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High-pressure metamorphism in Taiwan: from oceanic subduction to arc-continent collision?

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ABSTRACT

The Taiwan orogen has been the focus of a number of models of mountain building processes, but little attention has been paid to high-pressure (HP) metamorphic rocks that are found as exotic blocks intermingled within the deepest units of the mountain belt. In this study, we re-appraise from updated petrological and thermodynamic databases the physical conditions of HP metamorphism in Taiwan, and we combine our findings with available geochronological data to estimate the thermal history of these rocks. Our results indicate that peak metamorphic conditions of ~550 °C and 10–12 kbar have been followed by a rapid isothermal decompression, with exhumation possibly as rapid as burial. These units have subsequently been stored at a pressure of ~3 kbar for ~4–5 Myr, before their final exhumation, probably facilitated by the accretion of passive margin sequences during the Late Cenozoic collision. Therefore, HP units in Taiwan maintain a record of processes at depth from the early stages of oceanic subduction to the present arc-continent collision.

Introduction

Petrological and geochronological investigations of high-pressure (HP) metamorphic rocks have provided valuable insights into the kinematics of burial and exhumation of these materials (e.g. Chopin, 2003; Jolivet *et al.*, 2003; Ernst, 2005) and hence have been key in better understanding the mechanical and rheological aspects of the crust and lithosphere (e.g. Burov *et al.*, 2001; Gerya and Stockhert, 2006). This study focuses on HP rocks that have been reported in Taiwan (Liou *et al.*, 1975; Yui and Lo, 1989) (Fig. 1). The Taiwan mountain belt results from the collision between the Luzon volcanic arc and the Chinese continental margin, dated at ~6.5 Ma (Lin *et al.*, 2003). This collision followed the subduction of the South China Sea oceanic crust below the Philippine Sea plate, which initiated ~15 Ma ago (e.g. Huang *et al.*, 2006) and which is still active to the south of Taiwan along the Manila trench (e.g. Teng, 1990; Malavieille *et al.*, 2002). This young orogen consists mostly of metasediments, including remnants of the basement of the Chinese passive margin (Tananao Complex, TC) exhumed to the east (Ho, 1986) (Fig. 1). This young orogen is characterized by high rates of deformation and erosion (e.g. Simoes and Avouac, 2006) and has been intensively studied in terms of mountain building processes (e.g. Suppe, 1981; Dahlen and Barr, 1989; Fuller *et al.*, 2006; Simoes *et al.*, 2007). However, in these models, little attention has been paid to the HP metamorphic rocks reported within the TC along the suture zone (Fig. 1). These rocks are found in 'exotic' blocks that are characterized by totally different lithological and petrological properties from those observed in the surrounding TC schists (Liou, 1981). Two HP blocks have been described: the Juisui block with glaucophane schists and amphibolites (Liou *et al.*, 1975) and the Wanjung block with omphacite-bearing ultramafic rocks within a serpentinite melange (Yui and Lo, 1989). Because of extremely bad surface exposure, the tectonic relationship of these blocks to the bulk of the TC remains largely unclear. Petrological investigations (Liou *et al.*, 1975; Yui and Lo, 1989) indicate peak metamorphic conditions of ~400–450 °C and 6–8 kbar, which certainly need to be re-evaluated in light of more recent thermodynamic databases. Various geochronological techniques were applied to these HP rocks and provide constraints on the timing of the exhumation of these units. Jahn *et al.* (1981) obtained Rb–Sr ages on amphiboles from the Juisui blueschists in the range 8–14 Ma. Ages of 10–12 Ma were obtained by K–Ar (Juang and Bellon, 1986) and ^{40}Ar–^{39}Ar (Lo and Yui, 1996) on phengites from these blueschists. Lo and Yui (1996) retrieved ^{40}Ar–^{39}Ar ages of 4.5 Ma on phlogopites from the Wanjung rocks. It is to be noted that these HP units have geochronological ages only slightly older than the onset of the late Cenozoic collision.

The purpose of this study was to re-appraise the physical conditions of HP metamorphism in Taiwan. We re-investigated the mineralogy and petrology of these units on the basis of recent thermodynamic databases, which have undergone considerable improvement over the last years. When combined with geochronological ages, the *P*–*T* history of HP rocks provides possible insights into the kinematics of burial and exhumation during the transition from oceanic subduction to arc-continent collision.

Sampling and methods

In the Juisui area, no rocks were found in place because of extremely bad exposure conditions. All the samples were collected in two small rivers draining exclusively the HP units according to the map of Liou *et al.* (1975). A large diversity of rocks was found in the Juisui area: glaucophane schists (glnS – samples Y0403 a and Juisui02-1), garnet-epidote

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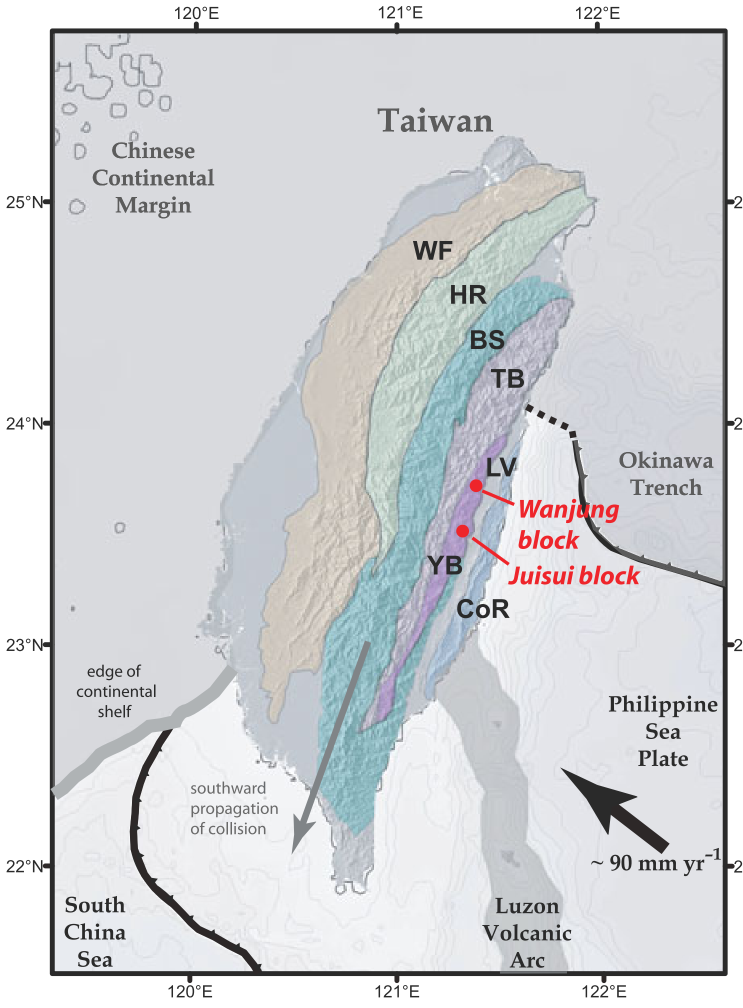

Fig. 1 Geological map of Taiwan and geodynamic context. Taiwan is composed of the Taiwan mountain belt to the west and the Coastal Range (CoR – remnant of the Luzon Arc) to the east. They are separated by the Longitudinal valley (LV), a deep elongated sedimentary basin that forms the suture between the two plates. The Taiwan mountain belt results from the collision between the Chinese continental margin and the Luzon volcanic Arc. From west to east, the Taiwan mountain belt is composed of the western foothills (WF – fold and thrust belt), the Slate belt, which includes the Cenozoic metasediments of the Hsuehshan Range units (HR) and the Backbone Slates (BS), and the Tananao complex (TC) consisting of pre-tertiary basement of the margin [Tailuko belt (TB) and Yuli belt (YB)]. Metamorphic grade associated with the late Cenozoic collision generally increases from west to east, reaching temperatures of up to ~500 °C in the eastern TC, with some complexities in the western slate belt (e.g. Beyssac *et al*., 2007).

amphibolites, epidote amphibolites (not described here, as no HP evidence was detected in these rocks) and garnet-bearing blackschists (grtS – samples Y0404 a, b, c and f). In Wanjung, the omphacite-bearing rocks (ompR – samples Y0402 a and b), possibly metagabbro, were collected from the abandoned serpentine quarry described by Yui and Lo (1989) as an inclusion within a serpentinite mélange. All these rocks may have an oceanic origin from deep sea sediments (glnS) to basalt (amphibolites) or gabbro (ompR).

For all the rocks, mineralogy was determined through optical microscopy, completed by X-ray diffraction. The chemical analysis of minerals was performed using a Cameca SX100 electron microprobe (Camparis, Université Paris VI) using standard conditions (15 kV, 10 nA) and the chemical standards described in Table 1. The garnet blackschists from the Juisui exotic block were analysed by the Raman spectroscopy of carbonaceous material (RSCM) technique, which provides a sensitive geothermometer for peak metamorphic temperature in such rocks (Beyssac *et al.*, 2002, 2004). The samples were analysed using the experimental conditions described by Beyssac *et al.* (2007) and following the procedure described by Beyssac *et al.* (2003). Results are summarized in Table 2.

Petrology and *P–T* history

Figure 2 illustrates representative mineral assemblages observed in the rocks from Juisui and Wanjung. All mineral abbreviations are after Kretz (1983) except for amphibole (am) and water (w). The glnS contains zoned amphiboles (Ca-am core and gln rim, and vice-versa), grt + phg as an early assemblage, and chl, ep, ab as a retrograde assemblage. The grtS contains grt locally retrograded to chl, phg and ab. More details regarding the petrology of these rocks may be found in Liou *et al.* (1975) or Liou (1981). Representative analyses and structural formulae of px, gln, grt, chl and phg for Juisui are given in Table 1. Ternary plots for phengite and garnets, and an amphibole compositional diagram, are given in Fig. 3. Blue amphiboles from the Juisui glnS are essentially sodic, with glaucophane compositions with average XMg values of 0.46 and $Fe^{3+}/(Fe^{3+} + Al^{VI})$ ranging between 0.31 and 0.45 (Fig. 3a). Phengites show variable composition in garnet blackschists and glnS (Fig. 3). High Si-content phengites with significant celadonite content (up to 45%) are observed within the glnS, whereas phengites from the grtS have intermediate compositions up to ~35% (Fig. 3b). Garnets generally show ferrous compositions with $X_{Alm} > 60\%$ in both the garnet blackschists and glnS from Juisui (Fig. 3c). In the Wanjung ompR, mineralogy is restricted to the presence of px, ep, minor ab and qtz for the peak assemblage, and late ab, chl and phl for the retrograde assemblage. Pyroxenes are omphacitic with variable jadeite

Table 1 Representative electron microprobe analysis of px, gln, am, grt, phg and chl in the glaucophane schists (glnS) and garnet blackschists (grtS) from Juisui and the omphacite-bearing rock (am, ompR) from Wanjung.

Mineral	Px	Px	Gln	Gln	Am	Grt	Grt	Phg	Phg	Chl	Chl
Sample	ompR	ompR	GlnS	GlnS	GlnS	GlnS	GrtS	GlnS	GrtS	GlnS	GrtS
SiO_2	57.14	56.86	54.04	53.00	46.53	37.40	36.98	48.81	45.82	25.80	24.32
TiO_2	0.03	0.02	0.02	0.04	0.24	0.00	0.16	0.03	0.06	0.00	0.05
Al_2O_3	13.23	9.34	8.33	7.53	9.44	20.84	20.89	24.86	31.39	19.05	20.85
FeO	2.07	2.67	18.99	20.19	22.83	25.13	29.99	6.11	3.41	27.51	28.32
MnO	0.05	0.23	0.27	0.18	0.30	8.51	2.83	0.04	0.03	1.38	0.54
MgO	6.70	9.47	6.17	6.99	6.80	2.47	1.39	2.50	1.96	13.46	12.03
CaO	11.61	15.50	1.04	2.54	6.33	5.63	9.46	0.05	0.10	0.10	0.12
Na_2O	8.78	6.12	6.52	6.13	4.01	0.05	0.06	0.31	0.64	0.04	0.04
K_2O	0.00	0.01	0.03	0.06	0.31	0.00	0.01	10.37	9.47	0.05	0.01
F	–	–	0.02	0.00	0.13	0.00	0.00	0.02	0.11	0.04	0.01
Total Structural formula	99.61	100.22	95.43	96.66	96.91	100.03	101.77	93.10	92.99	87.43	86.29
Si	2.00	2.01	7.88	7.71	6.93	3.00	2.91	3.41	3.15	2.78	2.66
Ti	0.00	0.00	0.00	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.00
Al	0.55	0.39	1.43	1.29	1.66	1.97	1.94	2.05	2.55	2.42	2.69
Fe2+	0.02	0.08	1.69	1.69	1.70	1.63	1.76	0.36	0.20	2.48	2.59
Fe3+	0.04	0.00	0.63	0.77	1.14	0.06	0.24	–	–	–	–
Mn	0.00	0.01	0.03	0.02	0.04	0.58	0.19	0.00	0.00	0.13	0.05
Mg	0.35	0.50	1.34	1.52	1.51	0.30	0.16	0.26	0.20	2.17	1.96
Ca	0.44	0.59	0.16	0.40	1.01	0.48	0.81	0.00	0.01	0.01	0.01
Na	0.60	0.42	1.84	1.73	1.16	0.01	0.01	0.04	0.09	0.01	0.01
K	0.00	0.00	0.01	0.01	0.06	0.00	0.00	0.92	0.83	0.01	0.00
F	–	–	0.01	0.00	0.06	0.00	0.00	0.00	0.02	0.01	0.00
Sum.	4.01	4.00	15.01	15.14	15.30	8.02	8.03	7.04	7.05	10.02	9.97
a_{Gln}			0.03	0.02							
X_{Jd}	0.55	0.39									
X_{Prp}						0.01	0.06				
X_{Mg}			0.44	0.47	0.53	0.15	0.08	0.42	0.51	0.45	0.43

Mineral abbreviations after Kretz (1983) except am for amphibole. Standards used for electron microprobe analyses are Fe_2O_3 (Fe), $MnTiO_3$ (Mn, Ti), diopside (Mg, Si, Ca), orthoclase (Al, K), albite (Na) and CaF_2 (F). Mineral abbreviations after Evans (1990). Fe^{3+}calculation after Droop (1987) except for chl and phg where $Fe_{tot} = Fe^{2+}$. Activity of gln after and X_{Jd} in px after Morimoto *et al.* (1988).

Table 2 Peak metamorphic temperatures in the Juisui garnet blackschist obtained from RSCM thermometry.

Sample	Nb spectra	R2	SD	*T*	SE
Y0404a	11	1.70	0.07	569	9
Y0404b	12	1.53	0.04	573	5
Y0404c	10	1.27	0.06	578	7
Y0404F	8	2.29	0.04	547	3

R2 ratio with standard deviation (SD), *T* with standard error (SE). See Beyssac *et al.* (2002) for more details.

content, X_{Jd}, ranging between 0.20 and 0.58 (Fig. 3d and Table 1).

To reconstruct the *P–T* history of the glnS, we used the petrogenetic grid of Evans (1990), which best corresponds to the observed compositions and activities of gln (0.020–0.036), grt (0.001–0.004), ep (0.38–0.42) and chl (0.01–0.02) (Fig. 4). In addition, (i) the reaction ms + chl + ab + w = pg + cel is used to set an upper *P* limit (no paragonite detected – Si_{max} = 3.4 in phengite) using PTAX (Berman *et al.*, 1987) with the Berman (1988) thermodynamic database and activity models of Massone (1995) for phengite and Evans (1990) for chlorite; and (ii) the Ti-content amphibole thermometer yields 430–500 °C for the glaucophane and 480–560 °C for the sodicalcic amphibole (Table 1) replacing glaucophane (Colombi, 1989). In the grtS, peak metamorphic *T* was estimated at ~550–580 °C with RSCM thermometry (Table 2). To constrain part of the retrograde path of the grtS, multi-equilibrium calculations were performed using the TWQ 2.02 program associated with the Berman (1988) thermodynamic database and completed by thermodynamic data and solid solution models for chlorite (Vidal *et al.*, 2001, 2005) and phengite (Parra *et al.*, 2002) following the procedure described in Vidal and Parra (2000). Calculations were performed in the NaKMASH system using grt–chl–phg–ab–qtz–w equilibria. In the ompR, the reaction of ab = jd + qtz was exploited to constrain peak *P* conditions using the highest jadeite content in pyroxene (X_{Jd} = 0.58). However, we do not have any constraint on *T*.

All results are summarized in Fig. 4. Peak metamorphic conditions for the glnS blocks are ~10–12 kbar and ~550 °C (epidote-blueschist to eclogite facies), whereas peak *P–T* conditions in Wanjung may vary between ~9 and ~13 kbar and in the range 350–550 °C. The *P–T* path during exhumation of the Wanjung block could not be determined. In the case of the Juisui block, retrograde mineral

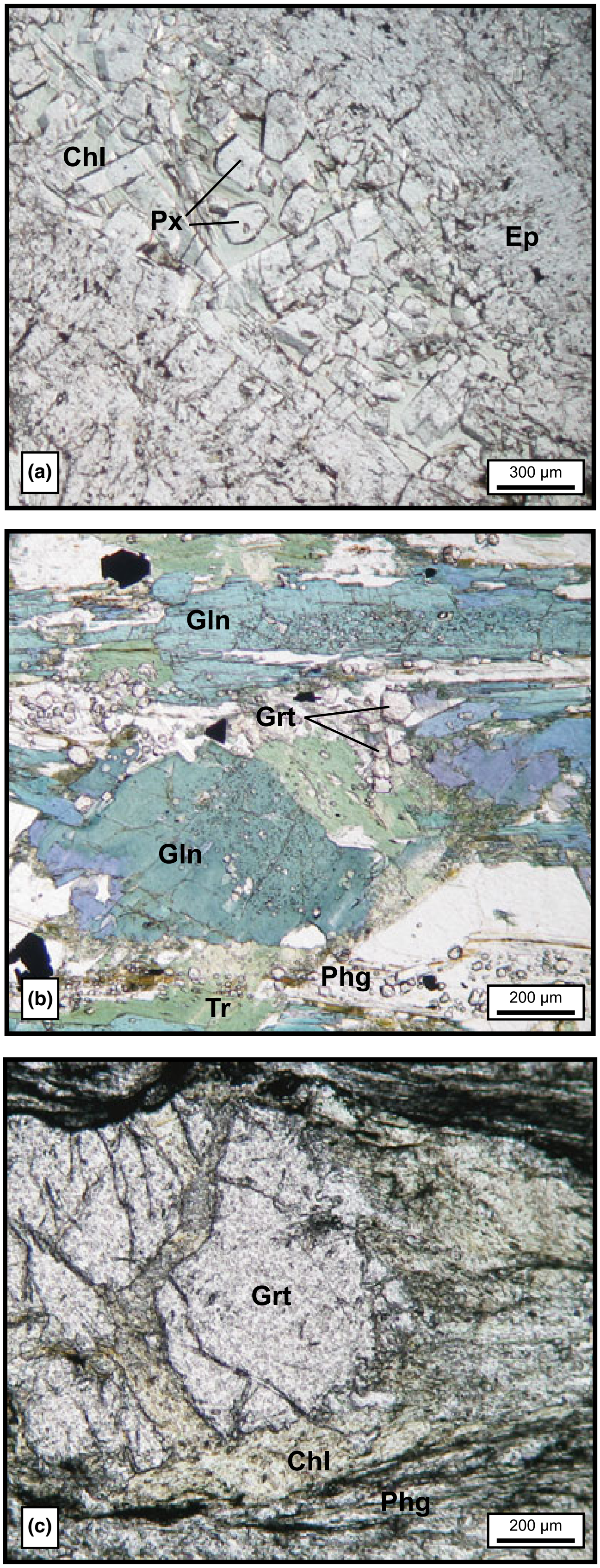

Fig. 2 Representative optical photomicrographs of mineral assemblages in high-pressure metamorphic rocks from Taiwan. (a) ep + chl + px assemblages in the Wanjung ompR. (b) Grt + phg + am assemblages in the Juisui glaucophane schist. Note the complex zoning pattern in the amphiboles. (c) Grt + phg + chl assemblages in the Juisui garnet blackschist. Mineral abbreviations after Kretz (1983), except for amphibole (am).

reactions for glnS and multi-equilibrium thermobarometry for grtS indicate a consistent exhumation path with isothermal decompression at ~500–550 °C from 10–12 to 4 kbar. In particular, peak temperature conditions indicated by mineral assemblages are consistent with those obtained by RSCM for the grtS. For both Wanjung and Juisui, pressure conditions of metamorphism are significantly higher than those previously described in the literature (Liou *et al.*, 1975; Yui and Lo, 1989).

Discussion: kinematics of exhumation of HP units in Taiwan

The *P–T* paths found for the HP Juisui and Wanjung blocks (Fig. 4) are combined in Fig. 5 with available geochronological constraints (Jahn *et al.*, 1981; Lo and Yui, 1996). Lo and Yui (1996) emphasized that ^{40}Ar–^{39}Ar ages could be interpreted as either crystallization or cooling ages. In the case of ultra HP conditions or of a low-geothermal gradient during burial and exhumation, ^{40}Ar–^{39}Ar ages have been interpreted as crystallization ages (e.g. Scaillet, 1996; Agard *et al.*, 2002). Considering the *P–T* paths obtained above (Fig. 5), the glnS were heated to temperatures (~500–550 °C) significantly higher than the closure temperatures commonly assumed for ^{40}Ar–^{39}Ar in phengites (~400 °C). It therefore seems plausible to consider that these geochronological constraints represent cooling rather than crystallization. This may not be totally the case for ^{40}Ar–^{39}Ar (Lo and Yui, 1996) and Rb–Sr (Jahn *et al.*, 1981) ages on amphibole because the probable closure temperature is much higher (~500 °C after Li *et al.*, 2000). However, these ages on

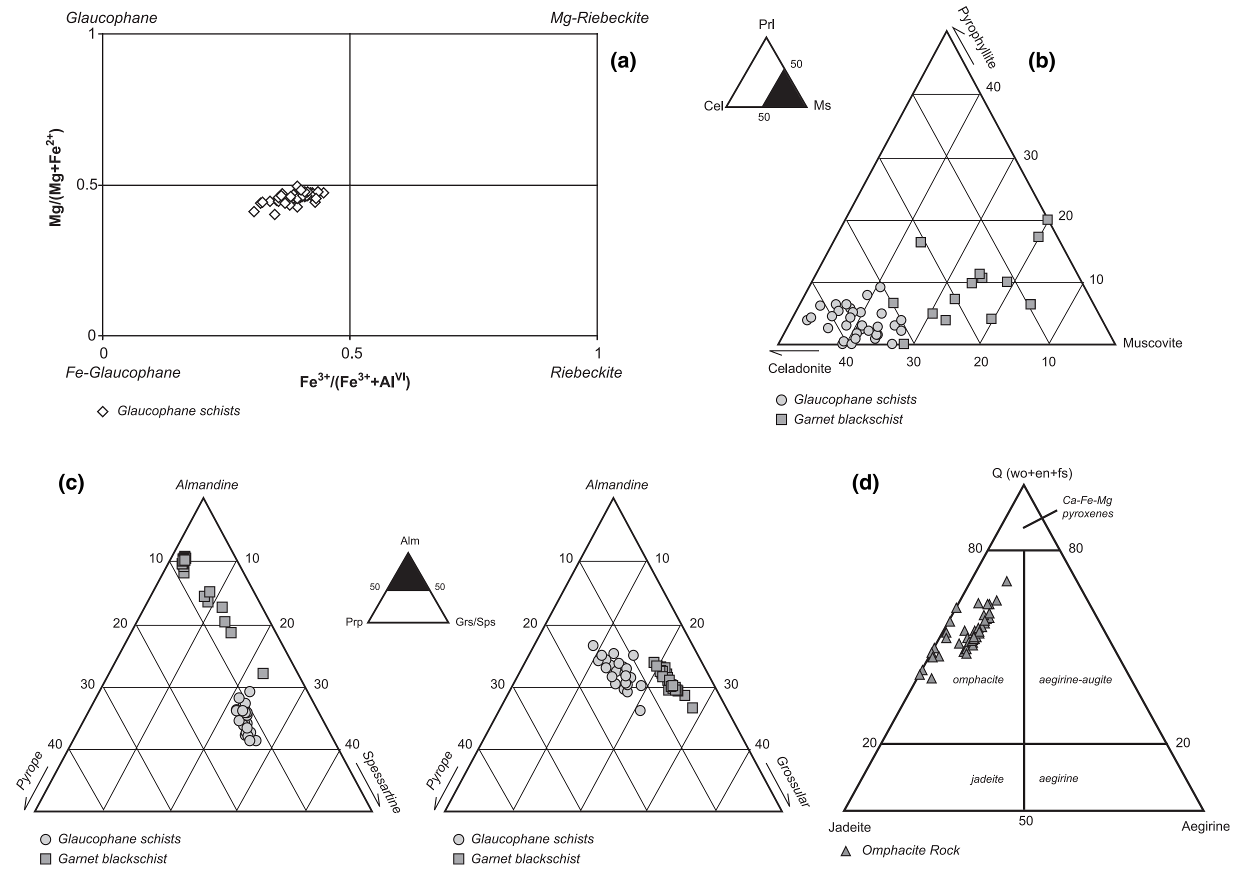

Fig. 3 Mineral compositions for the glaucophane schist and the garnet blackschists from Juisui (a–c) and the omphacite-bearing rocks from Wanjung (d). (a) Blue amphibole compositional diagram after Leake *et al.* (1997). (b) Cel + Ms + Prl ternary diagram of phengite compositions. (c) Alm–prp–sps and alm–prp–grs ternary diagrams of garnet compositions. (d) Composition of clinopyroxene after Morimoto *et al.* (1988). Mineral abbreviations after Kretz (1983).

amphiboles may not be easily interpreted, in particular for ^{40}Ar–^{39}Ar, as the age spectrum is highly disturbed (Lo and Yui, 1996), possibly because of the observed chemical zonations (Fig. 2). Because of a ~78 Ma Rb–Sr isochron obtained on amphiboles from Juisui amphibolites, some authors proposed that the HP stage was Cretaceous and occurred during the subduction of a Palaeo-Pacific plate and that these rocks were subsequently involved in the late Cenozoic collision, with greenschist metamorphism resetting most of the geochronometers. Because such a Cretaceous hypothesis relies on a single isochron for rocks with no HP evidence, and considering that all reliable geochronological data obtained on HP rocks are younger than 20 Ma, we tend to favour a Cenozoic age for HP metamorphism as initially proposed by Ernst and Jahn (1987). In this case, the timing of peak HP conditions would be after ~15 Ma (initiation of subduction) but before ~10 Ma when the rocks had already cooled down to ~400 °C. This also indicates that isothermal decompression from peak metamorphism to shallow P–T conditions of ~400 °C and ~3 kbar took ~5 Myr at most, with exhumation rates of at least ~7–8 mm yr^{-1}, and probably as fast as burial rates if this decompression lasted ~1 Myr. Exhumation of these units subsequently slowed down considerably sometime between ~10 and ~4.5 Ma, with rates of ~0.6 mm yr^{-1} on average (Fig. 5). A recent realm with faster exhumation rates of ~2.5 mm yr^{-1} on average occurred since 4.5–10 Ma. In Fig. 5, we compare this P–T–t path with that predicted for the eastern TC units in the thermokinematic model of Simoes *et al.* (2007). The Juisui and Wanjung HP blocks are embedded within the TC schists, but their structural relation remains largely unclear because of poor surface exposure. The observed serpentinite mélange in the Wanjung quarry supports the idea that these blocks are exotic relative to the bulk of the Taiwan mountain belt. Also, our findings strengthen the case for a tectonic contact between the HP and TC units. Indeed, the timing and the physical conditions of metamorphism are quite different for the HP blocks and for the TC schists (Fig. 4). Their P–T–t paths only become consistent at shallow depths and over the last ~2 Myr.

Rapid isothermal decompression after peak metamorphic conditions (Fig. 5), with exhumation possibly as fast as burial, is classically observed on HP bodies and is usually taken as evidence of forced flow within a

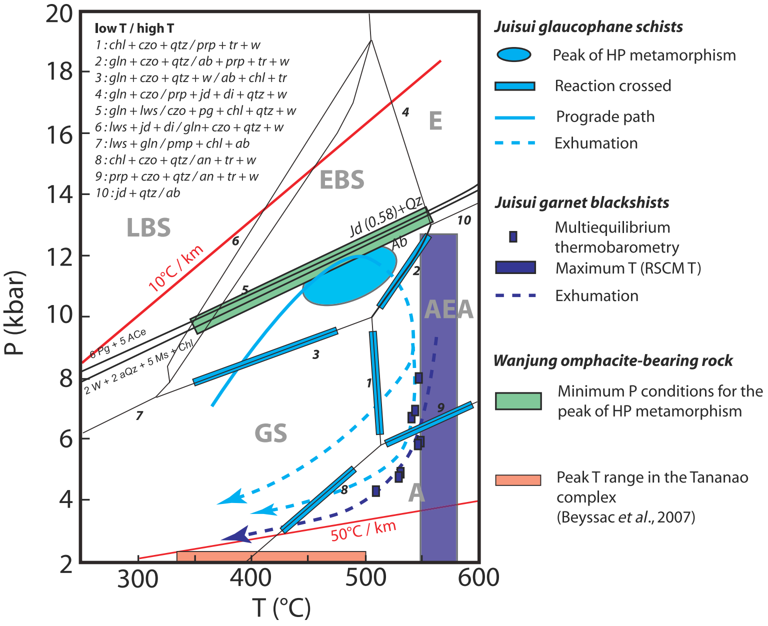

Fig. 4 Pressure–temperature diagram showing the *P–T* constraints for the HP metamorphic rocks from Juisui and Wanjung. For the Juisui glaucophane schist, the petrogenetic grid of Evans (1990) is selected for the observed compositions and activities of gln, grt, ep and chl and the *P–T* path is proposed following the textural information (compositional zoning in am, late grt). Note that the two exhumation paths through reaction 1 and 9 + 8 are equivalent. *P* is constrained by reactions 2 and 3 and from the Si-content based on the phengite barometer, whereas the Ti-content amphibole thermometer yields 430–500 °C for glaucophane and 480–560 °C for the sodic/calcic amphibole replacing glaucophane (see text). For the Juisui garnet-blackschist, the peak *T* is estimated from RSCM thermometry and the early exhumation path from multi-equilibrium thermobarometry. For the Wanjung ompR, *P* is estimated with the Ab = Jd + Qz reaction calculated with the highest jadeitic content in pyroxenes. Metamorphic facies are greenschist (GS), lawsonite and epidote blueschist (LBS and EBS), amphibolite (A), albite-amphibole amphibolite (AEA) and eclogite (E); see Evans (1990) for more details. Mineral abbreviations after Kretz (1983), except w for water.

subduction channel that develops as the mantle wedge is progressively hydrated (e.g. Cloos, 1982; Gerya *et al.*, 2002). Here, this hydration of the mantle wedge may have been limited, because peak metamorphic conditions have been attained quite rapidly after the initiation of oceanic subduction (< 5 Myr). In any case, the buoyant serpentinites observed in Wanjung, whether from the mantle wedge or from hydrothermal alteration of subducted oceanic crust, may have facilitated the initially fast exhumation of HP units. Between 10 and 4.5 Ma, exhumation of HP rocks decreased considerably and it is possible that these units were stored for some time at *P–T* conditions of 350–400 °C and ~3–4 kbar (Fig. 5). This is similar to results obtained in the numerical simulations of Gerya and Stockhert (2006) in which the upward movement of HP units may stop at the base of a rigid upper plate. Rigidity of the Philippine Sea plate is indicated by its subsequent limited deformation during the collision relative to the accreted series of the passive margin forming the bulk of the Taiwan mountain belt (e.g. Simoes *et al.*, 2007). Finally, the last stages of exhumation, since 4.5–10 Ma, may simply be related to the onset of mountain building by 6.5 Ma when arc-continent collision initiated. Indeed, exotic HP blocks stored at shallow depths may have been scraped off during accretion of the TC basement to the collisional wedge. However, structural and deformation analysis of HP units, in particular relative to their position within the TC schists, as well as additional constraints on their low-temperature history, are needed to refine and test this idea.

Conclusion

In this study, we have re-appraised the physical conditions of HP metamorphism in Taiwan. We find that these units have been buried to depths of ~35–40 km and that they have subsequently been rapidly exhumed to intermediate depths of ~11 km sometime between 15 and 10 Ma. As such, they have recorded the thermal conditions that prevailed during the early oceanic subduction prior to the collision dated at ~6.5 Ma in Taiwan. This collision and the subsequent accretion of passive margin sequences to the mountain belt have probably entrained these HP rocks up to the surface, where they appear now as exotic blocks intermingled within the TC schists along the suture zone. Although exhumation and preservation of these HP units may reflect specific rheological and lithological conditions (e.g. Raimbourg *et al.*, 2007), they possibly represent the only preserved thermal record of the transition from oceanic subduction to arc-continent collision in Taiwan and as such should be integrated into

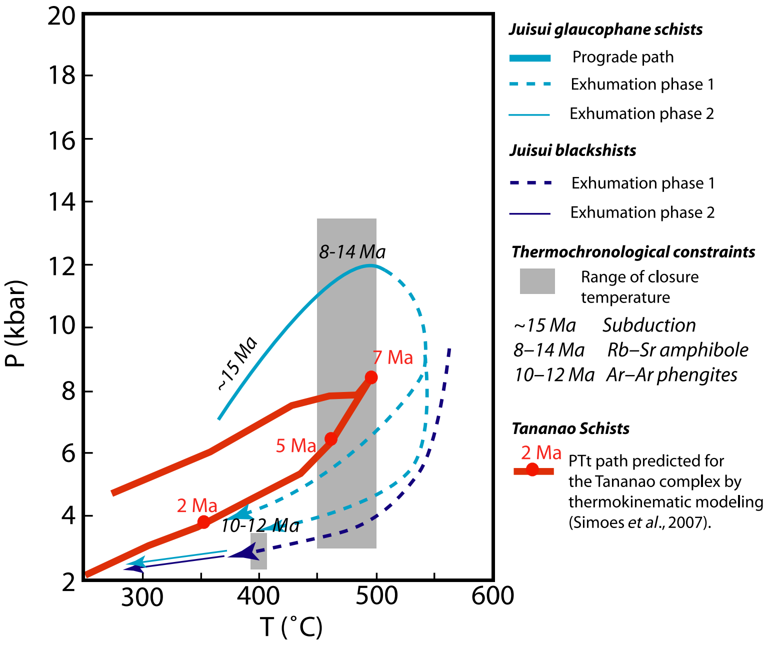

Fig. 5 Tentative *P–T–t* history for the HP metamorphic rocks from Juisui and Wanjung. PT path is calculated in the present study, ^{40}Ar–^{39}Ar ages are taken from Lo and Yui (1996) and Rb–Sr data from Jahn *et al.* (1981). The closure temperatures are taken from the source paper for ^{40}Ar–^{39}Ar, and the closure *T* for Rb–Sr on amphiboles is taken from Li *et al.* (2000). Given that peak metamorphic *T* are significantly higher than closure temperatures, we interpret the ^{40}Ar–^{39}Ar data as cooling rather than crystallization ages. In the case of the Rb–Sr ages on amphiboles, we leave here the possibility that these ages reflect crystallization and/or cooling (see text for details). The *P–T–t* path for the Tananao Complex is estimated from the thermokinematic model of Simoes *et al.* (2007) after the data of Beyssac *et al.* (2007). Exhumation phase 1 of Juisui and Wanjung blocks occurs prior to the late Cenozoic collision and exhumation phase 2 probably during the late Cenozoic collision.

future models investigating these complex phases of deformation.

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References

Agard, P., Monie, P., Jolivet, L. and Goffe, B., 2002. Exhumation of the Schistes Lustres complex: in situ laser probe Ar-40/Ar-39 constraints and implications for the Western Alps. *J. Metamorph. Geol.*, **20**, 599–618.

Berman, R.G., 1988. Internally-consistent thermodynamic data for minerals in the system $Na_2O–K_2O–CaO–MgO–FeO–Fe_2O_3–Al_2O_3–SiO_2–TiO_2–H_2O–CO_2$. *J. Petrol.*, **29**, 445–522.

Berman, R.G., Brown, T.H. and Perkins, E.H., 1987. GeO-calc – software for calculation and display of *P–T–X* phase-diagrams. *Am. Mineral.*, **72**, 861–862.

Beyssac, O., Goffe, B., Chopin, C. and Rouzaud, J.-N., 2002. Raman spectra of carbonaceous material in metasediments: a new geothermometer. *J. Metamorph. Geol.*, **20**, 859–871.

Beyssac, O., Goffé, B., Petitet, J.P., Froigneux, E., Moreau, M. and Rouzaud, J.N., 2003. On the characterization of disordered and heterogeneous carbonaceous materials using Raman spectroscopy. *Spectrochim. Acta A*, **59**, 2267–2276.

Beyssac, O., Bollinger, L., Avouac, J.P. and Goffe, B., 2004. Thermal metamorphism in the Lesser Himalaya of Nepal determined from Raman spectroscopy of carbonaceous material. *Earth Planet. Sci. Lett.*, **225**, 233–241.

Beyssac, O., Simoes, M., Avouac, J.P., Farley, K.A., Chen, Y.G., Chan, Y.C. and Goffé, B., 2007. Late Cenozoic metamorphic evolution and exhumation of Taiwan. *Tectonics*, **26**, TC6001, doi: 10.1029/2006TC002064.

Burov, E., Jolivet, L., Le Pourhiet, L. and Poliakov, A., 2001. A thermomechanical model of exhumation of high pressure (HP) and ultra-high pressure (UHP) metamorphic rocks in Alpine-type collision belts. *Tectonophysics*, **342**, 113–136.

Chopin, C., 2003. Ultrahigh-pressure metamorphism: tracing continental crust into the mantle. *Earth Planet. Sci. Lett.*, **212**, 1–14.

Cloos, M., 1982. Flow melanges – numerical modeling and geologic constraints on their origin in the Franciscan subduction complex, California. *Geol. Soc. Am. Bull.*, **93**, 330–345.

Colombi, A., 1989. Métamorphisme et géochimie des roches mafiques des Alpes Oues-centrales (géoprofil Viège-Domodossola-Locarno). *Mém. Géol.*, Lausanne, **4**, 1–216.

Dahlen, F.A. and Barr, T.D., 1989. Brittle frictional mountain building. 1. Deformation and mechanical energy budget. *J. Geophys. Res.*, **94**, 3906–3922.

Droop, G.T.R., 1987. A general equation for estimating Fe-3+ concentrations in ferromagnesian silicates and oxides from microprobe analyses, using stoichiometric criteria. *Mineral. Mag.*, **51**(361), 431–435.

Ernst, W.G. and Jahn, B.M., (1987). *Crustal accretion and metamorphism in Taiwan, a post-Paleozoic mobile belt*, Philosophical Transactions of the Royal Society of London, A321, 129–161.

Ernst, W.G., 2005. Alpine and Pacific styles of Phanerozoic mountain building: subduction-zone petrogenesis of continental crust. *Terra Nova*, **17**, 165–188.

Evans, B.W., 1990. Phase-relations of epidote-blueschists. *Lithos*, **25**, 3–23.

Fuller, C.W., Willett, S.D., Fisher, D.M. and Lu, C.Y., 2006. A thermomechanical wedge model of Taiwan constrained by fission-track thermochronometry. *Tectonophysics*, **425**, 1–24.

Gerya, T. and Stockhert, B., 2006. Two-dimensional numerical modeling of tectonic and metamorphic histories at active continental margins. *Int. J. Earth Sci.*, **95**, 250–274.

Gerya, T.V., Stockhert, B. and Perchuk, A.L., 2002. Exhumation of high-pressure metamorphic rocks in a subduction channel: a numerical simulation. *Tectonics*, **21**, Art. No. 1056.

Ho, C.S., 1986. A synthesis of the geologic evolution of Taiwan. *Tectonophysics*, **125**, 1–16.

Huang, C.Y., Yuan, P.B. and Tsao, S.J., 2006. Temporal and spatial records of active arc-continent collision in Taiwan: a synthesis. *Geol. Soc. Am. Bull.*, **118**, 274–288.

Jahn, B.M., Liou, J.G. and Nagasawa, H., 1981. High-pressure metamorphic rocks of Taiwan: REE geochemistry, Rb–Sr ages and tectonic implications. *Mem. Geol. Soc. China*, **4**, 497–520.

Jolivet, L., Faccenna, C., Goffe, B., Burov, E. and Agard, P., 2003. Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterranean orogens. *Am. J. Sci.*, **303**, 353–409.

Juang, W.S. and Bellon, H., 1986. Potassium-argon ages of the Tananao schist in Taiwan. *Mem. Geol. Soc. China*, **7**, 405–416.

Kretz, R., 1983. Symbols for rock-forming minerals. *Am. Mineral.*, **68**, 277–279.

Leake, B.E., Woolley, A.R., Arps, C.E.S., Birch, W.D., Gilbert, M.C., Grice, J.D., Hawthorne, F.C., Kato, A., Kisch, H.J., Krivovichev, V.G., Linthout, K., Laird, J., Mandarino, J.A., Maresch, W.V., Nickel, E.H., Rock, N.M.S., Schumacher, J.C., Smith, D.C., Stephenson, N.C.N., Ungaretti, L., Whittaker, E.J.W. and Youzhi, G., (1997). Nomenclature of amphiboles: Report of the Subcommittee on Amphiboles of the International Mineralogical Association, Commission on New Minerals and Mineral Names. *American Mineralogist.*, **82**, 1019–1037.

Li, S.G., Jagoutz, E., Chen, Y.Z. and Li, Q.L., 2000. Sm–Nd and Rb–Sr isotopic chronology and cooling history of ultrahigh pressure metamorphic rocks and their country rocks at Shuanghe in the Dabie Mountains, Central. *Geochim. Cosmochim. Acta*, **64**, 1077–1093.

Lin, A.T., Watts, A.B. and Hesselbo, S.P., 2003. Cenozoic stratigraphy and subsidence history of the South China Sea margin in the Taiwan region. *Basin Res.*, **15**, 453–478.

Liou, J.G., 1981. Petrology of metamorphosed oceanic rocks in the Central Range of Taiwan. *Mem. Geol. Soc. China*, **4**, 291–342.

Liou, J.G., Ho, C.O. and Yen, T.P., 1975. Petrology of some glaucophane schists and related rocks from Taiwan. *J. Petrol.*, **16**, 80–109.

Lo, C.-H. and Yui, T.-F., 1996. 40Ar/39Ar dating of high-pressure rocks in the Tananao basement complex. Taiwan. *J. Geol. Soc. China*, **39**, 13–30.

Malavieille, J. *et al.*, 2002. Arc-continent collision in Taiwan: new marine observations and tectonic evolution. *Geol. Soc. Am. Spec. Pap.*, **358**, 189–213.

Massonne, H.J., 1995. Experimental and petrogenetic study of UHPM. In: *Ultra High Pressure Metamorphism, Cambridge topics in petrology* (R.G. Coleman and X. Wang, eds), pp. 159–181. Cambridge University Press, Cambridge.

Morimoto, N., Fabries, J., Ferguson, A.K., Ginzburg, I.V., Ross, M., Seifert, F.A., Zussman, J., Aoki, K. and Gottardi, G., 1988. Nomenclature of pyroxenes. *Am. Mineral.*, **73**(9–10), 1123–1133.

Parra, T., Vidal, O. and Agard, P., 2002. A thermodynamic model for Fe–Mg dioctahedral K-white micas using data from phase equilibrium experiments and natural pelitic assemblages. *Contrib. Mineral. Petrol.*, **143**, 706–732.

Raimbourg, H., Jolivet, L. and Leroy, Y., 2007. Consequences of progressive eclogitization on crustal exhumation, a mechanical study. *Geophys. J. Int.*, **168**, 379–401.

Scaillet, S., 1996. Excess Ar-40 transport scale and mechanism in high-pressure phengites: a case study from an eclogitized metabasite of the Dora–Maira nappe western Alps. *Geochim. Cosmochim. Acta*, **60**, 1075–1090.

Simoes, M. and Avouac, J.P., 2006. Investigating the kinematics of mountain building in Taiwan from the spatiotemporal evolution of the foreland basin and western foothills. *J. Geophys. Res.*, **111**, B10401, doi: 10.1029/2005JB004209.

Simoes, M., Avouac, J.P., Beyssac, O., Goffé, B., Farley, K.A. and Chen, Y.-G., 2007. Mountain building in Taiwan: a thermokinematic model. *J. Geophys. Res.*, **112**, B11405, doi: 10.1029/2006JB004824.

Suppe, J., 1981. Mechanics of mountain building and metamorphism in Taiwan. *Mem. Geol. Soc. China*, **4**, 67–89.

Teng, L.S., 1990. Geotectonic evolution of Late Cenozoic arc-continent collision in Taiwan. *Tectonophysics*, **183**, 57–76.

Vidal, O. and Parra, T., 2000. Exhumation paths of high-pressure metapelites obtained from local equilibria for chlorite–phengite assemblages. *Geol. J.*, **35**, 139–161.

Vidal, O., Parra, T. and Trotet, F., 2001. A thermodynamic model for Fe–Mg aluminous chlorite using data from phase equilibrium experiments and natural pelitic assemblages in the 100 degrees to 600 degrees C, 1 to 25 kb range. *Am. J. Sci.*, **301**, 557–592.

Vidal, O., Parra, T. and Vieillard, P., 2005. Thermodynamic properties of the Tschermak solid solution in Fe-chlorite: application to natural examples and possible role of oxidation. *Am. Mineral.*, **90**, 347–358.

Yui, T.F. and Lo, C.H., 1989. High-pressure metamorphosed ophiolitic rocks from the Wanjung area, Taiwan. *Proc. Geol. Soc. China*, **32**, 47–62.