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Metamorphic Evolution of the Imjingang Belt, Korea: Implications for Permo-Triassic Collisional Orogeny

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Abstract

The Imjingang belt in the central Korean Peninsula is a strong candidate to represent the extension of the Dabie-Sulu ultrahigh-pressure (UHP) belt in China. This fold-thrust belt consists primarily of: (1) the northern, Jingok unit, characterized by Barrovian-type metapelites; and (2) the southern, Samgot unit, comprising calc-silicate rocks and amphibolites with or without garnet. The metamorphic grade of the Jingok unit increases southward from garnet through staurolite to kyanite zones. Peak metamorphic conditions estimated from the kyanite zone range up to ~11 kbar and 700°C. In contrast, no significant change in metamorphic assemblages is apparent in the Samgot unit. Characteristic minerals of the calc-silicate rocks include garnet, diopside, hornblende, scapolite, and plagioclase, and are compatible with upper amphibolite facies estimated from garnet amphibolite. P–T estimates from the Samgot amphibolites are generally in the range of 8.5–11.5 kbar and 660–780°C. These P–T estimates, together with near-isothermal decompression documented from the metapelitic unit, suggest that the Imjingang belt possibly evolved from eclogite-facies conditions along a clockwise P–T path.

The timing of peak metamorphism was previously estimated at ~250 Ma, based on Sm–Nd and Rb–Sr mineral isochron ages and monazite chemical ages. This result is corroborated by an ion microprobe (SHRIMP) U–Pb age of metamorphic zircon dated at 253 ± 2 Ma. $^{40}\text{Ar}/^{39}\text{Ar}$ ages of hornblende from the amphibolite suggest regional cooling through ~500°C at 230–225 Ma in the Samgot unit. Two biotite separates in the kyanite zone suggest cooling through ~300°C at ~220 and 160 Ma, respectively, in the Jingok unit. These results, in conjunction with peak metamorphism at ~250 Ma, indicate that high-P metamorphism in the Imjingang belt occurred during the Permo-Triassic, and that subsequent rapid cooling followed during exhumation of a thickened orogen, producing a clockwise decompression. This P–T–t evolution is compatible with that of the basement gneisses in the Gyeonggi Massif. Thus, we conclude that both the Imjingang belt and Gyeonggi Massif in the Korean Peninsula are products of continental collision at ~250 Ma and subsequent exhumation at ~230–220 Ma.

Introduction

THE TECTONIC EVOLUTION of the Korean Peninsula has been highlighted in the international geological community since ultrahigh-pressure (UHP) metamorphism in the Qinling-Dabie-Sulu belt, east-central China (Fig. 1A), was reported as a product of deep continental subduction. This suture zone is especially significant because of the widespread occurrence of relict UHP minerals and high-pressure (HP) assemblages that document the recovery of sialic crust subducted to mantle depths approaching and exceeding 100 km (Liou et al., 1998). UHP

parageneses include trace mineralogic relics requiring peak metamorphic conditions of 700–900°C and 28–35 kbar or more. Coesite and microdiamond inclusions in refractory minerals of UHP metamorphic rocks in the Dabie-Sulu belt attest to profound subduction of a leading salient of the old, cold Yangtze craton, now recognizable via tectonic exhumation and erosion (Ernst et al., 1995).

Does this remarkable cratonic collision belt extend farther east to the Korean Peninsula in the Imjingang belt and/or Gyeonggi Massif? Many investigators (e.g., Yin and Nie, 1993; Li, 1994; Ernst and Liou, 1995; Ree et al., 1996, 2001; Cheong et al., 2000; Chough et al., 2000; Cho, 2001, 2003; Ishiwatari and Tsujimori, 2003; Lee S. R. et al., 2003b; Cho and Kim, 2005; Oh et al., 2005) have discussed the possibility of extension of this

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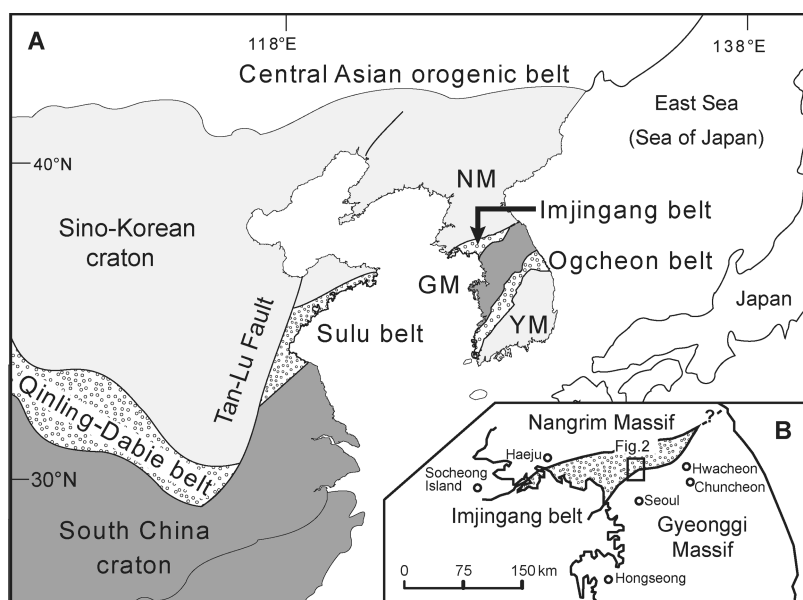


FIG. 1. A. Simplified tectonic province map of East Asia. Abbreviations: GM = Gyeonggi Massif; NM = Nangrim Massif; YM = Youngnam Massif. B. A schematic location map of the study area. Inset box shows the study area enlarged in Figure 2. Some locality names referred to in text are also shown.

Triassic collisional belt into Korea, but the location, or even the continuation of the suture across the Yellow Sea is contentious. Major ambiguities arise from the paucity of structural and geochronologic data as well as the apparent lack of high-pressure metamorphic rocks such as blueschists and eclogites in the Korean Peninsula.

Regional metamorphism at pressures greater than ~10 kbar remained undiscovered in the Korean Peninsula until the first report of HP amphibolites in the Imjingang belt by Cho et al. (1995). Since then, several workers have found similar or even higher pressure mafic rocks (e.g., Ree et al., 1996; Jeon and Kwon, 1999; Cho, 2003; Oh et al., 2005). In particular, Oh et al. (2005) recently reported relict omphacite preserved in garnet porphyroblasts from high-pressure granulites in the western Korean Peninsula, and suggested that the Sulu UHP belt likely extends into the Gyeonggi Massif rather than the Imjingang belt. Despite this suggestion, the Imjingang belt has been a strong candidate for the eastward extension of the Sulu belt, based on the similarities in structural characteristics, metamorphic ages, and P-T-t paths (e.g., Cho et al., 1995; Ree et al., 1996, 2001; Chough et al., 2000; Cho and Kim, 2005). Until now however, no detailed

studies on the P-T-t evolution have been available. The majority of the Imjingang belt is situated in the Demilitarized Zone and North Korea, but east-trending metamorphic units, the so-called Yeoncheon complex (Cho et al., 1995), occur in the northwestern portion of South Korea. In this study, we report petrologic and geochronologic data, and also review previous studies and summarize our new results on the P-T-t evolution of the Yeoncheon complex in the southern Imjingang belt.

Geological Outline

The Korean Peninsula, located between the Asian mainland and the Pacific active margin, consists of several metamorphic terranes—from north to south, the Nangrim Massif, Imjingang belt, Gyeonggi Massif, Ogcheon belt, and Yeongnam Massif (Fig. 1). The three massifs, primarily composed of Precambrian basement gneisses and schists, are separated by two Phanerozoic mobile belts. The Imjingang belt is an E-W-trending fold-thrust belt bisecting Precambrian basement rocks of the Gyeonggi and Nangrim massifs, as shown in Figure 1A. Although its exact boundaries are not well defined, this belt consists of various

tectonic units, including not only flysch and submarine volcanics of the Devonian Imjin Group *sensu stricto*, but also marine clastics and limestones of the Cambrian–Silurian Joseon Group; weakly metamorphosed pelites, limestones, and quartzites of the Neoproterozoic Sangwon Group; and medium- to high-grade metamorphic rocks of the Mesoproterozoic (?) to Neoproterozoic Yeoncheon complex (Cho et al., 1995; Paek et al., 1996, and references therein).

The Imjingang belt was first defined by North Korean geologists in the early 1960s, based on the occurrence of the Devonian Imjin Group, absent from the North China craton (Paek et al., 1996). This group consists of sedimentary and volcanoclastic sequences younging toward the south. Sedimentary rocks correlative with the Imjin Group are absent in South Korea, but metamorphosed equivalents of the Imjin Group occur south of the Demilitarized Zone (see below for geochronologic constraints). Moreover, these metamorphic rocks show E–W–trending foliations, which are conspicuous in the Yeoncheon area (Fig. 2) but are rare in other parts of Korean Peninsula. Consequently, the Yeoncheon complex trending approximately E–W has been designated as a part of the Imjingang belt (Cho et al., 1995). This contention accounts for the occurrence of metapelites such as biotite schist and andalusite–staurolite–kyanite schist reported by Paek et al. (1996) from the Imjin Group of North Korea.

Yeoncheon Complex

Petrology and geochemistry

The Yeoncheon complex, originally named the Yeoncheon Group (Yamaguchi, 1951), is divided by intervening Cretaceous tuffs and volcanics into western metasedimentary–amphibolitic rocks (Yeoncheon area) and eastern upper–amphibolite facies gneisses, amphibolites, and metagabbros (Gonamsan area) (Fig. 2). The former area represents the type locality for the Yeoncheon complex consisting mainly of two lithotectonic units: the northern, Devonian Jingok unit and the southern, Mesoproterozoic(?)–Neoproterozoic Samgot unit. The Jingok unit consists primarily of Barrovian-type metapelites increasing in grade southward from garnet through staurolite to kyanite zones. This metamorphic zonation polarity contrasts with the Dabie paragenesis (e.g., Hacker et al., 1998). Three metamorphic zones are defined on the basis of the first appearances of porphyroblastic garnet, staurolite, and kyanite, respectively, coexisting with

biotite, muscovite, plagioclase, and quartz (Cho et al., 1995; Ree et al., 1996). However, the presence of uncommon aluminosilicate minerals in the staurolite zone leads to uncertain definitions of the staurolite and kyanite zones. Although mineral assemblages are similar in two metamorphic zones, apart from the absence of primary chlorite in the kyanite zone, occurrences of porphyroblastic minerals are distinctly different. In the staurolite zone, staurolite occurs as small porphyroblasts less than a few millimeters, generally in the vicinity of ~1 mm, euhedral to subhedral garnet porphyroblasts. On the other hand, the kyanite zone is characterized by the occurrence of large staurolite porphyroblasts reaching 60 mm in size, and bluish green kyanite blades up to 20 mm in length. The widespread occurrence of complex zoning patterns is conspicuous in plagioclase (Ahn and Cho, 2000), but reverse zoning becomes predominant in the kyanite zone. Quartz veins are common in the Jingok unit, and are often folded or deformed to produce boudinaged patches on an outcrop scale (e.g., Jung et al., 1999). Of particular interest in the kyanite zone is the occurrence of large euhedral crystals of pink andalusite together with rare bluish kyanite in quartz veins. In addition, most andalusite-bearing quartz veins in the kyanite zone are strongly deformed or boudinaged (Fig. 3A). Their occurrence, together with a deformation fabric penetrative and continuous to the host rock (kyanite-zone schist), suggests that medium-temperature deformation was operative even after andalusite formation.

In contrast to the southward increase in metamorphic grade in the Jingok unit, no systematic change in mineral parageneses is apparent in the Samgot unit. This unit consists primarily of calc-silicates, marbles, and garnet amphibolites. Different layers of metasedimentary rocks are commonly intercalated at outcrop and thin-section scale. These intercalations form straight layers and are the product of ductile deformation of impure carbonate-rich sequences at high temperatures. The calc-silicate rocks are granoblastic and 0.5–3.0 mm in average grain size. Prograde assemblages of calc-silicate rocks consist of various combinations of calcite, quartz, Mg-diopside, scapolite, clinozoisite, hornblende, calcic plagioclase, K-feldspar (Or_{96-98}), almandine–grossular garnet, biotite, and aluminous titanite.

Mafic layers or boudins in the Samgot unit consist of garnet-free or garnet-bearing amphibolites.

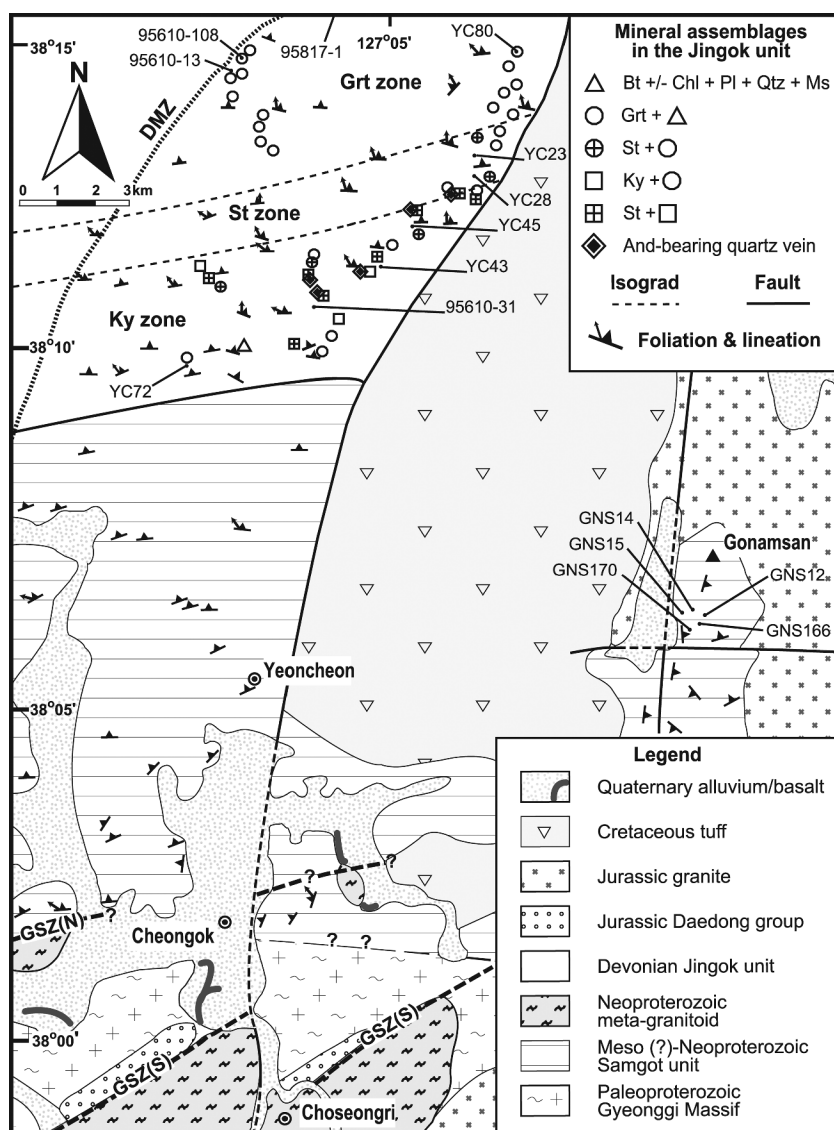


FIG. 2. A geologic map of the study area, compiled from various maps published by Cho et al. (1995), Ree et al. (1996), Kim et al. (2000), and Lee S. R. et al. (2003a). Strikes and dips of major foliation are shown for the Yeoncheon and Gonamsan areas. Also shown are the numbers of samples analyzed in this study. According to Paek et al. (1996), sedimentary formations of the Imjin Group occur to the west of the Jingok unit. Mineral abbreviations follow Kretz (1983). Abbreviations: DMZ = Demilitarized Zone; GSZ (S) and (N) = southern and northern boundaries of the Gyeonggi shear zone, respectively.

These amphibolites commonly occur as concordant layers, and rarely show discordant relationships with the calc-silicate rocks. Magmatic textures such as ophitic and cumulate textures are present in coarse-grained amphibolites derived from gabbroic rocks. In addition, chilled margins are rare

but present along the boundaries of amphibolites, suggesting an igneous origin for their protoliths. Mineral assemblages in the amphibolites are hornblende-pargasite + oligoclase-labradorite + garnet $\pm$ quartz $\pm$ clinopyroxene $\pm$ biotite. Rutile typically occurs as relict inclusions within ilmenite and

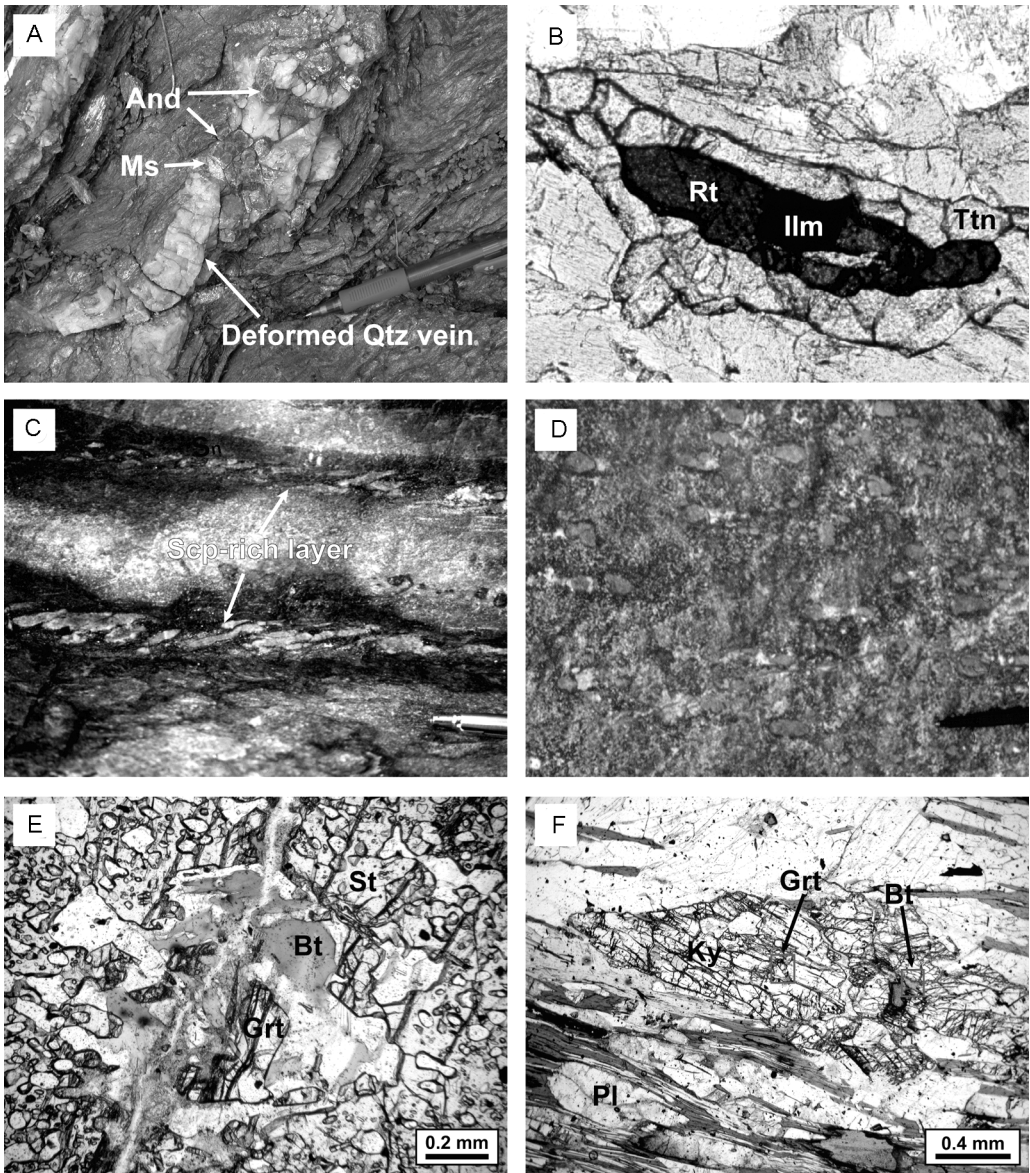


FIG. 3. A. Deformed quartz vein containing euhedral crystals of andalusite and muscovite. The sense of dragging in quartz veins is compatible with that of the host, suggesting top-down-to-the-north extensional movement. B. Photomicrograph showing ilmenite and rutile inclusions in titanite of amphibolite. Rutile grain is 0.65 mm in length. Plane polarized light. C. Alternating layers of scapolite-rich calc-silicates and garnet-bearing metapsammities. Elongate porphyroblasts of flattened scapolite are aligned to define the stretching lineation. This photograph is taken from an outcrop cut almost normal to the foliation and parallel to the lineation. D. Mineral lineation defined by an array of flattened garnet porphyroblasts in a hornblende gneiss. This sample was taken adjacent to the Gyeonggi shear zone and shows various microstructures including ductile deformation of hornblende. Note also felsic patches in the pressure shadows of elongate garnet, which are possibly the product of *in-situ* partial melting during high-temperature ductile deformation. Pen shows the approximate direction of lineation ($330^{\circ}/13^{\circ}$). E. Photomicrograph showing an assemblage of garnet, biotite, plagioclase and quartz included in large staurolite porphyroblast of a kyanite-zone schist. F. Photomicrograph showing a kyanite porphyroblast containing minute crystals of garnet and biotite.

titanite in amphibolites and calc-silicate rocks (Fig. 3B).

Major- and trace-element data indicate that amphibolites of the Samgot unit in the Yeoncheon area have a tholeiitic oceanic basalt affinity (Ree et al., 1996). In contrast, the amphibolites in the Gonamsan area are diverse, ranging from massive bodies lacking penetrative deformation fabrics to mylonitic-protomylonitic layers possibly transposed from mafic sills or dikes (Jeon and Kwon, 1999). In addition, cumulate textures together with layered structures are reported from meta-gabbroic amphibolites (Chang et al., 1987). However, the preservation of magmatic textures (Chang et al., 1987) suggests an igneous origin for the hornblende-bearing assemblages. This idea was later refuted owing to the occurrence of metamorphic garnet in many amphibolites (Jeon and Kwon, 1999). The majority of the Gonamsan amphibolites have trace-element chemistries of alkaline affinity but some are tholeiitic (Jeon and Kwon, 1999).

Structure

All the schists and gneisses of the Yeoncheon complex show major foliations generally dipping north to northwest, and contain ubiquitous stretching lineations (Fig. 2). These lineations mostly plunge 20–50° to the NNW–NW, and their orientations are similar to those reported from the Dabie-Sulu belt (Faure et al., 2001, 2003). An example from the Samgot unit is shown in Figure 3C, where large scapolite porphyroblasts in calc-silicates are elongated and aligned to give a lineation of 326°/40°. The stretching lineation of scapolite defines the normal sense of movement, possibly at medium temperatures. Moreover, elongate garnet porphyroblasts are common in both calc-silicate gneisses and garnet amphibolites of the Samgot unit. These flattened and stretched garnet porphyroblasts are uncommonly aligned to define mineral lineations of 330°/13° in the garnet amphibolite (Fig. 3D). Ductile elongation of garnet crystals suggests high-temperature deformation probably belonging to granulite- or eclogite-facies conditions (Ji and Martignole, 1994; Prior et al., 2000; Kleinschrodt and Duyster, 2002; Ji et al., 2003).

The boundary between the Imjingang belt and the Gyeonggi Massif is defined by a crustal-scale shear zone consisting primarily of mylonites-protomylonites of the Gamaksan alkaline metagranitoid and Gyeonggi basement rocks (Fig. 2; Kim et al., 2000; Lee S. R. et al., 2003a). The width of this

shear zone is ~4–5 km, but its boundaries are poorly constrained. Using the Sensitive High-Resolution Ion Microprobe (SHRIMP), the crystallization age of the metagranitoids has been dated at 742 ± 13 Ma (Lee S. R. et al., 2003a). The foliations in the overlying calc-silicates are parallel or subparallel to the Gyeonggi shear zone; those of the underlying crystalline basement gneisses and supracrustal sequences comprising quartzite and marbles are not strongly affected. The latter preserve the earlier deformation event represented by north-trending open folds (Choi et al., 1998; Kim et al., 2000). We interpret these geometric relationships to indicate a crustal-scale discontinuity between the Imjingang belt and the Gyeonggi Massif.

Structural relationships of the southern Imjingang belt, investigated by Ree et al. (1996) and Jung et al. (1999, 2002) suggest three major episodes of deformation: (1) initial contractional deformation (D_{n-1}); (2) another major contractional deformation (D_n) producing penetrative foliation; and (3) extensional ductile shearing (D_{n+1}). South-vergent structures with reverse (top-up-to-the-south) shear sense are common in the Jingok unit, whereas subsequent extensional deformation with normal (top-down-to-the-north) shear sense is pervasive in the Samgot unit (Ree et al., 1996). In the Gamaksan metagranitoid, extensional ductile shear zones are conspicuous, and possess mylonitic microtextures and structures indicating top-down-to-the-north transport. All the structural features are interpreted to result from D_{n+1} associated with extensional tectonic exhumation, following compressive deformation and crustal thickening (D_{n-1} and D_n) in a collisional belt. Prograde metamorphism was associated with D_{n-1} and D_n , whereas subsequent exhumation produced retrograde metamorphic minerals along a decompressional P-T-t path (Kim and Cho, 2005).

The extensional deformation in the study area is perhaps more obvious as shown by the occurrence of small sedimentary basins in association with the Gamaksan alkaline metagranitoid (Fig. 2). We envisage that ductile deformation resulting in mylonites at ~226 Ma (Kim et al., 2000) was eventually manifested in the development of extensional basins in the upper crustal section. The ENE-trending array of small basins consisting of clastic sequences, i.e., the Daedong Group, may correspond to this type of extensional basin resulting from gravitational collapse of an orogenically thickened crustal section. Our preliminary U-Pb ages of detrital zircons from sandstones of the Daedong

Group suggest that deposition occurred later than ~200 Ma (Jeon et al., 2005).

Metamorphic Conditions and P-T Paths in the Metapelites

The physicochemical condition of each metamorphic zone in the Jingok unit was estimated primarily using rim compositions of garnets and coexisting phases. Representative compositions used for geothermobarometric calculations are given in Tables 1–3. We applied the garnet-biotite geothermometer (Ferry and Spear, 1978; Berman, 1990) for estimating temperatures and a combination of garnet-aluminosilicate-quartz-plagioclase and garnet-plagioclase-biotite-muscovite geobarometers (Hodges and Crowley, 1985) for determining pressures.

P-T estimates from three metamorphic zones are in the range of ~480–630°C and 4–9 kbar, as shown in Figure 4; it also shows a pseudosection reported by Mahar et al. (1997). This pseudosection was constructed using a bulk composition similar to that of metapelitic rocks in the Jingok unit, and thus can approximate their mineral parageneses during metamorphic evolution. In particular, the pseudosection of Figure 4 is based on the K_2O -MnO-FeO-MgO- Al_2O_3 - SiO_2 - H_2O (KMnFMASH) model system that has an additional MnO component added to that of the common AFM system. The addition of Mn expands the garnet stability to low temperatures (Mahar et al., 1997; Tinkham et al., 2001). The P-T estimates shown in Figure 4 define a linear array of metamorphic field gradient. Both pressure and temperature increase from the garnet to staurolite zones, but those of the kyanite zone deviate from the trend. Pressures estimated from four samples of the kyanite zone vary widely, and temperatures overlap the staurolite zone, and part of the garnet zone (Fig. 4). This apparent inconsistency and wide variations in pressure estimations are attributed to partial retrogression during exhumation (see below).

Petrographic evidence can also potentially constrain the P-T history of metapelites, particularly in combination with the constructed pseudosection (Fig. 4). Two distinct assemblages consisting of garnet + kyanite + biotite + plagioclase + quartz, and garnet + staurolite + kyanite + biotite + plagioclase + quartz, are common in the kyanite-zone schists. Moreover, staurolite porphyroblasts enclose small domains of multiphase inclusions of garnet + biotite + plagioclase + quartz (Fig. 3E), and also

contain rare inclusions of kyanite. Kyanite porphyroblasts rarely contain minute crystals of garnet together with biotite and plagioclase (Fig. 3F). The pseudosection has two subdomains pertinent to the mineral assemblages described above (Fig. 4). Thus, paragenetic relationships based on inclusion minerals suggest that the kyanite-zone metapelites have passed through the garnet + kyanite + biotite field prior to the garnet + staurolite + biotite field. Garnet inclusions within kyanite porphyroblasts suggest that kyanite-zone metapelites reached the garnet + kyanite + biotite field following the garnet + biotite + chlorite field, through a garnet-consuming reaction such as garnet + chlorite + muscovite = kyanite + biotite + quartz + H_2O . This kyanite-in reaction is in marked contrast to that of typical Barrovian-type metapelites such as staurolite + chlorite + muscovite = kyanite + biotite + quartz + H_2O .

P-T conditions were also estimated using the compositions of minerals included in staurolite and kyanite porphyroblasts. Compositional zonings within garnet inclusions are absent except for enrichment in the spessartine component at the outermost rim. In particular, this Mn enrichment is evident in the resorbed garnet within staurolite porphyroblasts. Compositional differences between matrix and inclusion garnets indicate that the formation of high-temperature garnet preceded that of kyanite. Mn-depleted homogeneous cores of garnet inclusions were used for P-T calculations because Mn-enriched rims may represent the product of partial resorption. Plagioclase within kyanite porphyroblasts is more sodic (An_{35-38}) than that within staurolite (An_{42-46}). The calculated P-T estimates are in the range of ~665–710°C and 9–11.5 kbar, whereas those from the matrix give ~625–635°C and 6.2–7 kbar (Fig. 4). The former range is consistent not only with the metamorphic field gradient extrapolated from the garnet and staurolite zones, but also with mineral parageneses predicted from the P-T pseudosection (Fig. 4).

Andalusite-bearing veins with or without kyanite are common in the kyanite zone (see Fig. 2 for locations), and are indicative of large amounts of fluid flow owing to the low solubility of aluminum in metamorphic fluids (Anderson et al., 1987). This fluid infiltration is consistent with the occurrence of chlorite schists restricted to the fault zone along the southern boundary of the Jingok unit. A variety of P-T ranges estimated from the kyanite zone may be attributed in part to fluid infiltration resulting in significant retrogression probably during the

TABLE 1. Representative Compositions of Garnet in Metapelitic Rocks¹

Grade:	Garnet zone				Staurolite zone				Kyanite zone																
	95817-1		95610-108		95610-13		YC80		YC23		YC28		YC45		YC43		95610-31		YC72						
Sample:	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	"M, c"	"M, r"	"S, c"	"S, r"	K	K	M	M
SiO ₂	37.27	37.24	37.74	36.86	37.36	37.74	37.49	37.52	37.43	37.67	37.45	37.19	37.18	37.34	38.24	37.40	37.63	38.11	37.73	37.79	37.91	37.41	37.37	36.82	
Al ₂ O ₃	21.19	21.25	21.28	20.90	21.43	20.75	21.15	21.10	21.29	21.22	21.40	21.16	20.89	20.93	21.26	21.23	21.40	21.63	21.64	21.96	21.86	21.67	21.46	21.18	
FeO ²	26.22	27.44	27.61	27.48	28.63	27.20	30.57	30.57	32.10	31.68	29.38	28.80	30.50	30.59	32.10	32.43	30.09	32.24	31.82	30.89	31.49	31.37	31.42	30.58	
MgO	4.42	5.27	1.93	1.87	1.86	1.61	2.31	2.51	2.94	3.03	3.06	2.76	2.76	2.68	2.96	2.44	2.79	3.88	4.39	3.43	4.03	3.36	3.38	2.86	
MnO	9.37	6.62	4.85	5.59	3.90	4.46	2.34	1.68	0.62	0.66	2.38	2.67	1.72	1.61	0.31	0.92	5.01	1.42	0.13	1.75	0.13	0.46	3.61	6.29	
CaO	1.89	2.04	7.43	6.70	6.50	8.70	6.09	6.45	5.36	5.60	6.27	6.96	6.99	6.83	5.93	5.85	3.31	2.78	4.53	4.61	4.89	5.11	3.48	2.55	
Total	100.36	99.86	100.85	99.40	99.69	100.46	99.95	99.84	99.74	99.86	99.93	99.53	100.04	99.98	100.80	100.27	100.23	100.06	100.24	100.43	100.31	99.38	100.72	100.28	
Cations per 12 oxygens																									
Si	2.99	2.99	3.00	2.98	3.00	3.01	3.00	3.00	2.99	3.00	2.98	2.98	2.98	2.99	3.02	2.99	3.01	3.02	2.98	2.99	2.99	2.99	2.97	2.97	
Al	2.01	2.01	1.99	1.99	2.03	1.95	2.00	1.99	2.01	2.00	2.01	2.00	1.97	1.97	1.98	2.00	2.01	2.02	2.02	2.05	2.03	2.04	2.01	2.01	
Fe ²⁺	1.76	1.84	1.83	1.86	1.92	1.81	2.05	2.05	2.15	2.11	1.96	1.93	2.04	2.05	2.12	2.17	2.01	2.14	2.10	2.04	2.08	2.10	2.09	2.06	
Mg	0.23	0.24	0.23	0.23	0.22	0.19	0.28	0.30	0.35	0.36	0.36	0.33	0.33	0.32	0.35	0.29	0.33	0.46	0.52	0.40	0.47	0.40	0.40	0.34	
Mn	0.64	0.45	0.33	0.38	0.27	0.30	0.16	0.11	0.04	0.04	0.16	0.18	0.12	0.11	0.02	0.06	0.34	0.10	0.01	0.12	0.01	0.03	0.24	0.43	
Ca	0.38	0.45	0.63	0.58	0.56	0.74	0.52	0.55	0.46	0.48	0.54	0.60	0.60	0.59	0.50	0.50	0.28	0.24	0.38	0.39	0.41	0.44	0.30	0.22	
Total	8.00	8.00	8.01	8.02	7.99	8.01	8.00	8.00	8.00	8.00	8.00	8.02	8.04	8.02	7.99	8.01	7.99	7.97	8.01	7.99	7.99	7.99	8.02	8.03	
Fe/(Fe+Mg)	0.89	0.88	0.89	0.89	0.90	0.90	0.88	0.87	0.86	0.85	0.84	0.85	0.86	0.86	0.86	0.88	0.86	0.82	0.80	0.83	0.81	0.84	0.84	0.86	
Alm ³	0.59	0.62	0.61	0.61	0.65	0.59	0.68	0.68	0.72	0.71	0.65	0.64	0.66	0.67	0.71	0.72	0.68	0.73	0.70	0.69	0.70	0.71	0.69	0.67	
Prp ³	0.08	0.08	0.08	0.07	0.08	0.06	0.09	0.10	0.12	0.12	0.12	0.11	0.11	0.10	0.12	0.10	0.11	0.16	0.17	0.14	0.16	0.13	0.13	0.11	
Sps ³	0.21	0.15	0.09	0.13	0.09	0.10	0.05	0.04	0.01	0.01	0.05	0.06	0.04	0.04	0.01	0.02	0.11	0.03	0.00	0.04	0.00	0.01	0.08	0.14	
Grs ³	0.13	0.15	0.21	0.19	0.19	0.24	0.17	0.18	0.15	0.16	0.18	0.20	0.19	0.19	0.17	0.17	0.10	0.08	0.13	0.13	0.14	0.15	0.10	0.07	

¹ Abbreviations: M = garnet occurring in the matrix; S = garnet inclusion within staurolite; K = garnet inclusion within kyanite; c = core; r = rim.
² Total Fe as FeO.
³ Alm = Fe/M; Prp = Mg/M; Sps = Mn/M; and Grs = Ca/M, where M = (Fe + Mg + Mn + Ca).

TABLE 2. Representative Compositions of Biotite and Muscovite

Grade:	Garnet zone						Staurolite zone						Kyanite zone															
	95610-108			95610-13			YC80			YC23			YC28			YC45			YC43			95610-31			YC72			
Sample:	Bt	Ms		Bt	Ms		Bt	Ms		Bt	Ms		Bt	Ms		Bt	Ms		Bt	Ms		Bt	Ms		Bt	Ms		
	Bt	Ms		Bt	Ms		Bt	Ms		Bt	Ms		Bt	Ms		Bt	Ms		Bt	Ms		Bt	Ms		Bt	Ms		
SiO ₂	36.21	35.99	47.54	36.54	35.88	46.29	36.24	35.85	47.08	36.12	35.33	46.15	35.51	36.54	36.21	35.31	45.31	35.76	36.52	44.08	35.92	35.78	36.08	34.89	36.05	34.70	35.42	44.51
TiO ₂	1.16	1.47	0.29	1.42	1.51	0.45	1.55	1.50	0.43	1.70	1.58	0.40	1.58	1.77	1.63	1.52	0.37	1.51	1.64	0.38	1.64	1.44	1.81	1.60	1.45	1.80	1.69	0.62
Al ₂ O ₃	20.44	19.22	33.83	19.73	19.61	36.66	19.92	19.53	35.51	19.40	19.61	36.77	20.10	19.85	19.53	20.45	36.75	19.31	20.04	35.89	20.07	20.45	20.82	20.30	20.71	20.02	20.58	37.05
FeO ¹	17.20	17.38	1.13	17.39	17.92	1.40	17.36	18.30	1.31	17.21	17.66	1.01	16.85	16.29	16.40	17.27	0.85	17.22	17.12	1.31	17.69	17.09	16.31	15.69	16.47	17.65	16.60	0.83
MgO	11.29	10.55	1.25	11.08	11.00	0.70	10.73	10.73	0.98	11.01	10.75	0.68	11.01	11.63	11.60	11.23	0.60	11.50	11.37	0.65	10.96	10.87	10.90	11.94	10.70	10.89	10.67	0.43
MnO	0.12	0.10	0.03	0.14	0.10	0.02	0.11	0.09	0.04	0.11	0.01	0.03	0.04	0.01	0.02	0.00	0.00	0.12	0.08	0.03	0.06	0.03	0.06	0.04	0.13	0.22	0.15	0.00
CaO	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.05	0.02	0.06	0.02	0.06	0.01	0.00	0.02	0.02	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.01
Na ₂ O	0.22	0.20	0.36	0.16	0.15	0.70	0.12	0.10	0.55	0.20	0.18	0.76	0.20	0.13	0.24	0.26	0.91	0.16	0.15	0.93	0.17	0.21	0.33	0.33	0.28	0.14	0.16	0.90
K ₂ O	9.56	9.86	9.85	9.64	9.64	10.11	9.43	9.21	10.52	9.47	9.36	10.95	9.41	9.70	9.61	9.38	10.81	9.39	9.62	10.01	9.18	9.20	9.72	9.77	9.87	9.75	9.95	10.69
Total	96.20	94.77	94.29	96.07	95.81	96.34	95.46	95.30	96.46	95.23	94.54	96.75	94.77	95.93	95.24	95.44	95.60	94.94	96.54	93.30	95.69	95.06	96.03	94.56	95.66	95.18	95.30	95.04
Cations per 11 oxygens																												
Si	2.69	2.73	3.17	2.72	2.69	3.04	2.72	2.70	3.09	2.71	2.68	3.03	2.68	2.71	2.71	2.65	3.01	2.70	2.70	3.00	2.69	2.69	2.68	2.64	2.69	2.63	2.66	2.98
Ti	0.06	0.08	0.01	0.08	0.09	0.02	0.09	0.08	0.02	0.10	0.09	0.02	0.09	0.10	0.09	0.09	0.02	0.09	0.09	0.02	0.09	0.08	0.10	0.09	0.08	0.10	0.10	0.03
Al	1.79	1.72	2.66	1.73	1.74	2.84	1.76	1.74	2.75	1.72	1.76	2.85	1.79	1.74	1.72	1.81	2.88	1.72	1.75	2.88	1.77	1.81	1.82	1.81	1.82	1.79	1.82	2.92
Fe ²⁺	1.07	1.10	0.06	1.08	1.13	0.08	1.09	1.15	0.07	1.08	1.12	0.06	1.06	1.01	1.03	1.08	0.05	1.09	1.06	0.07	1.11	1.07	1.01	0.99	1.03	1.12	1.04	0.05
Mg	1.25	1.19	0.12	1.23	1.23	0.07	1.20	1.21	0.10	1.23	1.22	0.07	1.24	1.29	1.30	1.26	0.06	1.29	1.25	0.07	1.22	1.22	1.21	1.34	1.19	1.23	1.20	0.04
Mn	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Na	0.03	0.03	0.05	0.02	0.02	0.09	0.02	0.02	0.07	0.03	0.03	0.10	0.03	0.02	0.04	0.04	0.12	0.02	0.02	0.12	0.02	0.03	0.05	0.05	0.04	0.02	0.02	0.12
K	0.91	0.95	0.84	0.92	0.92	0.85	0.90	0.89	0.88	0.91	0.91	0.92	0.91	0.92	0.92	0.90	0.92	0.90	0.91	0.87	0.88	0.88	0.92	0.94	0.94	0.94	0.95	0.91
Total	7.81	7.82	6.92	7.80	7.82	6.99	7.77	7.79	6.99	7.79	7.81	7.03	7.80	7.79	7.81	7.83	7.04	7.82	7.79	7.04	7.79	7.78	7.79	7.86	7.81	7.85	7.81	7.05
Fe/(Fe+Mg)	0.46	0.48	0.34	0.47	0.48	0.53	0.48	0.49	0.43	0.47	0.48	0.45	0.46	0.44	0.44	0.46	0.44	0.46	0.46	0.53	0.48	0.47	0.46	0.42	0.46	0.48	0.47	0.52

¹Total Fe as FeO.²Biotite inclusion within staurolite.³Biotite inclusion within kyanite.

TABLE 3. Representative Compositions of Plagioclase¹

Grade:	Garnet zone						Staurolite zone						Kyanite zone										
	95817-1		95610-108		95610-13		YC30		YC23		YC28		YC45		YC43		95610-31		YC72				
Sample:	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	S	K	M	M			
SiO ₂	57.64	57.85	53.87	56.77	58.76	55.04	56.73	54.01	57.62	56.51	57.96	57.32	55.03	52.16	52.97	58.61	57.23	56.20	56.16	55.31	57.09	54.74	52.56
Al ₂ O ₃	26.71	26.72	29.49	27.84	26.65	29.24	27.30	29.62	26.87	26.75	26.80	27.48	28.70	30.45	29.61	26.65	27.25	28.00	28.19	28.55	27.57	29.12	30.56
CaO	7.79	7.60	10.73	8.97	7.41	10.04	8.08	11.04	8.30	8.77	7.99	8.40	10.09	12.37	11.83	7.65	8.48	9.32	8.85	9.40	7.93	10.45	12.00
Na ₂ O	6.71	6.98	4.88	6.23	7.03	6.13	7.00	4.82	6.32	6.50	7.06	6.18	5.34	4.34	4.48	6.65	6.32	5.74	6.50	6.29	6.90	5.27	4.25
K ₂ O	0.10	0.11	0.09	0.04	0.08	0.05	0.04	0.10	0.11	0.09	0.05	0.10	0.05	0.08	0.01	0.00	0.06	0.07	0.09	0.05	0.27	0.05	0.05
Total	98.95	99.25	99.06	99.85	99.93	100.49	99.15	99.59	99.23	98.60	99.86	99.48	99.20	99.40	98.90	99.56	99.33	99.32	99.79	99.60	99.76	99.63	99.43
Cations per 8 oxygens																							
Si	2.60	2.60	2.45	2.54	2.62	2.46	2.56	2.44	2.59	2.57	2.59	2.57	2.49	2.38	2.42	2.62	2.57	2.53	2.52	2.49	2.56	2.47	2.39
Al	1.42	1.41	1.58	1.47	1.40	1.54	1.45	1.58	1.42	1.43	1.41	1.45	1.53	1.63	1.59	1.40	1.44	1.49	1.49	1.52	1.46	1.55	1.64
Ca	0.38	0.37	0.52	0.43	0.35	0.48	0.39	0.53	0.40	0.43	0.38	0.40	0.49	0.60	0.58	0.37	0.41	0.45	0.43	0.45	0.38	0.51	0.58
Na	0.59	0.61	0.43	0.54	0.61	0.53	0.61	0.42	0.55	0.57	0.61	0.54	0.47	0.38	0.40	0.58	0.55	0.50	0.57	0.55	0.60	0.46	0.37
K	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00
Total	4.98	4.99	4.98	4.99	4.99	5.02	5.02	4.98	4.97	5.00	5.01	4.97	4.98	5.00	4.98	4.97	4.98	4.98	5.02	5.01	5.02	4.99	4.98
An ²	0.39	0.37	0.55	0.44	0.37	0.47	0.39	0.56	0.42	0.43	0.38	0.43	0.51	0.61	0.59	0.39	0.42	0.47	0.43	0.45	0.38	0.52	0.61
Ab ²	0.61	0.62	0.45	0.56	0.63	0.52	0.61	0.44	0.58	0.57	0.61	0.57	0.49	0.39	0.41	0.61	0.57	0.52	0.56	0.55	0.60	0.48	0.39
Or ²	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00

¹Abbreviations: M = plagioclase occurring in the matrix; S = plagioclase inclusion within staurolite; and K = plagioclase inclusion within kyanite.

²An = Ca/M; Ab = Na/M; and Or = K/M, where M = (Ca + Na + K).

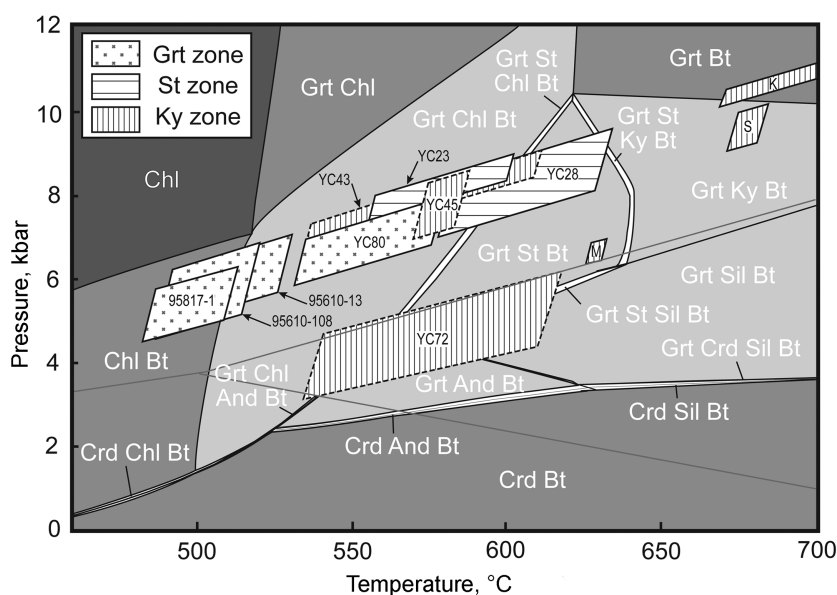


FIG. 4. P-T conditions estimated from metapelites of garnet, staurolite, and kyanite zones are shown on a pseudosection constructed by Mahar et al. (1997). Three kyanite-zone samples (YC43, YC45, and YC 72) gave variable P-T ranges, outlined by dotted lines, probably resulting from partial resetting of mineral compositions. On the other hand, three P-T boxes with solid outline, determined from single kyanite-zone schist (95610-31), represent the P-T estimates using the compositions of matrix minerals (M) as well as mineral inclusions in staurolite (S) and kyanite (K) porphyroblasts.

exhumation of thickened crust. Retrograde net-transfer reactions accompanying large amounts of fluid flow may also have played an important role and account for significant variations in the zoning patterns of plagioclase in the kyanite zone (Ahn and Cho, 2000). Taken together, P-T estimates, metamorphic field gradients and inclusion mineral parageneses define not only clockwise P-T paths, but also quasi-isothermal decompressional paths where prograde segments may reach the maximum pressure exceeding ~11 kbar.

High-Pressure Metamorphism of Garnet Amphibolites

Metamorphic conditions for the Samgot unit were estimated primarily from the garnet amphibolites consisting of calcic amphibole + plagioclase + garnet + quartz $\pm$ clinopyroxene $\pm$ biotite. This assemblage is typical for upper-amphibolite facies, and is compatible with the absence of wollastonite and lack of partial melting products in calc-silicate rocks. Most of the amphiboles in the garnet amphibolite compositionally approach magnesio- or

ferro-hornblende, tschermakitic to pargasitic hornblende, and ferroan pargasite. The Ti/Al ratios of calcic amphiboles increase from ca. 0.01–0.02 for inclusions within garnet to ca. 0.04–0.05 in the matrix, suggesting decompression during amphibolite formation (Ernst and Liu, 1998). Plagioclase grains of amphibolites vary widely in their compositions, but are mostly andesine and labradorite. Reverse zoning with calcic rims is common in plagioclase. Hornblende-plagioclase symplectites are also common around garnet grains, and ilmenite typically contains relict rutile. These occurrences, together with compositional variations in amphibole and plagioclase, suggest a decompressional P-T evolution for the garnet amphibolites.

P-T conditions of garnet amphibolites from the Yeoncheon area were estimated using various geothermobarometers by Cho et al. (1995) and Ree et al. (1996). Their results suggest a P-T condition of 8–11 kbar and 630–740°C (Fig. 5). Moreover, when the compositions of rutile and ilmenite enclosed by garnet were used, the garnet-plagioclase-rutile-ilmenite-quartz geobarometer of Bohlen and Liotta (1986) yields a slightly higher pressure of

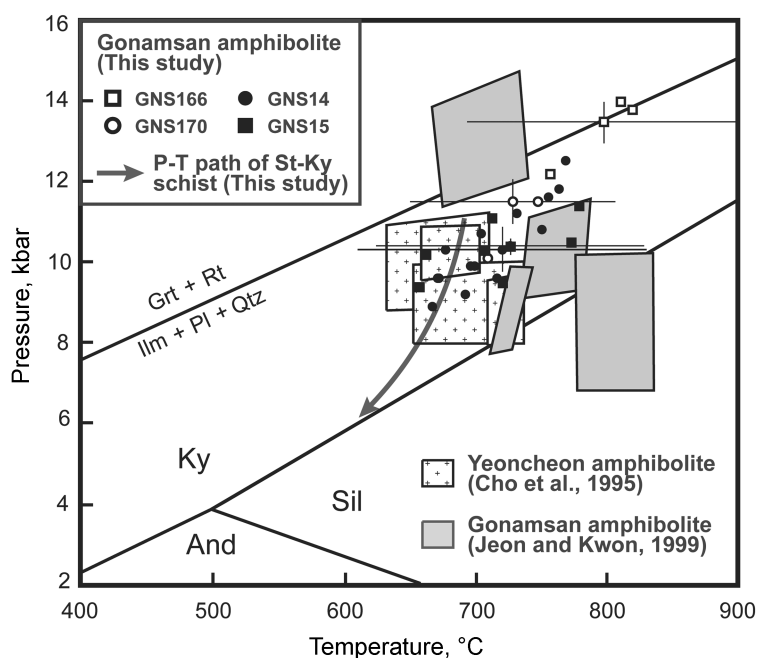


FIG. 5. P-T estimates from the Gonamsan amphibolites of this study are shown together with those of previous studies for the Yeoncheon and Gonamsan amphibolites (Cho et al., 1995; Jeon and Kwon, 1999). Error bars for the Gonamsan (GNS) samples are shown only for several data points for clarity. The equilibrium curve for the reaction, garnet + rutile = ilmenite + plagioclase + quartz, is derived using the analyzed compositions of each phase (Cho et al., 1995).

12.1–12.3 kbar at 700°C. Because rutile and ilmenite occur as relict phases mantled by titanite, this may represent higher pressure conditions than that recorded in the matrix of the garnet amphibolite.

Preliminary P-T conditions of 10–14 kbar and 700–790°C were reported from the Gonamsan area by Kim and Cho (1994) and Ree et al. (1996). However, no compositional and petrographical details were published. Representative compositions used for P-T calculations are given in Tables 4–6, and P-T estimates of four samples from the Gonamsan area are listed in Table 7. Metamorphic pressures and temperatures were calculated using the hornblende-garnet-plagioclase thermobarometry of Dale et al. (2000) that uses an independent set of four equilibria between end-members of garnet, hornblende, plagioclase, and quartz. These phase equilibria were calculated using the internally consistent thermodynamic data set of Holland and Powell (1998). Mineral assemblages of the analyzed samples consist of calcic amphibole + plagioclase + garnet + biotite + quartz ± epidote ± titanite. The majority of calcic amphiboles belong to an interme-

diate range of solid solutions between pargasite and tschermakite (Table 5). P-T estimates obtained from analyzed samples are in the range of 9–14 kbar and 660–820°C higher than that of the Yeoncheon area (Fig. 5). Similar P-T conditions of 8–11 kbar and 700–820°C were also estimated from the Gonamsan amphibolites by Jeon and Kwon (1999). They also suggested that the amphibolitic mylonites in the Gonamsan area experienced higher pressures of 9–13 kbar at 675–735°C (Fig. 5). Taken together, the metamorphic pressure and temperature of the Samgot unit appear to increase slightly eastward from 8–11 kbar and 630–740°C to 8–14 kbar and 675–820°C. Excluding one sample (GNS166), P-T estimates from both Yeoncheon and Gonamsan are in the range of 8.5–11.5 kbar and 660–780°C (Fig. 5). Hence, the Yeoncheon complex has experienced upper-amphibolite facies metamorphism at high pressures similar to those of eclogite facies. Moreover, the P-T estimates and the occurrence of relict rutile and the Ti/Al variations from core to rim of amphiboles suggest near-isothermal decompression in the Yeoncheon

TABLE 4. Representative Compositions of Garnet in Amphibolites

Sample:	GNS15		GNS14				GNS170			GNS166	
Point:	21	22	1	23	36	45	4	9	2	298	313
SiO ₂	37.84	37.95	38.13	37.73	37.78	37.91	37.48	37.26	37.54	38.53	38.64
Al ₂ O ₃	21.29	21.37	21.70	21.77	21.62	21.86	21.56	21.30	21.47	21.81	21.65
FeO ¹	26.88	27.52	24.82	27.15	27.26	26.91	26.23	26.48	26.10	24.60	25.69
MgO	3.69	3.33	4.75	4.38	4.81	5.09	3.00	2.75	3.01	4.48	3.85
MnO	0.55	0.56	0.36	0.65	0.60	0.49	1.98	1.80	2.11	0.10	0.19
CaO	9.74	9.80	9.61	8.27	7.92	7.83	10.09	10.21	10.34	9.77	9.89
Total	99.98	100.54	99.36	99.94	99.98	100.10	100.33	99.81	100.56	99.29	99.91
Cations per 12 oxygens											
Si	2.98	2.98	2.99	2.97	2.97	2.97	2.96	2.96	2.96	3.01	3.02
Al	1.98	1.98	2.00	2.02	2.00	2.02	2.01	2.00	1.99	2.01	1.99
Fe ²⁺	1.77	1.81	1.63	1.79	1.79	1.76	1.73	1.76	1.72	1.61	1.68
Mg	0.43	0.39	0.81	0.70	0.56	0.59	0.35	0.33	0.35	0.52	0.45
Mn	0.04	0.04	0.02	0.04	0.04	0.03	0.13	0.12	0.14	0.01	0.01
Ca	0.82	0.82	0.56	0.51	0.67	0.66	0.85	0.87	0.87	0.82	0.83
Total	8.02	8.01	8.01	8.02	8.03	8.03	8.04	8.04	8.04	7.98	7.98
Fe/(Fe+Mg)	0.80	0.82	0.67	0.72	0.76	0.75	0.83	0.84	0.83	0.76	0.79
Alm ²	0.58	0.59	0.54	0.59	0.59	0.58	0.56	0.57	0.56	0.54	0.57
Prp ²	0.14	0.13	0.27	0.23	0.18	0.20	0.11	0.11	0.11	0.18	0.15
Sps ²	0.01	0.01	0.09	0.01	0.01	0.01	0.04	0.04	0.05	0.00	0.00
Grs ²	0.27	0.27	0.18	0.17	0.22	0.22	0.28	0.28	0.28	0.28	0.28

¹Total Fe as FeO.²Alm = Fe/M; Prp = Mg/M; Sps = Mn/M; and Grs = Ca/M, where M = (Fe + Mg + Mn + Ca).

complex, and a possible evolution from a precursor eclogite-facies field.

Isotopic Ages and T-t Evolution

Geochronologic data available for the Imjingang belt are limited; consequently, protolith and metamorphic ages are poorly constrained. However, some recent studies using modern techniques (e.g., SHRIMP dating) provide relatively accurate and consistent isotopic ages. All available data are summarized below.

Protolith ages

The protolith ages of metasedimentary rocks in the Imjingang belt are difficult to determine in the absence of fossils, but can possibly be constrained from the emplacement age of amphibolites or the inherited zircon ages of metasedimentary rocks. Ree et al. (1996) analyzed nine amphibolites in the

Yeoncheon area and obtained a whole-rock Sm-Nd age of 824 ± 143 Ma. This errorchron date was interpreted to approximate the emplacement age of the Samgot amphibolite. Ree et al. (1996) also noted that the high $\epsilon_{\text{Nd}}(T)$ values of $+6.2 \pm 3.3$ estimated from the Samgot amphibolite are similar to those of depleted mantle at 824 Ma. This result is consistent with an oceanic setting of a basaltic protolith inferred from trace-element geochemistry. On the other hand, Cho et al. (2005) reported a SHRIMP U-Pb age of 861 ± 7 Ma dated from oscillatory-zoned, magmatic zircon grains in the Gonamsan amphibolite. It is thus likely that amphibolites originated as a result of Early Neoproterozoic magmatism in the Imjingang belt. As a corollary, sedimentary protoliths of the Samgot unit were apparently deposited prior to 860 Ma, inasmuch as amphibolites preserving rare chilled margins intrude calc-silicate rocks. These protoliths were possibly derived from sedimentary rocks of the

TABLE 5. Representative Compositions of Calcic Amphibole¹

Sample:	— GNS15 —		— GNS14 —		— GNS170 —			— GNS166 —			
Classification: ¹	Pfp	Fp	P	P	Fe	Hb	Fe	Paft	P	P	Afp
Point:	56	57	17	19	1	3	5	302	315	316	320
SiO ₂	38.50	39.72	42.98	40.71	42.68	41.73	43.53	42.97	42.59	43.40	41.52
TiO ₂	0.84	0.70	0.92	0.97	0.55	0.70	0.46	0.16	0.79	0.48	0.83
Al ₂ O ₃	16.09	13.93	13.43	15.50	12.52	13.64	11.95	15.57	14.13	14.63	16.02
FeO ²	19.51	20.02	14.72	15.61	18.96	19.66	18.48	17.03	15.45	16.24	16.42
MgO	7.37	7.67	10.67	9.37	8.45	7.89	9.15	8.40	9.96	9.37	8.66
MnO	0.13	0.17	0.00	0.07	0.33	0.31	0.29	0.04	0.00	0.03	0.01
CaO	11.06	10.99	11.67	11.32	10.76	10.50	10.43	9.32	11.17	11.56	11.30
Na ₂ O	1.50	1.50	1.49	1.56	1.68	1.88	1.56	1.20	1.33	1.49	1.43
K ₂ O	1.83	0.92	0.62	1.04	0.35	0.37	0.29	1.42	0.65	0.65	1.04
Total	96.83	95.63	96.51	96.14	96.26	96.68	96.14	96.11	96.06	97.85	97.22
Cations per 23 oxygens											
Si	5.90	6.12	6.40	6.14	6.48	6.33	6.56	6.44	6.37	6.40	6.19
Ti	0.10	0.08	0.10	0.11	0.06	0.08	0.05	0.02	0.09	0.05	0.09
Al	2.90	2.53	2.36	2.75	2.24	2.44	2.12	2.75	2.49	2.54	2.82
Fe ³⁺	0.49	0.61	0.23	0.27	0.35	0.41	0.44	0.24	0.33	0.22	0.25
Fe ²⁺	2.01	1.97	1.60	1.70	2.06	2.08	1.89	1.89	1.60	1.79	1.80
Mg	1.68	1.76	2.37	2.11	1.91	1.78	2.06	1.88	2.22	2.06	1.92
Mn	0.01	0.02	0.00	0.01	0.03	0.03	0.03	0.00	0.00	0.00	0.00
Ca	1.81	1.82	1.86	1.83	1.75	1.71	1.69	1.50	1.79	1.83	1.81
Na	0.45	0.45	0.43	0.46	0.49	0.55	0.46	0.35	0.39	0.42	0.41
K	0.36	0.18	0.12	0.20	0.07	0.07	0.06	0.27	0.12	0.12	0.20
Total	15.71	15.54	15.47	15.57	15.44	15.48	15.36	15.35	15.39	15.44	15.49
Na/(Na+K)	0.55	0.71	0.79	0.70	0.88	0.88	0.89	0.56	0.76	0.78	0.68
Fe/(Fe+Mg)	0.54	0.53	0.40	0.45	0.52	0.54	0.48	0.50	0.42	0.46	0.48

¹Classification of calcic amphiboles is based on Leake et al., 2004. Abbreviations: Pfp = potassian ferropargasite; Fp = ferropargasite; P = pargasite; Fe = ferroedenite; Hb = hornblende; Paft = potassian aluminoferrotschermakite; Afp = Paft and aluminoferropargasite.

²Fe³⁺ was recalculated using the method described by Dale et al., 2005.

Neoproterozoic Sangwon Supergroup, which are widespread along the northern boundary of the Imjingang belt. The geologic age of the Sangwon Supergroup has been recently confined to the Neoproterozoic, based on the discovery of bacterial microfossils in stromatolites at Socheong Island, westernmost South Korea (Fig. 1B; Lee S.-J. et al., 2003).

The timing of deposition of the Jingok unit is poorly constrained, but recent SHRIMP dating of detrital zircon grains (Cho et al., 2005) may provide constraints for the maximum depositional age. U-Pb ages of detrital zircon grains in a garnet-biotite paragneiss from the Gonamsan area are characterized by

two distinct populations at 447 ± 4 Ma and 397 ± 6 Ma, respectively. The latter probably constrains the depositional age of the Jingok unit to be younger than ~400 Ma. Thus, the protoliths of the Jingok unit most likely originated from the Devonian Imjin Group. This interpretation is consistent with the occurrence of staurolite-kyanite schists in both the Jingok unit and the upper Imjin Group of North Korea (Paek et al., 1996). However, Cho et al. (2005) suggested that the analyzed paragneiss is part of the Samgot unit, and consequently this unit would have been deposited later than ca. 400 Ma. Further mapping and radiometric dating are necessary to resolve these contrasting interpretations.

TABLE 6. Representative Compositions of Plagioclase in Amphibolites

Sample:	GNS15		GNS14		GNS170		GNS166	
Point:	66	67	49	50	8	17	4	6
SiO ₂	58.78	61.30	60.08	58.22	61.92	61.48	60.57	59.79
Al ₂ O ₃	25.53	24.12	24.78	25.98	23.09	23.74	24.46	24.36
CaO	7.31	5.40	6.06	7.49	4.80	5.01	5.67	5.91
Na ₂ O	7.57	8.73	8.69	7.64	9.29	8.92	8.52	8.51
K ₂ O	0.06	0.07	0.12	0.27	0.03	0.08	0.09	0.10
Total	99.26	99.62	99.73	99.60	99.13	99.22	99.31	98.66
Cations per 8 oxygens								
Si	2.64	2.73	2.68	2.62	2.77	2.75	2.71	2.70
Al	1.35	1.27	1.30	1.38	1.22	1.25	1.29	1.30
Ca	0.35	0.26	0.29	0.36	0.23	0.24	0.27	0.29
Na	0.66	0.75	0.75	0.67	0.81	0.77	0.74	0.74
K	0.00	0.00	0.01	0.02	0.00	0.00	0.01	0.01
Total	5.01	5.01	5.04	5.03	5.02	5.01	5.02	5.03
An ¹	0.35	0.25	0.28	0.35	0.22	0.24	0.27	0.28
Ab ¹	0.65	0.74	0.72	0.64	0.78	0.76	0.73	0.72
Or ¹	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01

¹An = Ca/M; Ab = Na/M; and Or = K/M, where M = (Ca + Na + K).

Peak metamorphic ages

The age of peak metamorphism in the Imjingang belt has been dated using various isotopic systems. From an amphibolite of the Yeoncheon area, Ree et al. (1996) dated mineral Sm-Nd and Rb-Sr ages (garnet + plagioclase + whole rock) at 249 ± 31 Ma and 222 ± 31 Ma, respectively. These ages were interpreted to be close to the metamorphic age, although the closure temperature of each isotopic system is uncertain. On the other hand, Jeon and Kwon (1999) reported a preliminary Sm-Nd mineral age of 263 ± 6 Ma from a garnet-biotite gneiss in the Gonamsan area. This Permian age is similar to the Th-U-Pb chemical age of monazite, dated at 255 ± 8 Ma from a kyanite-zone schist of the Jingok unit (Cho et al., 1996). More precise timing for peak metamorphism was provided by the SHRIMP U-Pb zircon age of metamorphic overgrowth, dated at 253 ± 2 Ma from a garnet-biotite gneiss in the Gonamsan area (Cho et al., 2005). All of these ages suggest that the peak metamorphism accompanying major contractional deformation took place during the Late Permian in the Yeoncheon complex.

Cooling and deformation ages

The K-Ar hornblende ages reported for the Samgot amphibolite by Ree et al. (1996) vary widely from 656 to 258 Ma, probably reflecting the heterogeneous distribution of excess Ar. Its presence was subsequently confirmed by the $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of several hornblende samples separated from the Samgot amphibolite. From two exceptional cases, the $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra of hornblende barely define plateau ages of about 230 Ma. Moreover, their $^{36}\text{Ar}/^{39}\text{Ar}$ isotope correlation ages suggest that regional cooling of the Samgot amphibolite through $\sim 500^\circ\text{C}$ occurred at $\sim 230 \pm 3$ and 223 ± 2 Ma. These cooling ages are consistent with an Rb-Sr muscovite age of 226 ± 1 Ma, dated from a mylonite in the Gyeonggi shear zone (Kim et al., 2000). Microstructures of quartz and feldspar in the mylonite further suggest that temperatures reached 500°C during ductile deformation in an extensional shear zone. Together with the growth of muscovite neoblasts in mylonites, this suggests that ductile shearing with a normal sense occurred during the Middle to Late Triassic (Kim et al., 2000). Moreover,

the NW-plunging lineations and top-down-to-the-north kinematics pervasive in the mylonites are also common in both the Samgot and Jingok units. This resemblance in structural patterns suggests that the timing for D_{n+1} in the Yeoncheon complex should be close to ~230–225 Ma.

Further evidence for Triassic cooling is provided by preliminary $^{40}\text{Ar}/^{39}\text{Ar}$ ages of muscovite and biotite separates from two kyanite-zone schists of the Jingok unit. In one sample, muscovite shows an internally discordant $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra, but its isotope correlation age is dated at ~205 Ma. On the other hand, biotite defines a plateau age of ~160 Ma, suggesting thermal influence from Jurassic granites which are widespread in the vicinity of the Imjingang belt. An older age component of biotite is preserved in another kyanite-bearing schist, where the biotite gave an isotope correlation age of 220 ± 1 Ma. It is thus apparent that this kyanite schist cooled relatively rapidly from ~500 to 300°C.

T-t evolution

Our preliminary $^{40}\text{Ar}/^{39}\text{Ar}$ age data together with available geochronologic data for the Imjingang belt are illustrated in a temperature-time diagram (Fig. 6). After peak metamorphism at about 660–780°C, both amphibolites and kyanite-zone schists experienced relatively rapid exhumation during the Triassic. Assuming closure temperatures of 500°C and 300°C for hornblende and biotite, respectively, the average cooling rate is estimated to be around or even greater than 15°C/Ma. Such rapid cooling is compatible with that reported from exhumation stages of orogenic belts such as the Dabie-Sulu belt (e.g., Hacker et al., 2000; Faure et al., 2003). Subsequently, thermal flux during the emplacement of the Jurassic granite has locally reequilibrated the $^{40}\text{Ar}/^{39}\text{Ar}$ systematics of biotite to produce a cooling age of ~160 Ma. The cooling history shown in Figure 6 is compatible with that reported for high-pressure blueschists and eclogites in the Dabie-Sulu belt.

Discussion

Tectonometamorphic evolution of the Imjingang belt

The Yeoncheon complex constitutes the southern part of E-W-trending Imjingang belt and consists of two lithotectonic units: (1) the metapelitic Jingok unit, and (2) the structurally underlying Samgot unit, which contains garnet amphibolites. The latter is underlain by Neoproterozoic Gamaksan meta-

TABLE 7. Average Pressures and Temperatures Calculated from the Gonamsan Amphibolites¹

Point numbers	avP	sdP	T	sdT
GNS15				
21-56-66	10.2	0.6	706	95
21-56-67	11.0	0.4	712	95
21-57-66	10.4	0.3	772	99
21-57-67	11.3	0.6	778	99
22-56-66	9.3	0.7	657	87
22-56-67	10.1	0.4	662	87
22-57-66	9.4	0.3	720	90
22-57-67	10.3	0.4	726	91
GNS14				
1-17-49	11.6	1.3	755	113
1-19-49	12.5	1.1	768	103
1-17-50	10.8	0.9	750	112
1-19-50	11.8	0.7	763	103
23-17-49	9.6	1.0	671	98
23-19-49	10.3	0.7	677	90
23-17-50	8.9	0.7	667	98
23-19-50	9.6	0.4	672	90
36-17-49	9.9	1.0	696	104
36-19-49	10.7	0.8	704	95
36-17-50	9.2	0.7	692	103
36-19-50	9.9	0.5	699	95
45-17-49	10.3	1.1	720	109
45-19-49	11.2	0.9	731	100
45-17-50	9.6	0.8	716	108
45-19-50	10.4	0.6	726	99
GNS170				
4-1-8	11.4	1.4	747	78
9-3-17	11.4	1.0	728	77
2-5-4	10.0	0.7	709	76
GNS166				
298-302-4	13.4	1.2	799	103
313-315-6	12.1	1.0	758	92
313-316-6	13.7	1.6	821	95
298-320-6	13.9	1.2	812	98

¹Numbers denote analytic points in Tables 4–6, used for P-T calculations.

granitoids which are variably deformed and represent mylonites to protomylonites of the Gyeonggi shear zone. SHRIMP U–Pb zircon ages (Cho et al., 2005) suggest that the protolith of the Jingok unit is likely to be identical to the Devonian Imjin Group reported in North Korea (Paek et al., 1996). Thus, any deformation event in the Yeoncheon complex should be younger than ~350 Ma. Kinematic indicators document early thrust movement followed by

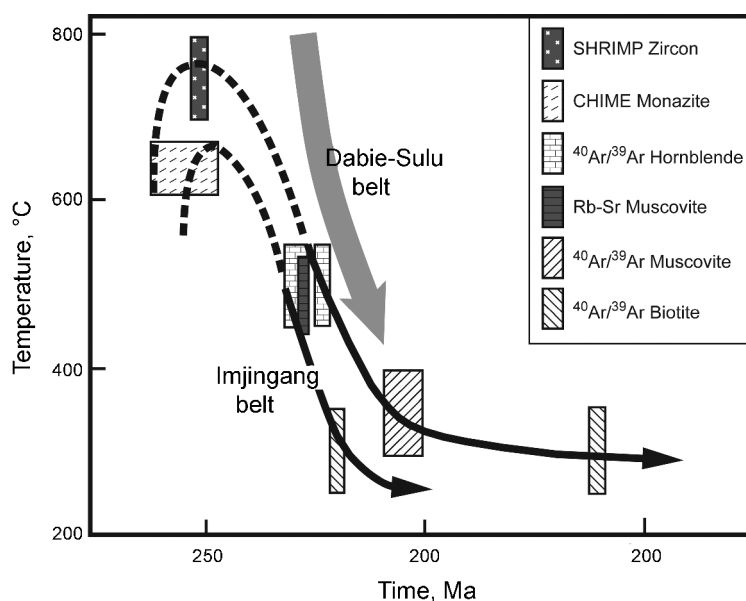


FIG. 6. A diagram showing the temperature-time (T-t) evolution of the Imjingang belt. Also shown for comparison is a schematic T-t path of the UHP rocks from the Dabie-Sulu belt (Zhang et al., 1994; Faure et al., 2003). Collisional orogeny in the Imjingang belt apparently preceded the Chinese orogeny by 20–30 m.y.

normal shearing and faulting in the Yeoncheon complex (Ree et al., 1996). The normal-sense movement characterized by top-down-to-the-north ductile shearing is predominant not only in the Gyeonggi shear zone, but also in the Samgot unit. Ductile deformation producing muscovite neoblasts in the Gamaksan mylonites was dated at ~226 Ma (Kim et al., 2000), which is consistent with $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 230–225 Ma recorded in hornblendes of garnet amphibolites.

The tectonometamorphic evolution of the Yeoncheon complex is represented by a clockwise P-T-time path, as shown in Figure 5. Both garnet amphibolites and staurolite-kyanite schists give pressures greater than 10 kbar at temperatures of ~750°C and 680°C, respectively. This HP condition is most likely the result of crustal thickening associated with collisional orogenesis. The timing of peak metamorphism was ~250 Ma, as verified by various isotopic systems including the SHRIMP zircon age. Synkinematic growth of garnet further suggests that the contractional deformation resulted from this Permo-Triassic tectonometamorphic event. Ductile deformation of feldspar and hornblende is apparent in strongly sheared amphibolites, implying that these garnet amphibolites were tectonically

exhumed from depths where temperatures exceeded 500–600°C. Moreover, based on the temperature-time relationship in Figure 6, the exhumation probably occurred rapidly at a rate of ~1–2 mm/yr during the Early to Middle Triassic. In summary, ductile extension in association with the Gyeonggi shear zone occurred within 20–30 m.y. of thrust displacement involving the Devonian strata in the Imjingang belt. This structural-temporal relationship is similar to that reported from Himalayan-type orogen (e.g., Liou et al., 2004) and favors gravitational collapse of a tectonically thickened crust. The extensional stress regime continued to produce an array of small transtensional basins along the Gyeonggi shear zone, consisting of molasse-type sedimentary sequences of the Daedong Group.

Continuation of the Sulu UHP belt into the Korean Peninsula

The occurrence of Devonian sequences is unique for the Imjin Group, because no correlative of this group is exposed in the Shandong Peninsula across the Yellow Sea. Moreover, two large Paleozoic basins in the Korean Peninsula, the Pyeongnam and Taebaeksan basins, are devoid of these middle Paleozoic strata (Chough et al., 2000). The absence

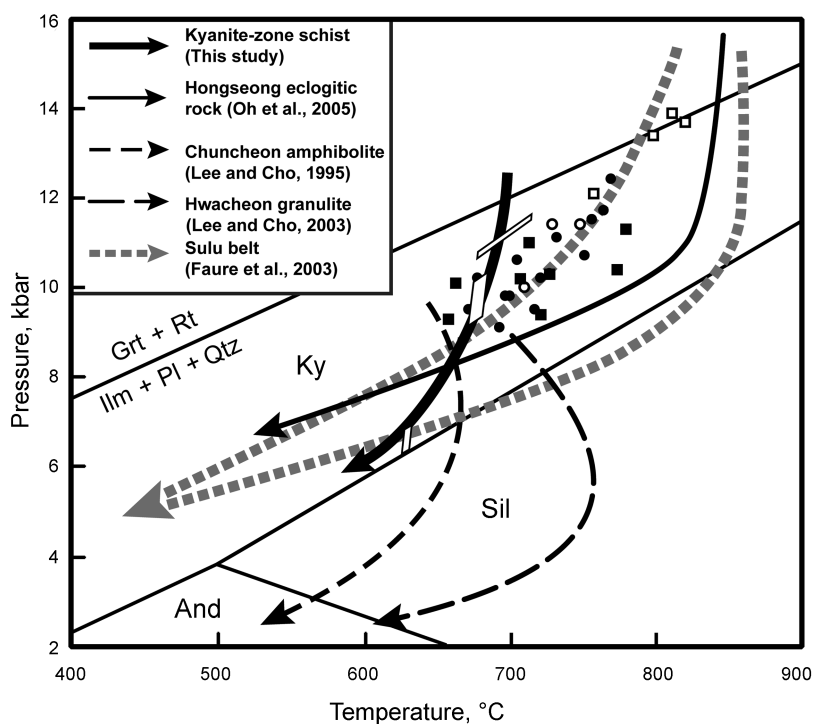


FIG. 7. A compilation showing various P-T-t paths of the Imjingang belt (this study), the Gyeonggi Massif (Lee S. R. and Cho, 1995; Lee S. R. and Cho, 2003; Oh et al., 2005), and the Dabie-Sulu belt (Hacker et al., 2000; Faure et al., 2003). Three boxes defining the P-T-t path of this study represent the P-T estimates from single kyanite-zone schist in Figure 4. Other symbols denoting the P-T estimates of garnet amphibolites are the same as those of Figure 5.

of Silurian–Devonian sequences is characteristic of the Sino-Korean craton; consequently, the Imjingang belt belongs to the South China craton. In addition, the U-Pb zircon ages of detrital components or inherited cores indicate the presence of Late Ordovician and Early Devonian age populations in the Imjingang belt (Cho et al., 2005). These data in conjunction with ~850–750 Ma magmatism corroborate the South China affinity of the Imjingang belt because the Neoproterozoic ages are common for the protoliths of eclogites and gneisses in the Sulu and Dabie belts (e.g., Hacker et al., 1998; Zheng et al., 2004). Thus, the extension of the Sulu belt into the Korean Peninsula is likely, but details on tectonic correlations may be subject to large uncertainties in the absence of ophiolites, eclogites, or UHP rocks on the Korean side. Nevertheless, as described below, P-T-t relations suggest that both the Imjingang belt and the Gyeonggi Massif experienced similar tectonometamorphism during the Permo-Triassic continental collision.

The P-T-t paths reported from the Gyeonggi Massif are comparable to those of metapelites and amphibolites in the Imjingang belt (Fig. 7). Figure 7 shows two P-T-t paths representative of the basement and supracrustal rocks in the Gyeonggi Massif (i.e., the Hwacheon granulites and Chuncheon amphibolites, respectively; see Fig. 1B for locations). Near-isothermal, clockwise P-T-t paths are characteristic for both terranes, indicating that thick-skinned crustal reworking has occurred in the Gyeonggi Massif. The timing of isothermal decompression is best estimated to be Triassic (Lee and Cho, 2003). Furthermore, the cooling through ~300°C is dated at ~210 Ma for the Chuncheon amphibolite (Lee S. R. and Cho, 1995). The clockwise P-T-t path is corroborated by the occurrences of relict kyanite throughout the Gyeonggi Massif (Lee K. J. and Cho, 1992; Cho and Kim, 1993; Ahn et al., 1998; Lee S. R. and Cho, 2003). Thus, high- to medium-pressure conditions were attained prior to widespread low-P/high-T metamorphism

resulting in sillimanite and cordierite-bearing assemblages in the Gyeonggi Massif.

Finally, Figure 7 shows another P–T path from the Hongseong area, Gyeonggi Massif, where Oh et al. (2005) recently reported the presence of relict omphacite inclusions in garnet porphyroblasts from mafic granulite. This “eclogitic” granulite was dated at 231 ± 3 Ma by Zhai and Guo (2005), who confirmed the Triassic high-P metamorphism based on SHRIMP zircon U–Pb ages. Thus, the P–T path of the Hongseong area is remarkably consistent with that of the Sulu belt (e.g., Faure et al., 2003) and compatible with P–T estimates from the Imjingang belt. This similarity in P–T–t relations does not support the suggestion of Oh et al. (2005) that the Hongseong area is a probable extension of the Sulu belt as opposed to the Imjingang belt. Instead, both the Imjingang belt and the Gyeonggi Massif probably represent deep burial during the Triassic collision. Local variation in terms of peak metamorphic conditions may be attributed at least partially to different degrees of retrogression or recrystallization following peak-pressure metamorphism. However, further geochronologic studies are necessary to understand tectonic implications of the apparent ~20 m.y. discrepancy in the timing of peak metamorphism between the Imjingang belt and the western Gyeonggi Massif. It is also noted from the quartz-vein assemblage that retrogression to lower temperatures probably crosses the kyanite-andalusite curve in the Imjingang belt (Fig. 7). A similar path is also apparent for the Hongseong area and the Sulu belt. The apparent near-isobaric cooling at mid-crustal depths contrasts with near-isothermal decompression at high temperatures, which produced sillimanite or cordierite-bearing assemblages in the eastern Gyeonggi Massif (Fig. 7). The contrasting cooling path during the Triassic exhumation event suggests that the Imjingang belt and the western Gyeonggi Massif likely resided at deeper levels than the eastern Gyeonggi Massif.

Conclusions

Petrologic and geochronologic data available in the Yeoncheon complex suggest that the southern Imjingang belt experienced a clockwise P–T–t path during the Permo-Triassic collisional orogeny. P–T conditions estimated from metapelites suggest that metamorphic temperatures and pressures apparently increase from ~450–550°C and 8 kbar in the

garnet zone to ~600–700°C and 11 kbar in the kyanite zone. Moreover, based on P–T estimates from inclusion vs. matrix assemblages and pseudosection analyses of mineral parageneses, clockwise P–T–t path is defined for metapelites of the kyanite zone. Similarly, P–T conditions calculated from garnet amphibolites are in the range of 8–14 kbar and 630–820°C. This wide range could be attributed to variable degree of partial retrogression during the exhumation, eradicating high-pressure minerals. The timing of peak metamorphism is estimated at ~250 Ma, whereas near-isothermal decompression is dated at 230–220 Ma. Thus, the Imjingang orogen was thickened during the latest Permian, and gravitationally collapsed, resulting in rapid cooling during the Triassic exhumation.

Metamorphic evolution of the southern Imjingang belt described above is compatible with a variety of clockwise P–T–t paths documented from the basement and supracrustal rocks in the Gyeonggi Massif. Collisional orogenesis prevailed in both the Imjingang belt and Gyeonggi Massif, but its extent and the maximum depth of descent remain to be solved. However, our result strongly suggests that Permo-Triassic crustal thickening in the Imjingang belt was closely linked to the continental collision in east-central China. Thus, in conjunction with the recent finding of “eclogitic” granulite-amphibolite in the Gyeonggi massif (Cho, 2003; Oh et al., 2005), we conclude that the Dabie-Sulu belt extends into the Korean Peninsula as the Imjingang belt and Gyeonggi Massif, together with the Ogcheon belt (Cho and Kim, 2005). Thus, eastward extension of the Dabie-Sulu belt through the Korean Peninsula (Ernst and Liou, 1995) remains a valid hypothesis.

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