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DISCOVERY OF KYANITE/STAUROLITE IN THE TANANAO METAMORPHIC COMPLEX, TAIWAN: A SUPPLEMENT

Shyh-Lung Hwang[1], Tzen-Fu Yui[2], Hao-Tsu Chu[3] and Pouyan Shen[4]

1. Department of Materials Science and Engineering, National Dong Hwa University, Hualien, Taiwan
2. Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan
3. Central Geological Survey, Taipei, Taiwan
4. Institute of Materials Science and Engineering, National Sun Yat-Sen University, Kaohsiung, Taiwan

ABSTRACT

Kyanite and staurolite are found as *submicron* inclusions in almandine-rich garnet from a metamorphosed Al, Fe-rich paleo-weathering horizon in the Tananao Metamorphic Complex, Taiwan (Hwang *et al.*, 2001). Submicron quartz, rutile/brookite and zircon are also present as associated phases. These submicron-scale minerals were suggested to have formed at >8.3-8.8 kbar and <660-690°C. This P-T condition is different from that (i.e., 5-7 kbar and 530-550°C) derived from rock matrix minerals, which include almandine-rich garnet, muscovite, chlorite, chloritoid, plagioclase, quartz, apatite and ilmenite (Yui *et al.*, 1992). Although these submicron inclusions in garnet may have formed during a preceding tectonic event, it is also quite probable that they are relics of a prograde P-T path during the Penglai orogeny.

Key words: submicron inclusions, kyanite, staurolite, Tananao Metamorphic Complex, Taiwan

INTRODUCTION

The Tananao Metamorphic Complex is the pre-Tertiary basement rock of Taiwan. It has experienced a complicated tectonic and metamorphic history (e.g., Yui *et al*., 1990). Although greenschist to amphibolite facies mineral assemblages have been reported in different rock types, typical high-grade metamorphic index minerals, such as staurolite and kyanite, were not found within the complex. Therefore, it was commonly believed that, except for local fibrolite-bearing migmatitc paragneiss near granitic intrusions and some amphibolite-facies exotic blocks, the highest metamorphic conditions of the Tananao Metamorphic Complex were likely lower than those of the staurolite zone (Chen and Wang, 1995). However, by using analytical electron microscopy (AEM), Hwang *et al*., (2001) recently reported the discovery of kyanite and staurolite as submicron inclusions in almandine-rich garnet from the Hoping area, eastern Taiwan and also presented pressure-temperature (P-T) limits for their formation. In this paper, which is an addendum of Hwang *et al.*, (2001), we will discuss some of the ambiguities in fitting this new discovery with available tectonic/metamorphic history.

GEOLOGICAL BACKGROUND OF THE TANANAO METAMORPHIC COMPLEX

The Tananao Metamorphic Complex consists of two parts: the western Tailuko belt and the eastern Yuli belt (Fig. 1) (Yen, 1963). The former is considered a Jurassic accretionary complex, while the latter, a Cretaceous accretionary complex (Yui *et al.*, 1990, 1998). The Tailuko belt is mainly composed of three rock units—phyllite-quartz-mica schist-metasandstone, metabasite-metachert-marble, and massive marble—intruded by Cretaceous granitic rocks. By contrast, the Yuli belt consists mainly of quartz-mica schist and ophiolitic rocks. Available age data suggest that the Tailuko Belt could have experienced three stages of metamorphism, each corresponding to one tectonic event: high-pressure metamorphism during the mid-Jurassic (tectonic event I), high-temperature metamorphism during the late Cretaceous (tectonic event II), and high- to medium-pressure metamorphism during the late Cenozoic (tectonic event III). The Yuli belt only experienced the latter two stages of metamorphism: high-pressure metamorphism during the late Cretaceous (tectonic event II), and high- to medium-pressure metamorphism during the late Cenozoic (tectonic event III) (Tab.1) (Liou and Ernst, 1984; Yui *et al.*, 1990, 1998).

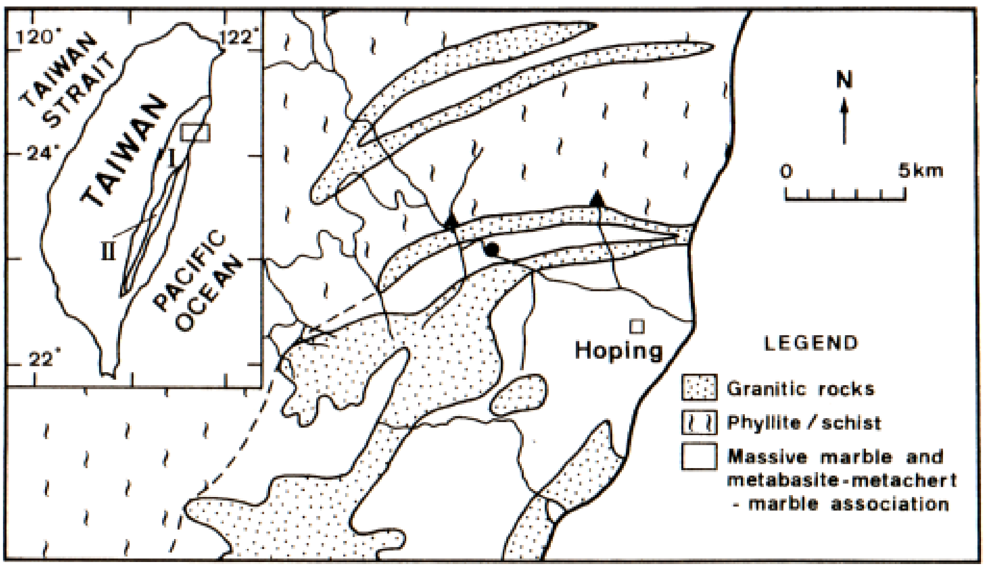

Figure 1. Simplified geologic map of the Hoping area, Taiwan (modified after Yui *et al*., 1994). Inset shows: I - the Tailuko belt and II - the Yuli belt of the Tananao Metamorphic Complex in Taiwan. Closed circle marks the sample locality of garnet-chloritoid rock studied by Hwang *et al*., (2001) and closed triangles mark the sample localities of garnet-bearing mylonite and pelitic schist studied by Lu (1992).

Table 1. Summary of tectonic/metamorphic events of Tananao Metamorphic Complex of Taiwan (Yui *et al*., 1998).

Metamorphic Belt	Tectonic Event Metamorphic age (Metamorphic Characteristics)		
	Event I (subduction)	Event II (subduction)	Event III (subduction-collision)
Tailuko Belt	~175 Ma (high P?)	> 95-85 Ma (high T)	~10 Ma - < 5Ma (high P) (medium P)
Yuli Belt	-	~110-100 Ma (high P)	~10 Ma - < 5Ma (high P) (medium P)

The T-P conditions for the first stage of metamorphism (tectonic event I) are not well constrained because no indisputable mineral assemblages have been reported. The T-P conditions for the second (tectonic event II) and the third (tectonic event III) stages of metamorphism were suggested to be 550-650°C/5 kbar and <350-475°C/2-4 kbar, respectively (e.g., Chu, 1981; Liou and Ernst, 1984; Ernst and Jahn, 1987; Lan and Wang Lee, 1992).

SUBMICRON-SIZE KYANITE/STAUROLITE POLYPHASE INCLUSIONS

Through AEM studies on almandine-rich garnets in the Hoping area of the northern Tailuko belt (Fig. 1), Hwang *et al*., (2001) identified submicron-size kyanite and staurolite inclusions in the garnet-chloritoid rock. First reported by Chiao (1991) and later noted by Yui *et al*., (1992, 1994), this garnet-chloritoid rock has a peculiar chemical composition. The rock changes gradually into a metabasite in the field and exhibits very high contents of Al (Al_2O_3 = 25.68 - 29.95wt%), Fe (FeO = 18.85 - 23.13wt%), Ti (TiO_2 = 3.76 - 6.76wt%), K (K_2O = 1.03 - 2.17wt%), Rb, Cs and Ba (Yui *et al*., 1994). Through detailed geochemical comparisons, it was demonstrated that the protolith of the garnet-chloritoid rock might have resulted from submarine weathering of a basaltic rock (Yui *et al*., 1994). The mineral assemblage in this rock consists of garnet, muscovite, chlorite, chloritoid, plagioclase, quartz, apatite and ilmenite. Micrometer-size inclusions, such as muscovite, chlorite, plagioclase, quartz, apatite and ilmenite, are common in garnet. The garnet is almandine-rich with prominent chemical zoning (i.e., Fe) at the rim. Based on the garnet-plagioclase-muscovite-quartz geobarometer (Hoisch, 1991) and garnet-phengite geothermometer (Hynes and Forest, 1988), the estimated formation conditions for these matrix minerals were 5-7 kbar and 530-555°C (Yui *et al*., 1992).

Submicron-size polyphase inclusions with mineral associations of kyanite-brookite-quartz (Fig. 2a), staurolite-brookite-quartz-zircon (Fig. 2b), staurolite-quartz-rutile (Figure 3 of Hwang *et al*., (2001)), kyanite-quartz-zircon-brookite (Figure 4 of Hwang *et al*., (2001)) and brookite-quartz-zircon were found to be assembled in faceted pockets following {110} of garnet in garnet core from the garnet-chloritoid rock sample LI-C studied by Yui *et al*., (1994). Note that sample LI-C has a porphoroblastic texture. It contains ~2 mm-size garnet porphoroblasts and matrix minerals such as muscovite, chlorite, chloritoid, plagioclase, quartz, apatite and ilmenite. The submicron inclusion assemblage of kyanite, staurolite, rutile and brookite is therefore different from that of the matrix. The well-developed low energy crystal faces of kyanite/staurolite/

brookite/rutile would exclude the possibility that they are of detrital origin. These submicron inclusions must represent an otherwise unrecognized metamorphic assemblage.

The formation condition of these submicron-size mineral inclusions can be constrained by the following two reactions:

3 ilmenite + Al_2SiO_5 + 2 quartz = almandine + 3 rutile (I)

6 staurolite + 12.5 quartz = 4 almandine + 23 kyanite + 6 H_2O (II)

These two reactions were experimentally determined by Bohlen *et al*., (1983) and Ganguly (1972)/Rao and Johannes (1979), respectively. Considering the polymorphism and solid solution effects, the P-T limit was then estimated to be >8.3-8.8 kbar and <660-690°C by Hwang *et al*., (2001) (Fig. 3). Owing to differences in mineral assemblage and metamorphic P-T conditions between the matrix minerals and the submicron inclusions of garnet-chloritoid rocks, Hwang *et al*., (2001) suggested that the submicron kyanite/staurolite inclusions denote an undocumented metamorphic event.

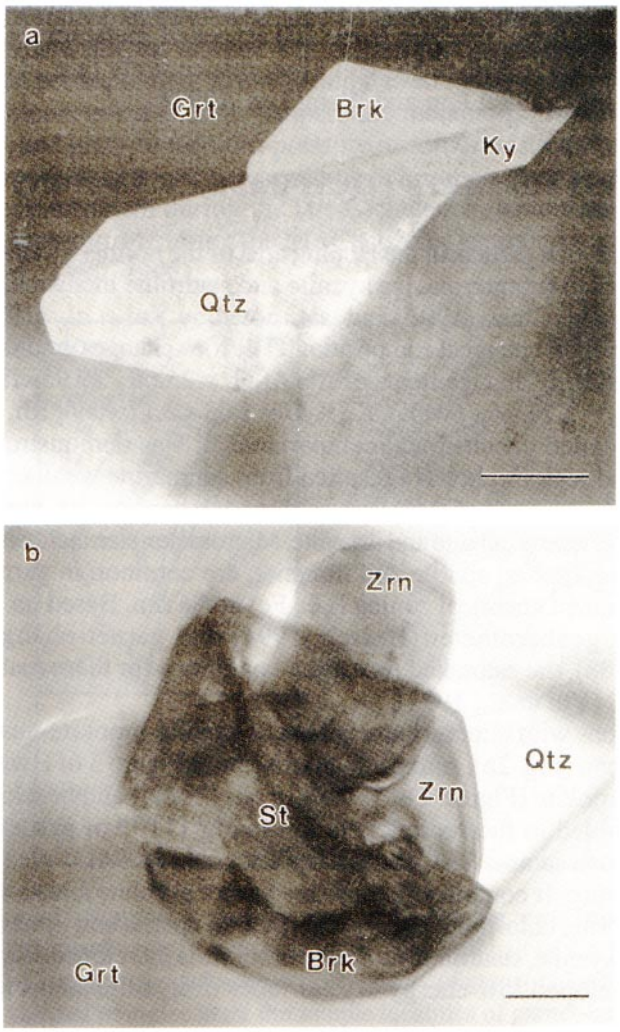

Figure 2. (a) Transmission electron micrograph (bright field image) of submicron inclusion assemblage kyanite (Ky), quartz (Qtz), and brookite (Bk) in garnet (Grt) from sample LI-C. (b) Transmission electron micrograph (bright field image) of submicron inclusion assemblage staurolite (St), brookite (Brk), quartz (Qtz), and zircon (Zrn) in garnet (Grt) from sample LI-C. Scale bar = 200 nm.

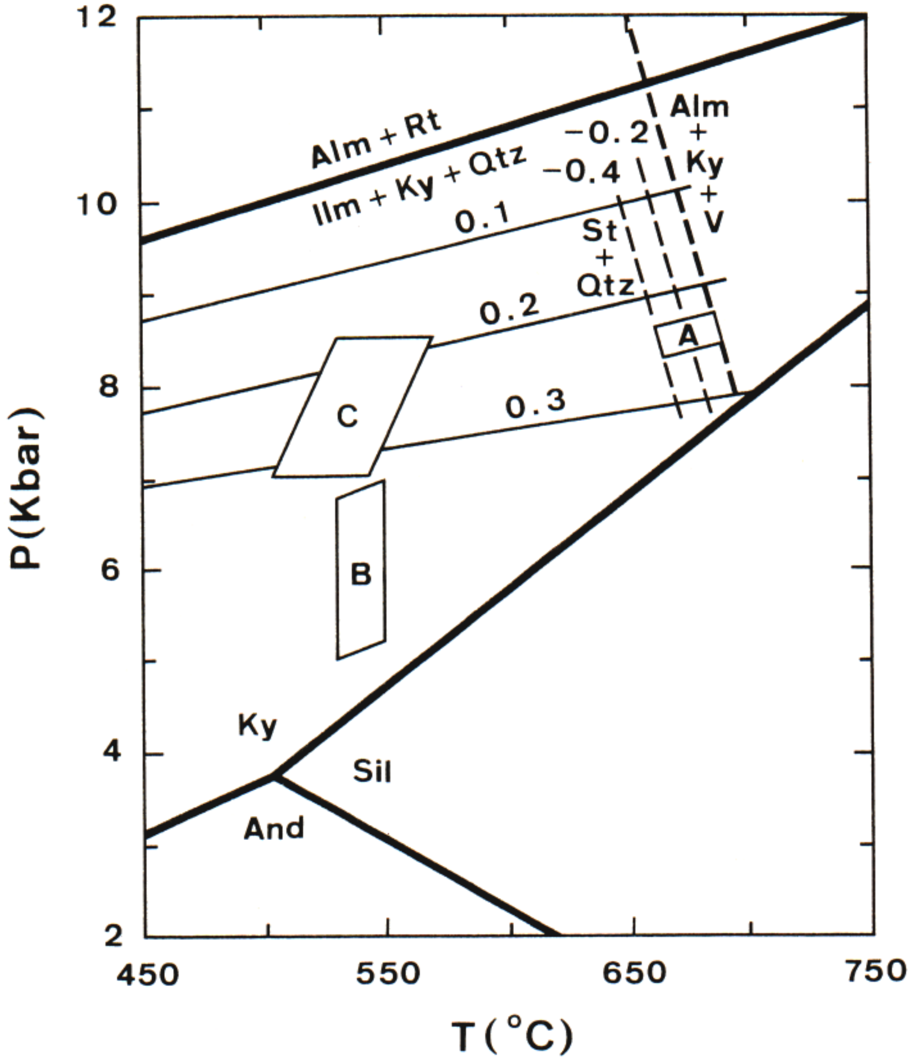

Figure 3. P-T diagram showing the location of Al_2SiO_5 triple point (Holdaway and Mukhopadhyay, 1993), and $log_{10}K$ isopleths for reaction (I) (solid, $K=a^3_{ilm}/a^3_{alm}$, Bohlen *et al*., 1983) and reaction II (dashed, $K=a^4_{alm}/a^6_{st}$, Ganguly, 1972). Box A (8.3-8.8 kbar and 660-690°C) represents the estimated limit of metamorphic P-T condition for the submicron kyanite/staurolite inclusions in garnet-chloritoid rock based on the intersections of reactions (I) and (II) adjusted for solid solution in garnet and staurolite (see Hwang *et al*., 2001). The estimated P-T condition for the matrix minerals of garnet-chloritoid rock, 5-7 kbar and 530-555°C (box B; Yui *et al*., 1992); and for the outer part of garnet in nearby mylonite/schist, 7-8.5 kbar and 500-570°C (box C; Lu, 1992), are also shown for comparison. Alm=almandine; Rt=rutile; Ilm=ilmenite; Ky=kyanite; St=staurolite; Qtz=quartz; V=H_2O; And=andalusite; Sil=sillimanite.

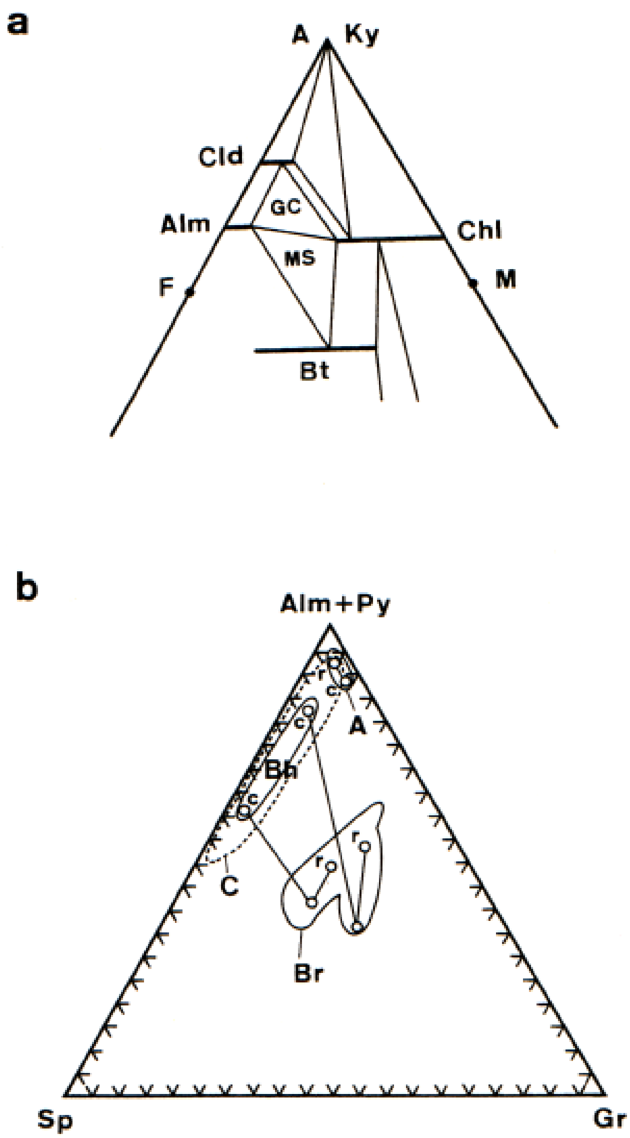

Figure 4. (a) Schematic AFM diagram of lower garnet zone showing mineral assemblages of matrix minerals in garnet-chloritoid rock (GC) and in mylonite/schist (MS) of the Hoping area discussed in the text. Mineral abbreviations: Ky-kyanite, Cld-chloritoid, Alm-almandine garnet, Chl-chlorite, and Bt-biotite. (b) Garnet compositional ranges of garnet-chloritoid rock (A; Yui *et al.*, 1992) and mylonite/schist (Bh: homogeneous core, Br: outer part of garnet with prograde chemical zoning; Lu, 1992) of the Hoping area. Garnet compositional range from Yuantoushan hornblende-absent biotite granite, pegmatite and migmatite (C; see Yui, 1993) is also shown for comparison. c: core and r: rim for representative data. Mineral abbreviations: Alm-almandine, Py-pyrope, Sp-spessartine, and Gr-grossular. The pyrope content in Hoping garnets falls in the range of 3-7%. The differences between groups of Hoping garnets are therefore mainly due to different contents of almandine, grossular and spessartine.

AMBIGUITIES CONCERNING TECTONIC/METAMORPHIC IMPLICATIONS

As previously mentioned, the Tailuko belt of the Tananao Metamorphic Complex purportedly experienced three stages of metamorphism (Tab. 1). The garnet-chloritoid rocks in the present study, which belong to the Tailuko Belt, should therefore have experienced these three stages of metamorphism, i.e., a high-pressure metamorphism during the mid-Jurassic, a high-temperature metamorphism during the late Cretaceous, and a high- to medium-pressure metamorphism during the late Cenozoic. Because the metamorphic T-P conditions (i.e., 530-555^{o}C and 5-7 kbar) for the matrix mineral assemblage of garnet-chloritoid rock are comparable to those of the second stage of metamorphism (i.e., 550-650^{o}C and 5 kbar), Hwang *et al*., (2001) postulated that the tectonic event II might have been responsible for the formation of matrix minerals in garnet-chloritoid rock. The submicron inclusions in garnet can thus be interpreted as the mineral assemblage formed during the prograde stage of this second tectonic event. Following exhumation, the rock experienced conspicuous retrograde metamorphism resulting in the matrix assemblage. Alternatively, the submicron mineral inclusions may be relics of tectonic event I. After their formation, these minerals were largely obliterated during the subsequent metamorphism/tectonic events and only a very small amount of these minerals were preserved as submicron inclusions in garnet. Although Hwang *et al*., (2001) preferred the latter interpretation and suggested that the submicron inclusions are part of the subduction mineral assemblage that formed during tectonic event I, it was also noted that the postulation is a tentative one without any age constraint.

In the Hoping area, garnet, however, not only occurs in garnet-chloritoid rocks but also in granitic mylonite and pelitic schist ~1 km to the north (Fig. 1) (Chiao, 1991; Lu, 1992). The latter rocks contain quartz, garnet, biotite, muscovite, chlorite, plagioclase as the major minerals and epidote, calcite, ilmenite, pyrite, apatite, tourmaline as the minor ones. Mineral inclusions in garnet are not uncommon but are too small to be identified (Lu, 1992). Kyanite and staurolite were not found either. The different mineral assemblage, as compared with the matrix minerals of the garnet-chloritoid rock, can be mainly attributed to different bulk-rock chemical compositions. As shown in Figure 4a, both garnet-chloritoid rock and mylonite/schist show garnet zone mineral assemblages in the AFM diagram (Miyashiro, 1994). The former is plotted above the garnet-chlorite join indicating a higher Al content.

Chemical compositions of garnet in these rocks have been reported by Yui *et al*., (1992) and Lu (1992). Garnet from garnet-chloritoid rocks has higher almandine component than garnet from mylonite/schist, probably reflecting different bulk rock chemistries. However, the latter garnet shows much more prominent chemical zoning (Fig. 4b). Lu (1992) showed that garnet from mylonite/schist possesses a chemically homogeneous core, which has a very low grossular content. Beyond the homogeneous core, the grossular/almandine content shows a sudden increase/decrease. Further toward the rim, the garnet then displays a prograde chemical zoning (Fig. 4b). Following the garnet-biotite geothermometer of Ganguly and Saxena (1984) and the garnet-biotite-plagioclase-muscovite geobarometer of Powell and Holland (1988), Lu (1992) showed that the responsible metamorphic T-P condition for the garnet rim would be 500-570^{o}C and 7-8.5 kbar (see Figure 3). Considering the uncertainties of geothermobarometers, i.e., ±50^{o}C and ±1 kbar (Essene, 1989), this estimate is comparable to that derived from matrix minerals of garnet-chloritoid rocks, i.e., 530-555^{o}C and 5-7 kbar. Although such a high T-P condition was generally attributed to the second stage of metamorphism (see above discussion), Lu (1992) postulated that the outer garnet with prograde chemical zoning was formed during the Penglai orogeny, i.e., tectonic event III in Table 1. If this correlation is correct, the kyanite/ staurolite inclusions in the garnet core of garnet-chloritoid rock would then be an undocumented mineral assemblage during the prograde stage of tectonic event III. Alternatively, these minute inclusions were formed during tectonic event II.

Note that the homogeneous garnet core of mylonite/schist garnet is chemically similar to garnets in the Yuantoushan hornblende-absent biotite granite, pegmatite and migmatite in the northern part of the Tailuko belt (Fig. 4b) (Yui, 1993, and the references therein). The latter garnets were probably formed during tectonic event II as a result of granitic intrusion (Yui and Jeng, 1990). Since different grossular content may imply different pressure conditions if garnet composition was buffered by the same mineral assemblage, the garnet core from mylonite/ schist may have been formed during the same tectonic event (II) as the garnet from the Yuantoushan granitics and migmatite. This low grossular content is also consistent with the conception that, generally speaking, the second stage of metamorphism in the Tailuko belt was a high T/low P one (Tab. 1). The submicron kyanite/staurolite inclusions in garnet-chloritoid rock, which yielded a pressure condition higher than 8.3-8.8 kbar (Hwang *et al*., 2001), would then more likely the result of the third stage of metamorphism. If this is the case, the rocks in the Hoping area may exhibit minerals that were formed at the highest T-P condition, i.e., at the greatest depth, as compared to rocks in other areas of the Tailuko belt during tectonic event III. That means the rocks in the Hoping area experienced the largest amount of uplift during this stage of tectonism. This is consistent with the notion that the Hoping area was the place where the indentation between the Eurasia and the Philippine Sea plate started during the Penglai orogeny (Lu and Malavieille, 1994).

Because of the Al-rich character of the garnet-chloritoid rock, the presence of staurolite and kyanite in this rock does not necessarily imply a metamorphic condition of staurolite or kyanite zone (e.g., Miyashiro, 1994). Without knowing whether biotite or chlorite was the coexisting phase, the submicron kyanite/staurolite inclusions could also have been formed under T-P conditions of higher garnet zone. One way to solve this problem is to see if kyanite and/or staurolite are also present as submicron inclusions in the outer part of garnet from the garnet-bearing mylonite and pelitic schist of the Hoping area. The mylonite and schist probably have chemical compositions similar to those of the typical Barrovian sequence (see Figure 4a). If the inclusions do exist, the highest T-P condition responsible for the formation of these kyanite/ staurolite inclusions would have, at least, reached that of the staurolite zone. Otherwise the temperature estimate for the submicron kyanite/staurolite inclusions by Hwang *et al*., (2001) is slightly high for a garnet zone metamorphism and must shift to a lower range. However, since the outer part of garnet in the garnet-bearing mylonite and pelitic schist exhibits a prograde chemical zoning profile (Lu, 1992), it is difficult to envision how this outer part of the garnet retained staurolite-zone mineral inclusions formed under an even higher T-P condition (unless the inclusions are relics of a previous tectonic event). As a corollary, the temperature estimate by Hwang *et al*., (2001) should shift to a lower range to accommodate the garnet zone metamorphism. Note that because the univariant mineral assemblage of reaction II was not observed coexisting in one submicron inclusion pocket, the temperature estimate indeed was suggested to be an upper limit (Hwang *et al*., 2001). Alternatively, it is also possible to shift reaction II to lower temperatures by reducing the water activity. For example, if the ambient water activity was 0.8, the temperature of reaction II would then decrease by about 60^{o}C following the thermodynamic calculations of Hwang *et al*., (2001). It should be noted that the low water activity theoretically also lowers the reaction temperature of staurolite decomposition/ chloritoid formation during retrograde. The estimated metamorphic temperature of chloritoid-garnet rock was 530-550^{o}C (Yui *et al*., 1992). This estimate is very close to the experimental results of staurolite decomposition/chloritoid formation conducted by Richardson (1968) in the presence of a nearly pure H_2O fluid phase. This suggests that in addition to a P-T drop, an increase of water activity through a decrease of other volatile components, such as CO_2 or CH_4, can trigger a subsequent decomposition of staurolite and the formation of chloritoid. Whether this kind of temporal variation of fluid composition did play a role in causing mineralogical change in the garnet-chloritoid rock during retrograde metamorphism is worthy future research.

CONCLUDING REMARKS

For any metamorphic complex, properly fitting the newly discovered mineral inclusions into the available tectonic/metamorphic history is sometimes difficult without suitable age constraints. The discovery of submicron kyanite/staurolite inclusions in the Tailuko belt of the Tananao Metamorphic Complex is an example in this regard. This paper illustrates that it is difficult to ascertain whether the reported submicron kyanite/staurolite inclusions were formed during the first or third stage of metamorphism. Sm/Nd garnet dating may be one way to solve this ambiguity. Furthermore, due to the peculiar bulk chemical composition, the presence of submicron kyanite/staurolite inclusions in the garnet-chloritoid rock does not necessarily imply a metamorphic condition equal to or higher than that of the staurolite zone. Fluid composition was also suggested to be one of the possible important factors.

ACKNOWLEDGMENTS

In the early 1980's, Professor C.M. Wang Lee boldly predicted that kyanite should be present in the Tananao basement. Almost 20 years later, this paper, as well as Hwang *et al*., (2001), suggests that her intuition was correct. We would like to dedicate the findings to Professor C.M. Wang Lee for her extraordinary perception. Helpful comments from two anonymous reviewers are appreciated. This work was supported by the National Science Council, Taiwan, ROC, under contract NSC85-2111-M-214-001.

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