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LETTER

Finding of talc- and kyanite-bearing amphibolite from the Paleoproterozoic Usagaran Belt, Tanzania

Keiko MORI[*], Tatsuki TSUJIMORI[*,**] and Nelson BONIFACE[**,***]

[*]*Department of Earth Science, Tohoku University, Sendai 980-8578, Japan*
[**]*Center for Northeast Asian Studies, Tohoku University, Sendai 980-8576, Japan*
[***]*Department of Geology, University of Dar es Salaam, Dar es Salaam, Tanzania*

We report a newly discovered assemblage of talc-kyanite in an amphibolite from the Isimani Suite of the Paleoproterozoic Usagaran Belt, central Tanzania. The amphibolite is characterized by the mineral assemblage of clinoamphibole, kyanite, talc with minor rutile, quartz, dolomite, and rare barite. The high $Fe^{3+}/(Fe^{3+} + Fe^{2+})$ ratio (0.48–0.80) of clinoamphibole and the presence of sulfate (barite) indicate a very-high oxidation state during metamorphism. *P–T* pseudosection modelling predicts that the studied talc- and kyanite-bearing amphibolites formed at high-pressure conditions ($P > 1.0$ GPa). Moreover, the modelling suggests formation of talc + kyanite + clinoamphibole at a highly oxidizing condition with CO_2 fluid. This talc-kyanite association provides an index of high-pressure metamorphism of the Usagaran Belt and marks the oldest record of the talc-kyanite association in regional metamorphism in the Earth's history.

Keywords: Talc, Kyanite, Amphibolite, High-pressure metamorphism, Usagaran Belt, Tanzania

INTRODUCTION

Occurrence of talc in crustal composition rocks is indicative of high-pressure conditions. Since recognition of the significance of talc-kyanite association by experimental studied by Schreyer and Seifert (1969), various talc-bearing mineral assemblages, such as talc-kyanite, talc-phengite, talc-paragonite, talc-epidote, and talc-lawsonite, in crustal metamorphic rocks have been reported as pressure-indicative assemblages from paleo-convergent plate boundaries of Neoproterozoic and younger orogens (e.g., Vrána and Barr, 1972; Kulke and Schreyer, 1973; Chinner and Dixon, 1973; Råheim and Green, 1974; Miller, 1977; Chopin, 1981; Zhang and Liou, 1994; Sisson et al., 1997; Zack et al., 2001; Johnson and Oliver, 2002; Okay, 2002). Most talc-bearing crustal metamorphic rocks are basaltic eclogites (e.g., Massonne and Kopp, 2005; Groppo and Castelli, 2010), and blueschist- and eclogite-facies metachert (piemontite-bearing metaquartzites) (Abraham and Schreyer, 1976; Izadyar et al., 2000; Ubukawa et al., 2007) and rare lawsonite-bearing metabasites (Okay, 2002). Another rare type of talc-bearing crustal metamorphic rock is the so-called 'whiteschist' which is characterized by the mineral assemblage talc + kyanite ± quartz or coesite (Schreyer, 1974; Chopin, 1984; Compagnoni and Hirajima, 2001; Franz et al., 2013). Excepting eclogites, talc-bearing metamorphic rocks have whole-rock compositions of very high $Mg/(Mg + Fe^{2+})$ ratio and very low Ca content (e.g., Franz et al., 2013). However, we found talc- and kyanite-bearing amphibolite from the Paleoproterozoic Usagaran Belt, Tanzania. The amphibolite is characterized by the mineral assemblage of talc + kyanite + clinoamphibole ± quartz ± dolomite. Although the occurrence of the famous 'yoderite-bearing whiteschist' with talc-kyanite association has been well known in the Neoproterozoic Mozambique Belt of Tanzania (Mautia Hill: McKie, 1959; Jöns and Schenk, 2004), this is the first finding of talc-kyanite association in the Paleoproterozoic orogen of Tanzania.

In this paper, we describe the paragenesis of a talc- and kyanite-bearing amphibolite and address geological significance. Throughout this paper we use the mineral abbreviations recommended by Whitney and Evans (2010) with the exception of yoderite (Yod).

GEOLOGICAL OUTLINE

The Paleoproterozoic Usagaran Belt in central Tanzania is

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K. Mori, keiko.mori.q4@dc.tohoku.ac.jp Corresponding author

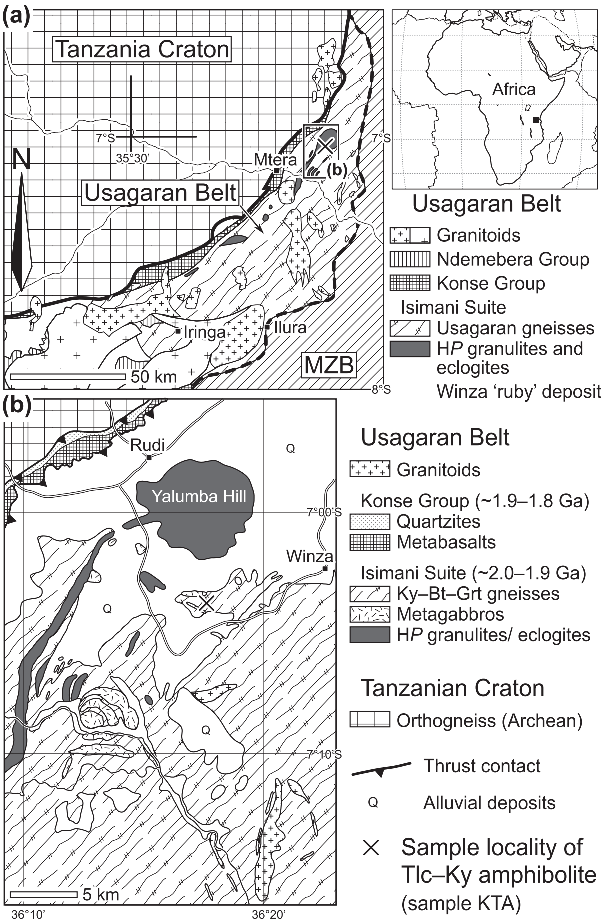

Figure 1. (a) A simplified geological map of the Usagaran Belt (modified from Legler et al., 2015) showing location of the Winza 'ruby' deposit. (b) Geological map showing lithological variations of the Isimani Suite of the Usagaran Belt near Winza.

located at the south-eastern margin of the Archean Tanzania Craton (Fig. 1a) and constitutes a NE-SW to E-W trending orogenic belt that borders to the Neoproterozoic Mozambique Belt (MZB) of the East African Orogen. The Usagaran Belt is subdivided into three major litho-tectonic units including the Isimani Suite and the Konse, and Ndembera Groups (e.g., Legler et al., 2015). In particular, the Isimani Suite is a subduction/collision-related geotectonic unit; the unit comprises of orthogneiss with kyanite-bearing paragneiss and mafic amphibolites that locally preserved high-pressure granulites and eclogites (e.g., Möller et al., 1995; Collins et al., 2004). The subduction and formation of the ~ 2.0 Ga eclogite with MORB affinity preserved at the Yalumba Hill (Möller et al., 1995) are concomitant with collision related garnet-bearing mafic-ultramafic body including a 'ruby' deposit near Winza, kyanite-biotite-garnet paragneiss (2.02-1.99 Ga) (e.g., Lenoir et al., 1994; Collins et al., 2004). The Ndembera and Konse Groups comprise relatively younger volcano-sedimentary and granitoid rock assemblages that formed between 1.92 and 1.8 Ga in the arc and back arc tectonic setting (Sommer et al., 2005; Bahame et al., 2016).

We have studied a specimen collected in a metamorphosed mafic to ultramafic body of the Isimani Suite from the village of Winza, about 5 km south of the Yalumba Hill eclogite (Fig. 1b). The body was mined locally to obtain gem-quality corundum (Schwarz et al., 2008). Metamorphic zircon from retrograded eclogites from the Yalumba Hill yielded U-Pb age of ~ 2.0 Ga (Möller et al., 1995).

SAMPLE DESCRIPTION

The talc- and kyanite-bearing amphibolite (sample KTA, Fig. 2a) consists mainly of clinoamphibole, kyanite, talc, with minor amount of rutile, dolomite, quartz, chlorapatite, zircon, and barite. Rare relict chromian spinel partially replaced by corundum is also found as accessory mineral; the occurrence of corundum reflects chemical equilibrium in local domains. Clinoamphibole (~ 0.3-2 mm in length) forms a granoblastic matrix that contains porphyroblastic kyanite (~ 1-5 mm in size). Both clinoamphibole and kyanite are closely associated with talc (Figs. 2b and 2c). Clinoamphibole contains inclusions of kyanite, quartz, talc, and dolomite. Fine-grained barite (typically <10 μm) occurs commonly with dolomite (Fig. 2d); the largest grain reaches ~ 0.2 mm in size. Identification of the minerals was based on a combination of optical property and chemical compositions obtained by FE-SEM with EDS.

Bulk-rock major elements composition of the sample KTA shows low SiO_2 (43.74 wt%), high Al_2O_3 (22.93 wt%), with MgO (12.31 wt%), Fe_2O_3 (6.47 wt%), CaO (9.94 wt%), and Na_2O (1.26 wt%); the loss of ignition was 2.91 wt%. The major elements together with high Ni (790 $\mu g \cdot g^{-1}$), Cr (770 $\mu g \cdot g^{-1}$), Sr (209 $\mu g \cdot g^{-1}$), and Ba (84 $\mu g \cdot g^{-1}$) and the presence of relict chromite (Cr#[= Cr/(Cr + Al)] ~ 0.34) strongly suggest that the protolith of the rock was an olivine-rich cumulus gabbro. Note that the bulk-rock analysis was carried out at the Activation Laboratories Ltd., Canada, using Code 4Litho Lithogeochemistry Package; the package uses fusion inductively coupled plasma optical emission spectrometry (FUS-ICPOES) and inductively coupled plasma mass spectroscopy (FUS-ICPMS) for the major and trace element analyses, respectively. Further details of whole-rock geochemistry will be published after further research development.

MINERAL COMPOSITIONS

Table 1 shows the representative major element composi-

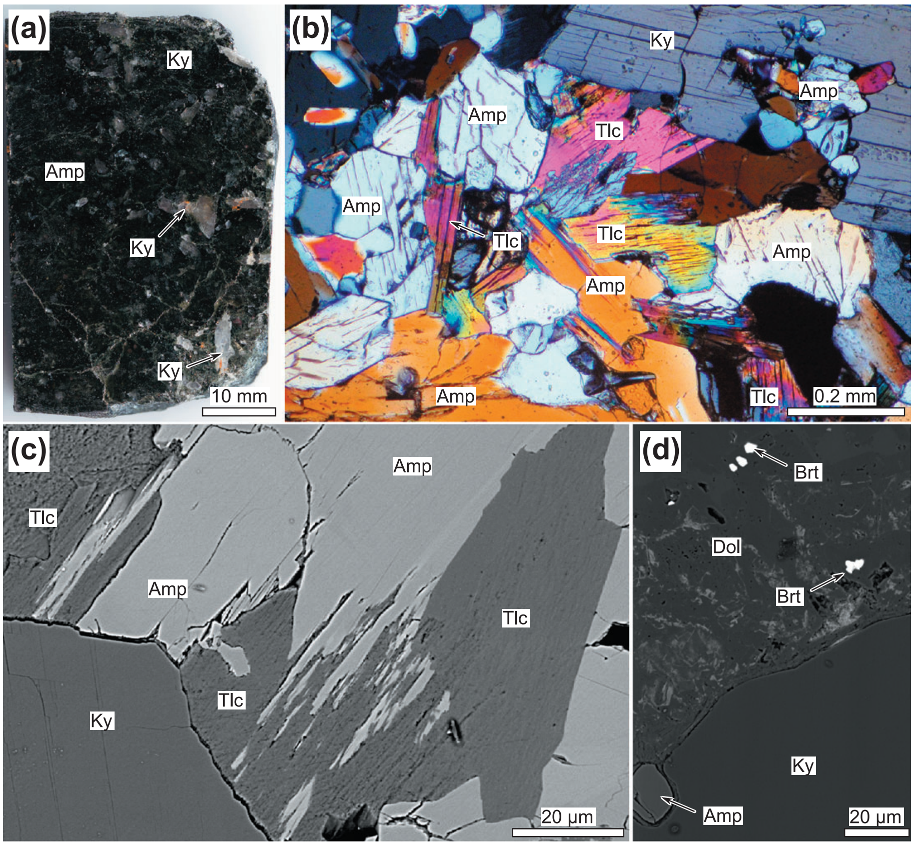

Figure 2. (a) Photograph of polished surface of talc- and kyanite-bearing amphibolite (KTA) from the Usagaran Belt, showing dark-greenish amphibole matrix with porphyroblastic kyanite. (b) Crossed-polarized photomicrograph showing talc-kyanite association with amphibole (KTA). (c) Back-scattered electron (BSE) image showing coexistence of kyanite, talc and clinoamphibole. (d) BSE image showing fine-grained barite (Brt) associated with dolomite (Dol).

tions of clinoamphibole, kyanite, and talc. The compositions were determined using the JEOL JXA-8800R electron microprobe at Tohoku University. The quantitative analyses were performed with a 15 kV acceleration voltage and a 12 nA beam current resulting in a 3 μm spot diameter; the oxide ZAF method was employed for matrix corrections and natural and synthetic silicate and oxide minerals were used for calibrations.

Clinoamphibole has a tschermakitic composition with Si = 6.2–6.5 a.p.f.u. (O = 23), $^{[B]}$Na (Na in the B-site) = 0.13–0.17, $^{[A]}$(Na + K) = 0.28–0.43, and Mg/(Mg + Fe^{2+}) = 0.88–0.94; Al_2O_3 content reaches up to 17.1 wt%. Notably the composition is characterized by high Fe^{3+}/(Fe^{3+} + Fe^{2+}) ratio (0.48–0.80), suggesting an oxidation state higher than magnetite-hematite buffer (Fig. 3). No significant chemical zonation was observed in clinoamphibole.

Kyanite contains 0.4–0.5 wt% Fe_2O_3.

Talc contains moderate Al (1.3–2.6 Al_2O_3 wt%; 0.10–0.20 a.p.f.u for O = 11) and low Fe [Mg/(Mg + Fe^{2+}) = 0.95]. The Al content is significantly higher than talc in coesite-bearing ultra-high pressure eclogite (e.g., Mattinson et al., 2004), but it is lower than yoderite-bearing talc-kyanite schist that formed at a peak pressure of 1.0–1.1 GPa (Jöns and Schenk, 2004).

DISCUSSION

Comparison with whiteschists worldwide

Talc-kyanite schist is synonymous with 'whiteschist' that occurs in high- to ultrahigh-pressure (UH*P*) rocks (Schreyer, 1974, 1988); note that the original definition of 'whiteschist' has been expanded to the UH*P* rock like coesite-bearing pyrope quartzite in the Dora-Maira Massif, Western Alps (e.g., Chopin and Schertl, 1999; Compagnoni and Hirajima, 2001). In the MASH (MgO-Al_2O_3-SiO_2-H_2O) system, the Tlc + Ky mineral assemblage is stable at higher pressure and temperature side of the Chl + Qz and/or Yod + Qz assemblage and at higher pressure and lower temperature side of the Crd + Yod assemblage (Schreyer and Seifert, 1969; Fockenberg and Schreyer, 1994). The whiteschists worldwide have protoliths of Mg-rich and low-Ca lithologies. Comparing with 'whiteschist' in the literature, our amphibolite has a Mg/Si atomic ratio (0.42) resembling to some whiteschists (e.g., Franz et al., 2013); the ratio is higher than that of average MORB (0.28). Ca/Si ratio (0.24) of the sample KTA is much higher than whiteschists worldwide (<0.08: Franz et al., 2013). However, it is noteworthy that the Mg/Si ratio and the high oxidation state of the sample KTA

Table 1. Representative electron-microprobe analyses of clinoamphibole, kyanite and talc

	Clinoamphibole			Kyanite	Talc		
wt%							
SiO_2	44.51	44.70	45.05	37.19	60.73	60.89	59.80
TiO_2	0.07	0.07	0.11	–	–	0.02	0.01
Al_2O_3	16.40	15.98	15.18	62.30	1.58	1.29	2.61
Cr_2O_3	0.14	0.07	0.19	0.10	0.10	–	–
FeO^*	6.61	7.33	7.05	0.34	2.50	2.48	2.69
MnO	0.01	0.11	0.05	0.02	0.07	–	–
MgO	15.01	15.20	15.40	–	28.71	28.93	27.76
CaO	12.23	12.19	12.31	0.02	0.01	0.02	0.05
Na_2O	1.83	1.67	1.59	–	0.09	0.03	0.12
K_2O	0.36	0.37	0.30	–	–	–	0.04
Total	97.17	97.69	97.23	99.97	93.79	93.66	93.08
O=	23	23	23	5	11	11	11
Si	6.295	6.280	6.361	1.005	3.943	3.955	3.914
Ti	0.007	0.007	0.012	–	–	0.001	<0.001
Al	2.734	2.646	2.526	1.984	0.121	0.099	0.201
Cr	0.016	0.008	0.021	0.002	0.005	–	–
Fe^{3+}	0.372	0.579	0.494	0.007	–	–	–
Fe^{2+}	0.410	0.282	0.339	–	0.136	0.135	0.147
Mn	0.001	0.013	0.006	<0.001	0.004	–	–
Mg	3.165	3.184	3.242	–	2.779	2.801	2.708
Ca	1.853	1.835	1.862	0.001	0.001	0.001	0.004
Na	0.502	0.455	0.435	–	0.011	0.004	0.015
K	0.065	0.066	0.054	–	0.000	0.000	0.003
Total	15.420	15.355	15.352	2.999	7.000	6.996	6.992

FeO^*, total Fe as Fe^{2+}.
Fe^{2+}/Fe^{3+} ratio of clinoamphibole was estimated based on total cation = 13 excluding Ca, Na, and K.

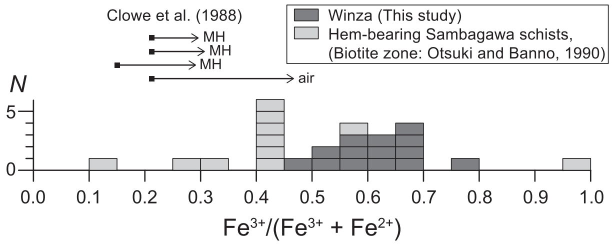

Figure 3. A frequency diagram showing $Fe^{3+}/(Fe^{3+} + Fe^{2+})$ ratio of clinoamphibole of the studied talc- and kyanite-bearing amphibolite. For comparison, clinoamphibole (mostly 'hornblendic') in hematite-bearing mafic schists of the biotite-zone of Sambagawa Belt, central Shikoku (Otsuki and Banno, 1990) is also shown. The arrows represent $Fe^{3+}/(Fe^{3+} + Fe^{2+})$ ratio of natural clinoamphiboles from starting materials to experimental run products (Clowe et al., 1988). MH, magnetite-hematite buffer.

shares a common feature with other whiteschists. Jöns and Schenk (2004) reported a Hbl-Ky-Tlc-Qz schist from the Mautia Hill, where is the type locality of yoderite. The mineral paragenesis of our sample might somewhat resemble the Hbl-Ky-Tlc-Qz schist associated with yoderite-bearing 'whiteschist' of the Mautia Hill. Although our sample does not bear hematite that was described in the Hbl-Ky-Tlc-Qz schist of the Mautia Hill, the occurrence of sulfate (barite) supports very high oxidation state during high-grade metamorphism (e.g., Tumiati et al., 2015; Wang et al., 2016).

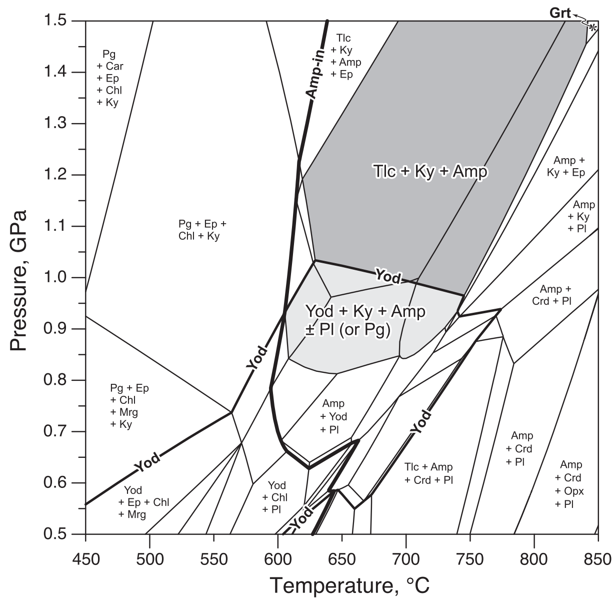

Figure 4. An equilibrium phase diagram of the sample KTA in the system Na-Ca-Mg-Fe-Al-Si-H-O-C with excess hematite, H_2O and CO_2. The stability fields of Tlc + Ky + Amp, Yod + Ky + Amp + Pl (or Pg), and garnet-bearing mineral assemblage (Grt) are highlighted; note that quartz, hematite, and dolomite are also stable in these fields. Bold lines represent the lower T limit of clinoamphibole (Amp-in) and the stability of yoderite (Yod).

P-T pseudosections

The stability field of talc + kyanite strongly depends on oxygen fugacity and the amount of CO_2 in fluid (e.g., Franz et al., 2013). Therefore, we performed a P-T pseudosection (equilibrium phase diagram) modeling using the THERIAK/DOMINO program (de Capitani and Petrakakis, 2010) with together thermodynamic dataset of Holland and Powell (1998) at a highly oxidizing condition (Fig. 4). We adopted the solid solution models of minerals that were used in Tsujimori and Ernst (2014). Treatment of yoderite was based on the approach of Franz et al. (2013). We assumed hematite, H_2O and CO_2 in excess; an excess of hematite is necessary to obtain Yod-bearing phase equilibria. Although solid solution models for clinoamphibole casts doubt on the reliability for Fe^{3+}-rich Ca-amphibole, the chemographic relations in P-T space are helpful in order to understand natural metamorphic parageneses.

As shown in Figure 4, the stability of Yod-bearing mineral assemblages at up to ~ 1.0 GPa gives a lower pressure limit of the Tlc + Ky + Amp assemblage. Because of the highly-oxidized condition to stabilize hematite, the stability field of garnet-bearing mineral assemblage is limited at $T > \sim 840$ °C and $P > \sim 1.5$ GPa. Saturation of CO_2 affects the stability of epidote. If we assume a CO_2-free system, epidote becomes stable instead of dolomite at the stability of the Tlc + Ky + Amp assemblage of Figure 4.

Geological significance

Both natural and experimental evidences have suggested that a highly oxidized condition is preferable for some talc-bearing mineral assemblages in crustal composition rocks (e.g., Fockenberg and Schreyer, 1994; Johnson and Oliver, 2002; Mattinson et al., 2004; Jöns and Schenk, 2004; Franz et al., 2013). The presence of barite as well as the high $Fe^{3+}/(Fe^{3+} + Fe^{2+})$ ratio of clinoamphibole strongly suggests a higher oxidizing condition than the MH (magnetite-hematite) buffer (Fig. 3). Our new finding might indicate that the talc-kyanite association in amphibolite is a result of high oxidation state during metamorphism. Either extensive oxidation of protolith or fluid-mediated syn-metamorphic oxidation would be a possible scenario.

Excepting talc-bearing eclogites, the occurrence of the ‘whiteschist’-like metamorphic rocks with the Tlc + Ky assemblage is rare. All ‘whiteschist’-like rocks in the literature are found in Neoproterozoic and younger orogens. However, our new finding of the talc- and kyanite-bearing amphibolite from a Paleoproterozoic orogen marks the oldest record of the Tlc + Ky assemblage. The ‘whiteschist’ has been considered as a petrotectonic indicator of high- (or ultrahigh-) pressure collisional metamorphism (Schreyer, 1974; Chopin, 2003). Our finding will give a new insight into not only the collisional metamorphism of ~ 2.0 Ga in the Usagaran Belt but also extensive oxidation event of the crustal rocks before or during metamorphism.

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REFERENCES

Abraham, K. and Schreyer, W. (1976) A talc-phengite assemblage in piemontite schist from Brezovica, Serbia, Yugoslavia. Journal of Petrology, 17, 421-439.

Bahame, G., Manya, S. and Maboko, M.A. (2016) Age and geochemistry of coeval felsic volcanism and plutonism in the Palaeoproterozoic Ndembera Group of southwestern Tanzania: Constraints from SHRIMP U-Pb zircon and Sm-Nd data. Precambrian Research, 272, 115-132.

Chinner, G.A. and Dixon, J. E. (1973) Some high-pressure parageneses of the Allalin Gabbro, Valis, Switzerland. Journal of Petrology, 14, 185-202.

Chopin, C. (1981) Talc-phengite: A wide spread assemblage in high-grade pelitic blueschists of the Western Alps. Journal of Petrology, 22, 628-650.

Chopin, C. (1984) Coesite and pure pyrope in high-grade blueschists of the Western Alps: a first record and some consequences. Contributions to Mineralogy and Petrology, 86, 107-118.

Chopin, C. (2003) Ultrahigh-pressure metamorphism: tracing continental crust into the mantle. Earth and Planetary Science Letters, 212, 1-14.

Chopin, C. and Schertl, H. P. (1999) The UHP unit in the Dora-Maira massif, Western Alps. International Geology Review, 41, 765-780.

Clowe, C.A., Popp, R. K. and Fritz, S.J. (1988) Experimental investigation of the effect of oxygen fugacity on ferric-ferrous ratios and unit-cell parameters of four natural clinoamphiboles. American Mineralogist, 5, 487-499.

Collins, A.S., Reddy, S.M., Buchan, C. and Mruma, A. (2004) Temporal constraints on Paleoproterozoic eclogite formation and exhumation (Usagaran Orogen, Tanzania). Earth and Planetary Science Letters, 224, 175-192.

Compagnoni, R. and Hirajima, T. (2001) Superzoned garnet in the coesite-bearing Brossasco-Isasca unit, Dora-Maira Massif, Western Alps and the origin of the whiteschists. Lithos 57, 219-236.

de Capitani, C. and Petrakakis, K. (2010) The computation of equilibrium assemblage diagrams with Theriak/Domino software. American Mineralogist, 95, 1006-1016.

Fockenberg, T. and Schreyer, W. (1994) Stability of yoderite in the absence and in the presence of quartz: an experimental study in the system $MgO-Al_2O_3-Fe_2O_3-SiO_2-H_2O$. Journal of Petrology, 35, 1341-1375.

Franz, L., Romer, R.L. and de Capitani, C. (2013) Protoliths and phase petrology of whiteschists. Contributions to Mineralogy and Petrology, 166, 255-274.

Groppo, C. and Castelli, D. (2010) Prograde *P-T* evolution of lawsonite eclogite from the Monviso meta-ophiolite (Western Alps): Dehydration and redox reactions during subduction of oceanic Fe-Ti oxide gabbro. Journal of Petrology, 51, 2489-2514.

Holland, T.J.B. and Powell, R. (1998) An internally consistent thermodynamic data set for phases of petrological interest. Metamorphic Geology, 309-343.

Izadyar, J., Hirajima, T. and Nakamura, D. (2000) Talc-phengite-albite assemblage in piemontite-quartz schist of the Sambagawa metamorphic belt, central Shikoku, Japan. Island Arc, 9, 145–158.

Johnson, S. P. and Oliver, G. J. H. (2002) High fO_2 metasomatism during whiteschist metamorphism, Zambezi belt, Northern Zimbabwe. Journal of Petrology, 43, 271–290.

Jöns, N. and Schenk, V. (2004) Petrology of whiteschists and associated rocks at Mautia Hill (Tanzania): Fluid Infiltration during high-grade metamorphism? Journal of Petrology, 45, 1959–1981.

Kulke, H. and Schreyer, W. (1973) Kyanite–talc schist from Sar e Sang, Afghanistan. Earth and Planetary Science Letters, 18, 324–328.

Legler, C., Barth, A., Knobloch, A., Mruma, A.H., Myumbilwa, Y., Magigita, M., Msechu, M., Ngole, T., Stanek, K.P., Boniface, N., Kagya, M., Manya, S., Berndt, T., Stahl, M., Gebremichael, M., Dickmayer, E., Repper, C., Falk, D. and Stephan, T. (2015) Minerogenic Map of Tanzania and Explanatory Notes for the Minerogenic Map of Tanzania 1:1.5 M, Geological Survey of Tanzania.

Lenoir, J.L., Liégeois, J.-P., Theunissen, K. and Klerkx, J. (1994) The Palaeoproterozoic Ubendian shear belt in Tanzania: geochronology and structure. Journal of African Earth Sciences, 19, 169–184.

Massonne, H.J. and Kopp, J. (2005) A low-variance mineral assemblage with talc and phengite in an eclogite from the Saxonian Erzgebirge, central Europe, and its P–T Evolution. Journal of Petrology, 46, 355–375.

Mattinson, C.G., Zhang, R.Y., Tsujimori, T. and Liou, J.G. (2004) Epidote-rich talc-kyanite-phengite eclogites, Sulu terrane, eastern China: P–T–fO_2 estimates and the significance of epidote-talc assemblage in eclogite. American Mineralogist, 89, 1772–1783.

McKie, D. (1959) Yoderite, a new hydrous magnesium iron aluminosilicate from Mautia Hill, Tanganyika. Mineralogical Magazine, 32, 282–307.

Miller, C. (1977) Chemismus and phasenpetrologische Untersuchungen der Gesteine aus der Eklogitzone des Tauernfensters, Österreich. Tschermaks mineralogische und petrographische Mitteilungen, 24, 221–277.

Möller, A., Appel, P., Mezger, K. and Schenk, V. (1995) Evidence for a 2 Ga subduction zone: Eclogites in the Usagaran belt of Tanzania. Geology, 23, 1067–1070.

Okay, A. I. (2002) Jadeite–chloritoid–glaucophane–lawsonite blueschists in northwest Turkey: Unusually high P/T ratios in continental crust. Journal of Metamorphic Geology, 20, 757–768.

Otsuki, M. and Banno, S. (1990) Prograde and retrograde metamorphism of hematite-bearing basic schists in the Sanbagawa belt in central Shikoku. Journal of Metamorphic Geology, 8, 425–439.

Råheim, A. and Green, D.H. (1974) Talc-garnet-kyanite-quartz schist from an eclogite-bearing terrane, Western Tasmania. Contributions to Mineralogy and Petrology, 43, 223–231.

Schreyer, W. (1974) Whiteschist, a new type of metamorphic rocks formed at high pressures. Geologische Rundschau, 63, 597–609.

Schreyer, W. (1988) Experimental studies on metamorphism of crustal rocks under mantle pressures. Mineralogical Magazine, 52, 1–26.

Schreyer, W. and Seifert, F. (1969) Compatibility relations of the aluminium silicates in the systems $MgO–A1_2O_3–SiO_2–H_2O$ and $K_2O–MgO–AI_2O_3–SiO_2–H_2O$ at high pressures. American Journal of Science, 267, 371–388.

Schwarz, D., Pardieu, V., Saul, J.M., Schmetzer, K., Laurs, B.M., Giuliani, G., Klemm, L., Malsy, A.K., Erel, E., Hauzenberger, C., Toit, G.D., Fallick, A.E. and Ohnenstetter, D. (2008) Rubies and sapphires from Winza, central Tanzania. Gems & Gemology, 44, 322–347.

Sisson, V.B., Ertan, I.E. and Avè Lallemant, H.G. (1997) High-pressure (~2000 MPa) kyanite- and glaucophane-bearing pelitic schist and eclogite from Cordillera de la Costa Belt, Venezuela. Journal of Petrology, 38, 65–83.

Sommer, H., Kroener, A., Muhongo, S. and Hauzenberger, C. (2005) SHRIMP zircon ages for post-Usagaran granitoid and rhyolitic rocks from the Palaeoproterozoic terrain of southwestern Tanzania. South African Journal of Geology, 108, 247–256.

Tsujimori, T. and Ernst, W. G. (2014) Lawsonite blueschists and lawsonite eclogites as proxies for palaeo-subduction zone processes: A review. Journal of Metamorphic Geology, 32, 437–454.

Tumiati, S., Godard, G., Martin, S., Malaspina, N. and Poli, S. (2015) Ultra-oxidized rocks in subduction mélanges? Decoupling between oxygen fugacity and oxygen availability in a Mn-rich metasomatic environment. Lithos, 226, 116–130.

Ubukawa, T., Hatanaka, A., Matsumoto, K. and Hirajima, T. (2007) Pseudosection analysis for talc–Na pyroxene-bearing piemontite quartz schist in the Sanbagawa belt, Japan. Island Arc, 16, 553–574.

Vrána, S. and Barr, M.W.C. (1972) Talc-kyanite-quartz schists and other high-pressure assemblages from Zambia. Mineralogical Magazine, 38, 837–846.

Wang, S.-J., Wang, L., Brown, M. and Feng, P. (2016) Multi-stage barite crystallization in partially melted UHP eclogite from the Sulu belt, China. American Mineralogist, 101, 654–574.

Whitney, D.L. and Evans, B.W. (2010) Abbreviations for names of rock-forming minerals. American Mineralogist, 95, 185–187.

Zack, T., Rivers, T. and Foley, S.F. (2001) Cs–Rb–Ba systematics in phengite and amphibole: An assessment of fluid mobility at 2.0 GPa in eclogites from Trescolmen, Central Alps. Contributions to Mineralogy and Petrology, 140, 651–669.

Zhang, R.Y. and Liou, J.G. (1994) Coesite-bearing eclogite in Henan Province, central China: detailed petrography, glaucophane stability and PT-path. European Journal of Mineralogy, 6, 217–233.

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