. Abbreviations: Jad = jadeite, Nat = natrolite, Ren = reneite, Rtl = rutile, Ttn = titanite and Ust = undetermined Sr-Ti silicate.

composition of rengeite varies from grain to grain and within individual grains, mainly in the total *REE* contents. The average of six measurements of *REE*-poor rengeite (Table 1) leads to the empirical formula,



on the basis of O = 22. The average of 3 measurements of *REE*-rich rengeite leads to the empirical formula,



on the basis of O=22. Consequently, the ideal formula is $Sr_4ZrTi_4Si_4O_{22}$.

The polymorphs perrierite and chevkinite have the ideal stoichiometry $A_4^{3+}B^{2+}C_2^{3+}Ti_2Si_4O_{22}$ (Ito, 1967) where *A* = *REE*, *B* = (Fe, Mg), *C* = (Fe, Al). They are distinguished by their different mono-

clinic β angle (113° and 100° respectively), associated with different cation–oxygen bond length patterns in their structures (Calvo and Faggiani, 1974): a rare example of bond length isomerism.

Titanium is an essential element in the perrierite-chevkinite group and the reported range of TiO₂ is 15 to 23 wt.%, corresponding to 2.35 to 3.47 titanium cations per formula unit (p.f.u.: O = 22). However, for rengeite these reach 30 wt.% or 4.09 p.f.u. *REE*₂O₃ is also assumed to be essential at 40 wt.%, corresponding to 2.77 to 3.82 p.f.u. But these reach only 10 wt.% or 0.65 p.f.u. for rengeite. Iron is also rich in the group (5 to 18 wt.% FeO, corresponding 0.86 to 3.13 p.f.u.). However, FeO is <2 wt.% (0.02 to 0.19 p.f.u.) for rengeite. The highest SrO content in the perrierite–chevkinite group is for strontio-chevkinite (20.48 wt.% or 2.30 p.f.u.) from fenite in the Paraná Basin carbonatite, Paraguay

TABLE 1. Representative chemical compositions for rengeite.

| <i>REE</i> -poor rengeite | | | | <i>REE</i> -rich rengeite | | | |
|--------------------------------|-------|---|-------|--------------------------------|-------|----------------------|-------|
| Wt.% | | cation number O = 22 | | Wt.% | | cation number O = 22 | |
| SiO ₂ | 22.58 | Si | 4.11 | SiO ₂ | 22.04 | Si | 4.14 |
| TiO ₂ | 29.88 | Ti | 4.09 | TiO ₂ | 23.60 | Ti | 3.33 |
| ZrO ₂ | 9.49 | Zr | 0.84 | ZrO ₂ | 10.11 | Zr | 0.93 |
| Nb ₂ O ₅ | 0.24 | Nb | 0.02 | Nb ₂ O ₅ | 1.33 | Nb | 0.11 |
| Ta ₂ O ₅ | 0.07 | Ta | 0.00 | Ta ₂ O ₅ | 0.01 | Ta | 0.00 |
| Al ₂ O ₃ | 0.20 | Al | 0.04 | Al ₂ O ₃ | 1.70 | Al | 0.38 |
| FeO | 0.10 | Fe | 0.02 | FeO | 1.19 | Fe | 0.19 |
| MgO | 0.00 | Mg | 0.00 | MgO | 0.00 | Mg | 0.00 |
| CaO | 0.43 | Ca | 0.08 | CaO | 0.52 | Ca | 0.11 |
| SrO | 34.32 | Sr | 3.62 | SrO | 28.24 | Sr | 3.07 |
| BaO | 0.13 | Ba | 0.01 | BaO | 0.16 | Ba | 0.01 |
| La ₂ O ₃ | 0.00 | La | 0.00 | La ₂ O ₃ | 2.73 | La | 0.19 |
| Ce ₂ O ₃ | 0.38 | Ce | 0.03 | Ce ₂ O ₃ | 4.81 | Ce | 0.33 |
| Pr ₂ O ₃ | 0.10 | Pr | 0.01 | Pr ₂ O ₃ | 0.63 | Pr | 0.04 |
| Nd ₂ O ₃ | 0.29 | Nd | 0.02 | Nd ₂ O ₃ | 1.40 | Nd | 0.09 |
| Sm ₂ O ₃ | 0.04 | Sm | 0.00 | Sm ₂ O ₃ | 0.06 | Sm | 0.00 |
| Total | 98.25 | Total | 12.89 | Total | 98.53 | Total | 12.92 |
| <i>REE</i> -poor rengeite | | | | | | | |
| <i>A</i> site: | | $(Sr_{3.62}Ca_{0.08}Ce_{0.03}Nd_{0.02}Ba_{0.01}Pr_{0.01})_{\Sigma 3.76}$ | | | | | |
| <i>B</i> site: | | $(Zr_{0.84}Ti_{0.09}Al_{0.04}Fe_{0.02}Nb_{0.02})_{\Sigma 1.01}$ | | | | | |
| <i>C</i> site: | | Ti _{2,00} | | | | | |
| <i>REE</i> -rich rengeite | | | | | | | |
| <i>A</i> site: | | $(Sr_{3.07}Ce_{0.33}La_{0.19}Ca_{0.11}Nd_{0.09}Pr_{0.04}Ba_{0.01})_{\Sigma 3.84}$ | | | | | |
| <i>B</i> site: | | $(Zr_{0.93}Ti_{0.01})_{\Sigma 0.94}$ | | | | | |
| <i>C</i> site: | | $(Ti_{1.32}Al_{0.38}Fe_{0.19}Nb_{0.11})_{\Sigma 2.00}$ | | | | | |

(Haggerty and Mariano, 1983). Strontium contents are generally low in perrierite, and 7.73 wt.% as maximum SrO content, corresponding to 0.87 p.f.u., has been reported for the material from syenite pegmatites in the Burpala alkali massif, North Baikal, Russia (Portnov, 1964). In rengerite, the SrO content reaches 34 wt.% which corresponds 3.62 p.f.u. Thus strontium contents and the occupancy in the *A* site of rengerite far exceed those in the perrierite–chevkinite group. Zirconium was detected in strontian perrierite (4.85 wt.% ZrO₂ or 0.46 p.f.u.) from Baikal (Portnov, 1964), in chevkinite (1.17 wt.% ZrO₂ or 0.11 p.f.u.) from California (McDowell, 1979) and in strontiochevkinite (10.60 wt.% ZrO₂ or 1.00 p.f.u.) from the Paraná Basin (Haggerty and Mariano, 1983). In rengerite, the ZrO contents reach 9.49 wt.% or 0.84 p.f.u. In summary, the chemical composition

of rengerite is characterized by very high Sr, Ti and Zr, and very low *REE* and Fe compared to other members in the perrierite–chevkinite group.

X-ray study

The X-ray powder diffraction pattern for rengerite was obtained using a Gandolfi camera of 114.6 mm diameter employing Ni-filtered Cu-K α radiation (Table 2). Single crystal studies were made by precession and a 4-circle diffractometer. Because rengerite is very poor in uranium and thorium, it is non-metamict and gives excellent powder data from unheated material. The refined unit-cell parameters are; $a = 13.97(1)$, $b = 5.675(7)$, $c = 11.98(1)$ Å, $\beta = 114.26(8)^\circ$ and $V = 866$ Å³. It is monoclinic, space group $P2_1/a$ and $Z = 2$. Long-exposure precession photographs show the very weak superstructure

TABLE 2. X-ray powder diffraction data for rengerite.

| <i>h</i> | <i>k</i> | <i>l</i> | d_{obs} | d_{calc} | <i>I</i> | <i>h</i> | <i>k</i> | <i>l</i> | d_{obs} | d_{calc} | <i>I</i> _{obs} |
|-----------|----------|----------|------------------|-------------------|----------|-----------|----------|----------|------------------|-------------------|-------------------------|
| 0 | 0 | 1 | 11.30 | 10.95 | vw | $\bar{4}$ | 2 | 5 | 1.78 | 1.78 | w |
| $\bar{2}$ | 0 | 1 | 6.97 | 6.87 | vvw | $\bar{6}$ | 2 | 3 | | 1.78 | |
| 2 | 0 | 0 | 6.45 | 6.38 | vw | $\bar{6}$ | 2 | 1 | 1.76 | 1.77 | vw |
| 0 | 0 | 2 | 5.49 | 5.47 | w | 6 | 0 | 2 | 1.74 | 1.75 | vw |
| $\bar{2}$ | 0 | 2 | 5.24 | 5.38 | vw | 4 | 0 | 4 | | 1.75 | |
| $\bar{1}$ | 1 | 1 | 5.04 | 5.02 | w | $\bar{8}$ | 0 | 3 | | 1.75 | |
| 2 | 0 | 1 | 4.77 | 4.73 | vvw | $\bar{8}$ | 0 | 2 | 1.71 | 1.73 | vvw |
| $\bar{1}$ | 1 | 2 | 4.16 | 4.12 | m | 0 | 2 | 5 | | 1.73 | |
| $\bar{2}$ | 0 | 3 | 3.98 | 3.94 | w | $\bar{3}$ | 3 | 2 | | 1.73 | |
| 0 | 0 | 3 | 3.69 | 3.65 | w | $\bar{8}$ | 0 | 1 | 1.68 | 1.68 | w |
| $\bar{3}$ | 1 | 1 | 3.62 | 3.60 | w | $\bar{3}$ | 3 | 3 | 1.67 | 1.67 | vw |
| 1 | 1 | 2 | 3.52 | 3.48 | w | 3 | 3 | 1 | 1.64 | 1.66 | w |
| $\bar{3}$ | 1 | 2 | 3.45 | 3.44 | w | $\bar{8}$ | 0 | 5 | | 1.65 | |
| 4 | 0 | 0 | 3.21 | 3.19 | m | 7 | 1 | 1 | 1.62 | 1.62 | w |
| $\bar{4}$ | 0 | 3 | 3.13 | 3.12 | s | 3 | 1 | 5 | | 1.62 | |
| $\bar{3}$ | 1 | 3 | 3.06 | 3.03 | vvs | $\bar{7}$ | 1 | 6 | 1.61 | 1.61 | vw |
| $\bar{2}$ | 0 | 4 | 3.00 | 3.00 | vs | $\bar{5}$ | 1 | 7 | | 1.60 | |
| 3 | 1 | 1 | | 2.98 | | 6 | 2 | 1 | | 1.60 | |
| 0 | 2 | 0 | 2.86 | 2.84 | s | $\bar{5}$ | 3 | 2 | 1.57 | 1.56 | vvw |
| 1 | 1 | 3 | | 2.77 | | 0 | 0 | 7 | | 1.56 | |
| 4 | 0 | 1 | 2.79 | 2.77 | m | $\bar{8}$ | 0 | 6 | | 1.56 | |
| 0 | 2 | 1 | | 2.74 | | $\bar{4}$ | 0 | 8 | 1.50 | 1.50 | vvwb |
| 0 | 0 | 4 | 2.75 | 2.74 | w | 8 | 0 | 1 | 1.49 | 1.49 | vvwb |
| $\bar{4}$ | 0 | 4 | 2.71 | 2.69 | w | $\bar{7}$ | 1 | 7 | | 1.48 | |
| $\bar{2}$ | 2 | 1 | 2.63 | 2.62 | vw | $\bar{3}$ | 3 | 5 | | 1.48 | |
| $\bar{1}$ | 1 | 4 | 2.60 | 2.61 | vvw | $\bar{8}$ | 0 | 7 | 1.45 | 1.45 | w |
| 2 | 2 | 0 | | 2.59 | | $\bar{2}$ | 2 | 7 | | 1.45 | |
| 0 | 2 | 2 | 2.55 | 2.52 | vw | $\bar{8}$ | 2 | 1 | | 1.44 | |
| $\bar{2}$ | 2 | 2 | | 2.51 | | 1 | 1 | 7 | 1.43 | 1.43 | vw |
| $\bar{5}$ | 1 | 2 | 2.51 | 2.50 | m | $\bar{8}$ | 2 | 5 | | 1.43 | |
| 2 | 2 | 1 | 2.44 | 2.43 | w | 0 | 4 | 0 | 1.42 | 1.42 | w |

TABLE 2 (contd).

| <i>h</i> | <i>k</i> | <i>l</i> | <i>d</i> _{obs} | <i>d</i> _{calc} | <i>I</i> | <i>h</i> | <i>k</i> | <i>l</i> | <i>d</i> _{obs} | <i>d</i> _{cal} | <i>I</i> _{obs} |
|-----------|----------|----------|-------------------------|--------------------------|----------|------------|----------|----------|-------------------------|-------------------------|-------------------------|
| 4 | 0 | 2 | 2.38 | 2.37 | vw | 5 | 3 | 2 | 1.38 | 1.38 | w |
| $\bar{6}$ | 0 | 2 | 2.34 | 2.33 | vw | 6 | 2 | 3 | | 1.38 | |
| $\bar{4}$ | 0 | 5 | 2.30 | 2.30 | m | 9 | 1 | 0 | 1.37 | 1.37 | vw |
| $\bar{6}$ | 0 | 1 | 2.27 | 2.27 | w | $\bar{10}$ | 0 | 2 | | 1.37 | |
| 0 | 2 | 3 | | 2.24 | | $\bar{7}$ | 3 | 2 | | 1.37 | |
| $\bar{3}$ | 1 | 5 | 2.20 | 2.20 | vs | $\bar{7}$ | 3 | 3 | | 1.37 | |
| $\bar{4}$ | 2 | 1 | | 2.19 | | 0 | 0 | 8 | | 1.37 | |
| $\bar{4}$ | 2 | 2 | 2.17 | 2.19 | vw | $\bar{8}$ | 2 | 6 | | 1.37 | |
| $\bar{6}$ | 0 | 4 | | 2.16 | | $\bar{5}$ | 3 | 6 | 1.34 | 1.34 | vw |
| 6 | 0 | 0 | | 2.13 | | $\bar{10}$ | 0 | 6 | | 1.33 | |
| 4 | 2 | 0 | 2.13 | 2.12 | vw | 4 | 4 | 0 | 1.30 | 1.30 | w |
| $\bar{4}$ | 2 | 3 | 2.11 | 2.10 | vw | $\bar{6}$ | 2 | 8 | | 1.29 | |
| $\bar{6}$ | 0 | 5 | | 1.98 | | $\bar{4}$ | 4 | 3 | | 1.29 | |
| $\bar{2}$ | 0 | 6 | 1.99 | 1.98 | vw | 6 | 2 | 4 | 1.27 | 1.27 | vw |
| $\bar{4}$ | 0 | 6 | | 1.97 | | $\bar{3}$ | 3 | 7 | | 1.27 | |
| 0 | 2 | 4 | 1.97 | 1.97 | w | 7 | 3 | 1 | 1.26 | 1.26 | vw |
| 2 | 2 | 3 | | 1.96 | | 0 | 4 | 4 | | 1.26 | |
| 6 | 0 | 1 | 1.95 | 1.94 | vw | 3 | 3 | 5 | | 1.26 | |
| 5 | 1 | 2 | 1.91 | 1.90 | vw | $\bar{5}$ | 3 | 7 | 1.25 | 1.25 | vw |
| $\bar{7}$ | 1 | 2 | 1.89 | 1.88 | w | $\bar{8}$ | 0 | 9 | 1.23 | 1.24 | vw |
| $\bar{7}$ | 1 | 3 | | 1.88 | | $\bar{11}$ | 1 | 4 | | 1.24 | |
| $\bar{2}$ | 2 | 5 | 1.83 | 1.83 | vw | 0 | 2 | 8 | 1.22 | 1.23 | vw |
| $\bar{7}$ | 1 | 1 | | 1.83 | | $\bar{11}$ | 1 | 5 | | 1.23 | |
| $\bar{7}$ | 1 | 4 | 1.83 | 1.82 | vw | $\bar{11}$ | 1 | 2 | 1.21 | 1.21 | vw |
| $\bar{1}$ | 1 | 6 | | 1.82 | | $\bar{6}$ | 4 | 2 | | 1.21 | |
| $\bar{5}$ | 1 | 6 | 1.80 | 1.80 | w | $\bar{4}$ | 4 | 5 | | 1.21 | |
| $\bar{6}$ | 0 | 6 | 1.79 | 1.79 | vw | $\bar{4}$ | 2 | 9 | | 1.21 | |
| | | | | | | $\bar{11}$ | 1 | 6 | | 1.21 | |

reflections corresponding to $5 \times c$ axis. The reported unit-cell parameters for members in the perrierite–chevkinite group are given in Table 3. The average unit-cell volume for chevkinite, perrierite and strontiochevkinite are 829, 842 and 844 \AA^3 , respectively. That for rengeite ($V = 866 \text{ \AA}^3$) is the largest in the group. It may be attributed to abundant Sr^{2+} with larger ionic radius in comparison to lanthanides. The crystal structure analysis is currently being performed by the authors.

Discussion

Site occupancy of cations

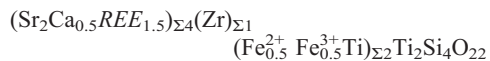
The crystal structures were analysed for synthetic compounds using the perrierite and chevkinite structures devised by Calvo and Faggiani (1974). According to them, the *A* site can be divided into

two crystallographic sites; the *A*(1) site has eight- to nine-fold coordination and the *A*(2) site has nine-fold coordination. In synthetic $\text{La}_4\text{Mg}_2\text{Ti}_3\text{Si}_4\text{O}_{22}$ with perrierite structure, the *B* and *C* sites are octahedral sites. The *B* site is the largest octahedral site which is completely occupied by Mg^{2+} . The *C* site is divided into *C*(1) and *C*(2) sites; the *C*(1) site is the second smallest octahedral site and is occupied by Ti^{4+} and Mg^{2+} , and the *C*(2) site is the smallest octahedral site, almost completely occupied by Ti^{4+} . The ionic radius of Zr^{4+} in six-fold coordination is the same as that of Mg^{2+} (0.72 \AA as determined by Shannon and Prewitt, 1969). Thus, it is very likely that Zr^{4+} occupies the *B* site rather than the *C*(1) site in rengeite. In the case of strontiochevkinite, $(\text{Sr}_2 \text{Ca}_{0.5} \text{REE}_{1.5})_{\Sigma 4} (\text{Fe}_{0.5}^{2+} \text{Fe}_{0.5}^{3+})_{\Sigma 1} (\text{Ti}_3\text{Zr}_1)_{\Sigma 4} \text{Si}_4\text{O}_{22}$, however, Fe and Zr occupy the *B* and *C* sites,

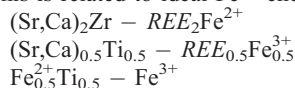
TABLE 3. Unit-cell parameters for rengerite, perrierite, chevkinite and strontiochevkinite.

| Locality | a (Å) | b (Å) | c (Å) | β (°) | V (Å ³) | Reference | Remarks |
|---|---------|---------|---------|-------------|-----------------------|-----------------------------|----------------|
| Rengerite | | | | | | | |
| Itoigawa-Ohmi, Japan | 13.97 | 5.68 | 11.98 | 114.26 | 866 | This study | unheated |
| Perrierite | | | | | | | |
| Nettuno, Italy | 13.59 | 5.61 | 11.61 | 113.28 | 813 | Bonatti (1959) | unheated |
| Oslo region, Norway | 13.70 | 5.66 | 11.83 | 113.79 | 839 | Segalstad and Larsen (1978) | heated |
| Nebraska, USA | 13.59 | 5.62 | 11.73 | 113.95 | 819 | Izett and Wilcox (1968) | unheated |
| Virginia, USA | 13.61 | 5.68 | 11.73 | 113.5 | 832 | Mitchell (1966) | unheated |
| North Baikal, Russia | 13.95 | 5.62 | 11.70 | 114.53 | 834 | Portnov (1964) | unheated |
| Urals, Russia | 13.52 | 5.65 | 11.71 | 113.3 | 822 | Ito (1967) | recrystallized |
| La ₄ Mg ₂ Ti ₃ Si ₄ O ₂₂ | 13.78 | 5.67 | 11.78 | 113.7 | 843 | Ito (1967) | synthetic |
| average of perrierite | 13.68 | 5.64 | 11.73 | 113.72 | 829 | | |
| Chevkinite | | | | | | | |
| Cape Ashizuri, Japan | 13.46 | 5.68 | 11.35 | 100.86 | 852 | Imaoka and Nakashima (1994) | unheated |
| Oslo region, Norway | 13.43 | 5.74 | 11.07 | 100.58 | 839 | Segalstad and Larsen (1978) | heated |
| Oslo region, Norway | 13.44 | 5.736 | 11.04 | 100.61 | 837 | Segalstad and Larsen (1978) | heated |
| Oslo region, Norway | 13.40 | 5.72 | 11.09 | 100.53 | 836 | Segalstad and Larsen (1978) | heated |
| Kansas, USA | 13.37 | 5.66 | 11.28 | 100.87 | 838 | Izett and Wilcox (1968) | unheated |
| Utah, USA | 13.37 | 5.67 | 11.24 | 100.72 | 837 | Izett and Wilcox (1968) | unheated |
| New Mexico, USA | 13.32 | 5.68 | 11.31 | 100.72 | 841 | Izett and Wilcox (1968) | unheated |
| Virginia, USA | 13.60 | 5.82 | 11.22 | 100.75 | 872 | Mitchell (1966) | unheated |
| New Hampshire, USA | 13.44 | 5.72 | 11.10 | 100.20 | 840 | Jaffe <i>et al.</i> (1956) | heated |
| Madagascar | 13.26 | 5.75 | 11.06 | 100.7 | 829 | Ito (1967) | recrystallized |
| La ₄ Fe ₂ Ti ₃ Si ₄ O ₂₂ | 13.50 | 5.75 | 11.10 | 101.0 | 846 | Ito (1967) | synthetic |
| average of chevkinite | 13.42 | 5.72 | 11.17 | 100.69 | 842 | | |
| Strontiochevkinite | | | | | | | |
| Sarambi, Paraguay | 13.56 | 5.70 | 11.10 | 100.32 | 844 | Haggerty and Mariano (1983) | unheated |

respectively (Haggerty and Mariano, 1983). Haggerty and Mariano (1983) did not refine the structure of strontiochevkinite. They have grouped the *B/C* cations in order of charge rather than intending to specify site occupancies. Their idealized formula can be rearranged to put Zr on *B*:



This is related to ideal Fe^{2+} -chevkinite by:



The first two of these substitutions are basically the same as those relating perrierite and rengeite, implying that rengeite is indeed the high- β analogue of strontiochevkinite. In the case of synthetic $\text{La}_4\text{Fe}(\text{Fe,Ti})\text{Ti}_2\text{Si}_4\text{O}_{22}$ with the chevkinite structure (Ito, 1967), Fe occupies both the *B* and *C* sites. It therefore appears that whether the *B* site is occupied by Fe or Zr depends on the overall chemical composition. The ideal formula of the perrierite–chevkinite group has been proposed as $\text{A}_4^{3+}\text{B}^{2+}\text{C}_2^{3+}\text{Ti}_2\text{Si}_4\text{O}_{22}$ (Ito, 1967). Using to the same format, the ideal formula for rengeite can be written as $\text{Sr}_4\text{ZrTi}_2\text{Ti}_2\text{Si}_4\text{O}_{22}$. The *A*, *B* and *C* sites in rengeite are occupied by Sr^{2+} , Zr^{4+} and Ti^{4+} ions instead of trivalent, divalent and trivalent cations, respectively. However, the charge is balanced within these three sites.

Paragenesis

In the blue and the lavender jades from Oyashirazu, rengeite occurs as anhedral and interstitial crystals between jadeite (Fig. 2*a,b,c*), suggesting that rengeite was formed after the crystallization of jadeite. However, in the lavender jade from the Kotaki-gawa river, rengeite shows fan-shaped aggregates with euhedral to subhedral jadeite in the natrolite matrix (Fig. 2*d*). This suggests that rengeite was able to form at the same stage of the crystallization of jadeite. In both cases rengeite is closely associated with rutile, titanite and zircon (Figs 2*c,d,f*), which may have been the sources for the Ti and Zr of rengeite, since these elements may be relatively immobile during metamorphism (Cann, 1970; Coish, 1977; Wood *et al.*, 1976; Tatsumi and Kogiso, 1995). Rengeite is considered to have crystallized by interaction between pre-existing minerals (rutile, anatase, titanite and zircon) and Sr-rich metamorphic fluid during later stage activity of high-*P/T* metamorphism.

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